EUROPEAN COMMISSION

SCIENCE
RESEARCH
DEVELOPMENT

THIRD EUROPEAN MARINE SCIENCE AND TECHNOLOGY CONFERENCE

Lisbon, 23-27 May 1998

PROJECT SYNOPSES
Volume II:
Strategic Marine Research

EUROPEAN COMMISSION

Edith CRESSON, Member of the Commission
responsible for research, innovation, education, training and youth.

DG XII/D-03 - Marine Science and Technology

Contact: Mr. K-G. Barthel - rue de la Loi, 200 (SDME 07/83), B-1049 Brussels
Tel: (32-2) 295 12 42 - Fax (32-2) 296 30 24 E-mail: klaus-guenther.barthel@dg12.cec.be

European Commission

THIRD EUROPEAN MARINE SCIENCE AND TECHNOLOGY CONFERENCE

Lisbon, 23-27 May 1998

Edited by
K.-G. Barthel, H. Barth, M. Bohle-Carbonell, C. Fragakis,
E. Lipiatou, P. Martin, G. Ollier, M. Weydert

PROJECT SYNOPSES

Volume II: Strategic Marine Research

EUR 18220 EN

Published by the EUROPEAN COMMISSION
Directorate-General XII – Science, Research and Development

LEGAL NOTICE: Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use which might be made of the following information.

A great deal of additional information on the European Union is available on the Internet.
It can be accessed through the Europa server (http://europa.eu.int).

Cataloguing data can be found at the end of this publication.

Luxembourg: Office for Official Publications of the European Communities, 1998

ISBN 92-828-2896-4 (Volumes I to VI)
ISBN 92-828-3035-7 (Volume II)

© European Communities, 1998
Reproduction is authorised provided the source is acknowledged.

Printed in Italy

PREFACE

In 1993 and 1995, MAST, the Marine Science and Technology Programme of the European Union, managed by Directorate General XII (Science, Research and Development) of the European Commission, and EUROMAR, a marine technology "umbrella" within the framework of the EUREKA initiative, organised the first 2 sessions of the so-called "MAST Days and EUROMAR Market". It would have been unthinkable not to plan a third edition in Lisbon on the occasion of the International Year of the Oceans. By and large, public awareness of the oceans as a major controlling factor of mankind's future seems to be growing, but there remains much to be done for promoting marine research and international co-ordination on this matter. The time has come to present a more complete view of research efforts carried out and co-ordinated on a European scale. Therefore, other actors have joined MAST and EUROMAR in organising the Lisbon conference: Directorate General XIV (Fisheries) of the European Commission, the Environment and Climate Programme in DG XII, and the secretariat of the European Marine and Polar Science (EMaPS) Boards. Hence the change of denomination to: Third "European Marine Science and Technology Conference"[1].

MAST dates back to 1989. The present programme, MAST-III, will terminate at the end of this year; its budget was 244 million ECU, a five-fold increase compared to MAST-I. The ultimate objective of research is to understand the functioning of marine systems around Europe, both in shelf and deep seas, and thus to help establishing the scientific and technical basis for their exploitation, management and protection.

Fisheries and aquaculture research was initiated at European Community level in 1988 and has taken since then several denominations: FAR 1988-92, AIR 1990-94, and now FAIR 1994-98. The programmes concentrated on the promotion of research in support of the Common Fisheries Policy, dealing with fisheries management, aquaculture, product development and, more recently, the interactions between fisheries, aquaculture and the marine environment.

The Environment research programmes of the 1970's and 80's already addressed issues of marine pollution and ecotoxicology. These topics have remained on the agenda of successor programmes: STEP (1989-92), Environment (1990-94) and the current Environment and Climate Programme (1994-98). Due to an obvious risk of overlap with MAST in the coastal zone, both programmes are co-operating on the management of projects on coastal ecosystems, in conformity with the so-called ELOISE science plan. Finally, the Environment and Climate Programme also supports some marine research, especially in sub-arctic seas, through climate-oriented projects.

By contrast with the EU programmes outlined above, EUROMAR is industry-led. Launched in 1986, it deals with the development, application and successful exploitation of Europe's advanced marine technology and tends to operate closer to the market than MAST. In recent years, it has become apparent that the scheme needs some adaptation to changing conditions in Europe and in the world. EUROMAR looks set to evolve into a form of network of manufacturers, research institutes and end-users.

---

[1] A really complete overview of marine and maritime research supported by the EU should include activities on renewable energies and industrial and material technologies managed by DG XII, as well as marine related activities in DG XVII (ENERGY), DG VII (TRANSPORT) and the Joint Research Centre (JRC) of the European Commission.

The European Marine and Polar Science (EMaPS) Boards were established in 1995 under the auspices of the European Science Foundation (ESF), and are served by a permanent secretariat hosted by ESF in Strasbourg. The boards are intended to improve co-ordination between European organisations in marine and polar science and seek to develop scientific strategies. The boards and the secretariat are also active in facilitating the implementation of scientific challenges of the future. In many ways, the roles of EMaPS and of the Commission can be seen as complementary and it is therefore natural that both bodies should co-operate closely.

As this preface is being written, the procedure leading to the adoption of the EU Fifth Framework Programme for the period 1998-2002 is under way. EU research ministers have agreed on the structure of FP5: it departs radically from that of its predecessors. In the place of the current so-called "specific" programmes, such as MAST, FAIR, Environment and Climate, we have a structure dominated by "key actions", e.g., for what relates to marine research: "global change, climate and biodiversity", "sustainable marine ecosystems", "sustainable agriculture, fisheries and forestry", "land transport and marine technologies". The novelty of the approach seems obvious, not least because it focuses on problems instead of processes, and stresses the need that the scientific community address socio-economic issues in preparing projects and implementing research.

This conference must therefore serve a dual purpose: to review the past decade of European marine research programmes, and to pave the way for future developments in this domain. All colleagues from the Commission, EMaPS and EUROMAR have to be thanked who joined their efforts in preparing such an outstanding blend of scientific sessions and discussion meetings. While it is left to the conference proceedings to capture the flavour of the discussions held at Lisbon, the project synopses presented here record the state of integration reached in recent years by the community of marine scientists in Europe.

Brussels, in March 1998

Jean Boissonnas
Marine Science and Technology

Willem Brugge
Fisheries and Aquaculture

TABLE OF CONTENTS (Volumes I - VI) Page

Foreword III

Table of contents V

Volume I Marine Systems 1

I.1. Marine systems research 1

I.1.1. Circulation and exchange of water masses 3

Observations and modelling of eddy scale geostrophic and ageostrophic circulation (OMEGA) 5

Climatic variability of Mediterranean paleo-circulation (CLIVAMP) 23

Tracing the water masses of the North Atlantic and the Mediterranean (TRACMASS) 25

Demonstrator for interoperability of oceanographic catalogs (DINOCAT) 33

I.1.2. Integrated ecosystem studies 37

Impact of a climatic gradient on the physiological ecology of a pelagic crustacean (PEP) 39

Microbial ecosystem dynamics (MEDEA) 49

Trans-Atlantic study of *Calanus finmarchicus* (TASC) 61

Ocean colour for the determination of water column biological processes (BIOCOLOR) 77

Dissemination and exploitation of a coupled hydrodynamical-ecological model for regional and shelf seas (COHERENS) 85

Effect of nutrient ratios on harmful phytoplankton and their toxin production (NUTOX) 99

Molecular ecology of the photosynthetic procaryote *Prochlorococcus*, a key organism of oceanic ecosystems (PROMOLEC) 105

Processes of vertical exchange in shelf seas (PROVESS) 117

The impact of appendicularians in European marine ecosystems (EURAPP) 131

Ecological effects of protection in Mediterranean marine reserves (ECOMARE) 139

I.1.3. Marine biodiversity 151

Biodiversity and genetics of algal populations BIOGAP 153

Maerl biodiversity, functional structure and anthropogenic impacts (BIOMAERL) 169

Integrating environmental and population variation: A model for biodiversity studies (AMBIOS) 179

Microbial diversity in aquatic ecosystems (MIDAS) 195

A register of marine species in Europe to facilitate marine biodiversity research and management 199

I.1.4. Processes and fluxes across the air/sea interface 207

Marine ecosystems regulation: Trace metals and carbon dioxide limitations (MERLIM) 209

ASGAMAGE, the ASGASEX MAGE experiment (ASGAMAGE) 211

I.1.5. Fluxes across the water/sediment interface 223

Hydrothermal fluxes and biological production in the Aegean (AG-HY-FL) 225

I.1.6. Sedimentary processes 227

European North Atlantic Margin : Quantification and modelling of large-scale sedimentary processes and fluxes (ENAM II) 229

Coring stable and instable realms in European seas (CORSAIRES) 239

Silicon cycling in the world ocean: The controls for opal preservation in the sediment as derived from observations and modelling (SINOPS) 253

Making seismic reflection profiles available to the wider scientific community: SEISCAN - Capturing a European legacy (SEISCAN) 265

I.2. Extreme marine environments 269

I.2.1. The deep sea floor 269

High resolution temporal and spatial study of the benthic biology and geochemistry of a north-eastern Atlantic abyssal locality (BENGAL) 271

Azores mid-oceanic ridge ecosystem studies: An integrated research programme on deep-sea hydrothermal transfers and fluxes (AMORES) 287

Sapropels and palaeoceanography : Palaeoceanographic, palaeoclimatic, palaeoenvironmental and diagenetic aspects of sapropel formation in the Eastern Mediterranean (SAP) 303

I.2.2. The ice-covered seas 313

Local ice cover deformation and mesoscale ice dynamics (ICE STATE) 315

European subpolar ocean programme phase 2: The thermohaline circulation in the Greenland Sea (ESOP 2) 329

Variability of exchanges in the northern seas (VEINS) 345

Baltic Air-Sea-Ice Study (BASIS) 353

I.2.3. The surf and swash zone 359

Interactions of physical and biological factors in the surf and swash zone of European rocky shores (EUROROCK) 361

Assessing the biological and physical dynamics of intertidal sediment systems: A remote sensing approach (BIOPTIS) 377

I.3. Regional seas research 391

I.3.1. The Mediterranean Sea 391

Mediterranean Targeted Project II: Mass transfer and ecosystem response (MTPII-MATER) 393

I.3.2. The Baltic Sea 413

Baltic Sea System Study (BASYS) 415

I.3.3. The Canary-Azores region and the Alboran Sea (Strait of Gibraltar) 431

Canary Islands Açores Gibraltar Observation (CANIGO) 433

I.3.4. The north-eastern Atlantic continental margin 449

Ocean Margin EXchange II - Phase I (OMEX II-I) 451

Ocean Margin EXchange II - Phase II (OMEX II-II) 469

Index of contact persons (Volumes I - IV)

Index of contracts (Volumes I - IV)

Volume II Strategic Marine Research 483

II.1. Coastal and shelf seas research 485

II.1.1. Coastal processes and morphodynamics 485

Prediction of aggregated-scale coastal evolution (PACE) 487

The kinematics and dynamics of wave-current interactions (KADWCI) 503

The morphological development of intertidal mudflats (INTRMUD) 521

Pre-operational modelling in the seas of Europe (PROMISE) 533

Coastal sediment transport assessment using SAR imagery (C-STAR) 549

Fluxes across narrow shelves: The Ebro delta case (FANS) 561

Surf and swash zone mechanics (SASME) 575

Prediction of cohesive sediment transport and bed dynamics in estuaries and coastal zones with integrated numerical simulation models (COSINUS) 585

Coastal study of three-dimensional sand transport processes and morphodynamics (COAST-3D) 591

Inlet dynamics initiative: Algarve (INDIA) 601

Sediment transport modelling in marine coastal environments (SEDMOC) 611

II.1.2 Structure and dynamics of shelf ecosystems 619

Biogas transfer in estuaries (BIOGEST) 621

Environmental cycling of selected persistent organic pollutants (POPs) in the Baltic Region (POPCYCLING) 633

Integrated management methods: Monitoring environmental change in coastal dune ecosystems (DUNES) 641

The eco-metabolism of estuarine intertidal flat (ECOFLAT) 655

Biogeochemistry of an acidic and metal-rich river-estuary system: Rio Tinto and Odiel, Ria Huelva and Gulf of Cadiz, south-west Spain (TOROS) 669

The role of buffering capacities in stabilising coastal lagoon ecosystems (ROBUST) 687

Biogeochemical interactions between the Danube river and the north-western Black Sea (EROS-21) 703

European salt marsh modelling (EUROSSAM) 715

Atmospheric nitrogen inputs into the coastal ecosystem (ANICE) 721

Baltic Sea cyanobacteria (BASIC) 727

Influence of rising sea level on ecosystem dynamics of salt marshes (ISLED) 741

Effects of climate induced temperature change on marine coastal fishes (CLICOFI) 747

Assessing the consequences of global changes for the Barents Sea region : The Barents Sea impact study (BASIS) 757

Changes in bacterial diversity and waters as affected by eutrophication (CHABADA) 763

Nitrogen cycling in estuaries (NICE) 779

Dynamic of matter transfer and biogeochemical cycles: Their modelling in coastal systems of the Mediterranean Sea (METRO-MED) 795

Entangled sulfur and carbon cycles in *Phaeocystis* dominated ecosystems (ESCAPE) 811

Comparative analysis of food webs based on flow networks: Effects of nutrient supply on structure and function of coastal plankton communities (COMWEB) 823

Physical forcing and biogeochemical fluxes in shallow coastal ecosystems (PHASE) 835

Marine Monitoring System 2000+ (MMS 2000+) 851

Feed-backs of estuarine circulation and transport of sediments on phytobenthos (F-ECTS) 859

Key coastal processes in the mesotrophic Skagerrak and the oligotrophic Northern Aegean: A comparative study (KEYCOP) 865

Importance of dissolved organic matter from terrestrial sources for the production, community structure and toxicity of phytoplankton of the European Atlantic and Baltic coastal waters; role of micropredators for transmission of toxins to commercial shellfish and fish larvae (DOMTOX) 867

Effects of eutrophicated seawater on rocky shore ecosystems studied in large littoral mesocosms (EULIT) 871

Long-term changes in Baltic algal species and ecosystems (BIOBASE) 877

II.1.3. Methods for monitoring, forecasting and management of shelf seas and coastal zones 881

Mesoscale Ocean Radar Signature Experiments (MORSE) 883

Coastal region long-term measurements for colour remote sensing development and validation (COLORS) 901

Operational modelling for coastal zone management (OPCOM) 907

A user-friendly tool for the evaluation of wave conditions at any European coastal location (EUROWAVES) 911

Testing monitoring systems for risk assessment of harmful introductions by ships to European waters 919

II.2. Coastal Engineering and Natural Defenses 929

II.2.1. Coastal structures 929

Performance of soft beach systems and nourishment measures for European coasts (SAFE) 931

Probabilistic design tools for vertical breakwaters (PROVERBS) 945

Scour around coastal structures (SCARCOST) 963

Validation of low-level ice forces on coastal structures (LOLEIF) 973

The optimisation of crest level design of sloping coastal structures through prototype monitoring and modelling (OPTICREST) 987

II.2.2. Remote sensing 995

Establishment of an airborne geoid mapping system for coastal oceanography (AGMASCO) 997

Volume III Generic Technologies 1007

III.1.1. Non-disturbing techniques 1009

Broadband acoustic scattering signatures of fish and zooplankton (BASS) 1011

Automated identification and characterization of marine microbial populations (AIMS) 1027

Sediment identification for geotechnics by marine acoustics (SIGMA) 1037

Transmission of electromagnetic waves through sea water for imaging parameter measuring and communications (DEBYE) 1045

Improved microstructure measurement technologies for marine near surface flux studies (MITEC) 1057

Applications of 3-dimensional electromagnetic induction by sources in the ocean (ISO-2D) 1069

Automatic diatom identification and classification (ADIAC) 1071

III.1.2. Underwater communication and orientation 1075

Propagation channel simulator (PROSIM) 1077

The development of a hydro-mechanical, multi-sensor towed undulating oceanographic vehicle for deployment from Ships-of-Opportunity (HYTOV) 1095

Long range telemetry in ultra-shallow channels (LOTUS) 1109

Shallow water acoustic network (SWAN) 1121

Long range shallow water robust acoustic communication links (ROBLINKS) 1133

III.1.3. Underwater viewing 1137

Detection of embedded objects (DEO) 1139

Three-dimensional sediment transport measurements by acoustics (TRIDISMA) 1155

Sonar technology for monitoring and assessment of benthic communities (BIOSONAR) 1171

The remote detection of sediment instability on the European continental margin and slope (POSEIDON) 1183

High resolution in *situ* holographic recording and analysis of marine organisms and particles (HOLOMAR) 1197

III.1.4. Marine biotechnology 1213

Bioactive marine natural products in the field of antitumoral, antiviral and immunomodulatory activity 1215

Microorganisms in deep sea vents and marine hot springs as sources of potentially valuable chemicals 1231

Marine bacterial genes and isolates as sources for novel biotechnological products (MARGENES) 1245

Biology of sponge natural products (SYMBIOSPONGE) 1253

Marine cyanobacteria as a source for bioactive (apoptosis-modifying) compounds with potential as cell biology reagents and drugs (CYANODRUGS) 1267

III.1.5. Submarine geotechnics 1273

Integrated system for analysis and characterization of the seafloor (ISACS) 1275

Characterization and observation of the seafloor with a new multi-beam front-scan sonar system (COSMOS) 1287

Grouted offshore piles for alternating loadings (GOPAL) 1299

Very high resolution marine 3D seismic method for detailed site investigation (VHR3D) 1301

Volume IV Advanced Systems 1317

III.2.1. Unmanned platforms and autonomous systems 1319

Geophysical and oceanographic station for abyssal research (GEOSTAR) 1321

Autonomous lander instrument platforms for oceanographic research (ALIPOR) 1335

Advanced manipulation for deep underwater sampling, Phase II (AMADEUS) 1347

Miniaturized and reconfigurable instrumentation for multipurpose survey with a mini autonomous underwater vehicle (MAUVE) 1367

A novel microsensor for measurement of liquid flow and diffusivity (MICRO-FLOW) 1381

Advanced ROV package for automatic mobile inspection of sediments (ARAMIS) 1391

A universal docking-downloading-recharging system for AUVs (EURODOCKER) 1403

Lightweight composite pressure housings for mid-water and benthic applications 1411

Advanced system integration for managing the coordinated operation of robotic ocean vehicles (ASIMOV) 1413

YOYO 2001: Ocean Odyssey (YOYO 2001) 1429

III.2.2. Oceanographic measurement and sampling equipment 1433

Operational modelling for regional seas and coastal waters (OPMOD) 1435

Electroanalytical instrumentation development for physico-chemical characterizations of trace metals in the marine environment (ELANI) 1443

Instrumentation for marine carbon dioxide measurements from remote platforms (IMCORP) 1459

Biofouling reduction on optical systems (BROS) 1471

Development of microsensors for use in the marine environment (MICROMARE) 1487

Upgrading flow cytometry for buoy mounted operation: First experimental implementation (CYTOBUOY) 1499

Voltammetric autonomous measuring probes for trace metals in the water column (500m, max.depth) and at water-sediment interfaces (6000m, max.depth) (VAMP) 1513

Gas hydrate autoclave coring equipment system (HYACE) 1529

Micro analytical system for total organic carbon in sea water (MASTOC) 1541

Trace metal monitoring in surface marine waters and estuaries (MEMOSEA) 1547

Ocean tomography operational and utilization support (OCTOPUS) 1553

Spectroscopy using optical fibers in the marine environment (SOFIE) 1559

III.2.3. Biosensors 1565

Biomarkers in marine sponges: Molecular approaches to assess pollutional risks and ecosystem health in the ocean to support management for its sust ainable use (BIOMARK) 1567

Volume V Fisheries and Aquaculture (AIR: 1990 - 1994)

Aquaculture 12

New in vitro approaches for fish protection in aquaculture: Application of cell and tissue cultures for pathogen detection and for development of vaccines (AIR1-CT92-36) 12

The development of a non physical fish fence system using combined infrasonic and electric fields (AIR1-CT92-113) 19

Assessment of aquacultural advantages following the cytogenetic induction of polyploids in commercially important shellfish (AIR1-CT92-168) 22

Improvement of the nutritional value, growth and resistance to stress of eels and sturgeon by controlling dietary lipids and conditions during intensive aquaculture (AIR1-CT92-186) 28

Microalgae biomass from photobioreactors as food fish and shellfish larvae (AIR1-CT92-286) 33

The development of new management strategies for desease control of commercially farmed fish (AIR1-CT92-308) 36

Improved identification and detection methods for fish pathogenic vibrio species (AIR1-CT92-341) 40

An aromatic dependent mutant of Aeromonas Salmonicida as a live vaccine for Furunculosis in Salmonid fish. Studies on the immune response of vaccinated fish and on the fate of bacteria after vaccination both in the vaccinated host and in the environment (AIR1-CT92-441) 43

The development of sensitive methods for detection of, and the optimisation of administration and determination of residue kinetics of therapeutic chemicals farmed salmonids (AIR1-CT92-642) 45

Fat deposition in farmed rainbow trout and European sea bass: nutritional control and gene expression of lipogenic enzymes (AIR2-CT93-801) 47

Neuroendocrine regulation of reproduction and induced breeding in the Mediterranean yellowtail (Seriola dumerilii, Risso 1810) AIR2-CT93-817 52

The interactions between hydrodynamics and dissolved oxygen concentration on fish health in intensive mariculture (AIR2-CT94-855) 58

Egg quality determinants in teleost fish (AIR2-CT93-1005) 62

Salmon mucosal immune system (AIR2-CT93-1055) 64

Development of a louse vaccine for salmon culture (AIR2-CT93-1079) 68

Fish protection in aquaculture: improvement of vaccine efficacy by studying stimulation of the fish immune response (AIR2-CT94-1334) 70

Effect of broodstock management and broodstock nutrition on quality of turbot Scophtalmus maximus production (AIR2-CT93-1449) 72

The role of thyroid hormones and their receptors in development and growth of the sea bream (AIR2-CT93-1483) 78

Development of DNA probes to determine the genetic sex in aquacultured fish species (AIR2-CT93-1543) 81

Studies of proliferative kidney disease with particular reference to prophylaxis and geographical distribution in Europe (AIR2-CT93-1570) 86

Sexual cycles and growth performance in the common sea-bream, Pargus pargus, in rearing conditions : Applications to spawners breeding and spawning induction (AIR2-CT93-1589) 89

Oral delivery of chemotherapeutics in marine larviculture of fish. Phase II: Optimization and applications (AIR2-CT93-1600) 93

Hygiene management and disease prevention in marine fish larviculture, by the adjustment and control of the microbiological environment (AIR2-CT94-1601) 97

Scallop sea bed cultivation in Europe (AIR2-CT93-1647) 101

Immunohistochemistry for research on diagnosis and pathogenesis on viral haemorrhagic septicaemia (VHS) virus infection (AIR2-CT93-1756) 106

Improved identification and taxonomy of atypical isolates of the fish pathogen Aeromonas salmonicida (AIR3-CT94-1884) 110

A comprehensive genetic study of cultured and wild stocks of gilthead sea-bream, Sparus aurata, and genetic assessment of several related species as candidates for aquaculture (AIR3-CT94-1926) 114

Utilisation of copepod diets for larviculture of halibut cod and turbot, and a review of published halibut research and cultivation data (AIR3-CT94-2094) 116

Minimising the interactions of cultured and wild fish: A comprehensive evaluation of the use of sterile, triploid, atlantic salmon (AIR3-CT94-2216) 121

Trophic capacity of the coastal areas for the culture of oysters, mussels and cockles (AIR3-CT94-2219) 125

Biological, agronomical and genetical bases for the large-scale cultivation and genetic improvement of Laminaria digitata (L.) (AIR3-CT94-2235) 129

Integrated management of red swamp crayfish populations in rice fields: An application of cleaner technologies and ecotechnology (AIR3-CT94-2432) 131

Hybridisation between escaped farmed Atlantic salmon and brown trout: Frequency, distribution, behavioural mechanisms and effects on fitness (AIR3-CT94-2484) 134

Development of mussel-specific expression vectors suitable for transgenic organisms: Implication in the establishment of mollusc continuous cell lines (AIR3-CT94-2487) 138

Fisheries Management and Fishing Technology 143

Assessment of the relationships between oceanographic parameters and spatial/temporal fluctuations of pelagic fish population characteristics using satellite images and acoustics (AIR1-CT92-314) 144

Investigation of the relative fishing effort exerted by towed demersal gears on North Sea human consumption species (AIR1-CT92-445) 148

Analysis of exploited fish stocks on Flemish Cap (AIR1-CT92-558) 150

Stock dynamics, interactions and recruitment in North-East Atlantic squid fisheries (AIR1-CT92-573) 155

Extension of the STCF technical interaction model and data collection of fishery data for 1991 for the North Sea (AIR1-CT92-711) 160

An assessment of the genetic consequences of the deliberate and inadvertent introduction of non-native Atlantic salmon into natural populations (AIR1-CT92-719) 162

Geostatistics for fish stock assessment (AIR2-CT94-1007) 166

Optimisation of a species selective beam trawl (AIR2-CT93-1015) 171

Shelf edge fisheries and oceanography study (AIR2-CT93-1105) 175

Selectivity of gill nets in the North Sea, English Channel and Bay of Biscay (AIR2-CT93-1122) 179

Mechanisms influencing long term trends in reproductive success and recruitment of Baltic cod: Implications for fisheries management (AIR2-CT94-1226) 181

Effects of property rights on the fishing industry and effectiveness for fisheries management policies (AIR2-CT93-1264) 186

Devolved and regional management systems in fisheries (AIR2-CT93-1392) 191

Co-ordination of research in fishery economics (AIR2-CT94-1489) 198

Study of factors affecting variability of trawl cod-end selectivity (AIR2-CT94-1544) 201

Towed fishing gear-reducing discards by consideration of all factors affecting selectivity (AIR2-CT93-1656) 204

Impact II - The effects of different types of fisheries on the North Sea and Irish Sea ecosystem (AIR2-CT94-1664) 207

Evaluation of stock enhancement of marine flatfish (AIR2-CT94-1732) 213

Alternative stimulation in fisheries (AIR3-CT94-1850) 218

Actions for coordinated research on European anchovy (AIR3-CT94-1855) 223

Bio-economic modelling of North Sea pelagic fisheries (AIR3-CT94-1906) 225

Co-ordination of the development of an improved method of measuring volume filtered by high speed plankton samplers (AIR3-CT94-1911) 228

Standardisation of national data bases for fisheries research data (AIR3-CT94-1923) 234

Project to enhance the European eel fishery and to ensure survival of the species (AIR3-CT94-1939) 236

Acoustic properties of fish and their exploitation in classification schemes for fish stock assessment (AIR3-CT94-2142) 241

European Artificial Reef Research Network (EARRN) (AIR3-CT94-2144) 245

Estimation of fish biomass in the Irish Sea by means of the annual egg production method (AIR3-CT94-2263) 250

Development of a mobile measurement system for the inspection of the engine power of fishing vessels at sea (AIR3-CT94-2398) 255

Feeding ecology of North Sea fish with emphasis on the data base of the 'Stomach Sampling Project 1991' for use in multispecies assessment (AIR3-CT94-2410- 257

Prevention of by-catch of small cetaceans in pelagic trawls by technical means 262
Upgrading of fishery products (AIR3-CT94-2423) 267

Maintenance of the fresh fish quality on board and on shore by means of modified atmosphere. Development of equipments, packages and procedures (AIR1-CT92-273) 268

Prolongation of shelf-life and quality of shellfish during storage and distribution (AIR1-CT92-365) 273

Conception, small scale production and nutritional evaluation of new dietary fibre ingredients from seaweeds and seaweed by-products (AIR1-CT92-518) 276

The identification of canned tuna species by characterisation of the nucleic acids (AIR2-CT94-1126) 283

Enzymatic ripening of pelagic fish species (AIR2-CT93-1141) 287

Predictive modelling of shelf-life of fish and meat products (AIR2-CT93-1251) 300

Improving the quality and safety of whole fresh fish (AIR2-CT94-1496) 303

Characterisation of TMAOase activity and inhibition of formation of formaldehyde and dimethylamine in fishery products (AIR3-CT94-1921) 307

Marketability of fish fed on diets rich in specific dietary lipids and promoted as healthy food: Investigations of consumer's decision processes (AIR3-CT94-2239) 309

Evaluation of fish freshness (AIR3-CT94-2283) 311

Volume VI Fisheries and Aquaculture (FAIR: 1994 - 1998)

Predicting the effects of environmental change on freshwater fish production (FAIR-CT95-0009) 8

A social science network for fisheries management(FAIR-CT95-0070) 11

Recruitment processes in cod and haddock: Developing new approaches (FAIR-CT95-0084) 17

Application and validation of the lipofuscin method in the assessment of crustacean age (FAIR-CT95-0131) 21

Selective breeding for stress tolerance in aquacultured fish (FAIR-CT95-0152) 25

Towards improved carbohydrate utilization by finfish: physiological, metabolic, molecular and genetic limitations of poikilothermy (FAIR-CT95-0174) 30

Accion concertada para el estudio biologico y pesquiero de gambas profundas del mediterraneo y mares adyacentes (FAIR-CT95-0208) 34

A calibration of different molecular markers for use in discrimination and management of stocks of commercially important fish species (FAIR-CT95-0282) 35

Recombinant vaccines against infectious pancreatic necrosis (IPN) in salmonid fish (FAIR-CT95-0353) 41

Common dentex, a prime new species for aquaculture. Development of methods for reliable egg production (FAIR-CT95-0407) 45

Spatio-temporal analysis of the fisheries resources, their environment and exploitation in the Mediterranean Sea: experimental uses of geographical information systems (FAIR-CT95-0419) 49

Genetical bases and variability of physiological traits involved in growth in Crassostrea gigas (FAIR-CT95-0421) 52

Assessment and reduction of the by-catch of small cetaceans (FAIR-CT95-0523) 54

Innovative integrated bio-economic models for the management of multi-species and multi-gear fisheries (FAIR-CT95-0561) 56

Consumption rates of predatory fish relevant for multispecies assessment in the North Sea and the Atlantic of Spain (FAIR-CT95-0604) 62

Developing deep-water fisheries: Data for their assessment and for understanding their interaction with an impact on a fragile environment (FAIR-CT95-0655) 64

Molecular basis of fish immunity for disease resistance (FAIR-CT95-0666) 76

Dynamics through natural and antropogenic causes of marine organisms: The effects of large scale ecological changes on fish and fisheries (FAIR-CT95-0710) 78

A study of roundfish and nephrops survival after escape from commercial fishing gears (FAIR-CT95-0753) 82

Specification and bioavailability of selenium from processed and tailor-made fishery products (FAIR-CT95-0771) 84

Monitoring biodiversity in the North Sea using groundfish surveys (FAIR-CT95-0817) 87

Salmonid protection in aquaculture: development of a fish herpesvirus as a vector for vaccination (FAIR-CT95-0850) 92

Foreign trade and seafood prices: Implications for the CFP (FAIR-CT95-0892) 94

Development, modelling & application of time temperature integrator system to monitor chilled fish quality (FAIR-CT96-1090) 96

Electrode probes for the rapid assay of sea food toxins (FAIR-CT96-1092) 101

Interaction between raw material characteristics and smoking process on quality of smoked salmon (FAIR-CT96-1101) 105

Biochemical changes and protein interactions leading to aggregation and toughening in frozen fish (FAIR-CT96-1111) 110

Spoilage and safety of cold-smoked fish (FAIR-CT96-1207) 114

Advanced methods for identification and quality monitoring of (heat)processed fish (FAIR-CT96-1227) 117

European fish ageing network (FAIR-CT96-1304) 121

Effect of processing technology on the quality of aquaculture feeds (FAIR-CT96-1329) 126

Precision and accuracy of tools in recruitment studies (FAIR-CT96-1371) 129

Improvements of tagging methods for stock assessment and research in fisheries (FAIR-CT96-1394) 131

Environmental and neuroendocrine control mechanisms in finfish reproduction and their applications in broodstock management (FAIR-CT96-1410) 134

Endocrine control as a determinant of larval quality in fish aquaculture (FAIR-CT96-1422) 136

Evaluation of mesh measurement methodologies for fisheries inspection and research (FAIR-CT96-1452) 139

Measurement of economic impacts of fishery management decisions - model-based approaches in specific fleet sectors (FAIR-CT96-1454) 144

Cephalopod resources dynamics: Patterns in environmental and genetic variation (FAIR-CT96-1520) 148

Selectivity database (FAIR-CT96-1531) 152

Development of predictive model of cod-end selectivity (FAIR-CT96-1555) 158

Investigations into the role of bacteria/dinoflagellate interactions in paralytic shellfish poisoning (FAIR-CT96-1558) 160

An intergrated study of interindividual competition and its relationships with feeding physiology and behaviour in cultured predatory fish (FAIR-CT96-1572) 162

Generation of highly informative DNA markers and genetic marker maps of Salmonid fishes - SALMAP(FAIR-CT96-1591) 164

Rhabdoviruses in wild marine fish in european coastal waters: Characterisation and significance for aquaculture (FAIR-CT96-1594) 166

Biology and management in the control of lice on fish farms (FAIR-CT96-1615) 168

Biology of sea-urchins under intensive cultivation (closed cycle echiniculture) (FAIR-CT96-1623) 173

Commercial fish and european estuaries - priorities for management and research (FAIR-CT96-1634) 176

Risk assessment of antimicrobial agent use in aquaculture (FAIR-CT96-1703) 182

Three-dimension analysis and visualization of the spatial structure of fish schools using multi-beam sonar image processing (FAIR-CT96-1717) 184

PTHrP in sea-bream development and physiology (FAIR-CT96-1742) 186

The influence of competitive interactions on the abundance of early benthic stage european lobster (Homarus gammarus (l.)), and hence on the carrying capacity of lobster habitat (FAIR-CT96-1775) 190

Management of high sea fisheries (FAIR-CT96-1778) 195

Aggregation patterns of pelagic commercial fish species under different stock situations and their impact on exploitation and assessment (FAIR-CT96-1799) 198

The implications for fisheries management systems of interactions between farmed and wild caught species (FAIR-CT96-1814) 200

Investigation and quantification of the stress associated with accumulation of carbon dioxide in eel farms with recirculating water (FAIR-CT96-1840) 205

Breeding improvement of Crassostrea gigas by nutritional and gametogenesis control (FAIR-CT96-1852) 207

The use of molecular genetic markers for the study of stock structury of anchovy (Engraulis encrasicolus) in the mediterranean and adjacent seas (FAIR-CT96-1899) 209

Early control of growth for fish production with special reference to muscle development, gene expression and temperature (FAIR-CT96-1941) 212

Sized-based tools for managing freshwater fish communities (FAIR-CT96-1957) 217

Development of sustainable aquaculture of arctic charr (FAIR-CT96-1981) 222

Bioeconomic modelling of the fisheries of the English channel (FAIR-CT96-1993) 225

Improving technical management in baltic cod fishery (FAIR-CT96-1994) 229

A review of acceptable means by which towed gear discards may be reduced in ICES areas VII and VIII (FAIR-CT96-2001) 231

Migration, distribution and spatial dynamics of plaice and sole in the north sea (FAIR-CT96-2079) 233

New cleaner production methods to reduce environmental impacts of the European fish transforming industry (FAIR-CT97-3016) 236

High performance gelatins from alternative sources (FAIR-CT97-3055) 238

Identification of species in processed seafood products using DNA based diagnostic techniques (FAIR-CT97-3061) 242

Optimisation of harvest procedures of farmed fish with respect to quality and welfare (FAIR-CT97-3127) 244

Investigation into the monitoring analysis and toxicity of toxaphene in marine foodstuffs (FAIR-CT97-3131) 246

Production of polyunsatured fatty acids (PUFAs) by algae: A complete bioprocessing concept for the large-scale production of high quality DHA-containing oils (FAIR-CT97-3146) 249

The evaluation of a simple, cheap rapid method of non-protein nitrogen determination in fish products through the processing/merchandising chain (FAIR-CT97-3253) 252

Experimental surveys for the assessment of juveniles (FAIR-CT97-3374) 254

Study of anti-oxidant systems in cultured marine fish in relation to growth, quality and disease resistance during early developmental stages (FAIR-CT97-3382) 257

Fish Ageing by Otolith Shape Analysis (FAIR-CT97-3402) 259

Improved diagnosis of Gyrodactylus parasites infecting aquacultured species (FAIR-CT97-3406) 262

Development and use of Cell Cultures for Commercially Important Aquatic Invertebrates (FAIR-CT97-3413) 265

Fish pasteurellosis: Applied Research on Vaccine Development (FAIR-CT97-3449) 269

Diachronic changes in growth rate of North Sea fish species in relation to anthropogenic activities (FAIR-CT97-3462) 271

Genetic diversity and parasitic infections of european hake (Merluccius merluccius) as descriptors of fishing impact on Mediterranean and Atlantic stocks (FAIR-CT97-3494) 274

Performance and Ecological Impacts of Introduced and Escaped Fish: Physiological and Behavioural Mechanisms (FAIR-CT97-3498) 278

Fish cysteine proteinase inhibitors and infectious diseases (FAIR-CT97-3508) 280

Impact of fishery and environment on hake recruitement in Northwestern Mediterranean (FAIR-CT97-3522) 282

Concerted Action: Promotion of common methods for economic assessment of EU fisheries (FAIR-CT97-3541) 286

A multidisciplinary evaluation and optimizaton of the production characteristics of different strains of commercially cultured flatfish (FAIR-CT97-3544) 289

Marteilia refringes studies: Molecular systematics and search for the intermediate hosts of the bivalve molluscs parasites (FAIR-CT97-3640) 291

Evaluation of MHC genes as quantitative trait loci for disease resistance in fish (FAIR-CT97-3643) 293

Freshwater crayfish and the crayfish plague fungus: Disease diagnosis and effects of fungal infection on immunity and reproduction (FAIR-CT97-3660) 295

Effects of Environmental Stressors on Antimicrobial activity in marine bivalve Molluscs (ESAM) (FAIR-CT97-3691) 297

Fish Sperm Viability as an Indicator of Environmental Pollution (FAIR-CT97-3755) 299

Concerted action workshop of minimum inhibitory concentrations of antimicrobials against fish pathogenic bacteria (FAIR-CT97-3760) 302

Molecular and physiological basis for the optimization of GnRH induced spawning techniques in farmed fish, in particular the sea bass (Dicentrarchus labrax) and the sea bream (Sparus aurata) (FAIR-CT97-3785) 304

Basis of sex determination and gonadal sex differentiation for sex control in aquaculture (FAIR-CT97-3796) 306

Sustainable fisheries. How can the scientific basis for fish stock assessments and predictions be improved? (FAIR-CT97-3805) 309

Reduction of adverse environmental impact of demersal trawls (FAIR-CT97-3809) 313

Impacts of marine xenobiotics on european commercial fish - Molecular effects and population responses (FAIR-CT97-3827) 315

Aquaculture of the Edible Red Seaweed Palmaria Palmata: Development of Techniques and Economic Analysis (FAIR-CT97-3828) 320

European network for the dissemination of aquaculture RTD information (FAIR-CT97-3837) 322

Concerted action on identification, management and exploitation of genetic resources in brown trout (Salmo trutta) (FAIR-CT97-3882) 326

Assessment of procedures for the development of a european standardised multi-site testing programme: Application to seabass, Dicentrarchus labrax (FAIR-CT97-3886) 332

Economics and the common fisheries policy: Perspectives for the future economic management of Europe's fisheries (FAIR-CT97-3900) 335

The significance of economic incentives in fisheries management under the CFP (FAIR-CT97-3936) 337

Cataracts in farmed fish - A multidisciplinary initiative for scientific progress (FAIR-CT97-3963) 341

Study on Eastern Atlantic and Mediterreenean Bluefin Tuna micrations using 'pop off satelite tags' (FAIR-CT97-3975) 344

The socio-economic impact of regional management of the Irish Sea nephrops and whitefish fisheries on profitability and employment in coastal communities (FAIR-CT98-3841) 347

Organic Salmon production and consumption: Ethics, consumer perceptions and regulation (FAIR-CT98-3372) 350

Aspects ethiques juridiques et sociaux de la gestion des peches en Europe (FAIR-CT98-3821) 353

Volume II

Strategic Marine Research

II.1. Coastal and shelf seas research

II.1.1. Coastal processes and morphodynamics

TITLE: Prediction of Aggregated-Scale Coastal Evolution (PACE)

CONTRACT NO.: MAS3-CT96-0002

COORDINATOR: Prof.dr. H.J. de Vriend
University of Twente
Civil Engineering & Management
P.O. Box 217
7500 AE Enschede
The Netherlands
Phone: +(31) 53 489 4320 Fax: +(31) 53 489 4040
E-mail: h.j.devriend@sms.utwente.nl

PARTNERS:

Mr. M. Capobianco
Tecnomare
3584 San Marco
30124 Venice
Italy
Phone (Fax): +(39) 41 796 711 (800)
E-mail: capobianco.m@tecnomare.it

Prof.dr. M.J.F. Stive
Delft Hydraulics
P.O. Box 177
2600 MH Delft
The Netherlands
Phone (Fax): +(31) 15 285 8585 (8582)
E-mail: marcel.stive@wldelft.nl

Dr. A.W. Niedoroda
Woodward Clyde International
c/o Limnos S.A.
Bruc 168, Entlo 2ª
08037 Barcelona
Spain
Phone (Fax): +(34) 3 457 2654 (9684)
E-mail: awniedo0@wcc.com

Dr. H.N. Southgate
HR Wallingford
Marine Sediments Group
Howbery Park
OX10 8BA Wallingford
UK
Phone (Fax): +(44) 1491 835 381 (539)
E-mail: hns@hrwallingford.co.uk

ASSOCIATED PARTNERS:

Dr. H. Hanson	Univ. of Lund	Lund (SE)
Dr. P. Cowell	Univ. of Sydney	Sydney (AUS)
Prof.dr. M.J.F.Stive	Delft Univ. of Techn.	Delft (NL)
Dr. H.J. Steetzel	Alkyon	Emmeloord (NL)
Dr. D.W. Dunsbergen	Rijkswaterstaat - RIKZ	Den Haag (NL)
Dr. P. de Boer	Univ. of Utrecht	Utrecht (NL)
Prof.dr. P. Blondeaux	Univ. of Genoa	Genoa (IT)
Dr. L. Hamm	SOGREAH Ingenierie	Grenoble (FR)
Prof.dr. R. Spigler	Univ. Roma Tre	Rome (IT)
Dr. R.J. Nicholls	Middlesex Univ.	Enfield (UK)
Prof.dr. B.A. O'Connor	Univ. of Liverpool	Liverpool (UK)
Dr. A. Falques	Un. Polit. de Catalunya	Barcelona (ES)
Dr. J. Jimenez	CIIRC	Barcelona (ES)

PREDICTION OF AGGREGATED-SCALE COASTAL EVOLUTION (PACE)

H.J. DE VRIEND

University of Twente
P.O.B. 217, 7500 AE Enschede, NL

SUMMARY

The prediction of coastal behaviour at space and time scales which are much larger than the inherent dynamic scales of the system considered is a non-trivial task, in spite of the recent increase of process knowledge and medium-term modelling expertise. The 36-month MAST-III project *Prediction of Aggregated-Scale Coastal Evolution* (PACE), which started on 1 February 1997, has the objective to investigate and develop prediction methods for this large-scale behaviour.

1. INTRODUCTION

Coastal morphological changes take place at a wide range of spatial and temporal scales, from individual grain motion through to the evolution of entire coastal systems at historical and geological time scales. Fig. 1 shows, that this scale range extends over at least ten orders of magnitude.

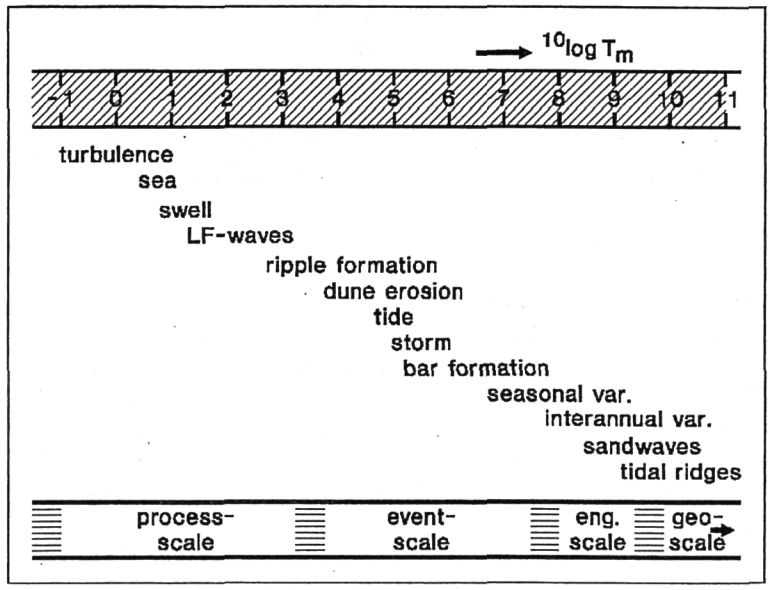


Figure 1. Scale range in coastal morphology

The prediction of coastal behaviour at the various scale levels is not a trivial task. The basic knowledge which has been incorporated in the mathematical models as developend in MAST-I and MAST-II (De Vriend, 1995) concerns mainly small-scale processes (waves, currents, sediment transport) and their dynamic interaction with the bed topography at small and intermediate scales. There are good reasons (non-linear dissipative feedback system, continuous energy input via random forcing) to question the possibility of such morphodynamic models to be used for long-term predictions just by running them long enough. For a further discussion on this matter, reference is made to the special discussion session on predictability of coastal morphology at this conference.

Data on larger-scale coastal changes, which are essential to asses the validity of models, are scarce and, by definition, it is too late to start monitoring at the moment the information is needed. Black-box empirical modelling techniques for data-abundant systems are therefore seldomly applicable here.

This poses a number of research questions, such as:
- Are there fundamental limitations to the long-term predictability of coastal morphological behaviour?
- To what extent can medium-term process-oriented morphodynamic models be used for long-term predictions?
- If not, how can they be aggregated to models which operate at large scales?
- Are there comprehensive datasets on large-scale coastal behaviour available and, if so, how can they be accessed?
- To what extent can these be used to derive empirical models of this behaviour?
- Are there other approaches of long-term prediction?

2. THE PACE-PROJECT

The PACE-project addresses these questions for sandy coasts, aiming at a range of validated large-scale prediction techniques for various scale levels. The approach is twofold, viz. top-down, attempting to derive generic knowledge and models from data, and bottom-up, starting from physical conservation principles. The scale levels considered are interannual, decadal and centennial/millennial.

Special attention is paid to rhythmic morphological features, such as nearshore bars, channel/shoal systems in tidal embayments, shoreface-connected ridges, and sandwave and sandbank systems on the seabed. We focus on the evolution of the *patterns* of these features, rather than on the behaviour of each individual element.

The project is subdivided into four Topics, two on data-analysis and modelling of interannual and decadal-scale morphological processes, one on century/millennium-scale processes and one on rhythmic features. Their coherence is outlined in Fig. 2. In each Topic, various partners from EU-countries collaborate with leading scientists from other parts of the world, who provide links with other research networks in this field.

Thus we get access to the world's most important data and models on large-scale coastal behaviour. A special Data Task Force has been established to make these data accessible to the participants.

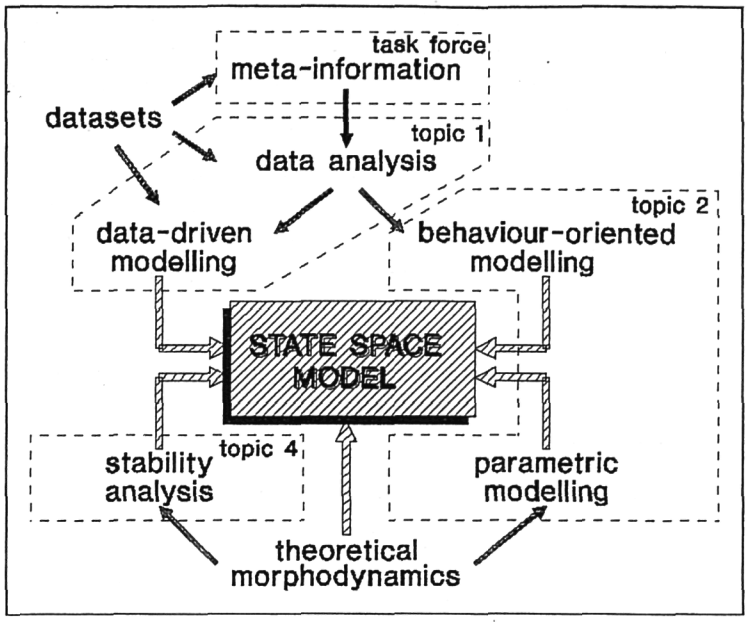


Fig. 2. Coherence of Topics (decadal scale)

3. TOPIC 1: INTERANNUAL AND DECADAL-SCALE BEHAVIOUR (DATA-ORIENTED)

3.1. Objectives and approach

Many coastal zone management issues and environmental impact assessments concern the coastal evolution on a scale from years to decades. The spatial extent is typically tens of kilometres alongshore and down to the middle or lower shoreface in the cross-shore direction.

Practical issues are the effects of human interference policy (coastal maintenance, long-term beach preservation schemes, mining concessions, land reclamation, etc.) and large engineering works, but also the vulnerability to extreme events (e.g. dune erosion) and the expected impacts of accelerated relative sea level rise, climatic change and changes in sediment supply.

The objectives of this Topic are to apply the same analysis techniques to data from various locations and to derive decadal-scale empirical and semi-empirical model concepts from this. The resulting models should be able to predict trends in the mean state of the coast, but also changes in the response to extreme events.

Key elements in the methodology are data analysis, data reduction and interpretation, data-driven modelling, model fitting and data-assimilation.

3.2. Data Task Force

The Data Task Force has identified and documented datasets from a variety of coasts. Table 1 gives a typical example of the resulting type of meta-information.

site	length of coast (km)	number of profiles	spacing (m)	depth-range or length of profile	dura-tion (yrs)	dates	time interval
Lincolnshire	38	18	1000-2000	intertidal (80 m)	31	1959-1990	month
Duck, NC	1	26	40	dune to d.o.c.	14	1981-1994	month
JARKUS, NL	500	2500	200-250	dune + beach	32	1963-1995	year
Terschel-ling, NL	10	70	100-200	foredune to -10 m	4	1993-1996	2 mnths
Lubiatowo, PL	2.7	5-28	100	dune to -5 m	31	1964-1995	6 mnths
Ocean City, MA	13	24	300-600	dune to -8 m	5	1988-1993	4 mnths
Ebro Delta, ES	35	36	1000	beach to -15 m	4	1988-1992	3 mnths

Table 1. Some datasets on profile evolution (d.o.c. = depth of closure)

Similar information is available on a number of important coastline datasets. Moreover, indicators of data quality are given and contact persons and access conditions are identified. For the latest update of the data report, see Hamm (1997).

More information on a number of Polish datasets, including animations, is available on Internet, via: *http://www.ibwpan.gda.pl/bi/dbase/dbmain.html*.

3.3. Interannual variability of nearshore bars

Since the development of a robust and easy-to-use video technique for the observation of nearshore bar behaviour (Lippman and Holman, 1989), extensive datasets on nearshore bar systems have become available (Holman, 1997). These datasets are so dense (many years of hourly data), that data-demanding techniques could be used for their analysis and for the establishment of data-driven models (e.g. neural networks).

Analyses so far seem to indicate, that the correlation of the observed bar behaviour with the input conditions is rather weak, even if lag and memory effects are taken into account. These analyses, however, can only be qualitative, as long as the whiteness due to wave-

breaking which is observed on the time-exposure video images cannot be translated accurately into bed topography. Part of the work in PACE is dedicated to this translation (e.g. Aarninkhof et al., 1997).

This part of PACE forms an important link to the NICOP-project, which is funded by the US Office of Naval Research and has the objective to facilitate the exchange between EU and US coastal research in the field of nearshore dynamics.

3.4. Data analysis and data reduction

Coastal morphological behaviour is a manifestation of a spatially 3-D, stochastically forced nonlinear dynamic system, usually with an unfavourable signal-to-noise ratio. The former implies, that variations in the observed behaviour do not necessarily refer to variations in the input conditions: the system may exhibit its own inherent behaviour, independent of the forcing. The small signal-to-noise ratio and the complexity of the phenomena requires data reduction in order to get insight into the observed behaviour.

The prime objectives of the work on data analysis and data reduction in PACE are (1) recommendations for the use of data analysis and reduction techniques for coastal morphological data, and (2) indications of the natural behaviour of coasts at various time scales, in terms of free (inherent) and forced (imposed) behaviour.

Analyses of the correlation between input and output for various coasts lead to the conclusion, that for each part of the profile free behaviour is dominant within a certain window of time scales, whereas forced behaviour dominates outside this window.

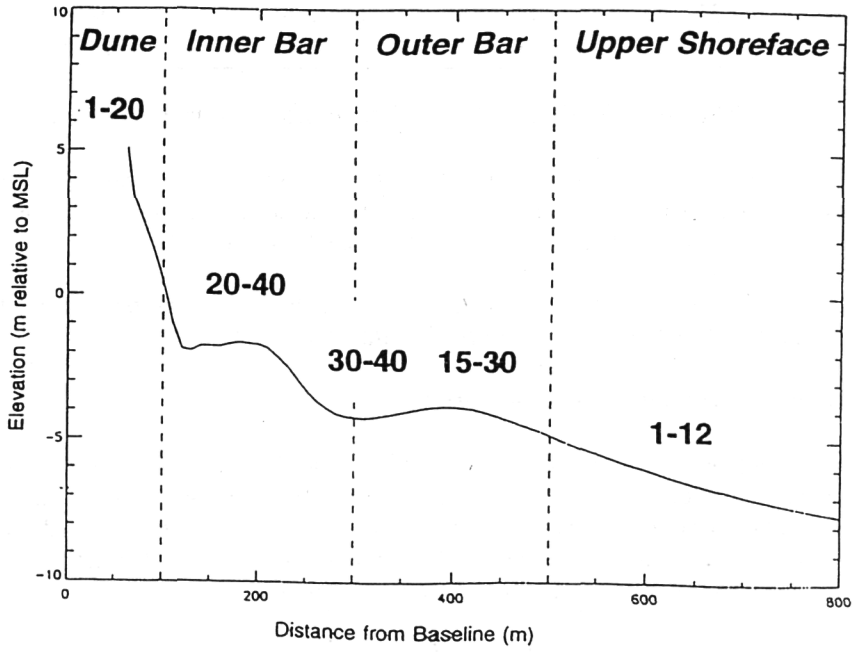


Fig. 3. Time-scale windows (in months) for fractal behaviour at Duck, N.C.; [Southgate and Möller, 1998]

One example is shown in Fig. 3, which results from a fractal analysis of bathymetric data from the upper shoreface at Duck, N.C. (Southgate and Möller, 1998). The basis of the approach is the presumption that the free behaviour of a nonlinear system like this will have a fractal structure.

Examples of data reduction techniques tested in PACE are:
- bulk statistics: mean, variance, range, correlation, frequency distribution, etc.
- Fourier-type techniques: Fast Fourier Transform, Random Sine Functions (Pruszak and Rozynski, 1997),
- eigenvector-techniques: Empirical Orthogonal Function (EOF)/Principal Component Analysis (PCA: e.g. Wijnberg and Terwindt, 1995), Canonical Correlation Analysis (CCA), Singular Spectrum Analysis (SSA), Principal Oscillation Patterns (POP; Hasselmann, 1993; Jansen, 1997a).
- other techniques: fractal analysis (Southgate and Möller, 1998) and cluster analysis (looking for "attractor" states).

The application of these techniques has a scientific dimension, viz. the identification of generic behaviour patterns, but also a user-oriented one, viz. a black-box description of how a certain stretch of coast behaves.

3.4. Depth of closure

Repeated observations of coastal profiles usually show a more or less sharp transition in morphological activity between the highly active nearshore zone and the much less active shoreface. The point of transition, expressed in terms of a water depth, is termed *depth of closure*. Thus, the d.o.c. is a natural boundary for nearshore morphological models.

In principle, the d.o.c. is time-scale dependent (cf. Stive et al., 1992; Capobianco et al., 1997): under extreme events, the shoreface will also move, which means that integrating over a longer time period yields a greater d.o.c. In line with this, the analysis of a variety of datasets (e.g. Nicholls and Birkemeier, 1997) has shown that closure models based on extreme wave statistics work well at the annual time scale, but tend to fail as the time scale increases and shoreface processes become more important.

In the near future, the work on closure will be extended to the empirical modelling of the profile envelope as a whole, including the point of closure.

3.5. Forced beaches

In contrast to the above terminology, the term "forced beaches" refers to beaches affected by human interference. The investigation of such beaches, apart from being practically most relevant, provides a link with the MAST-III project SAFE. The work in PACE focuses on the long-term effects of man-made structures and other types of human interference (e.g. repeated shore nourishments), with the ultimate goal to gather sufficient process knowledge to enable us to develop reliable predictive models.

Data analysis techniques as decribed in the foregoing were applied to data from nourished beaches, such as Ocean City, Silver Strand, Sylt Island and Terschelling. In addition, various types of models were used, such as:
- equilibrium profile models, including descriptions of the transport rate in terms of the

deviation from the equilibrium profile,
- multi-layer models, in which the profile is schematized as a sequence of mutually interacting layers (more or less like a multi-line model),
- empirical profile variability models, given the input wave statistics,
- shoreline change models, with various extensions of the functionality.

3.6. Time response and chronology

One of the questions which remain to be answered in large-scale coastal morphology is that of the role of chronology (sequencing) of effectively random forcing events. This may refer to individual storms, but also to longer-term "events" such as storm seasons, or even longer periods. Chronology is likely to be an issue, since we are dealing with a nonlinear dynamical system.

There are two fundamental difficulties in detecting chronology effects from field data. The first is to distinguish between the inherent dynamical behaviour of the system and its response to the forcing conditions (free vs. forced behaviour). Both are likely to occur to some degree, and both can lead to apparently random variations of the bed level. The second difficulty is that nature provides only one "realisation" of forcing and response, which eliminates the possibility of a statistical approach (unless additional assumptions are made).

Data analysis techniques, such as fractal analysis, enable us to distinguish between forced and free behaviour. Analyses of data in cases with a predominantly forced behaviour indicate that chronology effects probably (cf. Southgate and Capobianco, 1997). Further confirmation of this observation is only possible on the basis of more data.

Another way to investigate chronology effects is via numerical models. In principle, the "one realisation" problem does not occur there: one can run a model an arbitrary number of times with different (statistically equivalent) input time-series. Southgate (1995) describes such an investigation for a coastal profile. Further work along these lines is in progress within PACE.

3.7. Data-driven modelling

Data-driven modelling ranges from purely statistical extrapolation through to models in which the parameter setting is constrained by process knowledge. Time series extrapolation is a standard form of data-driven modelling. The basic assumption is, that the corresponding stochastic process is stationary and is described adequately by the lower moments (mean, variance, covariance function, power spectrum) of its probability distribution. Modelling boils down to describing these lower moments in terms of environmental conditions.

One problem with this approach is the high-dimensionality of the state to be described (note that every point of a coastal profile or a coastal area represents a dimension). Therefore, it is attractive to reduce the dimensionality by projecting the system's state onto a smaller number of variables via data reduction techniques.

Sophisticated versions of modelling on the basis of data reduction are Principal Orthogonal

Pattern (POP) and Principal Interaction Pattern (PIP) models, the former basically for linear, the latter for nonlinear systems. Further see Jansen (1997b).

4. TOPIC 2: INTERANNUAL AND DECADAL-SCALE BEHAVIOUR (MODEL-ORIENTED)

4.1. General

This Topic concerns the same spatial and temporal scales as Topic 1, but addressed from the modelling end. These scales require models at a higher aggregation level than detailed process-oriented models, but on the other hand the end user is interested in the risks involved in extreme events. So it is not only the long-term trend in the mean state of the coast which counts here, but also the long-term evolution of the system's reponse to extreme events, or to a sequence of less extreme events.

The objectives of this Topic are to develop and test a class of decadal-scale models based directly (process-based simulation models, formally averaged models) or indirectly (behaviour-oriented models) on first physical principles, and to validate them by comparison with field data and data-driven models. The resulting models should be able to predict trends in the mean state of the coast, but also changes in the response to extreme events.

Key issues in the methodology are identifying the relevant physical processes, long-term runs of process-based simulation models, formal avaraging of process-based simulation models, derivation of behaviour-oriented models (constituting equations, parameter identification), model intercomparison and validation, probabilistic approach of response to extreme events. The data to be used in this Topic are the same as in Topic 1.

4.2. Behaviour-oriented and parametric modelling

An alternative to data-driven modelling is "behaviour-oriented modelling", based on available knowledge and data, but not formally on small-scale process-descriptions. One example is the diffusion approach for large-scale coastal profile evolution (De Vriend et al., 1993). The approach can easily be extended with a longshore dimension, in order to include weak longshore variability, like in coastline models.

The one-line concept, which is probably the best established and robust modelling approach for large-scale coastal morphology at this moment, can be considered as a behaviour-oriented model, in that it is not formally derived from a 3-D description of the constituent processes. Modern model-fitting techniques (e.g. Reeve and Fleming, 1997) are now being tested in PACE.

Another example of behaviour-oriented modelling is the hinged-panel approach, which was originally developed for large-scale coastal profile modelling (Stive and De Vriend, 1995), but which also allows for extension with a longshore dimension. An application of such an extended panel model to the Ebro Delta is described by Jiménez and Sánchez-Arcilla (1997; see Fig. 4).

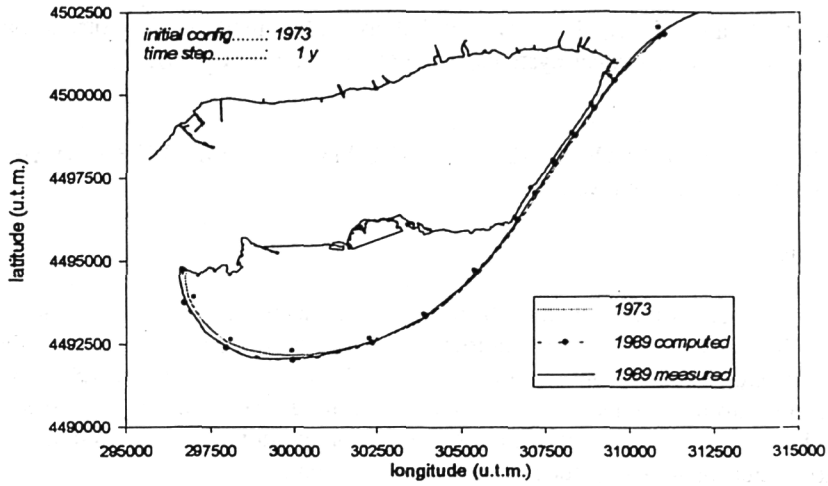


Fig. 4. Hindcast of decadal-scale evolution of the Ebro-delta coast [Jiménez and Sánchez-Arcilla, 1997]

4.3. Profile modelling

The work on profile modelling concerns:

(1) the equilibrium profile under breaking and non-breaking waves, including sediment transport relationships in terms of the deviation from this equilibrium profile;

(2) multi-frequency profile modelling, in which the profile is represented by an equilibrium profile (e.g. the Dean profile) and a series of harmonic functions in space; the model was tested against more sophisticated numerical models (e.g. Nicholson and O'Connor, 1995);

(3) multi-layer cross-shore modelling, in which the cross-shore transport is related to the deviation from the equilibrium profile, according to a discretized diffusion principle; some of the parameters are determined from simulations with process-based numerical models (parametric modelling).

There is a more or less continuous transition from these decadal-scale models to the very-large-scale models used in Topic 3.

A special problem is the parameter identification in nonlinear advection/diffusion-type profile models from data or other models. Although the basic equation is simple and straightforward, the inverse problem is rather complicated.

The concept of equilibrium profile has been tested against a large number of transects from Hel Peninsula, Poland (cf. Szmytkiewicz et al., 1997). The data confirm the validity of Dean's equilibrium profile, provided that the bars are smoothed out.

4.4. One-line modelling

One-line models are widely used for long-term coastline predictions, especially if it concerns the response to human interferences, such as coastal structures and beach nourishments. One of the test applications in PACE is the well-documented coastline evolution of island of Sylt, Germany, which has experienced severe erosion during the last centuries and can only be maintained by strong human interference.

On the basis of field data, an attempt is made to describe seasonal and interannual shoreline variations by including cross-shore transport in a one-line model. The preliminary results for the seasonal behaviour are promising, but the model's response to extreme events is still rather poor.

4.5. Compound multi-layer modelling

The multi-layer concept which was described in Section 4.3 has been extended with a longshore dimension, more or less in the same vein als multi-line models. Some of the model parameters in this PONTOS-model are based on results of detailed medium-term process-based models. This sequence of process-based medium-term and parametric long-term simulations was used to simulate the evolution of the Holland coast, and to predict the impact of a future seaward extension of Rotterdam harbour.

In conjunction with the SAFE-project, a first application to the island of Sylt was made. Further testing of the model against this well-documented case is foreseen.

4.6. End-user orientation

Although PACE definitely meets a demand from practice, its results need further processing before being robust tools for the end user (coastal zone manager, policy maker). To that end, coastal morphological predictions have to be translated into information on matters such as policy options, susceptibility to adverse developments, manoeuvering space, vulnerability, resilience, etc. An attempt to tune research objectives and end-user requirements is reported bij Rijkswaterstaat (1998).

Sánchez-Arcilla et al. (1998) introduce a number of *System State Indices*, i.e. simple parameters which describe the state of the system at a very high aggregation level. By combining a number of these quantities with a weight factor which reflects the importance attributed by the end user to the relevant stretch of coast, they come up with a *System Vulnerability Index*. This index is applied to the Ebro Delta coast, to characterise its response at various time scales: event scale, medium-term and long-term.

5. TOPIC 3: VERY-LARGE-SCALE MODELLING

Typical time scales in this class of application are centuries to millennia. The spatial longshore extent is typically one or more coastal cells, and the cross-shore extent ranges from the dune area through to the inner shelf.

Being able to hindcast coastal evolutions at these scales is not only scientifically challenging and practically useful (for instance to understand what past periods of rapid sealevel rise have done to the coast), it also provides an ultimate test of the understanding of the mechanisms which determine coastal behaviour at shorter (decadal) scales. Thus it contributes to the validation of long-term model concepts.

The objective of this Topic is to develop one or more dynamically sound and well-verified numerical model concepts for very-large-scale coastal behaviour, and to demonstrate their potential utility when used in a diagnostic or a prognostic mode.

Three existing very-large-scale profile model concepts, named *Cowell*, *Niedoroda* and *Stive*, respectively, are being tested on the same documented cases. Various such cases have been derived from geological data. An interesting new application concerns a well-documented part of the Washington coast, US.

The Cowell-model (Cowell et al., 1995) is basically geometrical, but satisfies the sediment balance (Fig. 5). The Niedoroda-model (Niedoroda et al., 1995) is essentially of the diffusion type, and the Stive-model (Stive and De Vriend, 1995) is based on a hinged-panel concept. Upon closer inspection, the three models turn out to have a number of essential properties in common.

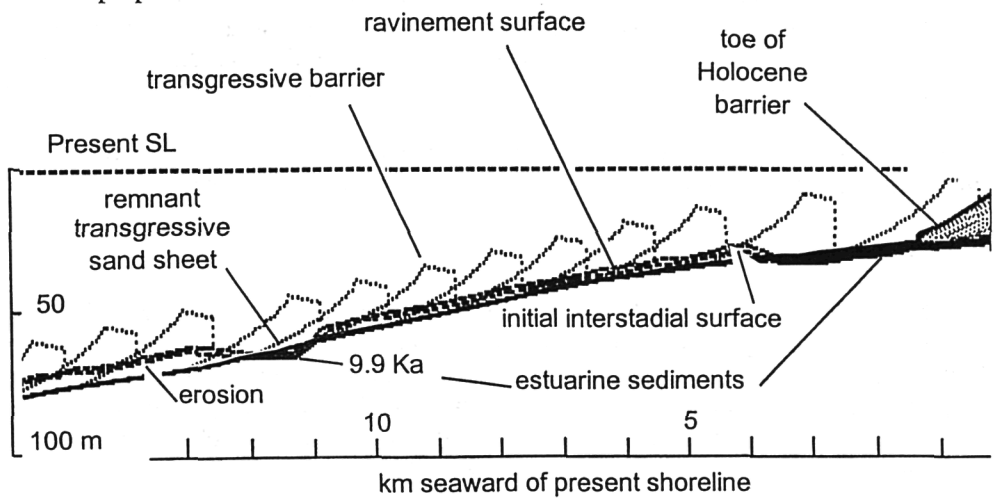


Fig. 5. Simulation of erosive transgression at Tuncurry, SE Australia
[also see Cowell et al. 1998a, 1998b]

Auxiliary process-oriented research on shoreface processes (e.g. Swift et al., 1997) has yielded a 2-D vertical shoreface and shelf model, which describes the 3-D water and (graded) sediment motion in the case of longshore uniformity. An interesting aspect is, that the low level of morphological activity on the shoreface and the shelf makes it easier to model long-term changes on the basis of short-term process descriptions.

A box-type model concept for tidal inlet systems (Stive et al., 1997) was developed and tested. Recently it has been extended to a continuum version, making use of elements of the Niedoroda model. This continuum model forms the largest-scale component of a sequence of models at consecutive scale levels which has recently been applied to predict the impact of a planned new extension of Rotterdam harbour at time horizons of 5, 50 and 300 years, respectively.

6. RHYTHMIC FEATURES

Bar systems and other rhythmic features, such as coastline waves, form a special class of phenomena in coastal morphology. Bar systems at a wide range of scales are nearly ubiquitous on sandy coasts and shelves. They are of great practical importance to any interference with the sea bed (see Hulscher, 1996), such as pipeline laying, sand mining,

dredging and maintenance of shipping channels, material dumping, etc. Nearshore bar systems are also claimed to have an effect on the susceptibility of a coast to erosion events.

Most rhythmic features cannot be explained from a rhythmic forcing of the morphodynamic system at their own time scale, for instance via the weather, nor are they likely to be relicts from the past. They are rather manifestations of the system's inherent dynamics, and would also occur if the forcing were stationary.

Earlier research has shown that this type of feature can be analysed very usefully via stability analyses of the mathematical equations which constitute the model. The objective of this Topic is therefore to perform and validate linear, weakly nonlinear and strongly nonlinear stability analyses of rhythmic and quasi-rhythmic features and to derive from these analyses long-term amplitude evolution models of features such as:

- oblique shoreface-connected ridge systems (e.g. Falqués et al., 1998),
- nearshore bar systems due to the dynamic interaction of edge waves and bed topography (Vittori et al., 1998),
- tidal sandbanks and sandwave-fields, etc. (e.g. Hulscher and Roelvink, 1997),
- channel/shoal systems in tidal inlets (e.g. Schuttelaars and De Swart, 1997).

Linear stability analyses yield information on the wave length, growth rate, orientation and propagation speed of the most unstable harmonic bed perturbation. Nonlinear analyses provide additional information on amplitude, type of instability, long-term evolution and predictability.

One example of the results achieved so far is shown in Fig. 6. The agreement with measured data is achieved without unacceptable tuning.

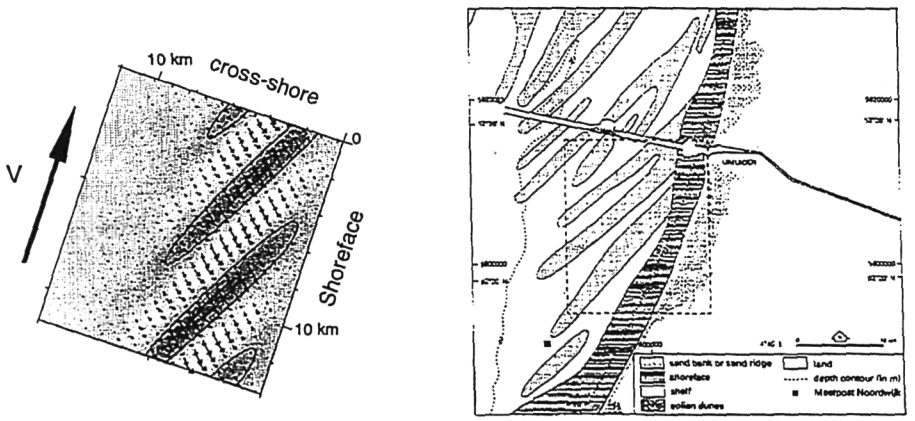


Fig. 6. Shoreface-connected ridge system on the Holland coast
left: from linear stability analysis; **right**: observed (Van de Meene, 1994)

A nonlinear anlysis of the interaction of synchronous edge waves and bed topography (Vittori et al., 1998) has shown that this explains the formation of cuspidal and crescentic inshore bar features.

The theoretical work on tidal sandbank and sandwave formation in shallow shelf seas has been verified against data on the occurrence of these features in the North Sea (Hulscher and Roelvink, 1997). The theoretically identified parameters were shown to discriminate between occurrence and non-occurrence, indeed.

Linear and nonlinear stability analyses of the behaviour of channel/shoal systems in short tidal embayments (Schuttelaars and De Swart, 1997) revealed that it is the nonlinear interaction which makes these systems migrate across the inlet.

7. CONCLUSION

We can conclude from the foregoing, that the prediction of large-scale coastal behaviour (LSCB) is a relevant research issue, in which a number of challenging question have to be answered. Research in this area is in full swing now, e.g. in the PACE-project. From the broad scatter of approaches in use, we can conclude that the prediction methodology is still in an early stage of development.

ACKNOWLEDGEMENT

This paper was written on behalf of the Technical Committee of PACE, under Marine Science and Technology contract no. MAS3-CT95-0002. The author is greatly indebted to the other members of the TC, viz. Michele Capobianco, Marcel Stive, Alan Niedoroda and Howard Southgate, and to the other colleagues who have gone through the effort of summarizing the work in the various parts of the project.

REFERENCES[1]

Aarninkhof, S.G.J., Janssen, P.C. and Plant, N.G., 1997. Quantitative estimations of bar dynamics from video images. In: *Coastal Dynamics '97*, ASCE, New York (in press).
Capobianco, M., Larson, M., Kraus, N.C. and Nicholls, R.J., 1997. Depth of closure: toward a reconciliation of theory, practice and evidence. In: *Coastal Dynamics '97*, ASCE, New York (in press).
Cowell, P.J., Roy, P.S. and Jones, R.A., 1995. Simulation of LSCB using a morphological behaviour model. *Mar. Geol.*, 126: 45-61.
Cowell, P.J., Hanslow, D.J. and Meleo, J.F., 1998a. The shoreface. In: A.D. Short (ed.): *Beaches and shoreface morphodynamics*. Wiley (in press).
Cowell, P.J., Roy, P.S., de Boer, P.L. and Cleveringa, J., 1998b. Simulating coastal systems tracts using the Shoreface Translation Model. *IAS Special Publ.*, Blackwell Sci. Publ., Oxford (in press).

[1] For further information on recent results of which no references are given below, we refer to the Year-2 Scientific Report of PACE, which is available through the coordinator.

De Vriend, H.J., 1995. G6/G8 Coastal Morphodynamics. In: M. Weydert et al. (Editors): *Marine Sciences and Technologies: Second MAST-days and EUROMAR-market*, Comm. of the European Communities, ISBN 92-827-5010-8, p. 631-650.
De Vriend, H.J., 1997. Prediction of aggregated-scale coastal evolution. In: *Coastal Dynamics '97*, ASCE, New York (in press).
De Vriend, H.J., Capobianco, M., Chesher, T., De Swart, H.E., Latteux, B. and Stive, M.J.F., 1993b. Approaches to long-term modelling of coastal morphology: a review. *Coastal Engineering*, 21(1-3): 225-269.
Falqués, A., Calvete, D., De Swart, H.E. and Dodd, N., 1998. Shoreface connected ridges: a simple mechanism for their initiation and evolution. Paper to be presented at *ICCE'98*, Copenhagen, June 1998.
Hamm, L. (Editor), 1997. *Summary of available datasets*. PACE Task Force on Datasets, Sogreah internal report 51 8906 R1.
Hasselmann, K.H., 1993. PIP's and POP's: the reduction of complex dynamical systems using principal interaction and principal oscillation patterns. *J. Geoph. Res.*: 11.015-11.021.
Holman, R.A., 1997. Bulk comparisons of the world's beaches. In: *Coastal Dynamics '97*, ASCE, New York (in press).
Hulscher, S.J.M.H., 1996. *Formation and migration of large-scale, rhythmic seabed patterns*. Ph.D. thesis, University of Utrecht, 143 pp., ISBN 90-939-1447-0
Hulscher, S.J.M.H. and Roelvink, J.A., 1997. *Comparison between predicted and observed large-scale sea bed features in the North Sea.* University of Twente / Delft Hydraulics Rept. H2487.
Jansen, H., 1997a. *POP-analysis of the Jarkus data set: the IJmuiden-Katwijk section.* Delft Un. of Techn., Fac. SIS, Rept. RIKZ-319, 55 pp.
Jansen, H., 1997b. *Advanced data analysis methods in morphodynamical research: a feasibility study of PIP and POP analysis of the Jarkus data set.* Delft Un. of Techn., Fac. SIS, Rept. 97-17, 32 pp.
Jiménez. J.A. and Sánchez-Arcilla, A., 1997. A conceptual model for barrier coasts behaviour: application to the Trabucador Bar (Ebro delta, Spain). In: *Coastal Dynamics '97*, ASCE, New York (in press).
Lippmann, T.C. and Holman, R.A., 1989. Quantification of sand bar morphology: a video technique based on wave dissipation. *J. Geoph. Res.*, 94(C1): 995-1011.
Nicholls, R.J. and Birkemeier, W.A., 1997. Morphological and sediment budget controls on depth of closure at Duck, NC. In: *Coastal Dynamics '97*, ASCE, New York (in press).
Nicholson, J. and O'Connor, B.A., 1995. A one-dimensional cross-shore transport model. In: W.R. Dally and R.B. Zeidler (eds.): *Coastal Dynamics '95*, ASCE, New York, p. 795-805.
Niedoroda, A.W., Reed, C.W., Swift, D.J.P., Arato, H. and Hoyanagi, K., 1995. Modelling shore-normal large-scale coastal evolution. *Marine Geology*, 126: 181-199.
Pruszak, Z. and Rozynski, G., 1997. Variability of multi-bar profiles in terms of random sine functions. Accepted for publication in *ASCE J. Waterway, PCO Eng.*
Reeve, D.E. and Fleming, C.A., 1997. A statistical-dynamical method for predicting long term coastal evolution. *Coastal Engineering*, 30(3-4): 259-280.
Rijkswaterstaat, 1998. *Predicting coastal evolution: tuning research objectives and end-user requirements*. Rijkswaterstaat, Nat. Inst. Coastal and Marine Mangt., Rept. RW 679.1.
Sánchez-Arcilla, A. and Jiménez, J.A., 1996. A morphological "mixed-type" model

for the Ebro Delta coast. In: B.L. Edge (ed.), *Coastal Engineering 1996*, ASCE, New York, 2806-2819.
Sánchez-Arcilla, A., Jiménez, J.A. and Valdemoro, H.I., 1998. The Ebro Delta: morphodynamics and vulnerability. Accepted for publication in *J. Coastal Res.*
Schuttelaars, H.E. and De Swart, H.E., 1997. Cyclic bar behaviour in a nonlinear model of a tidal embayment. In: F.M. Holly, A. Alsaffar, M. English and A. Szollosi-Nagy (eds.): *Managing Water: Coping with Scarcity and Abundance*, Proc. 27th IAHR Congress, ASCE, New York, p. 28-33.
Southgate, H.N., 1995. The effects of wave chronology on medium and long term coastal morphology. *Coastal Engineering*, 26(3/4): 251-270.
Southgate, H.N. and Capobianco, M., 1997. The role of chronology in long term morphodynamics; theory, practice and evidence. In: *Coastal Dynamics '97*, ASCE, New York (in press).
Southgate, H.N. and Möller, I., 1998. Fractal properties of beach profile evolution at Duck, North Carolina. Submitted to *J. Geoph. Res.*
Stive, M.J.F. and De Vriend, H.J., 1995. Modelling shoreface profile evolution. *Marine Geology*, 126: 235-248.
Stive, M.J.F., De Vriend, H.J., Nicholls, R. and Capobianco, M., 1992. Shore nourishment and the active zone: a time-scale dependent view. In: B.L. Edge (ed.), *"Coastal Engineering 1992"*, ASCE, New York, p. 2464-2473.
Stive, M.J.F., Ruol, P., Capobianco, M., Bixio, A. and Buijsman, M., 1997. A behaviour-oriented model for the evaluation of long-term lagoon-coastal dynamic interaction along the Po river delta. In: *Coastal Dynamics '97*, ASCE, New York (in press).
Swift, D.J.P., Zhang, Y., Carey, J.S., Niedoroda, A.W., Reed, C.W. and Steckler, M., 1997. Coastal evolution: modelling fabric and form at successive spatial scales. In: *Coastal Dynamics '97*, ASCE, New York (in press).
Van de Meene, J.W.H., 1994. *The shoreface-connected ridges along the central Dutch coast*. Ph.D.-thesis. KNAG/Netherlands Geographical Studies 174, Utrecht, The Netherlands, 222 pp.
Vittori, G., De Swart, H.E. and Blondeaux, P., 1998. Longshore periodic patterns of the sea bottom morphology: an improved model. Paper to be presented at *ICCE'98*, Copenhagen, June 1998.
Wijnberg, K.M. and Terwindt, J.H.J., 1995. Extracting decadal morphological behaviour from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis. *Marine Geology*, 126: 301-330.

TITLE: The Kinematics and Dynamics of Wave-Current Interactions (KADWCI)

CONTRACT: MAS3-CT95-0011

COORDINATOR:
Dr. Gareth Thomas
Dept. of Applied Mathematics, University College Cork, Cork, Ireland
Tel. +353 21 902432 Fax +353 21 270813
E-mail: ThomasGP@ucc.ie

PARTNERS

Dr. Richard Simons
University College London
Dept. of Civil & Environmental Engineering, Gower Street, London WC1E 6BT, UK
Tel: + 44 171 380 7723 Fax: + 44 171 380 0986
E-mail: R.R.Simons@ucl.ac.uk

Dr. Ad Reniers
Delft Hydraulics
PO Box 177, 2600MH Delft, The Netherlands
Tel: + 31 15 285 8893 Fax: + 31 15 285 8582
E-mail: Ad.Reniers@wldelft.nl

Prof. Dag Myrhaug
Norwegian University of Science & Technology
Dept. of Marine Hydrodynamics, Faculty of Marine Technology, N-7034 Trondheim, Norway
Tel: + 47 73 59 55 27 Fax: + 47 73 59 55 28
E-mail: Dagmyr@marin.unit.no

Dr. Georges Chapalain
Universite des Sciences et Technologies de Lille
Laboratoire d'Ecologie Numerique, Bâtiment SN3, 59655 Villeneuve d'Ascq Cedex, France
Tel: + 33 320 43 67 30 Fax: + 33 320 43 67 32
E-mail: Georges.Chapalain@univ-lille1.fr

Dr. Christopher Swan
Imperial College
Dept. of Civil Engineering, Imperial College Road, London SW7 2BU, UK
Tel: + 44 171 594 5999 Fax: + 44 171 594 6053
E-mail: C.Swan@ic.ac.uk

The Kinematics and Dynamics of Wave-Current Interactions

G.P. Thomas

Dept. of Applied Mathematics,
University College Cork,
Cork, Ireland

Summary

The project *The Kinematics and Dynamics of Wave-Current Interactions* (KADWCI) began on 1st February 1996 and will run for a duration of three years. It is a combination of mathematical and numerical modelling, large-scale experimental measurement and the employment and acquisition of field data. Results are available from all of the targeted areas and a brief description of some of these is provided in the paper.

1. Introduction

The importance of the interaction of water waves and currents to coastal engineering has long been recognised and the need for its study does not require justification. Indeed it is surprising that it has not received more attention, given the enormous amount of published literature on water waves in the assumed absence of currents and the reality that waves rarely exist without the presence of a current of one form or another. To the uninitiated the range of currents is also bewilderingly wide. Commonly occurring examples are large scale currents which change relatively little over considerable distances, wind driven currents which are particularly important near to the free surface but decay rapidly with depth, currents associated with flows around headlands or which occur in the vicinity of an estuary. The various interaction theories and numerical models must be capable of flow (and possibly bed-stress) prediction in each of these diverse examples. For such a range of circumstances and currents, the task of simultaneously describing all categories of wave-current interactions is a quite daunting one.

For coastal engineering applications, it is impossible to predict nearshore wave climate, beach profile development, coastal morphology or pollution dispersal without first having a reliable means of describing wave and current hydrodynamics. This is true whether predicting the kinematics of the upper flow, current-induced refraction and bottom shear stresses separately, or addressing the complete flow field in a single model. It is almost always necessary to provide very approximate models of wave-current interactions into large coastal area models. This is the case with many other related coastal engineering phenomena, simply because it is not yet possible to include high levels of sophistication into very large numerical models that attempt to provide as complete a picture as possible of the local environment.

Many commonly used models are still dependent on assumptions about the dominant physical processes that are not valid, and it is important that fundamental research continues on approaches that more accurately describe the natural phenomena and then convey this information to practising coastal engineers. The project is a continuation of work that originated both in MAST-I and MAST-II (in the G6-M and G8-M Coastal Morphodynamics projects) and parallel national programmes; it thus builds upon a firm foundation of co-operative existing work.

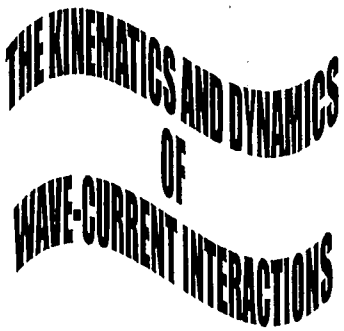
2. Project structure and strategy

The partnership is primarily comprised of the six participants listed on the frontispiece. There are also four *Affiliated Partners*: Delft University of Technology, Albatros Flow Research, the Danish Technical University and LEGI in Grenoble. The individual affiliated partners do not participate in a standard way: they may participate fully by way of zero funding, by sub-contract to the main participants or by simply providing expert advice as it is needed. Whatever the method of contribution, they have already provided considerable input, expertise and enrichment to the project.

The project work programme is organised into three principal Work Packages: *Regular Wave Kinematics*, *Irregular Wave Kinematics* and *Bed Stresses*, with each main work package sub-divided into three or four sections as necessary. This ensures that the work packages are relatively easy to manage and are tightly co-ordinated, with little duplication of effort. Only a small number of partners work on individual topics and the structure is chosen to link modelling to experiments or field data whenever possible. Although each work package has been designed for maximum operational efficiency it is not necessarily a stand-alone structure. Experimental programmes, whenever possible, have been designed to provide maximum output and may well provide a valuable contribution to all three work packages.

The project concentrates upon both the kinematics of the whole flow field and bed shear stresses: both are measured simultaneously in the experimental programmes whenever possible. The acquisition and employment of reliable field data to understand bed shear stresses forms an integral part of this project. All suitable data, whether from laboratory or field, is then used for input to numerical models, validation of existing models and assessment of real fluid effects. This approach, together with the fact that there are usually modellers within the experimental and field data groups, ensures that there is tight co-ordination between modellers and experimentalists. Sediments are not included and attention is primarily restricted to a rigid horizontal bed, but with both regular and irregular waves in two and three dimensions.

The development of predictive numerical models accompanies the experimental programmes and is specifically targeted at those areas for which the theories are not yet well developed. These include wave kinematics in 3-d (regular & irregular waves) and the prediction of kinematics and bed shear stresses simultaneously using complete flow models. However, it is to be stressed that experiments at small laboratory scale, large laboratory scale and in the field serve an illuminatory role, rather than just for model validation. Without such a role, consistent models for complicated natural phenomena cannot be developed.



The fundamental process approach adopted within this project is a vitally important one. If future success in the understanding and modelling of coastal morphology is to be ensured then the fundamental processes must be physically well-understood, well-modelled at a fundamental scale and approximated accurately in large-scale morphological models. This paper attempts to provide an overview of the project by presenting a number of selected topics to illustrate the variety of topics covered in a coherent manner.

3. Results to date

It is not possible in a brief survey paper to pay due regard to all of the work that has been completed within the project to date. There is much laboratory and field data; many of the mathematical models are of a very sophisticated nature and innovative numerical techniques have also been developed. It is more appropriate to attempt to represent the progress and achievements of the project by selecting a generic subset of the broad spectrum of the problems under consideration and then to either present the results obtained to date or describe work in progress. However, before reporting on selected topics, it is expedient to look at the concept of a current as typically employed in wave-current interaction studies.

The schematic in figure 1 shows a generic wave-current interaction in two dimensions and is included to provide a descriptive notational basis for the following work, without requiring a recourse to mathematical definitions. The surface wave profile shown is regular but the description is equally appropriate to a profile of the form $z = \eta(x,t)$ which varies irregularly with space and time.

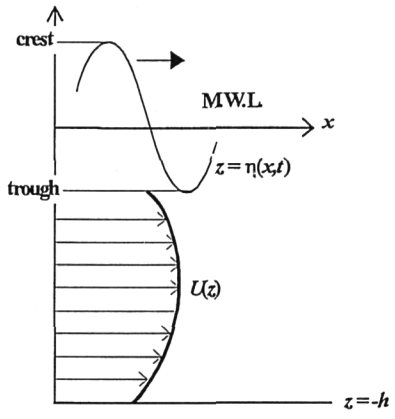


Figure 1. A schematic showing generic wave-current interaction in two dimensions.

In spite of the seemingly simple portrayal in figure 1, the concept of a current is open to discussion and dispute. The most usual and traditionally employed interpretation is one in which the current is considered to be separate from the wave motion and is associated with indicate the presence of some mean flow that does not depend on the presence of a wave field for its existence. However, this is not the only definition and it is known that the wavefield can play an important role in the generation of the current profile associated with some externally imposed mass flux; the mean mass flux associated with the waves can also be considered as representing a current. An extensive discussion on the topic is included in the recent review by Thomas & Klopman (1997).

For the present purpose two definitions of the current $U(z)$ will be relevant and there will be no ambiguity in the context in which each occurs. The first assumes that $U(z)$ is deemed known beforehand and that knowledge of the generative processes that produce $U(z)$ is not required. In the absence of a better terminology, models of this type can be labelled *reactive* and most traditional wave-current interaction models fall into this category. The second kind, designated *generative*, attempts to determine the function $U(z)$ which exists under certain specified conditions. As a general rule it is much easier to work with reactive models than with generative ones.

With the definition of a current established, and the difficulties acknowledged, the next step is to present the various aspects of the project work. The approach adopted is to start with the conceptually simplest cases, although these are not necessarily the easiest to deal with, and increase in complexity until the most difficult is attained. There are seven topics in total, beginning with the idealised two-dimensional regular waves depicted in figure 1 and ending with the acquisition and processing of field data.

3.1 Complete flow models for regular waves

A good understanding of local regular wave kinematics, in two dimensions, provides an important foundational basis for many modelling aspects of the whole project. It is fair to say that, within the broad field of wave-current interactions, only two-dimensional wave-current interactions in the absence of viscosity and turbulence are reasonably well understood. However, the influences of turbulence and viscosity have long been recognised as important mechanisms in the generation of phenomena such as slow drifts and wave-induced near-bed streaming. Both can be associated with sediment transport and for this reason it is important to address this major gap in the existing knowledge base.

To emphasise the existing position and to clearly identify the requirement for further model development, consider the experimental current profile shown in figure 2 that was obtained in a previous MAST programme by Klopman (1994). This corresponds to the case in which the waves and the current are in the same direction with the experimental data defined by water depth $h = 0.500$ m, wave frequency $\omega = 0.6944$ Hz and wave amplitude $a = 0.05987$ m. The predictions employing existing inviscid models are shown alongside in figure 3, in which the magnitude of the first harmonic of the horizontal wavelike velocity component $|u_1(z)|$ is plotted against the non-dimensional depth z/h.

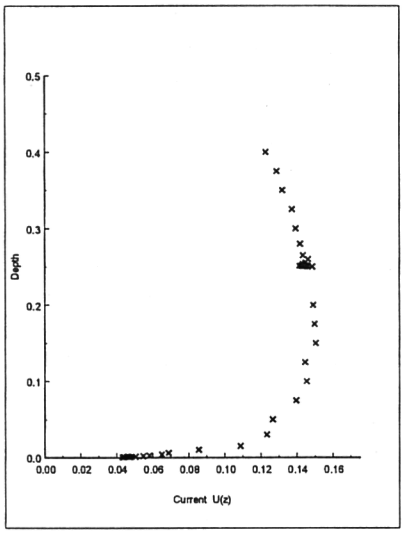


Figure 2. The current distribution $U(z)$ from Klopman (1994) appropriate for waves following a current.

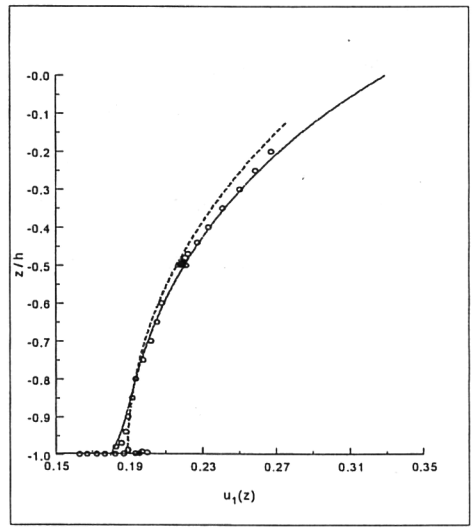


Figure 3. Prediction by inviscid models of $|u_1(z)|$ with non-dimensional depth z/h, —— Thomas & Klopman (1997); – – – depth-averaged current; o Klopman (1994).

Figure 3 shows that the inviscid models provide a good estimate over the vast majority of the flow domain. It is also clear that this is not true near to the bed. In addition, as the waves are weakly nonlinear in this case, it is to be stressed that very little difference is expected between the predictions of the linear and nonlinear models. Also shown in figure 3 is the prediction from an irrotational constant current model, based upon the depth averaged current, and this is seen to provide surprisingly good estimates over the water depth. The bottom 5% of figure 3, corresponding to 0.025m, is shown on an enhanced scale in figure 4, so that the shape of the data and the failure of the inviscid models can be readily identified.

From a comparison of figures 2 and 3, it can be seen that the inviscid model works reasonably well to within the layer defined by approximately the bottom 2% of the water column; corresponding to a physical distance of 0.01m. The standard practice in modelling wave-current interactions is to divide the fluid domain into two distinct regions: the main body of the fluid, which is effectively inviscid, and the shear layers at the free surface and near the bed where viscosity and turbulence are considered important. The applicability of this approach has been confirmed by the figures 3 and 4 presented above. Not surprisingly the region near to the bed has received considerably more attention than the shear layer at the free surface.

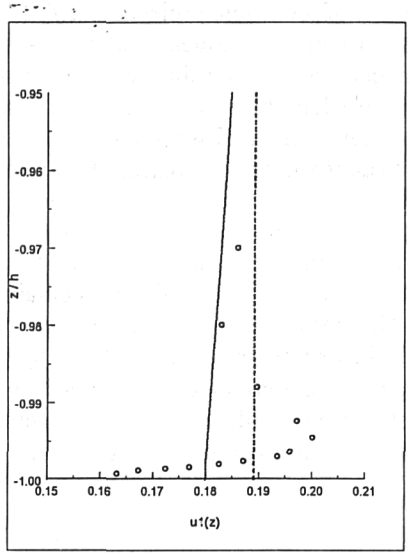


Figure 4. The bottom 5% of figure 3.

Bottom boundary layer models usually assume that the motion in the oscillatory bottom boundary layer can be modelled by allowing the presence of a uniform current at the upper extremity of the boundary layer, so that the vertical shear in the current distribution is neglected. A considerable number of turbulence and viscosity models have been developed to predict the bed shear stresses but this is readily acknowledged to be a very difficult task for flow over roughened beds, even with the constant current approximation. An excellent state-of-the-art assessment has been provided by Soulsby *et al* (1993).

A major difficulty with the usual boundary layer approach is that the shear present in the current at the edge of the boundary layer is not incorporated into the models. To remedy this deficiency, existing complete flow models have been extended and new ones developed within the project. These involve the development of innovative numerical schemes to provide accurate solutions over the whole of the flow field and clearly these must be coincident with the existing numerical schemes over the majority of the flow field. Such modelling is at a very early stage. Figure 5 illustrates the bottom 2% of the flow obtained by employing the new solutions methods corresponding to viscosity alone; the upper 98% is not shown as it coincides with the same portion of figure 3. The figure is taken from Madden *et al* (1997) and this paper also includes initial attempts to include turbulence. These preliminary results are very encouraging and work is continuing on the development of improved turbulence models.

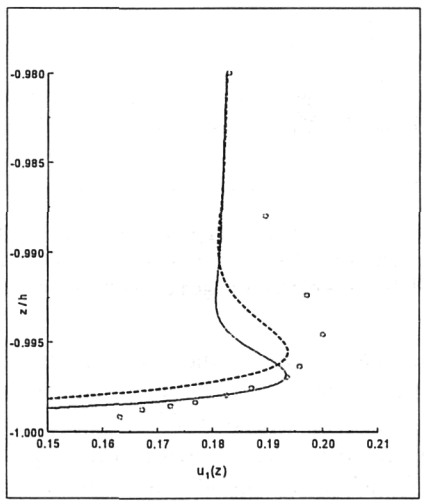


Figure 5. The profile of $|u_1(z)|$ against z/h in the absence of turbulence, —— ν = 1.0d-6; – – – ν = 2.0d-6; o Klopman (1994).

3.2 Experimental study on three-dimensional wave-current interactions

No satisfactory numerical models or general analytic solutions exist for wave-current interactions in three-dimensions when the current possesses both vertical and horizontal shear; this is true even when the waves are small and within the linear regime. The majority of existing models typically assume that the currents are large-scale, so that the waves may be considered locally uniform and that changes in the wave properties occur over length scales of many wavelengths. Ocean currents often satisfy this requirement but in the coastal environment both river outlets and tidal races can produce currents characterised by rapid variation in strength occurring over length scale of a wavelength.

A very major deficiency in regard to model development is that experimental data is simply not available for the case where the current possesses a jet-like character and may also vary in the vertical direction. The reasons for the scarcity of experimental data are clear: the difficulties and expense of constructing and financing suitable experimental facilities, together with the acquisition of expertise in performing experiments of this kind. An important experimental programme has been instigated within the project to study the refraction of near-linear regular waves in constant water depth by jet-like currents characterised by strong horizontal shearing. In addition the programme will eventually also provide benchmark data for the wider coastal engineering community.

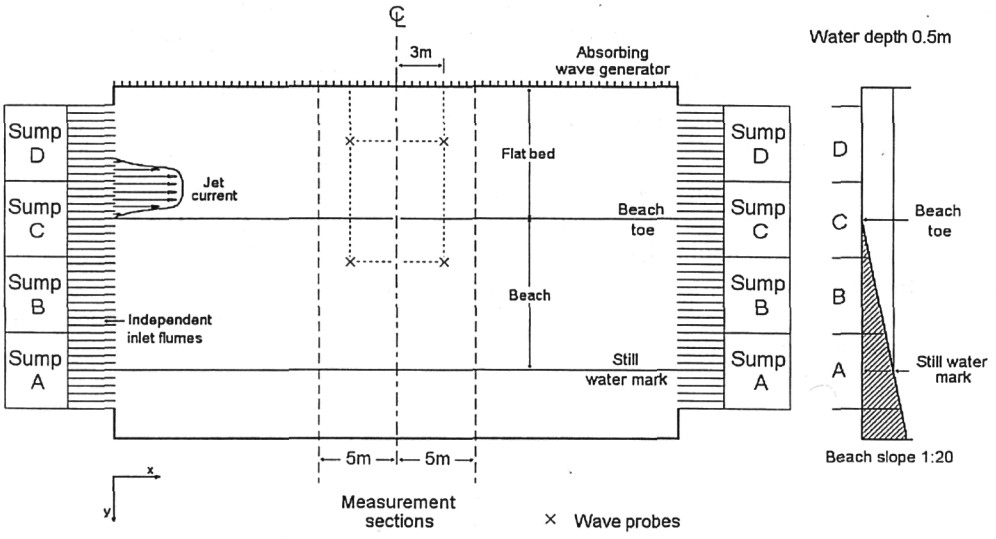


Figure 6. Schematic of the UK Coastal Research Facility at HR Wallingford

The experiments were conducted at the UK Coastal Research Facility (UKCRF) at HR Wallingford and this facility is shown schematically in figure 6. The overall dimensions of the facility are 54m by 27m and in cross-section it consists of a flat bed region between a multi-element wave generator and a beach region with a 1-in-20 slope. Waves can be generated at angles between $\pm 30^{\circ}$ to the shore-normal. Shore-parallel currents are produced using four independent pumps, each of which draws from and discharges into a dedicated sump. For each sump the discharge into, and out of, the basin is further controlled through ten undershot sluice gates and guide flumes allowing fine control of the cross-shore distribution of the current. For most of the present experiments the water depth was maintained at 500mm and some runs were made at 300m for specific test conditions.

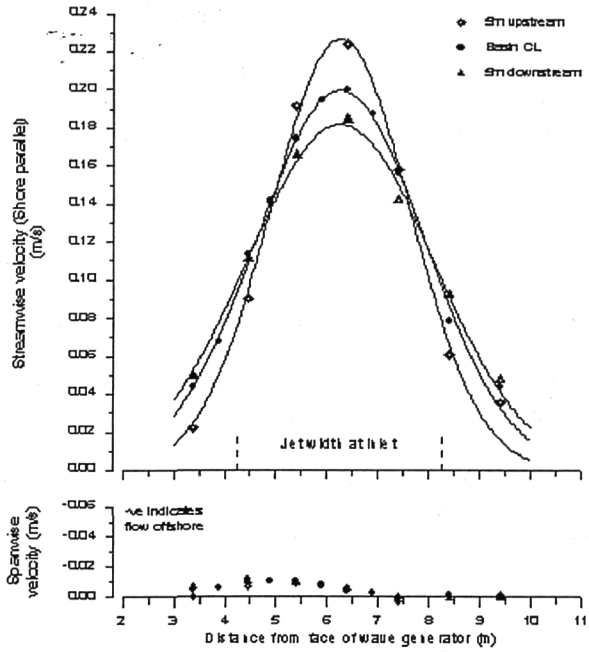


Figure 7. Development of depth-averaged jet current velocity distribution through measurement section in figure 6.

Figure 7 shows the stream-wise variation of the jet-like current profile for the measuring section shown in figure 6. The current value is depth-averaged and exhibits a spreading in the way that is to be expected. Such jets are naturally unstable but are also extremely difficult to generate satisfactorily within a closed facility. This can be seen from the lower portion of the figure, in which the shorewise current velocity component associated with the mechanism can be identified.

Preliminary results from the study and a more complete description of the facility are provided by MacIver & Simons (1997). Figure 8 shows the variation in the horizontal orbital velocity components across the current when waves of 0.8s period meet the current at a following angle of 30°. This figure has the same span-wise scale as employed in figure 7 and the refraction associated with the interaction can be clearly seen, with the maximum change in refraction being just over 10°. It should also be noted that the incident wave, propagating from the still water region across the jet current, can experience partial reflection while the transmitted wave will be refracted as it propagates through the current and onto the beach.

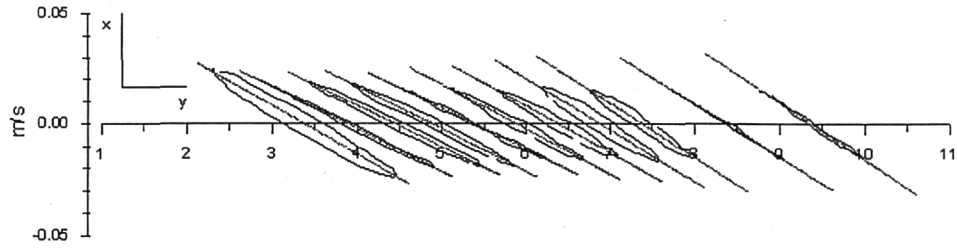


Figure 8. The oscillatory components of the horizontal velocity vector on a transverse section across the tank. The waves follow the current and are incident at angle of 30°.

A number of similar experiments have also been performed for regular waves meeting an adverse current at an angle of 30° and the test programme also includes some experiments with irregular waves. Representative stresses were measured in some tests by employing shear plates at a number of carefully selected locations. This important experimental programme supplies data to a number of components of the project.

3.3 Generation and structure of current profiles

The current profile shown in figure 2 for waves following the current was employed for the reactive wave-current viscosity and turbulence models outlined in §3.1. However, this straight presentation of a current profile hides a very intriguing property associated with current profiles and also an important one with regard to both flume experiments and engineering approximation. When the waves are adverse to the current then the current profile is not simply a mirror image of that presented in figure 2, i.e. it does not just possess the same magnitude and act in the opposite direction, but is instead markedly dissimilar.

This difference between the structure of the following and adverse currents is shown in figure 9, which incorporates figure 2, and the current in the absence of waves is also shown. Thus the interaction causes a change in the current profile and this change is clearly different in the following and opposing cases. In terms of engineering approximation and reactive modelling, it has long been established that the wave kinematics associated with the following current can be well approximated by employing a constant current with the same mass flux as the real current. For the adverse current, good approximations can be obtained by approximating the current by a linear profile. The rationale for adopting such an approach can be justified by consideration of the figure alone. These working approximations are surprisingly accurate in the region away from the bed and are reviewed by Thomas & Klopman (1997).

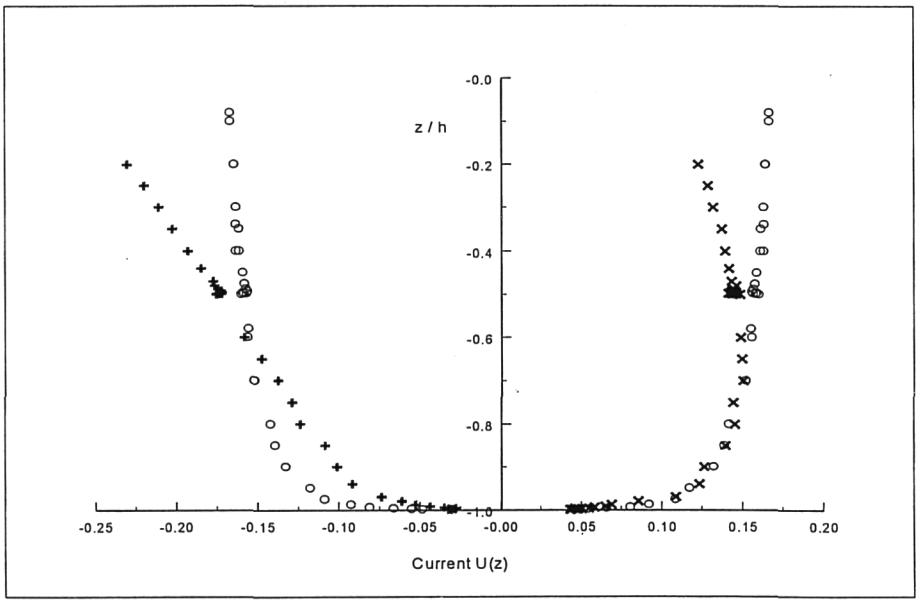


Figure 9. Experimental data of Klopman (1994) showing the difference between following and adverse current profiles. × adverse current, + following current, o no waves.

At this point we know how to predict the kinematics reasonably well when $U(z)$ is given but do not know how this change in profile occurs and the first step along this path of understanding is to identify the mechanisms that causes the change. Clearly this can only be due to the interactive process between the waves and current and must involve turbulence and/or viscosity as inviscid fluids do not possess any properties that can effect such a

momentum redistribution. It is also necessary to utilise generative models rather than the reactive ones and start with the current profile in the absence of waves.

Most standard wave theories adopt an Eulerian representation in which the whole velocity field is considered at any given time. This approach has generally worked satisfactorily but does possess some disadvantages, such as the ambiguity associated with the definition of a current outlined at the beginning of this section. If individual particles are followed then a Lagrangian representation is employed and the position of an individual particle is given as a function of time; this too has disadvantages with regard to current definition. A more recent representation is the Generalised Lagrangian Mean (GLM) description and this combines the advantages of the more traditional approaches to overcome many of the existing difficulties. This has been employed by Groeneweg and Klopman (1998) to predict the current changes due to the wave-current interaction as is presented in figure 10.

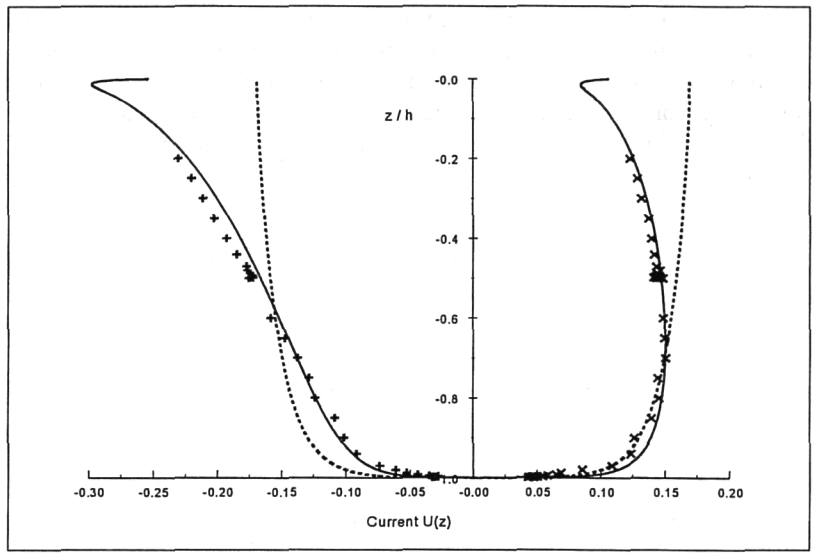


Figure 10. The predictions from Groeneweg & Klopman (1998) of following and adverse current profiles. —— predicted profiles, - - - analytic model of no-waves current profile, ×, + measured data.

The agreement between theory and experiment is very encouraging and confirms that the changes in profile are primarily due to the influence of turbulence. Note that measured currents are only available below the wave trough when waves are present and up the horizontal free surface in the absence of waves.

3.4 Secondary currents in wave-current experiments

The GLM model of Groeneweg & Klopman, with predictions presented above, is not the only attempt to explain the change in current profile when the waves are present, although it is the most successful to date. Another model of interest is the quasi three-dimensional model of Dingemans *et al* (1996), which employs the so-called Craik-Leibovich (CL) Vortex Force. Once more the mathematical details are confined to the original papers but the predictions of the model have important consequences for experimentalists attempting to conduct studies on wave-current interactions in wave flumes. While the current profile for waves with following current is given by figure 2, there is also cross-current variation due to finite-width flume effects. This manifests itself as a set of complete large-scale circulation cells similar to Langmuir circulations. The direction of rotation depends upon whether the waves follow or

oppose the current and the appropriate pattern for waves following the current is shown schematically in figure 11. Waves adverse to the current suggest a circulation in the opposite direction.

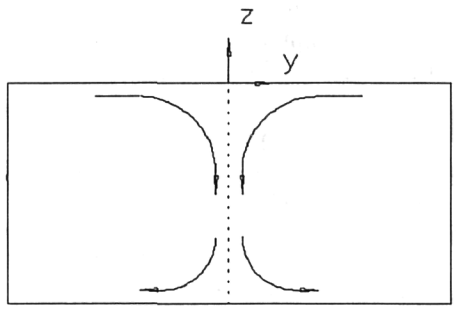


Figure 11. Schematic of lateral mean flume circulation when the current follows the waves.

The question then arises as to the magnitude of the velocities associated with the circulations and then as to whether or not they can be avoided. The supplementary question is easier to answer: they can be delayed in formation but not prevented. Determining the magnitude is a much more difficult problem and the predictions by Dingemans *et al* corresponding to the experimental data depicted in figures 2 and 3 for current and wavefield is shown in figure 12. In this figure, the horizontal and vertical dimensions shown correspond to the cross-section of the flume dimensions and test conditions. The maximum velocity associated with the circulation has a magnitude of about 0.020 m/sec, occurring at the centreline, whereas the mean value of $U(z)$ in figure 2 is approximately 0.16 m/sec.

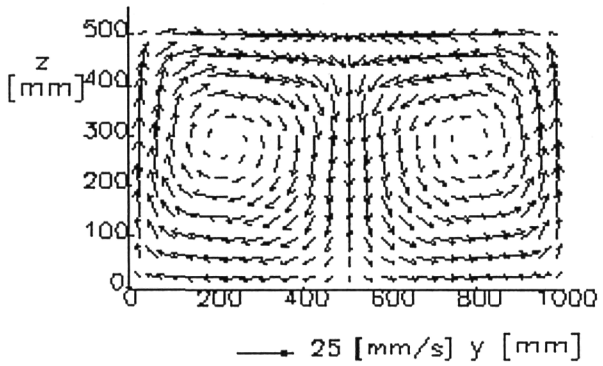


Figure 12. Predicted lateral circulation pattern for experimental profile shown in figure 2.

The hypothesis has a number of implications for laboratory experiments associated with coastal engineering applications. Perhaps the most obvious one is that lateral variations in the current profile must be taken into account in wave kinematic studies. Another potentially important one is related to the bottom boundary layer: the predicted maximum velocities occur at the boundaries and at the centreline of the flume and the occurrence at the bottom boundary has implications for sediment transport studies.

A set of experiments was instigated within the project by Klopman (1997), with the sole intention of measuring the secondary flow circulations and then comparing the experimental findings with the predictions outlined above. Both following and adverse currents were employed, as was a current in the absence of waves, and the experimental conditions were essentially a repeat of those yielding the centreline current profiles along the flume shown in figure 9. The comparison between theory and experiment showed qualitative agreement with the predictions. In each case the secondary circulations were clearly detected and the circulations were in the directions predicted by the theory. However, the details of the predicted and measured circulations did not agree, with over-prediction of velocity magnitudes and non-symmetric circulation cells being the most obvious discrepancies. Investigation by experiment and modelling is continuing.

3.5 Experiments on irregular waves with strongly-sheared currents

The interaction between currents and irregular waves has not generally received the attention that it deserves and the reasons for this are clear: modelling is difficult and experiments are not easy to perform. However, this very important subject must be considered as the most general case of a wave-current field and cannot therefore be ignored within any respectable project involving coastal engineering applications of wave-current interactions.

The standard approach to modelling wave-current interactions with irregular waves is to assume that the current is locally uniform and this is true for the simplest case of two-dimensional flow within the linear wave regime. It is also important to acknowledge the possible influence of vorticity and viscous / turbulence mechanisms, which may play more significant roles on differing frequency components. As this is a very difficult task, the study has begun with an experimental programme to assess the influence of vorticity and the applicability of existing reactive numerical models. The experiments were conducted in a narrow wave flume at Imperial College, London, which has been constructed especially for studies involving currents with a strong vertical shear near to the free surface. Such currents constitute models of wind generated currents and the facility also possesses the ability to include wind effects when necessary. The work outlined below will be described more fully by Swan & James (1998)

The experimental procedure determines the measured spectral changes as irregular waves propagate onto a strongly sheared following current, so that the waves can be taken to originate in still water and then progress onto the current. A Pierson-Moskowitz spectral form is used, defined by a wind velocity of 1.66 m/s, and the mean water depth in the flume is 0.70m. The significant wave height H_s and zero-upcrossing period T_z corresponding to the experimentally measured data on quiescent water and the wave-current combination are H_s = 0.062m, H_s = 0.045m and T_z = 0.943secs, T_z = 0.928secs respectively. Under such parameters the wavefield may be described as weakly nonlinear.

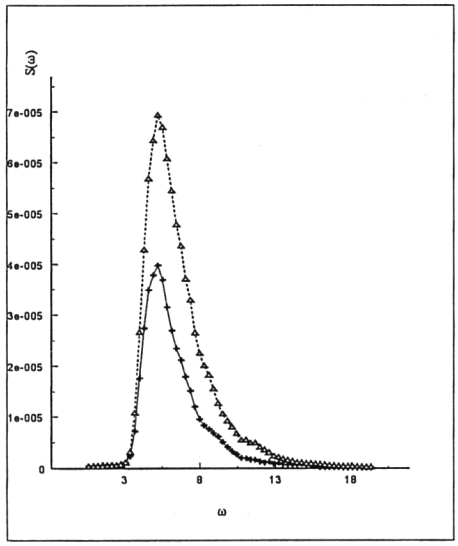


Figure 13. The measured spectral density $S(\omega)$ with and without a current, Δ waves alone, + waves and current.

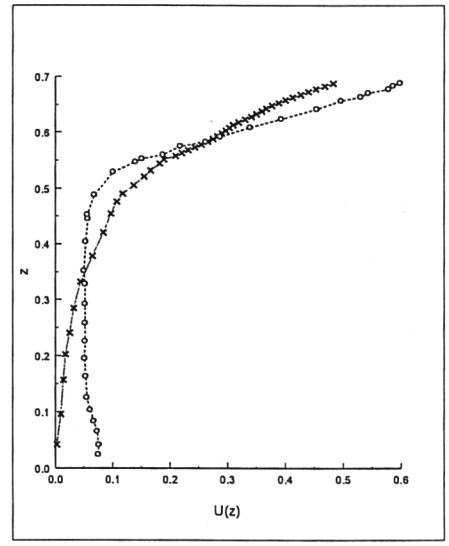


Figure 14. The vertical current profile $U(z)$, in a Lagrangian representation, with and without waves, o current alone, × waves and current.

The influence of the wave-current interaction is demonstrated in figures 13 and 14 in rather a dramatic manner. Figure 13 shows the input spectrum for the waves on quiescent water and the change induced by the wave-current interaction, with a reduction in H_s of approximately 25%. The accompanying change in the current profile due to the presence of waves in figure 14 clearly shows that if reactive models are to be applied to describe the interaction, then the current employed must be the profile when waves are present. This change is in current profile is analogous in some ways to the situation considered in §3.3 for regular waves but the circumstances are different as the current profile is markedly different. With the importance of the current now demonstrated, it is now necessary to determine whether the current shear is an important factor in this process or whether most of the change could be predicted by inclusion of a Doppler shift with a uniform current.

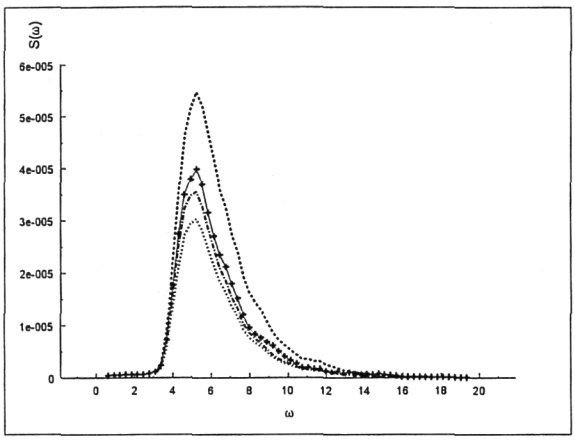


Figure 15a. Predicted and measured S(ω) for the wave-current spectrum of figure 13, + measured spectrum, - - - Fifth order Stokes wave, depth-averaged current, - · - Second order linear shear theory, ···· Fifth order Stokes wave, surface current value.

A number of well-known existing regular wave numerical models were employed on a frequency component basis to predict the spectrum corresponding to the amended current profile shown in figure 14. These correspond to Stokes fifth-order models for two possibly representative uniform currents: the first corresponds to the depth-averaged mean and the second to a current with the same value as the real current at the surface. A second order model in which the current was approximated by a linear profile was also employed and in this case the wave field is irrotational. The predictions are seen in figure 15a to be generally woefully inadequate. This confirms that the vorticity distribution in the current is an important factor.

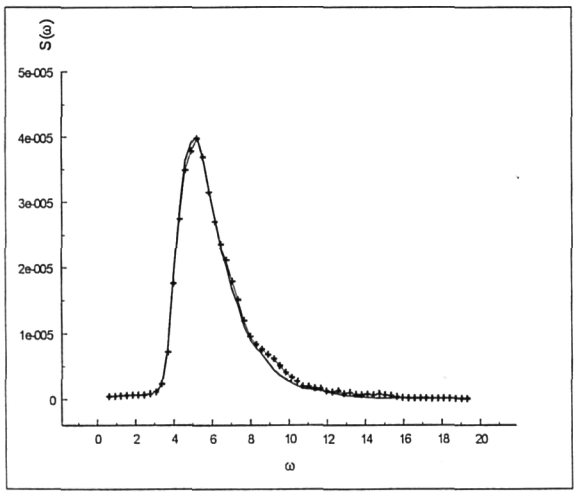


Figure 15b, As for figure 15a, on a slightly enlarged scale.
+ measured spectrum, — 8th order streamfunction model.

The final model employed was a streamfunction model, which accurately models the current and has been validated for regular waves. This is clearly seen in figure 15b to provide an excellent prediction, confirming the earlier hypothesis on the importance of vorticity. However, these comments should be taken in context of the current profile employed, with a strong vertical shear, and not generalised to profiles of the form shown in figure2.

3.6 Seabed shear stresses under irregular waves

The prime purpose of studying bed stresses within any coastal engineering project is to enable good predictions to be made in the field. Clearly the step from developing a mathematical model or obtaining laboratory data to possessing the ability to predict bed stresses reliably and accurately in the physical environment is a very major one. The standard approach is one of incremental improvement, so that better models are implemented after they have been validated. As model development utilises reliable field data for calibration and validification then an obvious requirement is that good field data is available for model calibration. In a study on the prediction of bed stress under random waves interacting with tidal currents, data has been employed from two sites. These are a test site in the Strait of Juan de Fuca, Washington State and at the EDDA site in the North Sea; the water depth was18m and 70m respectively and the sites are shown in figures 15 and 16.

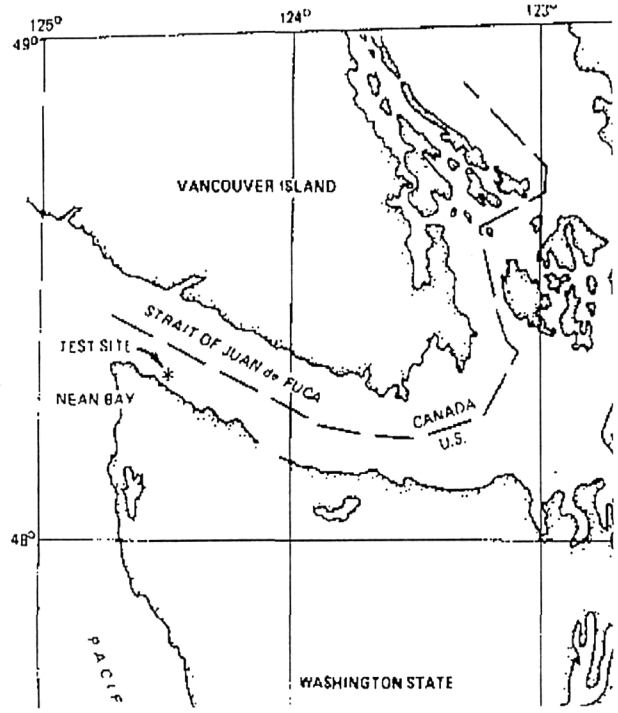


Figure 15. Site of field data measuring point in the Strait of Juan de Fuca, Washington State, USA.

The Strait of Juan de Fuca data was collected over the winter of 1980-81 as part of the Pipeline Field Measurements Program (PFMP). The seabed roughness was of gravel type, about 5 cm in diameter on average. No measurements were made of suspended sediments but sediment stratification was probably minimal due to the bottom configuration. Orthogonal horizontal components of total (wave plus tidal current) velocity were measured at the five elevations ranging from 0.24 to 3.66m from the seafloor using flowmeters mounted on a mast fixed to a base platform.

The EDDA North Sea data was collected over the winter of 1984-85. Measurements included flow velocity close to the seabed, seabed configuration (ripples), suspended sediment concentrations, steady current over the water column, and waves by using a directional buoy. Orthogonal horizontal components of wave plus tidal current velocity were measured at six nominal elevations ranging from 0.10 to 5.00m from the seabed using acoustic current meters. The seafloor was generally flat and uniform, consisting mainly of fine sand and the mean grain size diameter for the bottom sediments was 0.20 mm

All models employing real data by necessity require a number of simplifying assumptions concerning the local wave field, the structure of the seabed and often in the data processing. As the bottom shear stresses were not measured directly, it was necessary to estimate them from the velocity data by fitting a damped oscillator model fit to the data. Three different

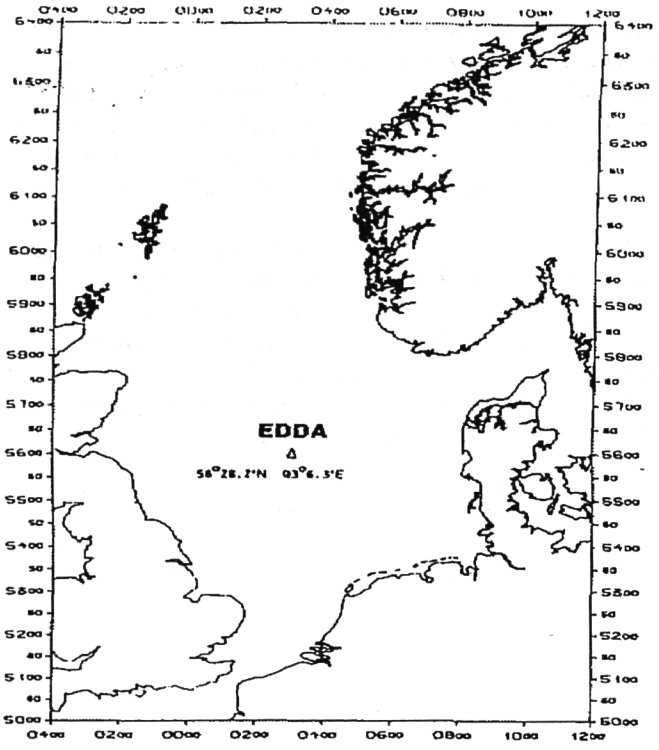


Figure 16. The EDDA site in the centre of the North Sea.

quantities representing the irregular waves within 12-minute records were used when predictions and estimates of seabed shear stresses are compared. These are the root-mean-square, significant and maximum values and are indicated by the suffices *rms*, *s* and *max* respectively. Details of the procedures are presented by Myrhaug et al (1998) and in the earlier papers referenced therein.

The three significant values of the bed stress τ/ρ for the Estimated Field Measurements (EFM) and Predicted-to-Measured ratios (P/EFM) are given in Table 1. These results include the PFMP data and the North Sea/E23 storm data using the z_0 values 0.25 cm (from the fitted logarithmic flow model) and 0.50 cm (taken as a representative upper value for the observed ripple geometry), respectively.

	τ_{rms}/ρ		τ_s/ρ		τ_{max}/ρ	
Record No.	EFM	P / EFM	EFM	P / EFM	EFM	P / EFM
PFMP -1	189	0.95	266	1.00	404	1.07
2	137	1.03	194	1.07	290	1.17
3	186	0.87	262	0.91	394	0.99
E23 -1	86	0.66	122	0.69	184	0.76
2	85	0.66	119	0.70	179	0.77
3	75	0.62	106	0.65	159	0.73
4	76	0.59	107	0.63	161	0.70
5	73	0.59	104	0.62	156	0.70
6	71	0.60	101	0.62	152	0.69
7	70	0.56	100	0.58	149	0.66
8	67	0.58	94	0.60	141	0.68

Table 1. Estimated Field Measurements (EFM) and Predicted-to-Measured ratios (P / EFM) of τ_{rms}/ρ, τ_s/ρ and τ_{max}/ρ for the Juan de Fuca (PFMP) and EDDA sites (E23) All EFM data is in cm^2/s^2

It is clear from Table 1 that the best agreement is obtained for the PFMP and that there is significant difference in the degree of agreement between predicted and estimated values of shear stresses for the PFMP data and the North Sea data. Work is continuing on this problem but the main reason is almost certainly due to the presence of moveable bed effects and suspended sediments in the North Sea data. This suggests that models including random waves and moveable bed effects with sediments in suspension are needed for the EDDA site.

3.7 Acquisition of tidal current profiles and field data

The necessity has been clearly established in the previous subsection for reliable field data. A particular requisite for the present project is that the field data can provide the current profile over a good degree of the water depth with attention directed towards the region close to the bed, so that the importance of shear can be assessed. Three series of field experiments have been completed to date and these took place in April, May and September of 1997.

Two sites were chosen near the French coast of the English Channel in the southernmost part of the North Sea, close to Merlimont and Hardelot. These are shown in figure 18, together with the tidal current for the region as predicted by the 3-D coastal dynamics model of Smaoui & Chapalain (private communication). Both sites are characterised by tidal currents that may be considered as essentially parallel to the coastline and the seabed is both sandy and locally horizontal. The mean water depth at each site is 20m and these shallow waters are characterised by strong tidal currents and wind-generated surface gravity waves.

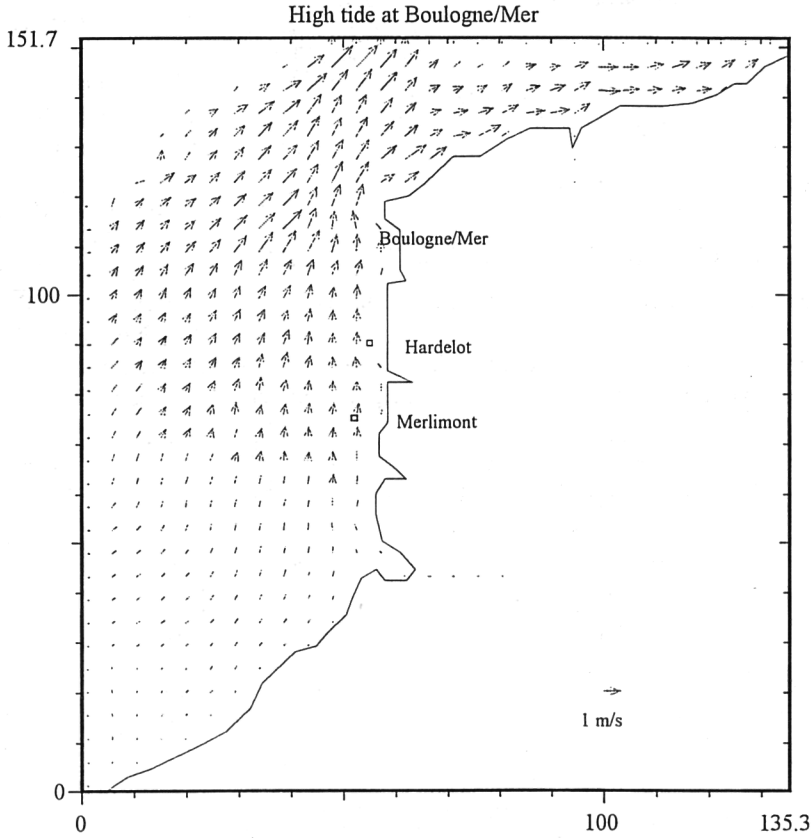


Figure 18. The velocity field at high tide at Boulogne/Mer. The horizontal and vertical scales are in km and the velocities are in m/sec. Measuring sites are shown by open squares.

The data presented here refers only to preliminary findings for the Merlimont site. These data sets are still being processed and will appear in published form under the authorship of Thais & Chapalain (Univ. of Lille). There is also the possibility that further data may emanate from the sites with funding supplied from a parallel national programme.

Velocity measurements were made at distances of 0.18m, 0.48m, 0.80m and 1.28m above the bed by employing an instrumented benthic platform with current meters capable of measuring simultaneously in two directions. A typical four-day data set of constant tidal currents is shown in figure 19 and represents the horizontal variation in current profile at a height of 0.80m above the bed. Each point defines a nine-minute average value and the horizontal and vertical axes correspond to the same horizontal and vertical axes respectively in figure 18. The ellipses at all four measuring points are geometrically similar and are of the same orientation, with the property that the velocity increases in magnitude with the distance from the bed. The maximum current is seen to lie in a direction approximately parallel to the coast, confirming the prediction in figure 18. Each ellipse shows a pronounced deformation in the top right-hand area and this is attributed to the presence of a nearby large sandbank to the north-east of the measuring site.

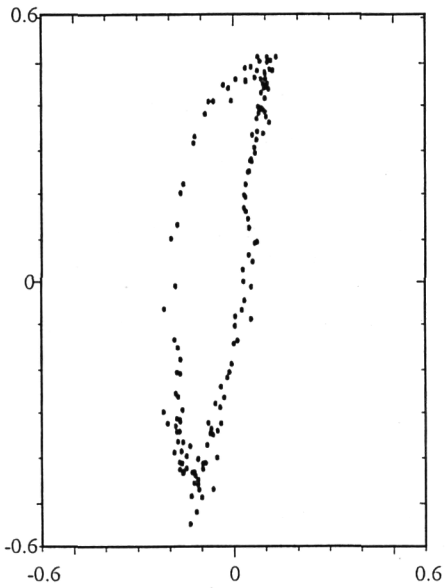


Figure 19. Ellipse of horizontal components in m/s of current velocity at 0.80m above bed, measured over a four-day period. Directionality as in figure 18.

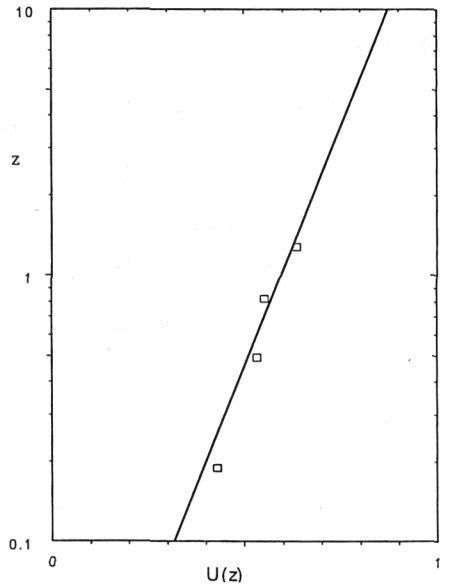


Figure 20. Current profile $U(z)$ with depth z on a semi-logarithmic scale, □ field data, —— semi-logarithmic fit to data.

The vertical profile of the maximum current amplitude at Merlimont is shown in figure 20 on a semi-logarithmic scale. A straight line fit to the data is also included in the figure and for a semi-logarithmic scale this corresponds to the universal wall law for a turbulent boundary layer. However there are insufficient points to determine the exact profile over the complete vertical section.

Current profiles of the type shown in figure 20 are essential input for the models presented in §3.1 and it is reassuring to note that the data from the Merlimont site appears to be of a form that can be genuinely represented by two-dimensional wave-current interaction models. There is some existing work on wave-current interactions for tidal currents from an earlier MAST programme described by Soulsby *et al* (1993) and this includes both kinematics and bottom boundary layer modelling. For the present application the Soulsby paper includes an analytic formula that appears to describe tidal current profiles in a universal manner and preliminary considerations suggest that it will also fit the data in figure 20.

Summary

An overview of the project has been given by way of a brief description of the progress on a number of important and interesting selected topics in the field of wave-current interactions. In each case it has been clearly demonstrated that not only has there been considerable effort expended but also that the problems tackled have been relevant ones of practical engineering interest, in the main where little or no work has previously been done. It has been equally clearly demonstrated that there has been considerable success to date. These conclusions hold for all of the topics described and similar conclusions apply for those not included in this review. This success is particularly outstanding for the pioneering experimental programmes on three-dimensional interactions and irregular waves interacting with a strongly-sheared current; the output data from these experiments will undoubtedly provide definitive benchmark data for future reference.

References

Dingemans M.W., van Kester J.A. Th.M., Radder A.C. & Uittenbogaard R.E. 1996 *The effect of the CL-vortex force in 3-D wave-current interaction.* Proc. 25th Int. Conf. on Coastal Eng., Orlando, Florida, USA, ASCE

Groeneweg J. & Klopman G. 1998 *Changes of the mean velocity profiles in the combined wave-current motion described in a GLM formulation.* To appear in J. Fluid Mech.

Klopman G. 1994 *Vertical structure of the flow due to waves and currents.* Progress Report H840.30, Part 2, Delft Hydraulics.

Klopman G. 1997 *Secondary circulation of the flow due to waves and currents.* Delft Hydraulics Rep. No. Z2249

MacIver R.D. & Simons R.R. 1997 *Wave refraction in a horizontally sheared current in the UKCRF.* Proceedings of Coastal Dynamics '97, Plymouth, UK, ASCE.

Madden N., Stynes M. & Thomas G.P. 1997 *On the development of complete flow models for wave-current interactions.* Proceedings of Coastal Dynamics '97, Plymouth, UK, ASCE.

Myrhaug D., Slaattelid O.H. & Lambrakos K.F. 1998 *Seabed shear stresses under random waves: predictions versus estimates from field measurements.* To appear in Ocean Eng.

Soulsby R.L., Hamm L., Klopman G., Myrhaug D., Simons R.R. & Thomas G.P. 1993 *Wave-current interaction within and outside the bottom boundary layer.* Coastal Eng. 21, 41-69.

Swan C. & James R.L. 1998 *Random waves on a vertically sheared current.* Abstract accepted for 26th Int. Conf. on Coastal Eng., Copenhagen, Denmark.

Thomas G.P & Klopman G. 1997 *Wave-current interactions in the near-shore region.* In 'Gravity waves in water of finite depth', ed. by J.N. Hunt, Advances in Fluid Mechanics, Computational Mechanics Publications, 255-319.

TITLE: The Morphological Development of Intertidal Mudflats (INTRMUD)

CONTRACT NO: MAS3-CT95-0022

COORDINATOR:

Prof. K.R. Dyer
Institute of Marine Studies
University of Plymouth
Plymouth PL4 8AA, UK
Tel.no.(Fax): +44 1752 232420 (232406)
E-mail: k.dyer@plymouth.ac.uk

PARTNERS:

Dr. D. Paterson
Gatty Marine Lab
University of St. Andrews
St. Andrews, Fife. KY16 8LB, UK
Tel.no. (fax): +44 1334 463467 (463443)
E-mail: d.paterson@st-andrews.ac.uk

Dr. G. Blanchard
Centre Recherche Ecologie Marine et Aquaculture
L'Houmeau, BP 5
F-17137 L'HOUMEAU, France
Tel.no. (fax): +33 5 46 50 94 40 (06 00)
E-mail: gblancha@rochel.ifremer.fr

Dr. M. Pejrup
Institute of Geography
University of Copenhagen
Oester Voldgade 10
1350 Copenhagen K, Denmark
Tel.no. (fax): +45 35 322626 (322501)
E-mail: mp@geogr.ku.dk

Dr. A. Cramp
Dept. Earth Sciences
University of Wales, Cardiff
PO Box 914
Cardiff CF1 3YE, UK
Tel.no. (fax): +44 1222 874335 (874326)
E-mail: Cramp@ cardiff.ac.uk

Dr. R.S.J. Whitehouse
HR Wallingford
Howbery Park
Wallingford OX10 8BA, UK
Tel.no. (fax): +44 1491 835381 (825743)

Dr C. Bessineton
CSLHN
4 Rue du Colonel Fabien
76083 Le Havre, France
Tel.no. (fax): +33 02 35 42 60 90 (22 47 50)
E-Mail: 106472.3220@compuserve.com

Prof. J. Terwindt
Dept Geography
University of Utrecht
PO Box 8011 3508 TC Utrecht
The Netherlands
Tel.no. (fax): +31 30 2532749 (2540604)
E-mail: j.terwindt@frw.ruu.nl

K. Kuyper
Delft Hydraulics
PO Box 177, 2600 MH Delft
The Netherlands
Tel.no. (fax): +31 15 2858535 (2858582)
E-mail: cees.kuyper@wldelft.nl

Dr. L. Stal
Neth. Inst. Ecology Centre for Estuarine
Coastal Ecology, PO Box 140
NL-4400 AC Yerseke, The Netherlands
Tel.no. (fax): +31 113 577497 (573616)
E-mail: stal@cemo.nioo.knaw.nl

Dr. P. Bassoullet
IFREMER Centre de Brest, BP 70
29280 PLOUZANE, France
Tel.no. (fax): +33 2 98 22 43 44 (45 94)
E-mail: pbassoul@ifremer.fr

Dr. O. Cazaillet
SOGREAH
BP 172, 38042 Grenoble
CEDEX 9, France
Tel.no. (fax): +33 4 76 99 04 22 (04 39)
sogreah-labo@dial.oleane.com

Dr. P. Galichon
Port Autonome du Havre
BP 1413, 76067 Le Havre
CEDEX, France
Tel.No. (fax): + 32 74 7400 (7429)

THE MORPHOLOGICAL DEVELOPMENT OF INTERTIDAL MUDFLATS INTRMUD

K.R. DYER
Institute of Marine Studies
University of Plymouth
Plymouth PL4 8AA, UK

Abstract

1. INTRODUCTION

Intertidal mudflats fringe many hundreds of kilometres of the coasts of NW Europe and protect them from inundation with only modest dyke defences. The wide expanse of mudflats attenuates the waves, and in the short term eroded sediment is generally redeposited on the flats. It appears that the mudflat morphology can obtain an equilibrium with the sediment supply and the physical processes, with biology playing a crucial role in the balance. Though mudflats are composed of mixtures of sand and mud, they exhibit cohesive properties, and are generally extremely soft and difficult to work on. They are areas of great environmental importance in terms of birdlife, and as nursery grounds for fish.

There are a number of general concepts that appear to govern mudflat characteristics, but they are not well tested or understood. Mudflats undergo cycles of erosion and deposition, and it is considered that a mudflat undergoing erosion has a concave upwards profile, and one experiencing deposition has a convex profile. At the upper end of the mudflats there are normally salt marshes where vegetation can be important in trapping sediment and enhancing deposition. The sediment is carried across the mudflats in suspension, and there is a zone in water only a few decimetres deep at the edge of the tide in which suspended sediment concentrations are high. During emersion the mud surface is exposed to drying by evaporation and by wind. The strength of the surface mud and its resistance to erosion varies with the degree of drying, and duration of exposure. Additionally, the surface mud contains diatoms and worms which exude carbohydrates in the form of slimes (generally known as extra-cellular polysaccharides EPS). These coat the mud and provide extra resistance to erosion. Thus the biology can feed-back on the sediment properties and onto the physical processes to help the stability of the mudflats.

The balance between erosion and deposition seems to be a delicate one, and many mudflats appear to have gone from being basically depositional to erosional in recent years. It is not clear whether this is due to changes in the sediment supply because of man's activities, eg. by coast defences, and control of the river discharge of sediment, or whether it is a result of sea level rise. Sea level appears to be rising globally at about 1mm per year, and this is predicted to increase because of global warming. The observed increase in temperatures may also affect the ecology of the mudflats, thereby changing their resistance to erosion.

At the moment there is not an accepted classification of mudflats which can help understanding of the progression of events during change in mudflat morphology, or the controlling factors. This is an essential first step so that the relative importance of the processes can be then scaled, be parameterized by experiments and the results incorporated in models that can be of help to the environmental managers.

INTRMUD aims to investigate the characteristics of a number of mudflats in NW Europe in order to establish a classification which reflects the morphological effects of variations in such parameters as: tidal range and phase, wave climate, sediment physical and biological properties, biological community structure etc. This will propose a series of conceptual models of mudflat development. Experiments will be carried out using harmonized methods to quantify the processes and their interactions. These will be formalized into algorithms which can be tested and used in computer models assisting consideration of the effects of climate change, sea level rise and anthropogenic pressures.

2. WORKPLAN

There are tidal controls on the timing of exposure with major differences across NW Europe. At some places high water at spring tides always occurs at around midday, and at others low water occurs at the same time. The timing is governed by the phase of the S_2 tidal constituent, with spring low tide occurring between 0900 and 1500hr when the phase is between 90^0 and 270^0 . Figure 1 shows that there are likely to be major differences in exposure timing in the Dollard Estuary in the Netherlands, and the Humber Estuary in England. There are further contrasts in the range and the asymmetry of the tide, the Humber being macrotidal and flood dominant, and the Dollard being mesotidal and ebb dominant. A comparison between these two contrasting areas may be expected to reveal the dependency of the mudflat characteristics on these driving forces. These sites have been the locations of other national experiments, and INTRMUD aims to supplement their data and expand their scope, making them comparable.

Two major joint interdisciplinary experiments were planned involving the various partners in investigating the tidal time scale variation of the hydrodynamics, the sediments and the biology of the Dollard and the Humber. In each of those areas longer term measurements were undertaken to examine the morphological effects of the seasonal changes and of storms. In addition the partners carried out complementary experiments on other sites to encompass a wide range of mudflat types. The mudflats on which work has been carried out are shown on Figure 1.

The data from these measurements have been fed into a data base that requires definition of a range of standard characteristics of mudflats, in terms of shape, physical forcing parameters, sediment properties, and biological and biochemical characteristics. Each mudflat is divided into three zones relating to the extent of covering and uncovering during spring and neap tides. From these data empirical relationships should be definable to provide a classification of the mudflats. The classification forms the basis of exploratory modelling which investigates the sensitivity of mudflats to changes in the drivers.

3. RESULTS

Classification

At the moment insufficient data has been assembled in the data base to allow a classification to be developed. However, a descriptive typology has been proposed (Dyer, 1998). This is seen as a first step in exploring the relationship between the characteristics and properties of mudflats and their environmental situation, and when quantified should lead to a classification scheme. The principles of the typology has been applied to the Molenplaat mudflat in the Scheldt Estuary, with reasonable success. The classification scheme and the existing data are being mounted on the World Wide Web. This will enable other workers to

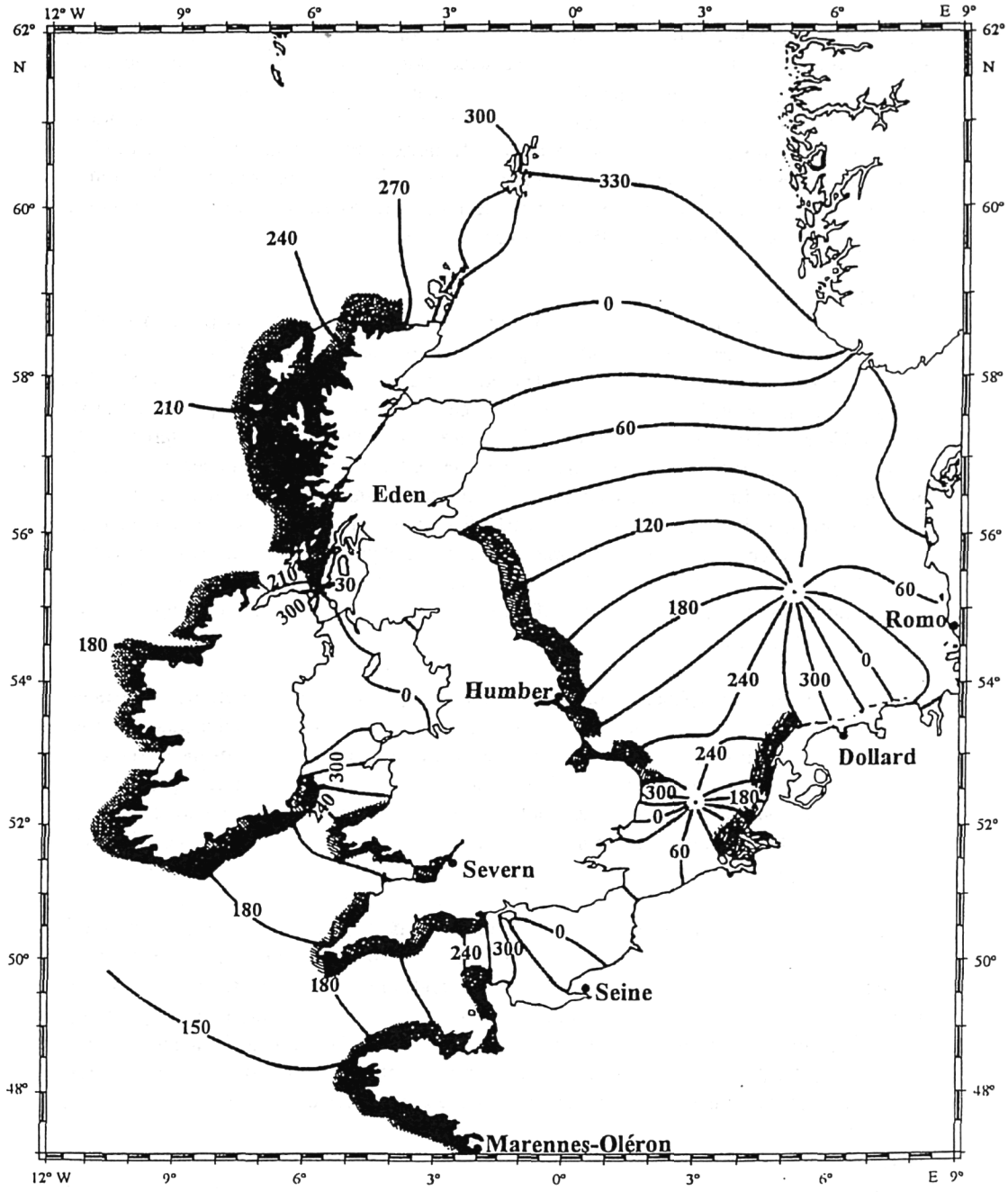


FIGURE 1 Location Plan of North West Europe. Shaded areas are where S_2 phase 90 - 270 and where low water spring tide occurs 0900-1500 hours. Also shown are the locations of the national experimental sites

access the data, and it is hoped that they will feed in data on their own flats. This will extend the data base and, in particular, make it global rather than exclusive to NW Europe.

Dollard Estuary

The first joint experiment was carried out on the Heringsplaat in the Dollard Estuary in May 1996. The site was determined by the location of the BOA platform from which long term measurements were being taken. Hydrodynamic measurements were made from the platform, and measurements of the sediment properties and the biological characteristics made around the site during low water. The overall elevation profile is convex, but long term measurement showed little detectable change. The mudflat was almost devoid of bedforms, though there were small decimetre scale drainage channels and extensive biological surface roughness features relating to *Arenicola* and to elevated patches covered with diatoms. The edge of the incoming tide had suspended sediment concentrations that approached 1 gml^{-1}, with high organic contents of up to 35%. This appeared to be lifted off the sediment surface and was a part of the production that occurred during low water exposure. The flocs in suspension were elongated stringers, indicative of high organic content, with a settling velocity of about $1mm^{-1}$, and mean size of about 600 microns. They would settle raidly at high water. During the last part of the ebb tide the water velocity was higher, showing the ebb dominance, but the suspended sediment concentrations were lower. Thus the overall sediment flux was in a landward direction. The result of this was to produce a landward increase in the organic content and a fining of the sediment.

The sediment had a high sand content and seemed to be undergoing regular deposition. Experiments with the erosion instruments SEDERODE and ISEF showed that the threshold of erosion was in the range 0.01 to 0.14 Nm^{-2} (Kornman & de Deckere 1998), and appeared to be inversely related to the mud content, though it was thought that there was also a relationship to the patchy nature of the sediment surface biofilms. Nematode worms appeared to inhibit the diatom production of EPS, and it appeared that the quality of the EPS varied, affecting the size of the flocs relative to the EPS content. *Corophium* also grazes on the diatoms and causes resuspension of sediment, resulting in higher suspended sediment concentration for the same wind velocity.

Humber Estuary

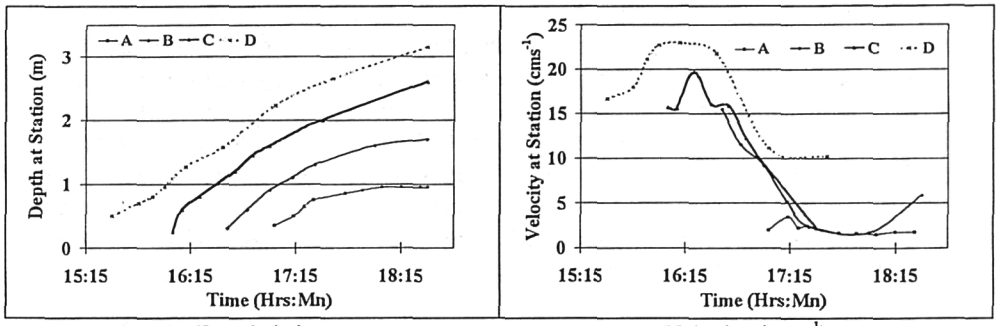
The second joint experiment was held on the Skeffling mudflats near the mouth of the Humber Estuary in July 1997. This was the site of the previous LISP measurements (Black & Paterson, 1998). In contrast to the Dollard, these mudflats are covered with extensive bedforms which were best developed at midtide level. These comprise shore normal ridge and runnel features with a wavelength of about 2-5m and heights of 10-30cm. These are cut by drainage channels up to 2m deep. The channels hold running water throughout the low water period and aerial photographs show that they are virtually stationary features over the timescale of decades in the midtide region.

Two core experiments were completed, with simultaneous measurements obtained from four stations positioned along a cross shore transect. Station A was positioned at the salt marsh edge, station B was about 500m offshore from the salt marsh, station C was sited above the midtide level and station D was located just below the midtide level.

The first core experiment was designed to investigate the variations across the mudflats of the hydrodynamics by water column measurements at the four stations, followed by measurements of the sediment characteristics during exposure at the same positions. The

second core experiment concentrated on measuring the variation in sediment properties across the ridge-runnel features, again simultaneously at the four stations. Thus the variation of sediment properties with time, depth in the sediment, across bedforms and across the mudflats can be quantified. In addition the partners were able to undertake their own experiments to compare with their own national sites, and an intercomparison between four different erosion instruments was made.

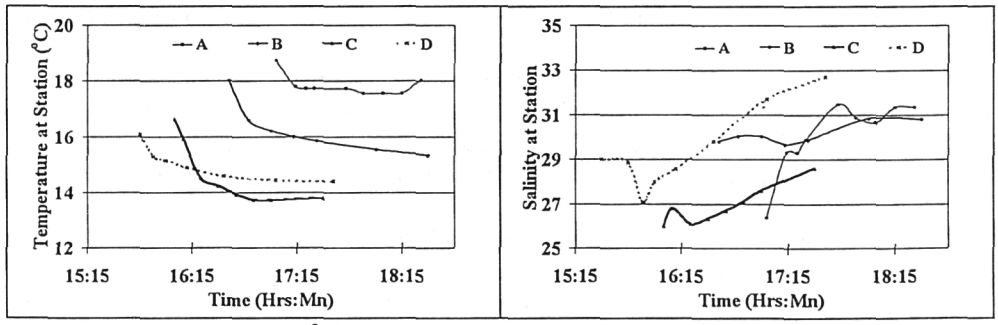
The water column measurements of the first core experiment showed that the initial flow of the flood tide across the flats reached velocities of 0.5 ms^{-1} and carried suspended sediment concentrations of up to 1 gl^{-1}. Figure 2 shows typical depth and velocity data from an afternoon flood tide.



Depth (m) Velocity (cms^{-1})

FIGURE 2. Water column measurements, flood tide, Humber Estuary.

The highest velocity occurred at about the midtide level, when the water level was rising most rapidly, and at that time the shear stresses were sufficient to erode sediment. The velocities on the ebb tide were less, and coupled with the calm sea conditions, produced a landward flux of sediment over the tide. Since the suspended sediment on the ebb was coarser in grain size, an accumulation of finer material on the upper flats is likely, and this was confirmed in the surface sediment distribution. The grain size of the sediment decreased landwards, whilst the organic content increased. The overall sedimentation rate was estimated to be about 6-7 mmy^{-1}.

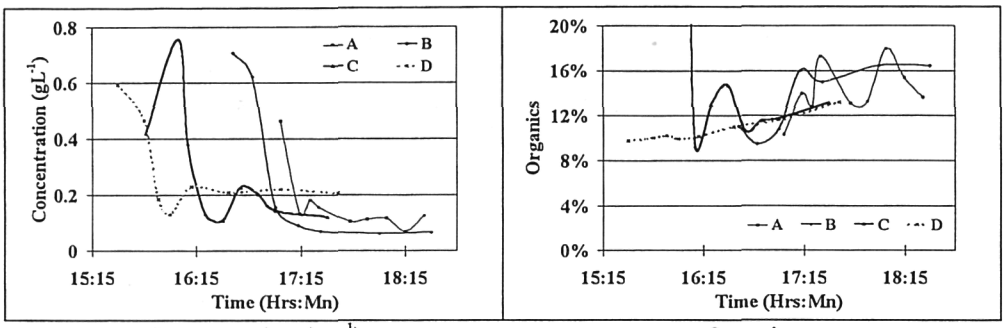


Temperature (°C) Salinity

FIGURE 3. Water column measurements, flood tide, Humber Estuary.

Figure 3 shows typical temperature and salinity data from the same flood period. There were unexpectedly high variations of both salinity and temperature in the water during the

tide, with salinity variations from 28-32, and temperature variations of 4-5^{0}C. Generally at high water salinities were maximum and temperatures minimum. These variations are anticipated to have considerable biological consequences.



Concentration (gL^{-1}) Organics

FIGURE 4. Water column measurements, flood tide, Humber Estuary.

Figure 4 illustrates typical (depth mean) suspended sediment concentration and suspended organic content data. Concentrations were greatest in the shallow water's edge at the beginning and end of tidal immersion, reaching maximum values of about 0.8 gmL^{-1} in about 20 centimetres of water. The high flow velocities during the shallow water period eroded the surface sediment during flood inundation and a turbid alongshore strip of water was advected up across the mudflat. Concentrations decreased to around 0.2 gmL^{-1} around high water.

Organic content was measured as a percentage by weight of the sediment, and provided an indication of the biological content of the suspended sediment. Generally the organic content increased with depth, varying from 8% in very shallow water to 15% around high water. During the flood period this trend was attributed to the resuspension of the surface biofilm and accumulation of organic material in the shallows as the leading waters edge propagated towards station A.

Within the sediment there was little apparent effect of drying out decreasing the moisture content during the tide, except on the upper flats. This was despite intense solar heating. Figure 5 shows moisture content variations with time for station A. The moisture contents were statistically lower in the last 2 hours of the exposure period than compared to the 2 hours immediately following tidal uncovering.

Typical depth profiles of moisture and organic contents from station B are illustrated in figure 6. The measurements contrasting the ridges and runnels showed that within the surface 2 cm the crests were statistically lower in both moisture and organic content, higher in EPS and colloidal carbohydrate and lower in biomass. The crests had a higher erosion shear stress than the troughs. Nevertheless, at a depth of a few centimetres the moisture and organic contents showed no effective difference between ridges and runnels and the carbohydrate contents showed remarkable consistency with other estuaries. In contrast with the Dollard there are very few *Corophium*, but densities of *Macoma* reach 2700 m^{-2}.

Since the potential erosion of sediment only affects the upper few mm of sediment, detailed analysis of this depth is needed. Microscale analysis of the vertical structure of the sediment was carried out by the application of low-temperature scanning electron microscopy on

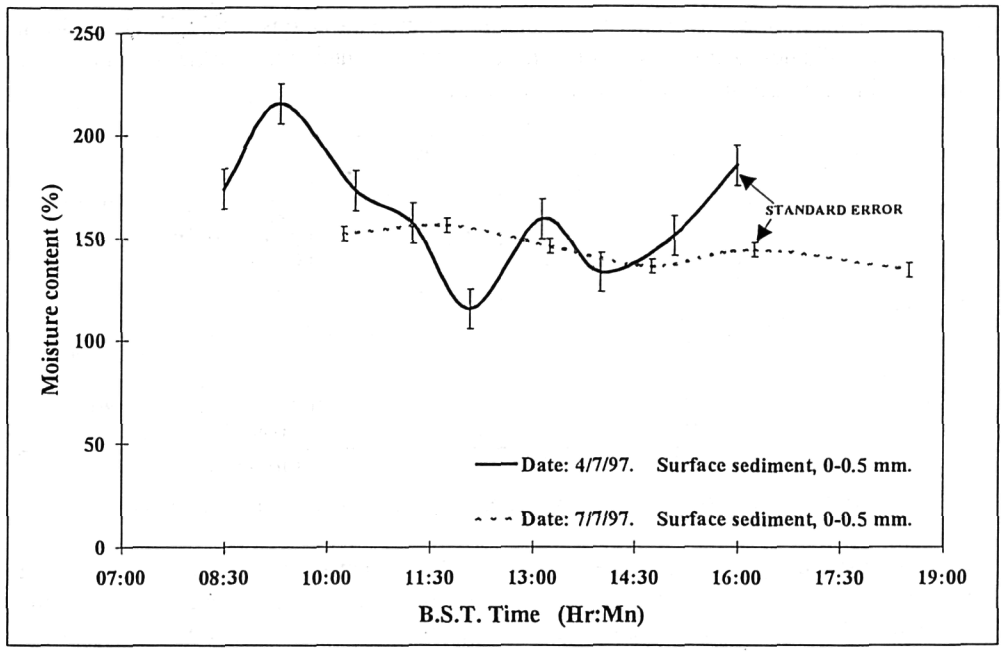


FIGURE 5. Temporal variation of sediment moisture content, Station B.

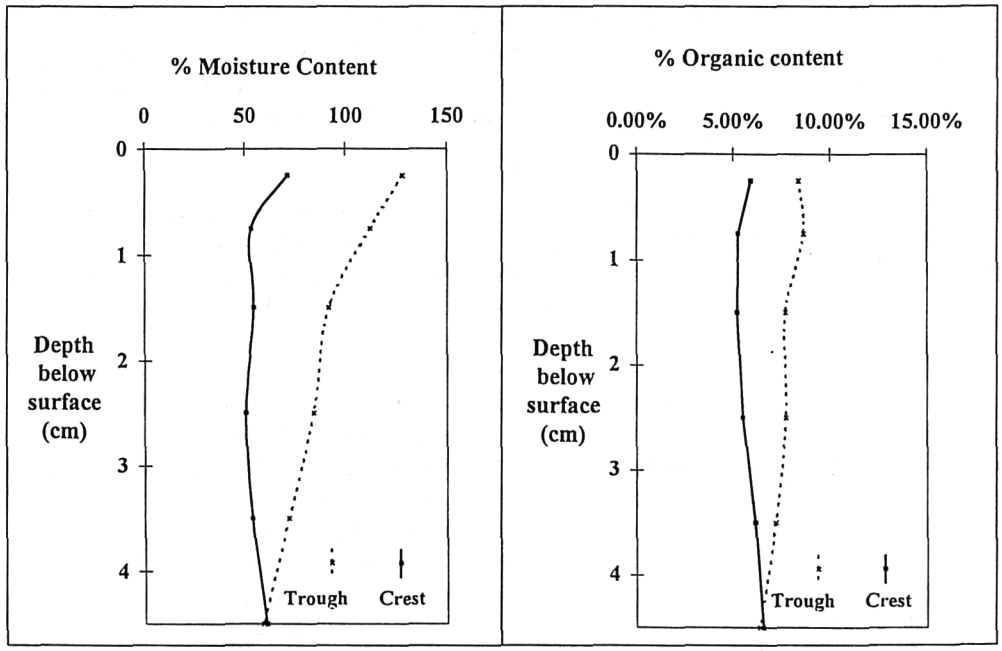


FIGURE 6. Typical depth variation of moisture and organic content, at Station B.

cores frozen using the Cryolander device (Wiltshire et al 1997). The surface 1mm on the upper flats was relatively rich in organic matter and diatoms, whereas the other zones were relatively devoid of colonization.

Erosion measurements were made simultaneously at the stations across the mudflats with over 100 measurements taken in one day. The results are being integrated for comparison. However, initial results suggest that the values of erosion shear stress ranged from 0.12 Nm^{-2} to 0.45 Nm^{-2} (Mitchener et al 1998). The lowest values were found in the runnels and the higher values on the crests. On the upper flats there was a clear increase in erosion shear stress over the exposure period.

Long term measurements over a full year have been obtained on the lower mudflats using an electromagnetic flowmeter, a depth sensor, temperature and salinity sensors, an optical backscatter gauge for suspended sediment concentration, and an acoustic elevation sensor. The results show that there is erosion during the early flood and late ebb, but deposition around high water. There is a very slow accumulation tide-by-tide when the weather is calm, but overall erosion when waves are present. This emphasises the delicate balance that exists on the mudflats.

The data when fully analysed will allow formulation of processes and calibration data which will assist the development of quantitative models of sediment transport over the intertidal, and the response of the bed properties and biology. The core data has been prepared as an Excel spreadsheet which will be made available to non-INTRMUD scientists.

Other sites

The Baie de Marennes-Oleron is similar to the Humber in tidal range and in the presence of bedforms. However, the bed is less stable than the Humber in the top 2mm. The long term sedimentation rate on the ridges is of the order of 0.3 $cmyr^{-1}$, whereas the short term rate is of order 5 $cmyr^{-1}$. In the runnels the long term rate is of order 0.1 $cmyr^{-1}$, and the short term rate is approximately 20 $cmyr^{-1}$, but there is a paradox in that sediment greater than 100yr old is within 5 cm of the surface. This is related to the presence of layers of fluid mud within the runnels, that do not form part of the permanent bed. The biological and biochemical characteristics have been thoroughly documented. Microphytobenthos variability is high, and it has a fast response to tidally driven changes. Patchiness is high, but persistent seasonally, and the distribution suggests that there is control by nutrient inputs. Chlorophyll-a shows an expected seasonal variation which is largest at the surface, but which decreases with depth. In the water the chlorophyll-a is highest in shallowest water, indicating pickup off the bed. Sediment flux measurements indicate a landward sediment flux at spring tides, but waves produce a tendency for seaward flux. The channels appear to produce a seaward flux when the flats have a landwards flux. Thus there are indications that a great deal of sediment cycling occurs across the mudflats and it is likely to be important to represent this in modelling.

In the similarly macrotidal Severn Estuary the biological effects are dominated by the tidal and wave effects. Winter storms have eroded the mudflats down to their Flandrian clay substrate, and it will be interesting to examine the recovery to the normal accretionary state.

The Eden estuary is small and sheltered with a smaller tidal range, and the flats are divisable into three zones. The upper flats were dominated by cyanobacteria and diatoms, the middle flats by *Enteromorpha*, and the lower flats by diatoms. Measurements over a year have shown an increase in elevation of the flats during the summer, with erosion over the autumn. This seems to be the result of sediment trapping by the filamentous algae in the summer, and release in the autumn. Organic matter and water content were about constant over the year on the upper flats, but lower down there was a doubling of both properties, as well as carbohydrate, in the summer. There seems to be an import of organic carbon into the surface sediments during the summer, which may come from outside the estuary, or from deeper sediment via bioturbation.

In the Romo estuary the mudflats are restricted in size, but are accreting rapidly. Typical erosion and deposition rates are 1-5 $mmwk^{-1}$, with peak values of 15 $mmwk^{-1}$. Deposition occurred in the spring and summer, and erosion in the autumn, in agreement with the seasonal change in the prevailing winds. The depth of the top layer that is repeatedly reworked is 2-6 cm. Typical values for the threshold of erosion range from 0.16 to 3 Nm^{-2}, and the values correlate well with distance down the mudflat, chlorophyll-a content, and with the numbers of *Hydrobia ulvae*. Since the currents alone were not sufficient to erode the sediment, erosion depended on the presence of waves. Maximum concentrations of suspended sediment occurred on the flood tide, and this is thought to be the result of erosion of the less dense mud on the lower flats and advection shorewards. One particular aspect being studied is the role of ice in modifying these mudflats. During the cold winter of 1996 extensive ice floes formed on the intertidal, were picked up by storms and deposited on the upper flats carrying large quantities of sediment within them. Their melting created hummocks which remain after a considerable time, and which are not being very readily colonized by the local fauna. This event carried more sediment landwards than several years of equivalent tidal and wave movement.

In the Seine Estuary an area of artificially created mudflats and an area of rapidly accreting mudflats are being monitored to determine how anthropogenic manipulation affects their properties and stability.

Most of the above studies are producing empirical relationships between variables that will be important in creating algorithms to be used in mathematical models. Process modelling has also been carried out to explore the relationships between the temperature cycle within the sediment and wetting/drying and solar insolation; microphytobenthic primary production; the bioturbation effects of *Hydrobia ulvae;* the velocity and suspended sediment profiles during inundation; and assessment has been made of long term morphodynamic modelling (Roberts & Whitehouse 1997).

4. DISCUSSION

It is apparent that there is a very delicate balance on mudflats between accretion and erosion. The balance depends on processes of erosion occurring in the very shallow water at the front and end of the tide. This is partly tidal, with the tidal velocities depending on the position on the mudflat and how that relates to the rate of tidal rise, and the slope of the mudflat, which together determine how much water has to flow across a unit width to produce the tidal rise further inland. Additionally, wave effects appear to be extremely important in controlling the direction of the sediment flux.. As the waves are of small height, but acting in very small depths their effect provides a challenge for modelling. The presence of bedforms is a further

complication as they are of the same scale as the water depths and are likely to affect the water flow throughout the depth.

The time scales of the erosion and deposition are similar to the timescales required for biological response and for consolidation. Consequently, the properties of the bed and the contained fauna and flora are likely to interact with those driving the sediment transport. The biological influence on the erosion threshold of the mud appears to be well represented by the chlorophyl-a and carbohydrate contents, though there seems to be evidence of a quality factor in the cohesive property of the EPS. The amount of these substances relates to the interaction of diatoms with various grazing animals, but it appears to be reasonably constant between estuaries despite different grazers being dominant, eg. nematode worms, *Corophium, Macoma, Hydrobia etc.* Their integrated effect appears to produce very similar results.

At the moment we are beginning to understand the primary interactions and effects. Prediction of them is probably a long way off, but we are in the position of having sufficient knowledge to empirically relate cause and effect. This is a beginning for improvement of our capability for maintaining environmental quality.

5. REFERENCES

Black, KS & Paterson, DM. 1998. The LISP (Littoral Investigation of Sediment Properties) experiment. In 'Sedimentary Processes in the Intertidal Zone'. Black, KS, Paterson, DM & Cramp, A. Journal Geological Society Special Issue (in press)

Dyer, KR. 1998. The typology of intertidal mudflats. In 'Sedimentary Processes in the Intertidal Zone'. Black, KS, Paterson, DM & Cramp,A. Journal Geological Society Special Issue (in press)

Kornman, BA & de Deckere, E, 1998. Temporal variation in sediment erodibility and suspended sediment dynamics in the Dollard Estuary. In 'Sedimentary Processes in the Intertidal Zone'. Black, KS, Paterson, DM and Cramp, A, Journal Geological Society Special Issue (in press)

Mitchener, HJ, Lee, SV & Whitehouse, RJS. 1998. Erodibility measurements at Skeffling, Humber Estuary, 3-9 July 1997. HR Wallingford Report TR 52

Roberts, W & Whitehouse, RJS, 1997. Long-term morphodynamic modelling of Intertidal mudflats. HR Wallingford Report TR 48

Wiltshire, KH, Blackburn, J & Paterson, DM, 1997. The Cryolander: A new method for fine-scale in situ sampling of intertidal surface sediments. Journal Sedimentary Research. **97.** 977-981.

TITLE: **PRE-OPERATIONAL MODELLING IN THE SEAS OF EUROPE-PROMISE**

CONTRACT NO: **MAS3 CT950025**

COORDINATOR: Dr. D. Prandle
Proudman Oceanographic Laboratory, Bidston Observatory,
Birkenhead, L43 7RA, UK
Tel.no. (Fax) 44 151 653 8633 (6269)
E-mail: dp@pol.ac.uk

PARTNERS:

M. Regener, J Sundermann
Institute für Meereskunde
Troplowitzstr. 7
D-22529 Hamburg, Germany
Tel.no. (Fax) 49 40 4123 2606 (4644)
E-mail: regener@ifm.uni-hamburg.de

K. Duwe, H. Baumert
HYDROMOD
Bahnhofstr. 52-54, D-22880 Wedel
Germany
Tel.no. (Fax) 49 4103 13343 (3317)
E-mail: duwe@hydromod.de

W. Rosenthal, H. Gunther, R. Riethmuller
GKSS Forschungszentrum Geesthacht GmbH
Max Planck Straße
D-21502 Geesthacht
Germany
Tel.no. (Fax) 49 4152 87 1516 (1565)
E-mail: rosenthal@gkss.de

H. Gerritsen
WL Delft Hydraulics
P.O. Box 177, 2600 MH
The Netherlands
Tel.no. (Fax) 31 15285 8470 (8718)
E-mail: herman.gerritsen@wldelft.nl

G. Chapalian
University of Lille
Laboratorie d'Ecologie, Bâtiment SN3
F-59655 Villeneuve d'Ascq
Tel.no. (Fax) 33 320 43 6730 (4910)
E-mail:chapalain@univ-lille1.fr

J. Monbaliu
Hydraulics Laboratory
Katholieke Universiteit Leuven, de Croylaan 2
B-3301 Haverlee, Belgium
Tel.no. (Fax) 32 16 321 660 (989)
E-mail:jaak.monbaliu@bwk.kuleuven.ac.be

J. Ozer
The Management Unit of the North Sea
Mathematical Models (MUMM)
Gulledelle 100, B-1200 Brussels, Belgium
Tel.no (Fax) 32 2773 2121 (2770 6972)
E-mail: mummjo@camme.ac.be

J. Carratero, E. Alvarez
Clima Maritimo-Puertos del Estado
Dept. de Fisica-Universidad de Alcalac/Avda
del Partenon 10, 28042 Madrid, Spain
Tel.no. (Fax) 34 152 45 568 (506)
E.mail: juancc@puertos.es
E.mail: enrique@puertos.es

A. Jenkins
Nansen Environmental and Remote Sensing Centre
Edvard Griegs vei 3a, N-5037, Solheimsviken
Bergen, Norway
Tel.no. (Fax) 47 55 297 288 (200 050)
E-mail: alastair.jenkins@nrsc.no

H. Wensink
ARGOSS
P.O.Box 61, 8325 ZH Vollenhove
Netherlands
Tel.no. (Fax) 31 527 242 299 (016)
E-mail: han.wensink@argoss.nl

PRE-OPERATIONAL MODELLING IN THE SEAS OF EUROPE-PROMISE

D. Prandle

Proudman Oceanographic Laboratory
Bidston Observatory, Birkenhead
Merseyside, L43 7RA, UK

SUMMARY

Environmental and Financial imperatives urgently require the effective application of oceanographic knowledge for appropriate development of the coastal zone. This knowledge base must be synthesised within pre-operational numerical models linked to related observational/ monitoring networks constructed on an international basis. This international (European) approach involves long term planning, to: establish and maintain the monitoring network; train personnel in the necessary organisational and scientific skills, and link the operational centre(s) for real-time data assimilation. This new challenge requires rigorous evaluation of both existing models and the associated data used for: initialising, forcing and verification.

PROMISE aims to expedite the implementation of operational oceanography and comprises European groups with wide experience in real-time modelling and monitoring. Applications are primarily in the North Sea and concentrate on the simulation of suspended sediment in the near-shore zone. This applications aims to exploit recent rapid developments in both in-situ and remote sensing techniques for measuring SPM.

The project aims are:
(i) to assemble high resolution comprehensive data sets
(ii) to use these data sets to test pre-operational models
(iii) to improve these model systems by (a) expanding their physical realism, (b) improving quality and quantity of observational data and (c) by further development of real-time data assimilation techniques.

1. INTRODUCTION

The primary objective is to identify how modelling and monitoring capabilities need to be developed and combined to provide estimates of coastal - nearshore sediment exchanges. The traditional focus of coastal engineering on the response of beaches to waves has been extended to consider coastal-nearshore sediment exchange, reflecting concerns arising from acceleration in: climate change (sea level and storminess), offshore aggregate extraction, steepening of cross-shore slopes, adoption of soft-defence strategies (inc. beach nourishment) and recognition of large-scale interdependencies.

Such large-scale sediment exchanges cannot be measured directly - not even the resultant impact on bathymetry. Thus models are required, linking dynamical simulations of tide, surge, wave and turbulence to 'dispersion' modules representing the erosion, transport and deposition of a range

of sediment types. Monitoring is required to develop the sediment algorithms, determine the accuracy of each modelling component and assess the integrated forecast of sediment transport.

The requirement for dynamical coupling of model components and subsequent evaluation against observations emphasises the need for a Pre-Operational modelling approach. The North Sea was adopted as a focus because of the existence of forecasting systems for: tides, surges and waves. The wave models required development for fine-scale application in near-shore shallow regions. Likewise the turbulence models required development to incorporate wave-tide-surge interactions. Extensive data sets were then required to develop and assess these various modules

independently and overall. Data from national monitoring experiments off the coasts of the UK, Germany, France and Spain have been made available for this purpose.

Subsequent sections describe: the scope of these observational data sets (2), development in spectral wave models for propagation in shallow water (3), single point models of turbulence and suspended particulate matter (4). Section, (5), considers additional efforts required to develop operational oceanographic capability in N.W. Europe, and section (6) examines the associated user requirements.

2. OBSERVATIONAL DATA SETS

Observational experiments involve enormous cost and scientific effort in instrument design, preparation and deployment and thence in data processing and analyses. Recognising this, a major goal of PROMISE is to assemble comprehensive, readily accessible, observational data sets against which a wider community can develop models.

The Zisch and North Sea Project data, used extensively in PROMISE, illustrate the longer term value of such data sets. The similarly comprehensive coastal data sets from Holderness and Sylt Romo are described below. PROMISE also compiled important coastal data sets from the French and Spanish coasts. Figure 1 indicates these regional foci.

(a) Holderness

The Holderness Coastal Experiment (Prandle 1994) originated as a component of the UK LOIS programme, it aimed at understanding and ultimately predicting coastal erosion. The Holderness coast was chosen because of its rapid rate of erosion (20 m glacial till cliffs eroding at an average rate of 1.7 m/year) and its reasonable homogeneity over a 20 km section. The requirement was for continuous monitoring of representative conditions over a winter period providing data both for developing and verifying numerical models and background descriptions for occasional more intensive localised process studies. The core period chosen was from October '94 to March '95, pilot studies were made in November - December '93 with a follow-up phase between October '95 to January '96. The range of sea-borne, insitu and remote sensing data collected at Holderness is indicated by the schematic shown in figure 2.

The Holderness data set should become an international test-bed for tidal, wave and sediment modelling on a regional basis. The wave component has already been widely used. The suspended sediment time series encapsulate the desired characteristics of successive intervals of tide then wave-dominated regimes. Simulations of these intervals, initially separately and subsequently in combination, are progressing as planned.

(b) Sylt Romo Bight (North German Bight)

The Sylt-Romo Bight, located at the border between Denmark and Germany, is a semi-closed Wadden Sea lagoon of approximately 1000 km^2. Exchange of water and material proceeds through one deep tidal gully. Tidal elevation and currents are controlled by the water level of the German Bight. The development of waves depends on a complex interaction of local winds, tidal elevation, tidal current directions and the local topography.

In the last years, the Sylt-Romo Bight was subject to intense interdisciplinary research on the exchange of material and energy between the different compartments of the ecosystem. Considering the sediment budget a substantial sediment loss over the last hundred years with a 50 percent loss of the intertidal areas was identified. In one hypothesis these effects were attributed to the increase of intense storm events with parallel reduction of retention areas due to coastal protection measures.

Over several months periods during 1996 and 1997 the sediment dynamics during stormy and calm weather periods were continuously recorded at selected locations of the main gullies and one tidal flat position. These measurements which were organised and financed by the GKSS Research Centre Geesthacht, were completed by two two-week ship cruises to gather profiles along the tidal gullies. Observations of the microturbulent structures over a tidal cycles (the PROMICSOS campaign) enhance the measured time series. The requirement was a consistent data set comprising meteorological, hydrodynamic (including waves) and suspended sediment parameters to develop and test a numerical coupled sediment transport model and its individual atmospheric, wave, current and suspended sediment dynamics components. Four three week periods containing significant wind events were selected as benchmark tests for flat water models. These data are carefully documented and accessible via the World Wide Web.

In the framework of this extensive measuring campaign a joint PROMISE - MICSOS (PROMIX) experiment was conducted. This experiment was aimed at deriving a suitable data set of both the turbulent kinetic energy (TKE) and its dissipation rate. The PROMIX experiment covered two tidal cycles and consisted of highly resolving ADCP measurements and microstructure measurements of the dissipation rate of TKE. Data of both the TKE and its dissipation rate are needed to validate the 1D turbulence-SPM-wave interaction model. Jointly cooperating two PROMISE partners (IfM and GKSS) were directly involved in the PROMIX experiment, in which the IfM was responsible for the experiment. The microstructure measurements were carried out by Meerestechnik-Elektronik GmbH (Trappenkamp, Germany).

3. WAVE MODELLING

The wave group within PROMISE has coalesced to build on earlier collaboration in WASA, ECAWOM, SCAWVEX and the WISE sub-group of WAM. The main goal of the first year activities for wave modelling was to achieve a common implementation of the third-generation spectral wave model WAM Cycle 4 - suitable for dissemination. The goals of the second and third year are to extend this 'deep water' version for high spatial resolution application in shallow water and dynamic coupling to a hydrodynamic model to satisfy the requirements for sediment transport modelling.

The model intercomparisons on the North Sea scale (POL Report 47) have clearly established the (deep water) characteristics to which model applications are sensitive. Extensive tests were conducted on the intercomparison of the different implementations; on the comparison against buoy measurements (figure 3) and with ERS-1 and TOPEX/POSEIDON satellite altimeter data. WAM Cycle 4 has been successfully applied to hindcast wind waves in the North Sea. Statistical analysis of buoy or satellite data and model results indicated that the current North Sea implementation is of comparable quality as other implementations cited in literature. The intercomparison exercise did not reveal any significant differences in model results between the POL and the KULeuven/MUMM implementations, although boundary conditions and grid resolution were quite different. Small differences in bathymetry are also not very important. The wind fields provided by meteorological offices (UKMO / DNMI) seemed to be of comparable and good quality.

The subsequent phase of shallow water development introduces a number of fundamental questions including: emerging importance of various terms (Luo et al 1998), requirements for enhanced temporal and spatial resolution and associated alternative numerical solutions. Likewise such applications expand the requirement for computing capacity, bathymetric resolution and accuracy. The shallow water version of the model has significantly improved efficiency in coastal areas, making operational use more feasible. The results from North Sea and regional models with grid scales down to 2.4 km resolution are compared with wave data obtained from buoys, radar and satellites during the winters of 94/95 and 95/96. Using these results it is possible to assess the accuracy and suitability of models like WAM for operational use in shallow water areas. Still more detailed sensitivity tests are needed. A subsequent problem (not within the scope of PROMISE) concerns the linkage of these shallow-water WAM applications to specific beach applications.

The last phase consisting of the dynamical linking of tide/surge models and wave models has started. A flexible and robust framework, limiting the changes needed to individual model components while keeping the overhead down, is being built and is undergoing testing.

Within the technical framework of WAM cy-4 a wave model using turbulent diffusion as a key dissipation mechanism was developed in the last years (Gunther and Rosenthal, 1992). The model was designed for to nonuniform and instationary systems (Schneggenburger et al 1997). The model forced by the local measured winds and computed water level and current fields very 15 minutes was successfully used to hindcast a storm period in the Sylt-Romo-Bight. The strong influence of the local current, water depth and changes of the effective fetch on the wave development could be demonstrated. The agreement with measurement collected during the Sylt-Romo-Campaign was remarkable (Schneggenburger at al 1998).

4. SINGLE POINT MODELS OF TURBULENCE AND SUSPENDED PARTICULATE MATTER (SPM)

The parallel EC initiative (EU MAST Workshop, Bergen 8-10.08/96) focusing on rationalisation of turbulence modelling contributed significantly to the associated goals within PROMISE. The report (POL Report No. 48) outlines progress in YEAR 1 in relation to tidal applications. Extension to include the effects of surface waves was completed in year 2. Meanwhile applications of these models both directly to the regional data sets and incorporation into wider-area models is progressing as planned.

One-dimensional generic turbulence-SPM-wave interaction models were derived in order to investigate the role of turbulence in relation to SPM and density stratification on a microscale in space and time. The results are planned to improve existing multi-dimensional SPM-models on a pre-operational level.

Two versions of a one-dimensional turbulence-SPM-wave interaction model were established: Version (A) considers cohesive SPM (i.e. flocs), version (B) focuses on non-cohesive material (i.e. sand). Starting point was the k-e model as described by Baumert & Radach (1994) and Burchard & Baumert (1992).

To derive the generic turbulence-SPM-wave interaction model (version A), the k-e model has been considerably improved and extended by the inclusion of a transport module for SPM, which includes sinking and diffusion processes. At present, only a single floc size is considered. However, further development will lead to a minimum of three size classes. As version A includes only cohesive materials, the processes of erosion and sedimentation are not implemented i.e. there is no exchange with the bed in version A of the model. In order to be able to resolve the fluffy layer close to the bottom, a non-uniform spatial grid was introduced.

Version B of the model considers non-cohesive SPM and hence, in addition to the advection and diffusion processes, also includes resuspension and sedimentation processes, after Sheng & Villaret (1989). It is also necessary to allow the grid to adapt to the time dependent variation in water depth (moveable bed), thus also changing the model's domain of integration.

Both model versions have been extended by a gravity wave surface and a corresponding bottom boundary condition. the surface boundary condition includes the effect of breaking surface waves on the TKE budget, i.e. breaking wind waves cause an energy flux into the water column. We adopted an ideal proposed by Craig and Banner (1994) relating the flux of energy through the sea surface to the wind friction velocity depending on the surface roughness height. At the bottom a homogeneous Neuman condition for the TKE equation was applied. The corresponding surface boundary condition for the dissipation rate of TKE is of the Diriclet type and was derived from an analytical solution of the balance of dissipation and diffusion of TKE very close to the surface.

Implementing the wind wave boundary condition we followed the work of Grant and Madsen (1979) in the form applied by Davies and Lawrence (1995). This approach relates the apparent bottom roughness felt by the current to the combined action of wind waves and current. Depending on the water depth the combined action of wind waves and current lead to an increased bottom friction and subsequently influences the bottom processes regarding the SPM dynamics.

A first test of the model was conducted for the site of the FLEX experiment (1976), from which the required meteorological forcing data and measured temperature profiles for validation of the model results were available. First results showed that the characteristic features of the vertical temperature gradient are well reproduced. Furthermore, turbulence microstructure parameters showed reasonable values.

Further model runs against suitable PROMISE data sets will test the model and related processes in more detail (figure 4, Simpson et al 1996).

5. OPERATIONAL MODELLING

A clear conclusion regarding the observational data sets is the inadequacy (accuracy and resolution) of the bathymetric data and the wind data. Moreover questions of copyright/ proprietary rights to both these frequently arise.

The development of generic modules and the ready availability of general purpose model codes have removed much of the mystique that traditionally surrounded marine modelling centres. Present day concerns concentrate on how best to optimise the model formulations and associated forcing data for the required applications. Thence "Rationalisation" often implies accessing the most appropriate: algorithms/numerical solutions, bathymetry and related model set-up data, initial, coastal and open-sea (ocean-ocean) boundary conditions, surface forcing, assimilation and verification data. Whilst the long-term solution may be fully integrated atmospheric-ocean-shelf-sea-coastal-estuarine-hydrological operational models, shorter term expedients need to be developed.

The report (POL Report 49) on remote sensing/assimilation recognises a number of salient features of such expedients. The most useful remote sensing techniques should be:

- for sediments: optical data, including AVHRR and Landsat/SPOT. Improved quality should become available with the launching this year of SeaWIFS on SeaSTAR
- for beach processes and coastal erosion, SAR can be useful for monitoring, in addition to the traditional optical sensors
- for winds, scatterometer for global-scale; SAR images for fine-scale (1km resolution) have poor temporal coverage
- for waves, altimeter for wave height. SAR can be used for swell in exposed areas such as the Bay of Biscay
- for temperature fronts, thermal infrared images (AVHRR/ATSR)
- for current fronts, SAR gives qualitative information, but with poor temporal coverage.

Spatial variations in the currents are now used to monitor shallow-water bathymetry.

There is generally a trade-off between the spatial resolution of satellite data and its available temporal coverage. Continuous, nearly global coverage is afforded by geostationary meteorological satellites, and coverage several times daily is available for NOAA AVHRR. These optical and infra-red data are only available under cloud-free conditions, which is a significant disadvantage for mid-latitude locations which are subject to frequent poor weather.
Passive microwave and radar sensors can penetrate cloud cover, but the former sensors generally have rather too poor resolution for covering North Sea scales. The detail available in SAR images is good, but the coverage is only every few days at present, though there is a possibility of improvement in data coverage with the use of the recently launched RADARSAT.

When interpreting remote sensing data it is important to consider that satellites only observe the Earth's surface. In order to achieve three-dimensional marine information and forecasts, remote sensing data together with in-situ data must be assimilated in numerical models. There has, over the last decade, been a rapid development of various data assimilation methods which can be used with ocean hydrodynamic and ecosystem models. At present, however, none of these methods are used operationally, at least partly because the necessary observational data are either insufficiently accurate or do not provide sufficiently good coverage. In a fully operational system the access time for the most recent observations also becomes important. Real time analyses and

predictions from the European weather services must be used to ensure a proper forcing of the model and to make it possible to generate realistic predictions of the marine system.

A further aspect of PROMISE addresses optimizing the modelled North Sea hydrodynamics, given known or assumed uncertainties in field data and model parameters and input (ten Brummelhuis et al 1997). Similarly, the sensitivity of modelled SPM behaviour to such uncertainties and assumptions is analysed.

Extensive rationalisation exercises have been undertaken to illustrate the range of variability in model performance as functions of differences in: formulation (figure 5), data prescription and model operation. Likewise the adequacy of related databases (meteorological, geological, bathymetric) has been assessed. The task of quantifying the sensitivity of net estimates of sediment transport to the full range of 'impact' variables is ongoing - the aim being to prioritorise the requirements necessary to extend predictability.

Significant problems are to get the various models to communicate with each other at suitable space and time intervals and to distribute the model results in a way suitable for end users. For example, it is necessary to produce some kind of parameterization of the results of detailed turbulence models in order for them to be applied in hydrodynamic/sediment transport models at a North Sea scale. It is also necessary to obtain input/forcing data and data for model verification on space and time scales suitable for the models. This applies no less to remote sensing data than to field observations.

This project illustrates the challenge of integrating the expertise of specialists in modelling, monitoring, remote sensing and data assimilation to provide a state-of-the-art assessment of the accuracy and limitations of estimating sediment fluxes. The parallel applications of a suite of models to a range of coastal sites provides broad insights into the underlying problems and the scope for extending predictability.

6. DISSEMINATION AND EXPLOITATION

The challenge of dissemination to the external user community was addressed by convening a 'User-Group' meeting which included sessions on: existing operational services, planned future developments and developments in monitoring, technology and assimilation. This communication of research activities was followed by accounts of the related requirements of users (including flood defence, port operators, coastal management, ecologists, oil and gas and naval). The attendance by 60 participants from 10 European countries ensured enthusiastic participation.

The singular facet of this meeting was the pragmatic focus engendered by the participation of users, model operators, scientists and monitoring experts. Exciting opportunities are presented by the rapid advances in: computational power, monitoring technology and systems, scientific understanding and numerical methods. However, investment and the associated progress will depend on demonstrable benefits to end users. The pace will be dictated by our ability to collaborate in maximising the potential off past investments as well as careful planning for the future. Initiatives are needed to develop structured research, development and evaluation programmes to parallel the GOOS plans for the period 2000-2005. There is a well-defined need for great accuracy, resolution and reliability of existing services. The ultimate goal is a fusion of environmental data and knowledge utilising fully the communications and computational capacities to optimise sustainable development of our marine environment (figure 6).

References

Baumert, H. and G. Radach (1992) Hysteresis of turbulent kinetic energy in nonrotational tidal flows: a model study. J. Geophys. Res. Vol. **97**, 3669-3677.

ten Brummelhuis, P.G.J., Gerritsen, H. and Van der Kaaij, T (1997) Sensitivity analysis and calibration of the hydrodynamic PROMISE model using adjoint modelling techniques. Delft Hydraulics Research Report Z2025/Z2047.

Burchard, H. and H. Baumert (1995) On the performance of a mixed-layer model based on the k-, turbulence closure. J. Geophys. Res. Vol. **100**, C5, 8523-8540.

Craig, P. and Banner, M. (1994) Modelling wave-enhanced turbulence in the ocean surface layer. Journal of Physical Oceanography, 24 (12), 2546-2559.

Grant, W.D. and Madsen, O.S. (1979) Combined wave and current interaction with a rough bottom. Journal of Geophysical Research, 84 (C4), 1797-1808.

Davies, A.M. and Lawrence, J. (1995) Modelling the effect of wave-current interaction on the three dimensional wind driven circulation of the eastern Irish Sea. Journal of Physical Oceanography, 25 (1), 29-45.

Jenkins, A.D., G, Evensen., E. Bjørgo., H. Espedal., E, Korsbakken., K. Kloster., T. Hamre., V. Jensen., P. Samuel., D. Durand., M. Gómez Lahoz., J. Carlos Carretero., C de Valk., K. Mastenbroek., R.J. Vos., H. Gerritsen. and P.G.J ten Brummelhuis. Remote Sensing Applied to Operational Models - North Sea. POL Report no 49, 1997.

Luo, W., Flather, R. and Monbaliu, J. (1998) Modelling effect of mean current on bottom friction dissipation in a third generation model (WAM), abstract submitted to ICCE-conference, Copenhagen.

Monbaliu, J., R. Flather, J.C. Carretero and H. Gerritsen: "Wave modelling in the Promise Project" , Oceanology 98, Brighton, 1998.

Monbaliu, J., M.Y. Zhang., K. De Backer., J. Hargreaves., W. Luo., R. Flather., J.C. Carretero., M. Gomez Lahoz., I. Lozano., M Stawarz., H. Günther., H. Rosenthal. and J. Ozer. WAM Model Intercomparisons - North Sea. POL Report No 47, 1997.

Nöhren, I., K, Duwe. and H, Baumert. PROMISE Literature Review on Turbulence, Wave and Suspended Matter Transport Modelling. POL Report No 50, 1997.

Prandle, D. The Holderness Coastal Experiment '93-'96. POL Report No 44. 1996.

Regener, M., B. Szilagyi. and H. Baumert. The Generic 1-D turbulence-SPM model. POL Report No 48, 1997.

Sheng, Y.P., Villaret, C. (1989) - Modelling the effect of suspended sediment stratification on bottom exchange processes. J. Geoph. Res., Vol. **94**, No C10, 14.429 - 14.444.

Schneggenburger, C., Günther, H. and Wosenthal, W. (1997) Shallow water wave modelling with non-linear dissipation. Dt. Hydrogr. Z., 49 (2/3), in press.

Schneggenburger, C., Günther, H. and Rosenthal, W. (1988) Shallow water wave modelling with nonlinear dissipation: Application to small scale tidal systems. In: Proceedings of the 5th International Workshop on Wave Hindcasting and Forecasting, January 27-30, 1998, Melbourne, Flordia, USA.

Simpson, J.H., Crawford, W.R., Rippeth, T.P., Campbell, A.R. & Josepth, V.S.C. (1996) The vertical structure of turbulent dissipation in shelf seas. J. Physical Oceanography. 26(8), 1579-1590.

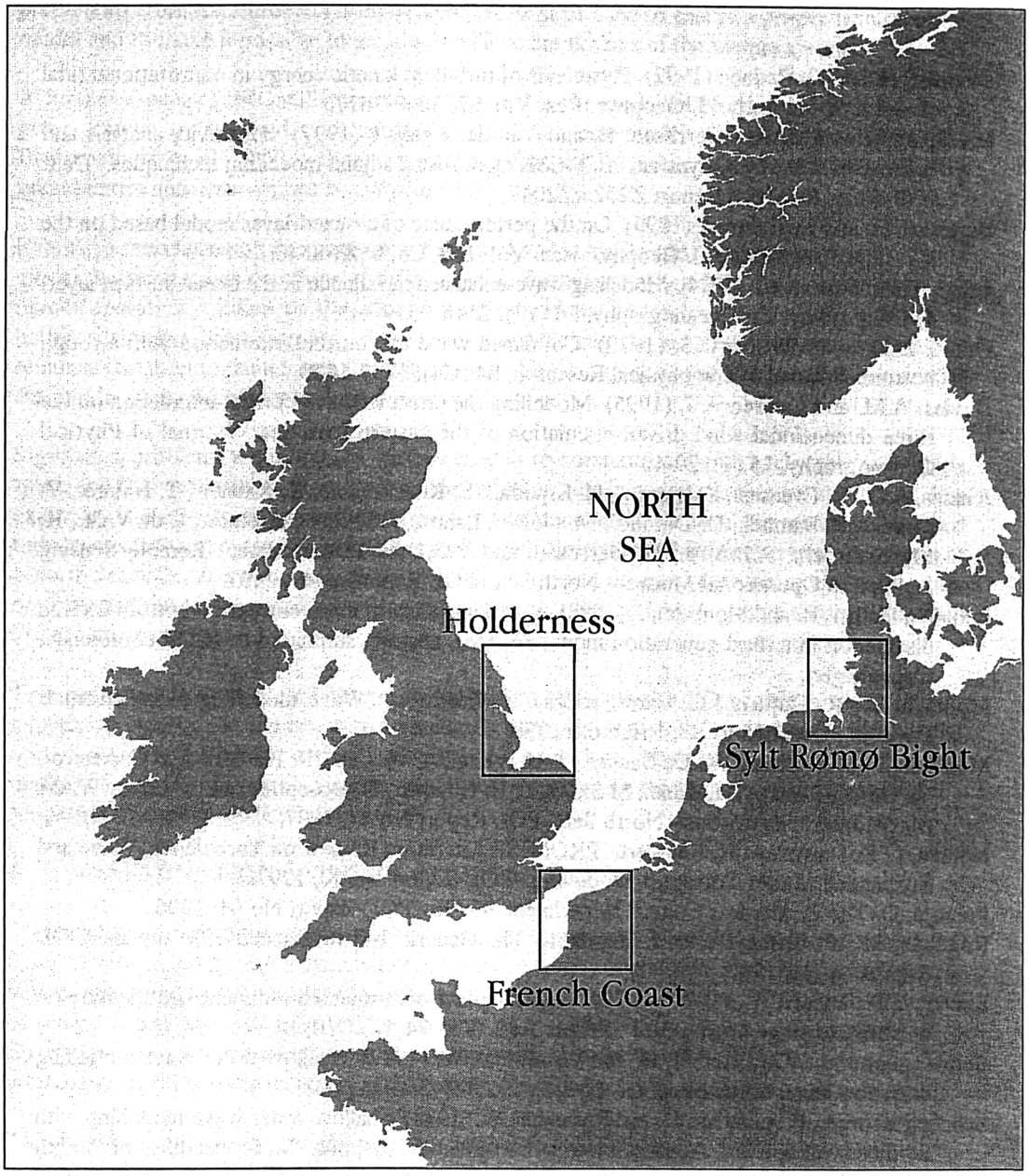


Figure 1. Regional foci within North Sea simulations.

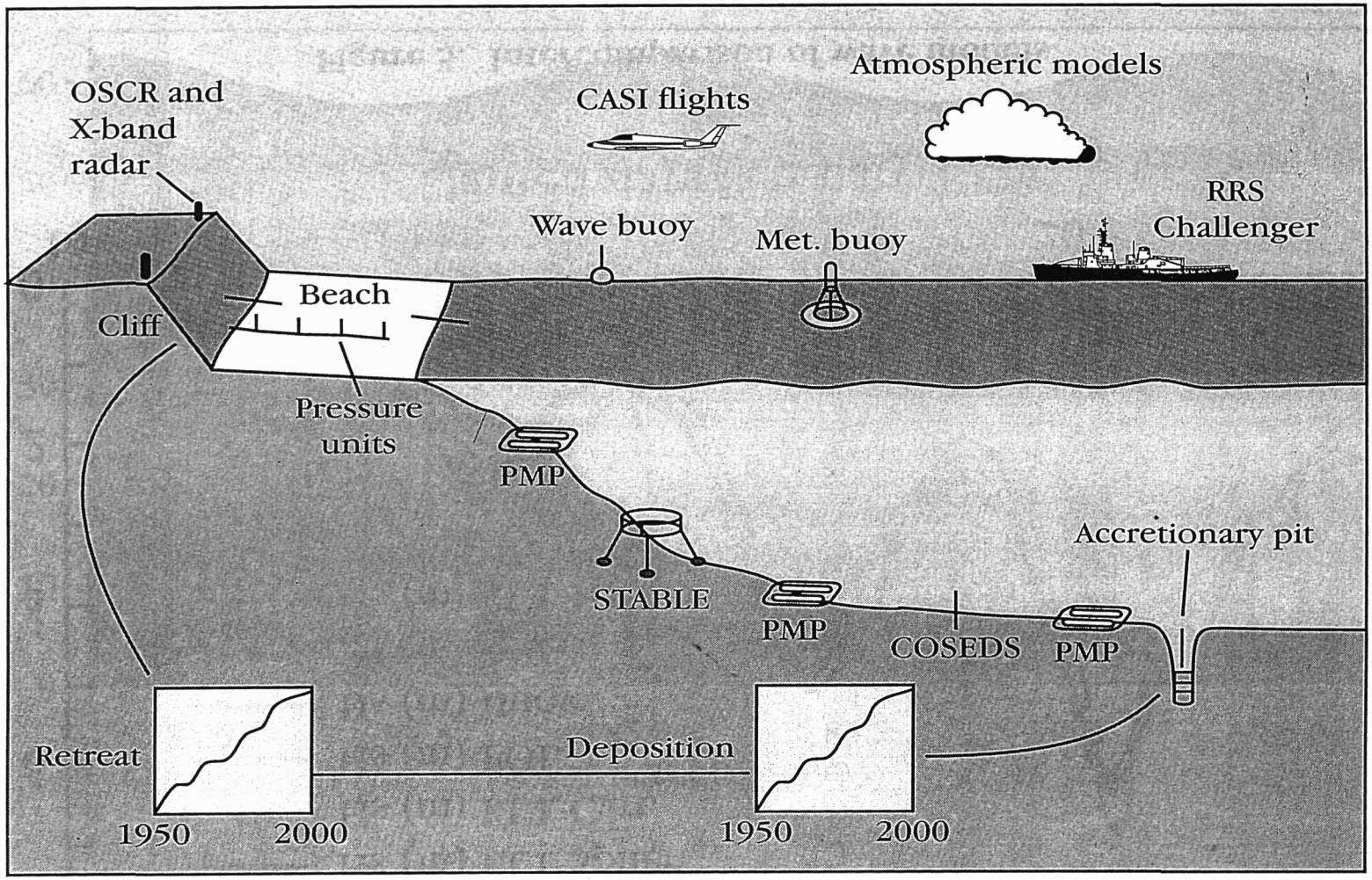


Figure 2. Schematic of regional observation exercise (Holderness).

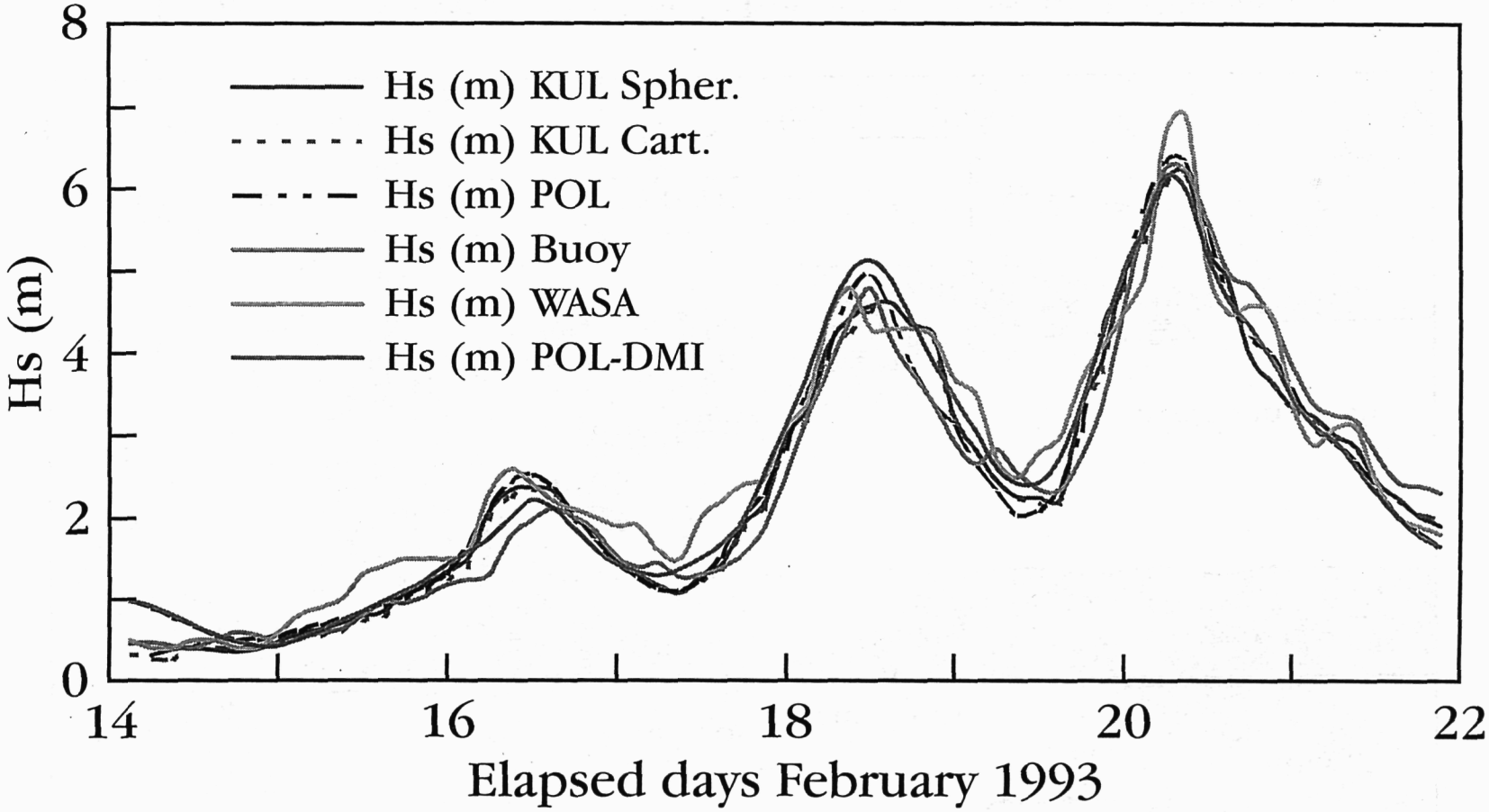


Figure 3. Intercomparison of wave models.

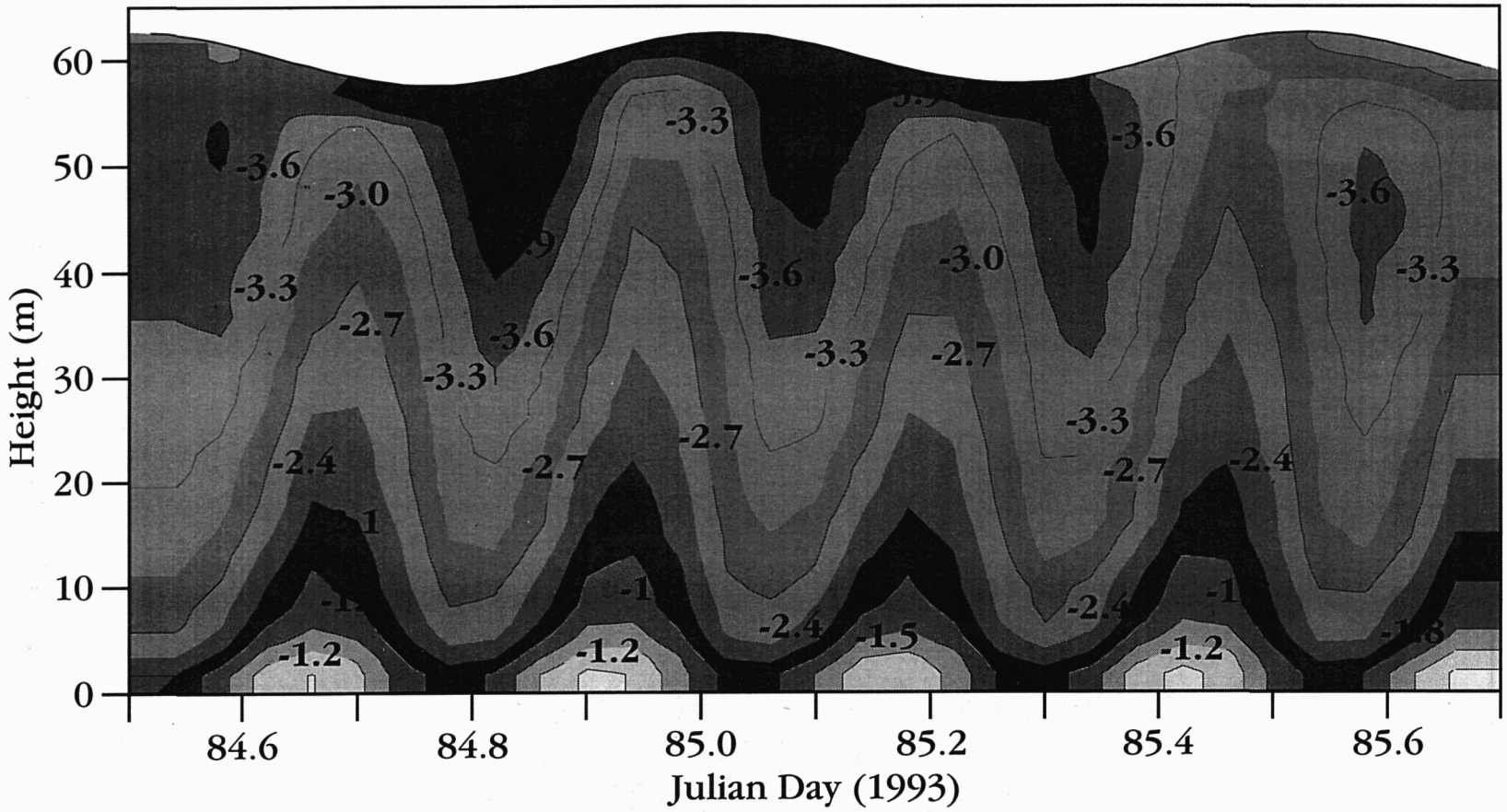


Figure 4. Model simulation of turbulent dissipation rate.

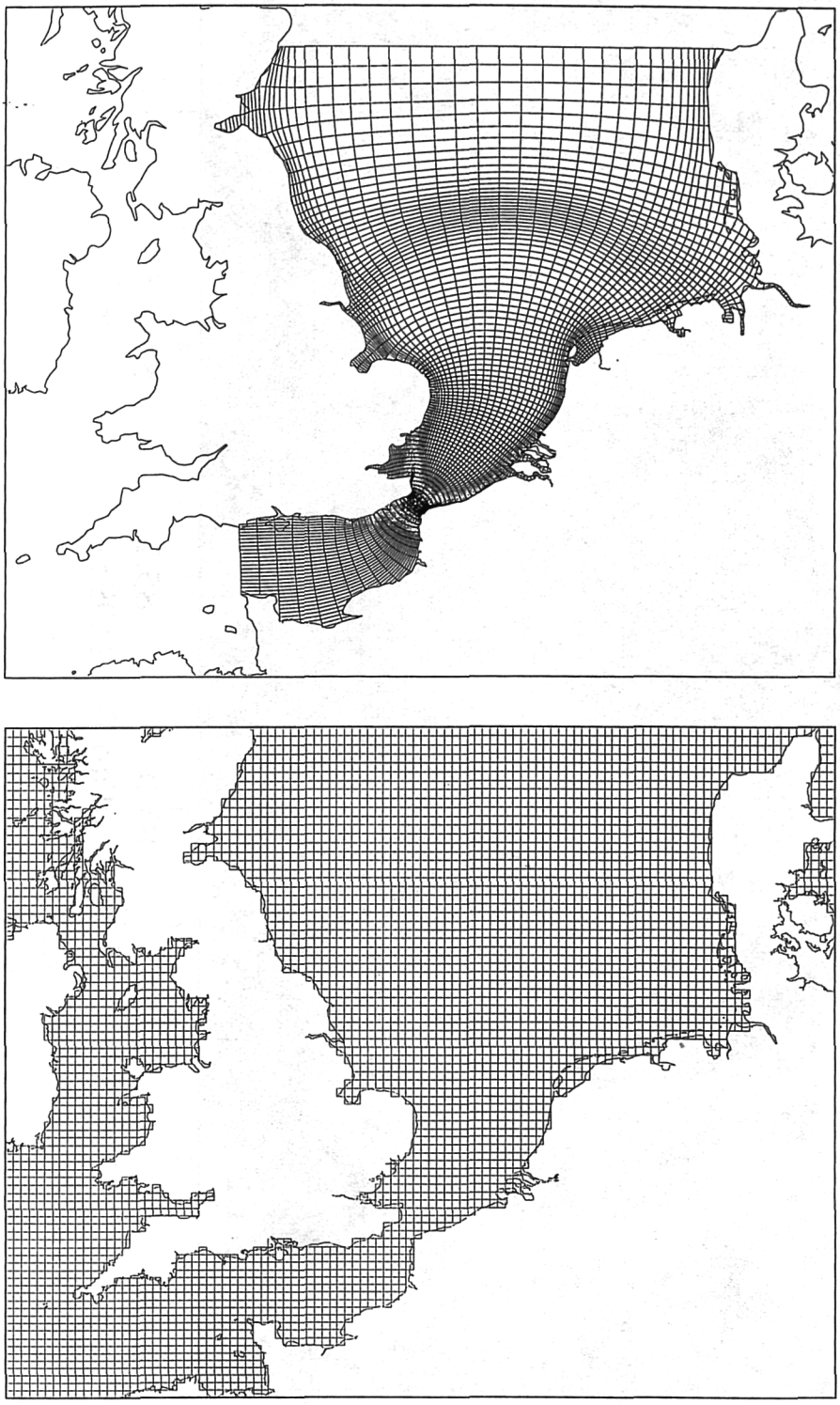


Figure 5. Examples of different model grids.

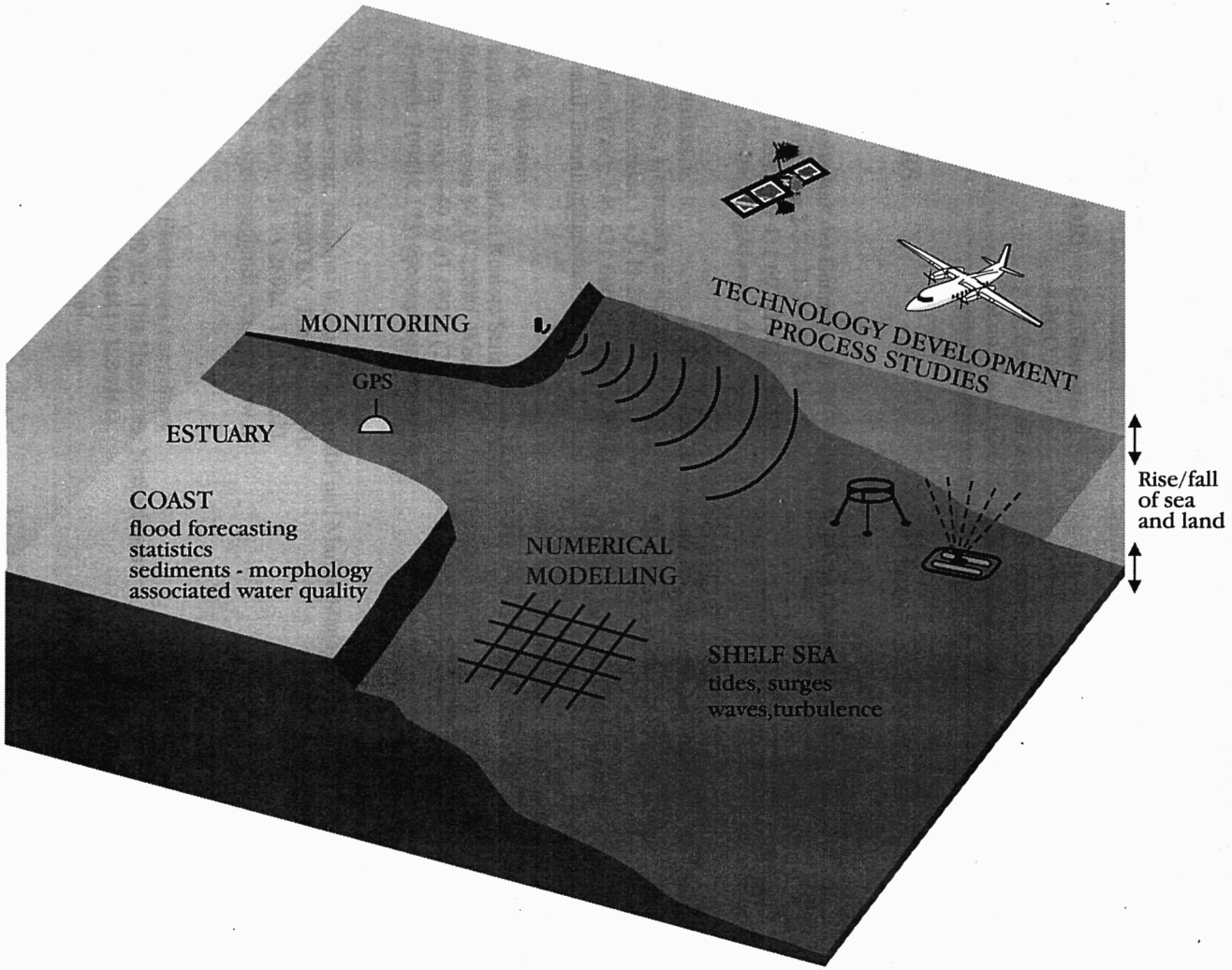


Figure 6. Operational Oceanography.

TITLE: Coastal Sediment Transport Assessment using SAR imagery (project **C-STAR**)

CONTRACT NO: MAS3-CT95-0035

COORDINATOR:
G.J. Wensink
ARGOSS
P.O. Box 61, 8325 ZH Vollenhove, NL
Tel.no. (Fax): +31 527 242299 (242016)
E-mail: info@argoss.nl

PARTNERS:

S. Stolte
Forschungsanstalt der Bundeswehr für Wasserschall- und Geophysik (FWG)
Klausdorfer Weg 2-24, D-24148 Kiel, D
Tel.no. (Fax): +49 431 6074108 (7204150)
E-mail: Stolte@fwg.ki.eunet.de

I. Hennings
GEOMAR, University of Kiel
Wischhofstrasse 1 - 3, D-24148 Kiel, D
Tel.no. (Fax): +49 431 600 2312 (600 2941)
E-mail: ihenning@geomar.de

V.R. Wismann
Institute for Applied Remote Sensing (IFARS)
Bahnhofstrasse 54, D-22880 Wedel, D
Tel.no. (Fax): +49 4103 13922 (7469)
E-mail: 100412.1731@compuserve.com

J. Vogelzang
Rijkswaterstaat, National Institute for Coastal and Marine Management/RIKZ (RWS),
P.O. Box 20907, 2500 EX The Hague, NL
Tel.no. (Fax): +31 15 2691111 (2618962)
E-mail: j.vogelzang@mdi.rws.minvenw.nl

H. Greidanus
TNO Physics and Electronics Laboratory
P.O. Box 96864, 2509 JG The Hague, the Netherlands
Tel.no. (Fax): 31 70 3740441 (3280961)
E-mail: greidanus@fel.tno.nl

C. Vernemmen
University of Gent, Research Unit for Marine and Coastal Geomorphology
Krijgslaan 281 S8, B-9000 Gent, BE
Tel.no. (Fax): +32 9 264 4695 (4970)
E-mail: carlos@selifa.rug.ac.be

W. Alpers
University of Hamburg, Institut für Meereskunde, Fernerkundung
Troplowitzstrasse 7, D-22529 Hamburg, D
Tel.no. (Fax): +49 40 4123 5432 (5713)
E-mail: alpers@ifmsun1.ifm.uni-hamburg.de

I. Robinson
University of Southampton, Department of Oceanography
European Way, SO14 3ZH Southampton, Hampshire, UK
Tel.no. (Fax): +44 1703 595000 (593059)
E-mail: isr@soc.soton.ac.uk

K.D. Pfeiffer
HYDROMOD
Bahnhofstrasse 52, D-22880 Wedel, D
Tel.no. (Fax): +49 4103 13057 (3317)
E-mail: pfeiffer@hydromod.de

H. Gerritsen
Delft Hydraulics
P.O. Box 177, 2600 MH DELFT, NL
Tel.no. (Fax): +31 15 285 8585 (8582)
E-mail: Herman.Gerritsen@wldelft.nl

ADVISOR:

G.P. de Loor
Benoordenhoutseweg 277, 2596 BJ THE HAGUE, NL
Tel.no. (Fax): +31 70 3243442
E-mail: gpdeloor@kivi.nl

The Bathymetry Assessment System

G.J. WENSINK, G.H.F.M. HESSELMANS, C.J. CALKOEN

ARGOSS,
P.O. Box 61, 8325 ZH Vollenhove, the Netherlands

SUMMARY

In the presence of current and wind, submerged topographic features of the sea bed produce contrasts in radar images. These contrasts can be quantitatively understood and modeled, based on hydrodynamics and electromagnetic scattering theory. A suite of models has been developed based on the generally accepted imaging mechanism, which consists of three steps: (1) surface current modulation by the bathymetry, (2) modulation of the (small) wave spectrum by wave-current interaction, and (3) radar backscattering by the sea surface. In order to invert this depth-radar backscatter relation, a data assimilation scheme has been developed. These numerical models have implemented, leading to the Bathymetry Assessment System (BAS). An example of an application in the Dutch coastal waters is presented.

1. INTRODUCTION

Bathymetric data of shallow seas are of vital importance for shipping, fishery and all kinds of offshore activities as well as coastal management. Traditionally, depth information is collected from ships using (single or multi beam) echo sounders. Bathymetric surveys are therefore time and cost consuming. Remote Sensing methods may improve the efficiency of bathymetric surveys, since they give an instantaneous overview over large area's at relatively low costs.

In 1969 de Loor c.s. discovered that under suitable conditions (moderate wind and strong tidal current) bottom topography is visible in radar images [De Loor and Brunsveld van Hulten, 1978; De Loor, 1981]. This was a great surprise: the sea surface is an almost perfect conductor at radar frequencies and, as a consequence, the microwave radiation does not penetrate into the water column, but reflects from the surface only. In 1978 the SEASAT satellite was launched, carrying for the first time an imaging radar in space. The nice images of bottom structures in the Southern Bight of the North Sea and in the Nantucket Shoals at the eastern coast of America further demonstrated the potential of microwave techniques.

The results of SEASAT aroused much interest in the phenomenon, both from the experimental and from the theoretical side. Alpers and Hennings [1984] came with the first model of the imaging mechanism. This model proved to be essentially correct, not only for bottom topography but also for other phenomena causing surface current variations like internal waves, fronts and ship wakes. It could also be applied to the optical window, especially when looking into the reflection of the sun on the sea surface. Surface expression of bathymetry can, under suitable conditions, even be observed with the naked eye, a fact known for centuries by sailors and fishermen.

The ERS-1, carrying a C-band Synthetic Aperture Radar (SAR), was launched succesfully in 1991. It was followed by ERS-2 in 1995. Now radar images became available at a regular base. This motivated a number of studies, supported by the Netherlands Remote Sensing Board (BCRS) and the European Commission (EC), in which the various submodels in the imaging mechanism were improved and practical applications were considered. Given the depth of an area, the wind speed and its direction, and the tidal phase, it is now possible to predict quantitatively, with reasonable accuracy, how a radar image will look like. This is nice from a scientific point of view, but for practical use one would like to go the other way round: predict the depth given the radar image. This is not feasible by analytical inversion of the imaging model, due to its complexity. Therefore numerical techniques were developed to achieve this, leading to the Bathymetry Assessment System (BAS). BAS constructs a depth map from one or more radar images (and a reduced number of traditional echo soundings. The soundings are needed to adjust some model parameters which are not well known. They are also used as constraints to the depth map. One may view the BAS as an "intelligent interpolator" which interpolates between transects of echo soundings using the depth information in radar images. The accuracy of the resulting depth map depends, of course, on the distance between the transects.

2. ZEEGAT VAN AMELAND

On the west side of Ameland two coastal sections are subject to severe erosion. The current policy of Rijkswaterstaat "Dynamic preservation" aims at maintaining these sections by means of supplying additional sand. However, given the current rate of erosion, especially in the coastal section 2-4 km (location with respect to the "Rijksstrandpalen"), there is some doubt as to whether or not all sections can be preserved effectively by supplying additional sand. Maintaining the current coastline requires an optimal use of available resources.

The options proposed to solve the management problems of Ameland will be analysed by morphological studies, literature searches, field measurements and model calculations. For the execution of the calculations, detailed knowledge of the seabed topography within the project area in the neighbourhood of the tidal channel of Ameland is required.

The current method of maintaining the coastline of West Ameland might not be optimal. This raises the following question:

> How can one optimise management and control of the western part of the coastal area of Ameland using knowledge of the morphology and the underlying physical processes.

The ultimate goal of the product group Bornrif is to optimise the coastline maintenance of western Ameland.

In order to achieve this goal the various options for the solution of the coastal problems will be investigated. The dynamics of the morphological processes in the whole area around the tidal channel of Ameland will be studied using for instance numerical models. The interaction with the adjacent coastal area will be included in these studies as well. Therefore the study area includes the tidal channel, the outer delta (Bornrif) and part of the flood basin.

The morphological and hydrodynamic models use certain types of (irregular) calculation grids. Traditionally, the soundings are projected in to the calculation grid. In order to cover the whole grid, sounding measurements of several years are used. In a dynamic area such as the one that contains the tidal channel of Ameland, results of such an approach turn out to be unrealistic. The thus constructed bathymetric map is not only outdated but inconsistent as well. For example, if the bottom topography of one half of a highly dynamic tidal channel has been measured in another period as the other half, the two halves may not match. The poor quality of such a bottom topography assessment has a major influence on the quality of the model calculations.

The aim of this study is to obtain the complete seabed topography of the project area representing the situation in April/May 1996 by using the Bathymetry Assessment System. The Bathymetry Assessment System will be applied to radar backscatter images (SAR) and combined with available soundings of the project area.

3. BATHYMETRY ASSESSMENT SYSTEM

Under favourable meteorological and hydrodynamic conditions (moderate winds of 3 to 9 m/s and significant tidal currents of 0.5 m/s or more), air- or space borne Synthetic Aperture Radar (SAR) imagery shows features of the bottom topography of shallow seas (Alpers and Hennings 1984, Vogelzang et al., 1989).

The imaging mechanism of mapping sea bottom topography by imaging radar consists of three stages (a more detailed mathematical formulation is given in Calkoen et al., 1993):

(1) Interaction between (tidal) flow and bottom topography results in modulations in the (surface) flow velocity. This relation can be described by several models with an increasing level of complexity: continuity equation, shallow water equations, and the Navier Stokes equations.
(2) Modulations in surface flow velocity cause variations in the surface wave spectrum. This is modelled with the help of the action balance equation, using a relaxation source term to simulate the restoring forces of wind input and wave breaking.
(3) Variations in the surface wave spectrum cause modulations in the level of radar backscatter. To compute the backscatter variations a simple Bragg model can be used, but also available are two-scale and first iteration Kirchoff (Holliday) models.

Based on the above three stage mechanisms, a suite of computer models has been developed and operationalized at ARGOSS. Models with different levels of complexity and physical detail are available for each step. These models describe the flows, waves and electromagnetic scatter and can be used for a quantitative analysis of radar imagery.

In its most basic form, the three models described above consist of:

(1) The continuity equation relates current velocity in the direction perpendicular to bottom features (u_p) and depth (d) : $u_p=c/d$. c is a constant. The current velocity is proportional to the inverse of the depth. The current velocity in the direction parallel to the features in the bottom topography is constant according to the continuity equations.

(2) The Action Balance Equation describes the sources and sinks of action caused by wind input, dissipation and non-linear wave interactions: $dA/dt=S$. Relying on weak hydrodynamic interaction theory an equilibrium (action) spectrum can be assumed. First order Taylor expansion yields a linear source term $S_{lin}(A)=-\mu(A-A_{eq})$. S describes the relaxation of the action spectrum (A) towards its equilibrium value A_{eq}.

(3) First order Bragg scattering is the simplest model for relating the radar cross section of the sea surface, σ_0, to the wave height spectral density Ψ: $\sigma_0 = 8\pi(k\cos\theta)^4|G_{\alpha\beta}(\theta)|^2[\Psi(q_B)+\Psi(-q_B)]$, with θ the angle of incidence and k the radar wavenumber. The function G contains the polarisation dependence with subscripts α and β referring to the polarisation of the incoming and scattered radiation, respectively. The radar cross section is proportional to the wave height spectral density evaluated at (plus or minus) the Bragg wavenumber q_B given by: $q_B=2\,k\sin(\theta)$.

This suite of computer models generate the radar backscatter given the bathymetry and the wind. In order to invert this depth-radar backscatter relation, a data assimilation scheme has been developed, minimizing the difference between the calculated and the measured radar backscatter by adjusting the bottom topography.

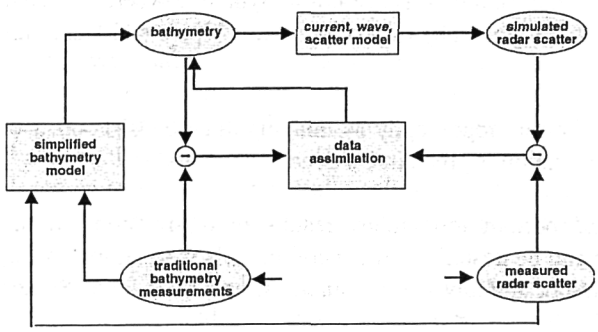


Figure 1 Bathymetry Assessment System

The imaging model in BAS contains two-dimensional models. This means that the flow and the wave field need not be schematised as one-dimensional, in the same direction as the radar look direction. However, a fully two-dimensional data assimilation scheme for BAS is presently not yet available. At the moment two one-dimensional limits of BAS are available: one in which the main depth variations are supposed to lie perpendicular to the flow direction and one in which the depth variations are mainly parallel to the flow. These two limiting cases are called the sand wave system and the channel system, after their main application. The structure of this modular system is shown in figure 1.

4. RESULTS

4.1. PROJECT AREA

The Bathymetry Assessment System has been applied in the "Zeegat van Ameland" area, which is shown in figure 2. The purpose of the project is to assess the applicability of (the current version of) the BAS and assess its accuracy as a function of the distance between section lines.

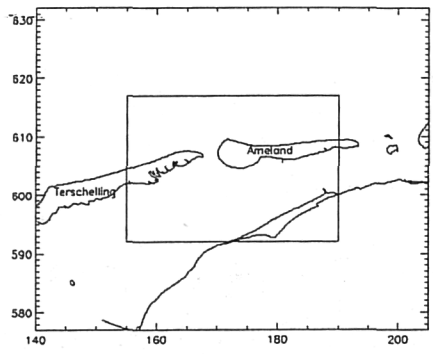


Figure 2 Map of the northern part of the Netherlands showing the project area. The axes show the location in the "Rijksdriehoek" coordinate system.

The area of interest, is a tidal inlet in between the Dutch islets Terschelling and Ameland in the Waddenzee, north of the Netherlands. The area measures 35 km by 25 km. The project area lies approximately between 5° 23' and 5° 55' E, and 53° 19' and 53° 33' N.

The Bathymetry Assessment System requires, amongst others, SAR data and a limited number of sounding data. Most important are the SAR images from which the depth maps are constructed. The limited number of ship's soundings are needed to calibrate model parameters in BAS. Other required *in situ* measurements are: the wind speed and direction, and the tidal phase from which the flow field and the water elevation is computed. In this study the following data sets were obtained: ERS-1 images, hydro-meteorological conditions, sounding data, positioning data.

A list of acquired images is shown in table 1. This table also lists the hydro-meteorological conditions at the recording times of the radar images.

orbit	frame	date	time (GMT)	time (MET)	wind speed [m/s]	wind direction [degrees] (from North)	tidal phase Harlingen
5122	1071	April 12, 1996	21:38	22:38	4	60	+6h40
5287	2529	April 24, 1996	10:37	11:37	9	210	-1h25
25189	2529	May 09, 1996	10:34	11:34	11	30	-2h19
6289	2529	July 03, 1996	10:37	11:37	10	200	-0h48
6790	2529	Aug 07, 1996	10:37	11:37	9	210	-5h03

Table 1 Inventory of available ERS-1 SAR imagery and hydro-meteo conditions during SAR data acquisition.

All images were recorded mid 1996. Note that more images have been recorded in this period by ESA. However, not all are suited for our purpose. A moderate windspeed is required. Experimental evidence gathered in the North Sea yield a suitable windspeed range between 3 and 9 to 10 m/s. Inspection of several images of the Dutch and German Wadden Sea shows that wind conditions exceeding 10 m/s might be suitable as well. Furthermore, strong (tidal) currents are needed. Current velocities can be estimated from tide tables and current maps. The recording times were used to assess the current conditions in the project area. Note that suitable conditions in the North Sea may not coincide with optimal conditions for the Wadden Sea area or the tidal channel of Ameland. Based on the tide tables and current maps

a pre-selection of the images was made. Images with a maximum current velocity were selected and ordered from ESA. As an example the ERS image of May 09, 1996 is shown in figure 3.

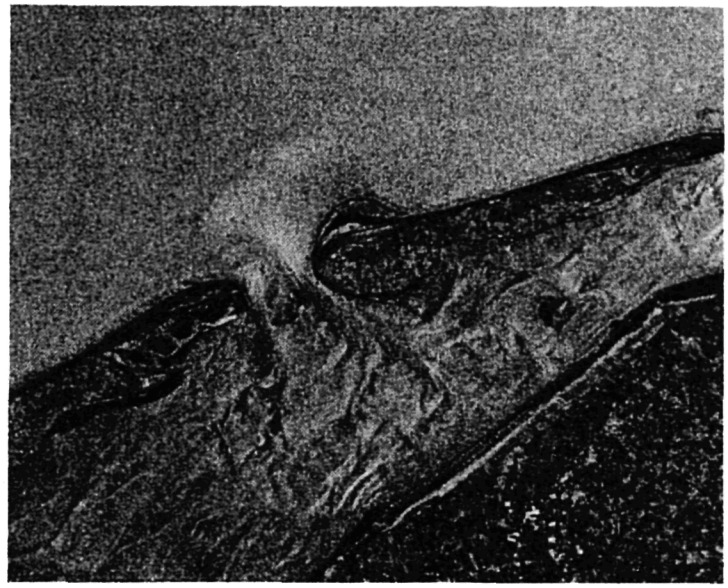


Figure 3 ERS SAR image of May 9, 1996.

Soundings were obtained from different sections of Rijkswaterstaat, (RIKZ, DNN and DNN-MD). The set of soundings consists of:

1 Soundings (vaklodingen) recorded in 1996. The distance between the section lines is 200 m (west of the line X=160) or 1000 m (east of the line X=160).
2 Soundings (Jaruslodingen) recorded in 1996. The distance between the section lines is 500 m.
3 Additional soundings recorded at request by mid 1996 over the tidal flats.
4 Soundings of some major tidal channels as recorded in 1996.
5 Soundings of some major tidal channels as recorded in 1995.
6 Soundings (vaklodingen) recorded in 1993.
7 Gridded soundings compiled in 1993. The grid spacing is 25 m. These gridded 1993 data are presented in figure 11. The gridded data do not cover the whole project area.

The position of the sailed tracks of each set of the soundings acquired in 1996 (vaklodingen) is shown in figure 4. In figure 5 a bathymetric map based on the gridded soundings of 1993 is shown.

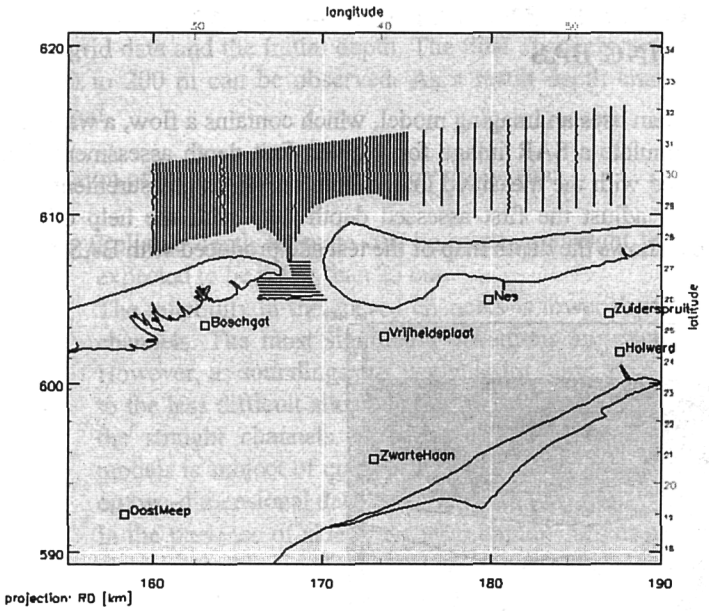


Figure 4 Soundings (vaklodingen) acquired in 1996 by RWS.

At some locations the ship's soundings reveal small scale depth variations along tracks. These undulating features can reach heights of more than 50 cm at wave lengths of approximately 30 m, which is the resolution of the ERS SAR. This means that the SAR images cannot resolve these short sand waves and therefore neither can BAS.

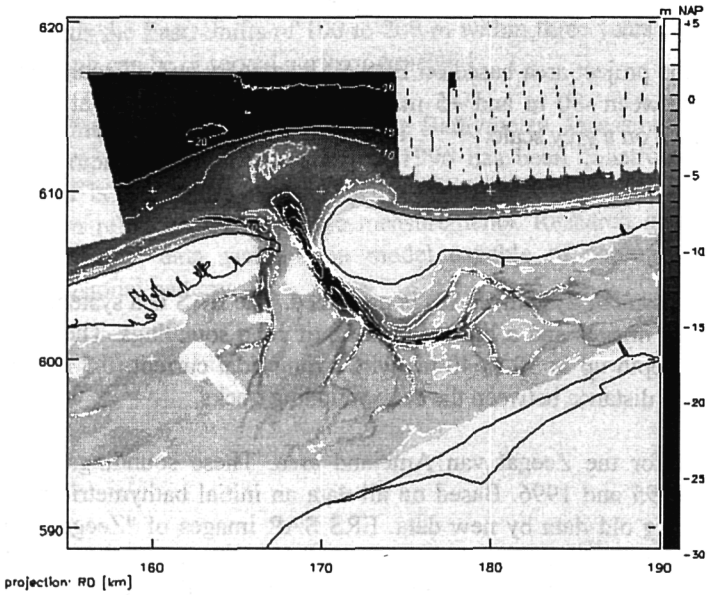


Figure 5 Sea bed topography based on gridded soundings compiled in 1993. Grid spacing is 25 m.

4.2. COMPUTATION OF THE "ZEEGAT VAN AMELAND" BATHYMETRY USING BAS

The Bathymetry Assessment System uses an imaging model, which contains a flow, a wave and a radar backscatter model, to simulate a SAR image for a given first depth assessment. The simulated SAR image is compared with the measured images and the ship's measurements and observed differences are used to adjust the first assessed depth map with the help of data assimilation techniques. Figure 6 shows the depth map of the test site produced with BAS.

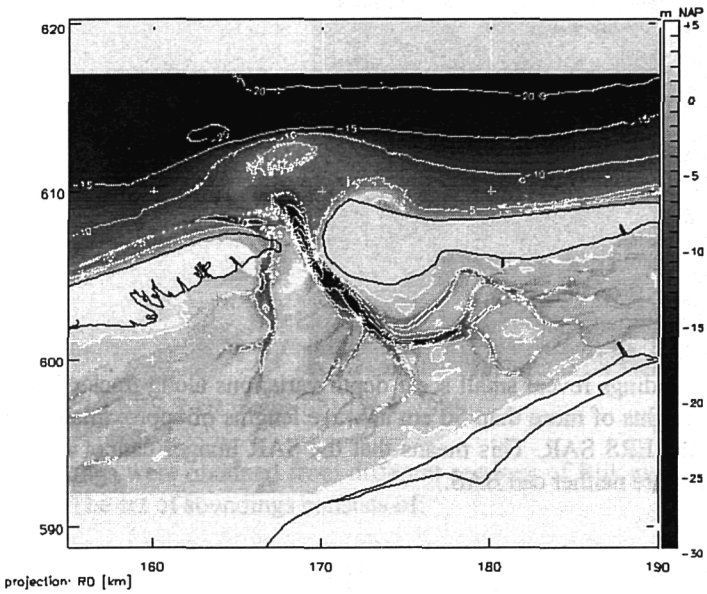


Figure 6 Bathymetric map of the project area based on ERS SAR imagery and all soundings. The depth range is between -30 m and +5 m. Contour levels are drawn at 10 m interval. Depth is shown on a grey scale.

5. CONCLUSIONS

In this paper the Bathymetry Assessment System (BAS) is presented. The BAS is a system that constructs depth maps from radar images and a limited number of echo soundings. The BAS can be applied in shallow seas (depth up to 30 to 40 m) with strong tidal current (0.5 m/s or more). Its accuracy depends on the distance between the echo sounding tracks.

Soundings have been collected for the Zeegat van Ameland area. These soundings were measured in 1993 (or before), 1995 and 1996. Based on all data an initial bathymetric map has been constructed, by replacing old data by new data. ERS SAR images of "Zeegat van Ameland" have been collected for the period from April to August 1996. Based on these SAR data, using the soundings for calibration, an up to date bathymetric map of the area has been produced.

The seabed topography as calculated using BAS, shows significant differences with both the 1993 grid data and the initial depth. The tidal channels tend to move to the east. Movements of 100 to 200 m can be observed. As a result depth changes of 6 meters or more can be observed.

Inspection of the calculated bathymetry shows that

- Reliable depth estimate can be made in straight tidal channels. The rms accuracy is expected to be better than 25 cm.
- The reliability in the curved channels is lower than that obtained for the straight tidal channels. The most significant deviations are expected for the most dynamic areas. However, as soundings are available for these area, the contribution of BAS is limited to the less difficult situations. The accuracy in these areas is expected to be similar to the straight channels. Data assimilation techniques to deal with two-dimensional models is subject of current research. Preliminary results show that an approach based on two-dimensional data assimilation is feasible.
- In the presence of side branches complex current patterns may occur. BAS in general yields plausible results. However, in some complex cases, the model clearly fails, and one has to rely on the measurements.
- In the outer delta a significant change (decrease in depth) in the bottom level is observed for the Ameland coastal area. The area is so-called accretion area (see: Kust *2000 definitiestudie: Bornrif). This change is also visible in the raw radar imagery.
- Given the smooth nature of the tidal flats, the rms depth accuracy is expected to be better than the accuracy in the straight tidal channels.

Inspection of the bathymetric maps (figures 5 and 6) shows that the Bathymetry Assessment System is able to detect changes in bottom topography. The channel movement tends to be towards the East. Shifts of 100 to 200 m within three years can be observed. In the outer delta shoaling can be observed north of Ameland.

It is finally concluded that using the Bathymetry Assessment System a coherent bathymetric map representing the situation in 1996 has been constructed. In some complex cases the model is not yet able to produce a depth map with sufficient accuracy. In these cases the system relies on the available measurements. Research is in progress to developed a two-dimensional data assimilation model capable of coping with these more complex two-dimensional patterns.

REFERENCES

1 Alpers, W., and Hennings, I., A theory of the imaging mechanism of underwater bottom topography by real and synthetic aperture radar. *Journal of Geophysical Research*, **C89**, 10529-10546, (1984)

2 Calkoen, C.J., Wensink, G.J. and Hesselmans, G.H.F.M., *ERS-1 SAR imagery to optimize the NOURTEC ship-based bathymetric survey: feasibility study*, Delft Hydraulics report H1875, November 1993.

3 Calkoen, C.J., and Wensink, G.J., Use of ERS-1 SAR imagery to optimize ship-based bathymetric surveys in the Waddenzee: feasibility study. Delft Hydraulics report H1985, December 1993.

4 Hesselmans, G.H.F.M., SAR survey Zeegat van Ameland, ARGOSS, November 1996.

5 Hesselmans, G.H.F.M., Update SAR survey Zeegat van Ameland, ARGOSS, December 1997.

6 De Loor, G.P., and Brunsveld van Hulten, H.W., Microwave measurements over the North Sea. *Boundary Layer Meteorology*, **13**, 113-131 (1978)

7 De Loor, G.P., The observation of tidal patterns, currents and bathymetry with SLAR imagery of the sea. IEEE Journal of Oceanic Engineering, **6**, 124-129, (1981)

8 Vogelzang, J., Wensink, G.J. de Loor, G.P.,Peters, H.C. Pouwels, H., and van Gein, W.A., *Sea bottom topography with X-band SLAR*, BCRS report BCRS-89-25, (1989)

TITLE: Fluxes Across Narrow Shelves. The Ebro delta case

CONTRACT NO: MAS3-CT95-0037

COORDINATOR: Dr. Agustin Sánchez-Arcilla
Laboratori d'Enginyeria Marítima
Universitat Politècnica de Catalunya
Gran Capità s/n, mòdul D-1
08034 Barcelona, Spain
Tel. +34 3 401 6468, Fax. +34 3 401 7357
Email: arcilla@etseccpb.upc.es

PARTNERS:

Prof. John H. Simpson
School of Ocean Sciences
University of Wales, Bangor,
Menai Bridge, LL59 5EY Gwyneed, U.K.
Tel. +44 1 248 382844, Fax. +44 1 248 716367
Email: oss035@bangor.ac.uk

Dr. Alan M. Davies
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead, Merseyside L43 7RA, U.K.
Tel. +44 151 658 8633, Fax. +44 151 653 6269
Email: amd@ua.nbi.ac.uk

Prof. Philippe Fraunié
Laboratoire de Sondages Electromagnetiques
de l'Environnement Terrestre - CNRS (D0705)
Université de Toulon et du Var
BP 132, 83957 La Garde Cedex, France
Tel. +33 4 94 14 24 16, Fax. +33 4 94 14 24 17
Email: fraunie@lseet.univ-tln.fr

Dr. Albert Palanques
Instituto de Ciencias del Mar
Consejo Superior de Investigaciones Científicas
Paseo Juan de Borbón s/n
08039 Barcelona, Spain
Tel. +34 3 221 6450, Fax. +34 3 221 7340
Email: albertp@icm.csic.es

ASSOCIATED PARTNERS:

Prof. Bjørn Gjevik
Matematisk Institutt, Universitetet i Oslo
Postboks 1053 Blindern
0316 Oslo, Norway
Tel. +47 22 85 5856, Fax. +47 22 85 4349
Email: bjorng@math.uio.no

Dr. Antonio Cruzado
Centre d'Estudis Avançats de Blanes
Consejo Superior de Investigaciones Científicas.
Camí de Santa Bárbara s/n
17300 Blanes, Spain
Tel. +34 72 33 6101, Fax. +34 72 33 7806
Email: cruzado@ceab.es

Dr. Marcel J.F. Stive
Delft Hydraulics
P.O. Box 152
8300 AD Emmeloord, The Netherlands
Tel. +31 15 285 8585, Fax. +31 15 285 8582
Email: marcel.stive@wldelft.nl

SUBCONTRACTORS:

Dr. Damià Gomis
Departamento de Física, Facultad de Ciencias
Universidad de las Islas Baleares
Carretera de Valldemossa, km. 7,5
07071 Palma de Mallorca, Spain
Tel. +34 71 17 3236, Fax. +34 71 17 3426
Email: dfsdgb4@ps.uib.es

Dr. Jean-Jacques Naudin
Laboratoire Arago (UA 117), Observatoire
Océanologique - CNRS, G.R. "Interactions
Continent-Océan" (GDR 909), B.P. 44
66651 Banyuls sur Mer, France
Tel. +33 4 68 88 73 77, Fax. +33 4 68 88 59 46
Email: naudin@arago.obs-banyuls.fr

THE FANS MAST-III PROJECT

A. SÁNCHEZ-ARCILLA[1], J.H. SIMPSON[2], P. FRAUNIÉ[3], A.M. DAVIES[4], A. PALANQUES[5], B. GJEVIK[6], M.J.F. STIVE[7], A. CRUZADO[8], D. GOMIS[9] AND J.-J. NAUDIN[10]

[1] Maritime Engineering Lab (LIM/UPC), ETSECCPB, Catalonia University of Technology, Jordi Girona, 1-3, 08034 Barcelona, Spain.
[2] School of Ocean Sciences, University of Wales - Bangor, Menai Bridge, LL59 5EY Gwyneed, U.K
[3] Laboratoire de Sondages Electromagnetiques de l'Environnement Terrestre - CNRS, Université de Toulon et du Var, BP 132, 83957 La Garde Cedex, France
[4] Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead, Merseyside L43 7RA, U.K
[5] Instituto de Ciencias del Mar (CSIC), Paseo Juan de Borbón s/n, 08039 Barcelona, Spain.
[6] Matematisk Institutt, Universitetet i Oslo, Postboks 1053 Blindern, 0316 Oslo, Norway
[7] Delft Hydraulics, P.O. Box 177, 2600 MH Delft, The Netherlands
[8] Centre d'Estudis Avançats de Blanes, CSIC, Camí de Santa Bárbara s/n, 17300 Blanes, Spain
[9] Departamento de Física, Universidad de las Islas Baleares, 07071 Palma de Mallorca, Spain.
[10] Laboratoire Arago, Observatoire Océanologique, BP 44, 66651 Banyuls sur Mer, France.

1. SUMMARY

This paper describes the status of the FANS project, after 1.5 years of project development. FANS stands for FLUXES ACROSS A NARROW SHELF. THE RELEVANCE OF NEARSHORE/SHELF/SLOPE INTERACTIONS IN THE EBRO DELTA REGION.

After a short presentation of the project aims and motivation the methodology used in FANS is described. Some initial results are presented next, with emphasis on what is better established after only 1.5 years of project duration, and less than 1 year after the last field campaign. This leaves out of this paper many interesting results (on the effect of turbulent mixing, on the effect of "coastal" and "slope" boundary layers, on the nutrient budget for the Ebro continental shelf, on the role of river mouth process for shelf circulation and "fertilization", etc.), which will be presented in due time.

The paper ends with a short review of the dissemination/exploitation activities carried out during the first half of FANS.

2. INTRODUCTION

The general aim of FANS (MAST-III Programme, grant no. MAS3-CT95-0037) is to improve the knowledge on water fluxes and associated sediment and nutrient fluxes in narrow shelves, in which nearshore and continental shelf may interact to determine across-shelf dynamics. The main scientific aim of the project is to study the coupling between nearshore, shelf and slope processes. The project rationale envisages a synergetic use of observational/experimental, remote sensing and numerical modelling techniques applied to a suitable test area.

Unlike on extensive North Atlantic shelves, the flow dynamics on narrow shelves are strongly influenced -and sometimes determined- by nearshore and slope processes. Narrow shelves may be regarded as regions constrained by two "boundary layers" that merge and control processes across the continental shelf.

From another point of view, narrow shelves can be seen as "buffer zones" through which processes occurring on the continental slope may influence the nearshore dynamics and vice-versa. Moreover, the absence of swell and wind waves in micro-tidal narrow shelf environments during the summer period open new questions such as the role that shelf processes have in driving nearshore flows.

Many unsolved fundamental questions are linked to the narrow shelf concept. For instance, it is not known yet "how narrow" a narrow shelf has to be so that the shelf circulation is basically steered by nearshore and slope processes, nor "how wide" a narrow shelf has to be so that local forcings (winds, wind-waves, density gradients due continental outflows, etc.) are the dominant driving agents. The coupling between nearshore and slope dynamics across narrow shelves has not been much studied and may constitute a very interesting case to test theories and models developed for the nearshore, shelf and slope domains.

The Spanish Mediterranean coast is an appropriate environment for basic studies addressing the aforementioned topics. In particular, the Ebro delta area extending from Cape Salou to the Columbretes Islands (see figure 1) is a particularly convenient test site for a generic study. The locally-obtained gain in understanding will be exportable to other narrow shelf environments and will also help to improve understanding of the role of nearshore and slope processes on wider shelf environments.

Given the high pressure of touristic and industrial use which is applied to the proposed study area, the local knowledge on shelf fluxes gained through FANS will be also valuable for local applied research purposes, such as impact assessment and coastal vulnerability studies to be conducted in the framework of new coastal management strategies. The advance in understanding and improvement of the corresponding numerical models will help to develop a proper basis for the management of shelf and coastal resources on the coast of Catalunya and at many other narrow shelf systems in the Mediterranean and elsewhere. As an example, better coastal water quality simulations will be achieved from models including a refined turbulence closure tuned for the specific conditions encountered in narrow shelf systems.

3. RATIONALE

The strategy to achieve the FANS objectives is based on two elements:

i) acquisition and analysis of field and remote-sensing data from the study domain at an event-scale and from daily to weekly averaged scales (information derived from the observational programme of the FANS project. See figures 1 to 3).
ii) numerical simulations of the nearshore-shelf-slope domain, "switching" on and off the main climatic drivings (river discharge, wind, general circulation and free-surface waves) and analyzing the corresponding oceanographic responses (water, sediment and nutrient fluxes).

As for the coupling between nearshore and shelf domains, the development of this strategy corresponds to a methodology which focuses on three key-points:

1. Physical analysis of the coastal boundary layer, in terms of "perceived" roughness and mixing coefficients.
2. Physical analysis of the river mouth dynamics and mixing as a boundary condition for shelf dispersion patterns.

3. Observational analysis of inner shelf sedimentary fluxes, related to nearshore and shelf hydrodynamic conditions.

These analyses are sustained by both the FANS observational programme (which includes nearshore-shelf-slope quasi-synoptic oceanographic surveys, two cross-shelf instrumented transects and synoptic 2DH satellite and video images) and the project numerical workpackages.

The main results available so far, presented in the sample figures here included, make reference to the importance of the nearshore/shelf/slope coupling in determining shelf dynamics for a region such as the Ebro delta. It is, therefore, a quantification -based on scientific knowledge, numerical simulations and field observations- of the interactions at the land-ocean border which, as expected, turn out to be very significant for a narrow-shelf region.

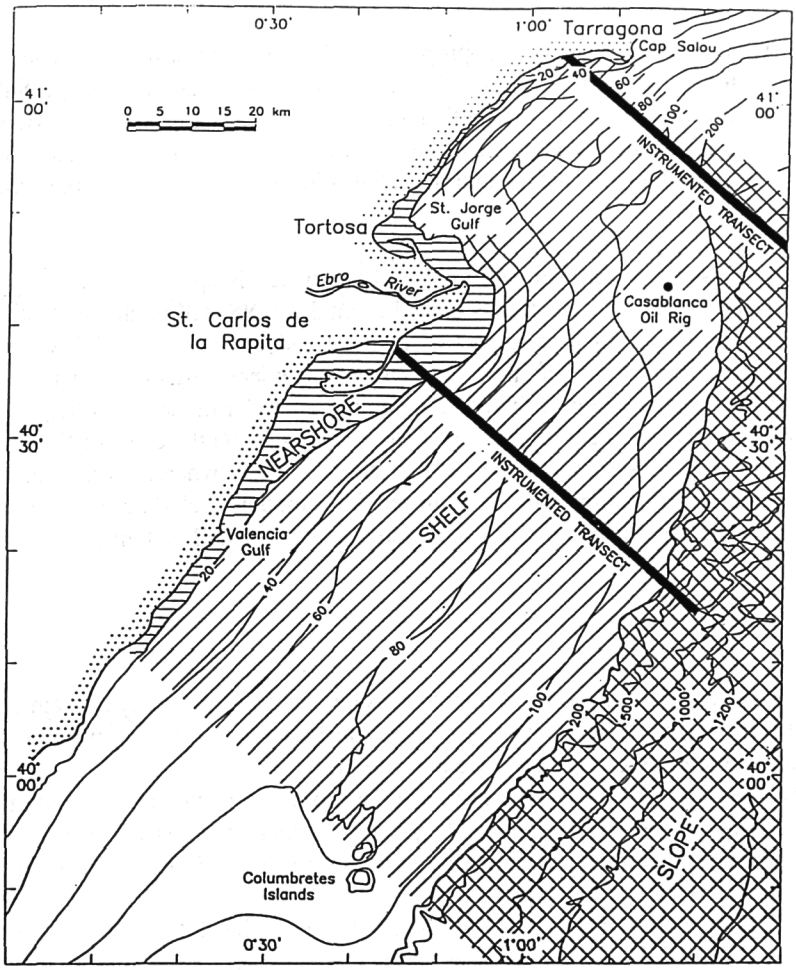


Figure 1: Study domain in FANS

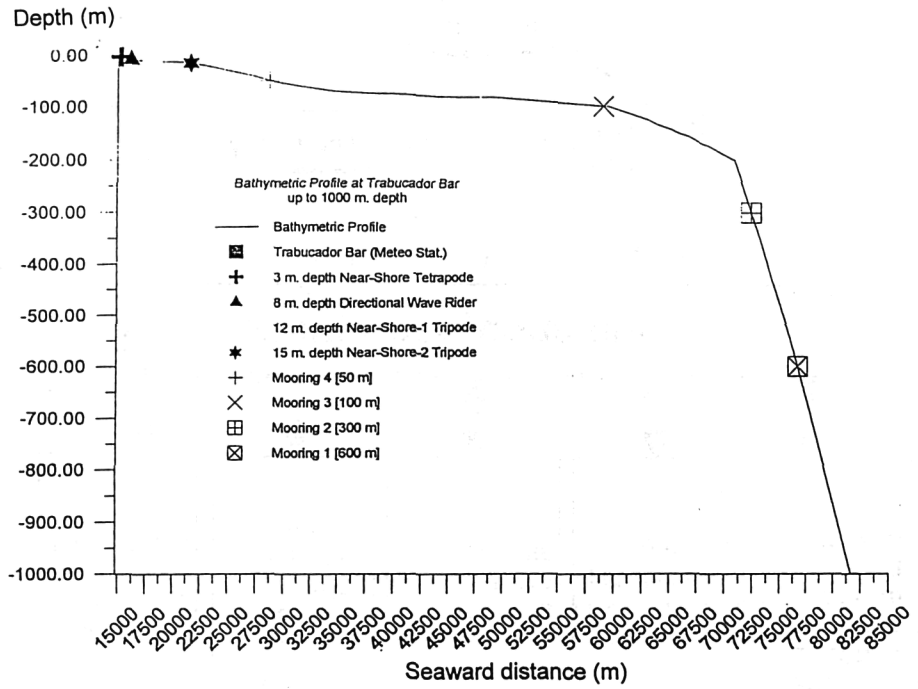


Figure 2: Instrumentation of a FANS transect for time series observations

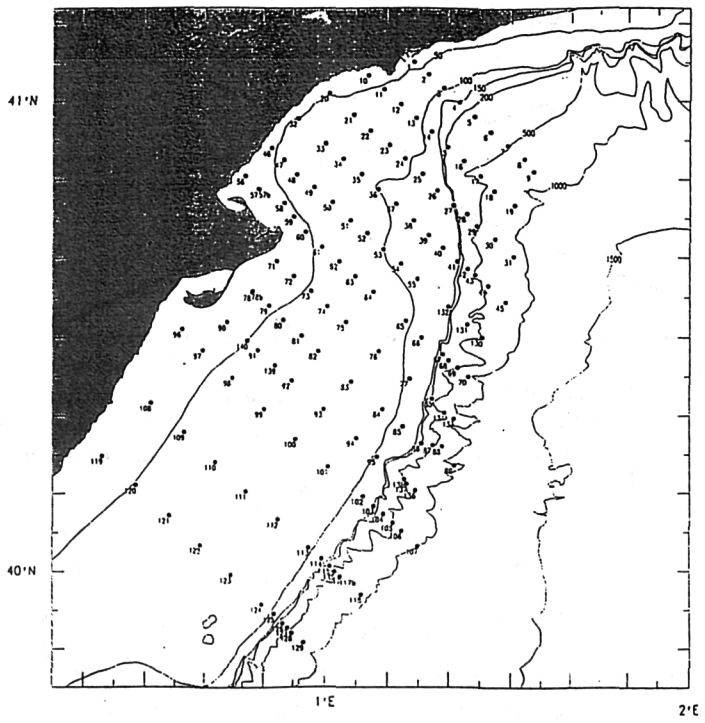


Figure 3: Station map of a FANS oceanographic cruise

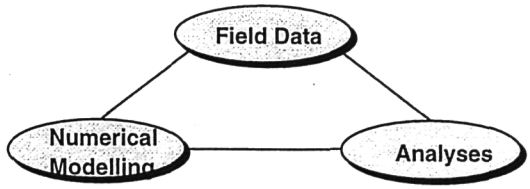


Figure 4: FANS methodology

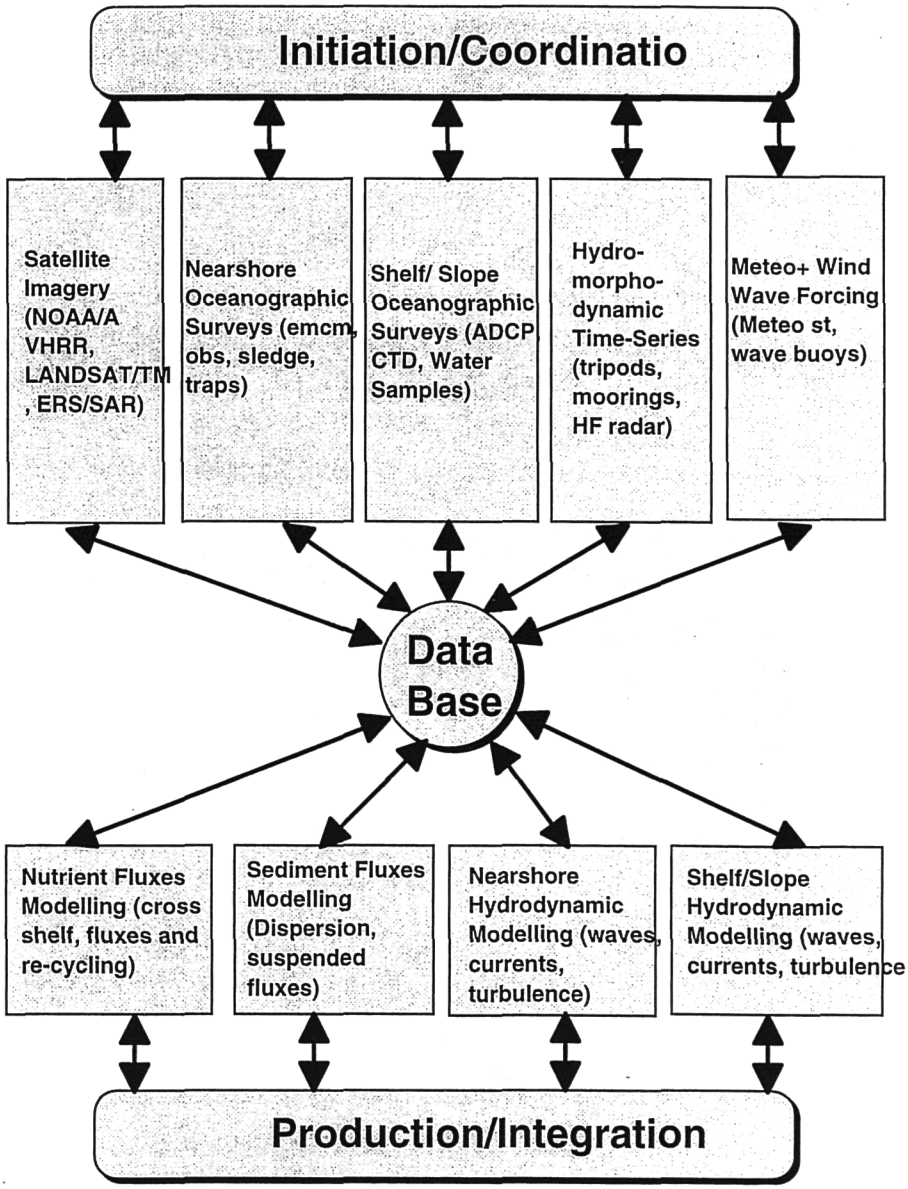


Figure 5: The central role of data management in FANS

4. SOME INITIAL RESULTS

The November 1996 and February 1997 FANS cruises and contemporary high-resolution satellite images showed that the northern part of the gulf of Valencia was occupied by a mesoscale anticyclonic gyre (see figure 6) which favoured the transport of suspended matter at the nearshore/shoreface domains in a north-northwestward direction opposite to the general circulation (see figures 7 and 8). This gyre extended as north as Cape Tortosa in November 1996, which resulted in the fact that, although the Ebro river discharge conditions were extremely low on that occasion (of the order of 100 m^3/s according to the data supplied by the river authority), patches of low salinity water could be advected across the shelf to a long distance from the river mouth (see figure 9). On the gulf of St. Jordi area north of the Ebro delta, smaller cyclonic vortexes were seen to capture suspended matter from the nearshore/shoreface domains and to transport it to the shelf on smaller length scales.

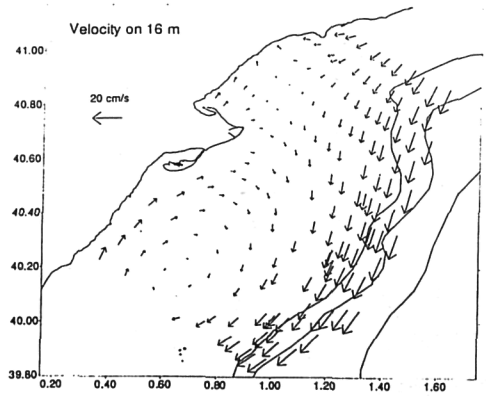


Figure 6: Surface ADCP velocities during the FANS 2 cruise

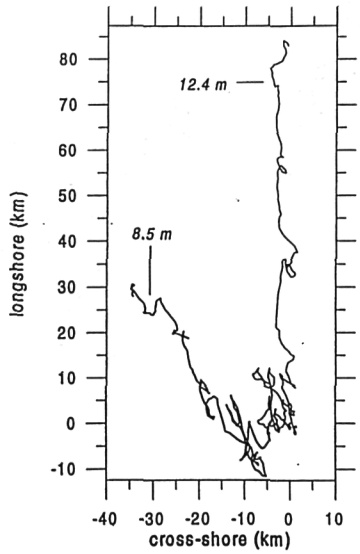


Figure 7: Progressive vector diagrammes of time series of current measurements acquired at the shoreface on 8.5m and 12.4m bottom depths (December 1996-January 1997)

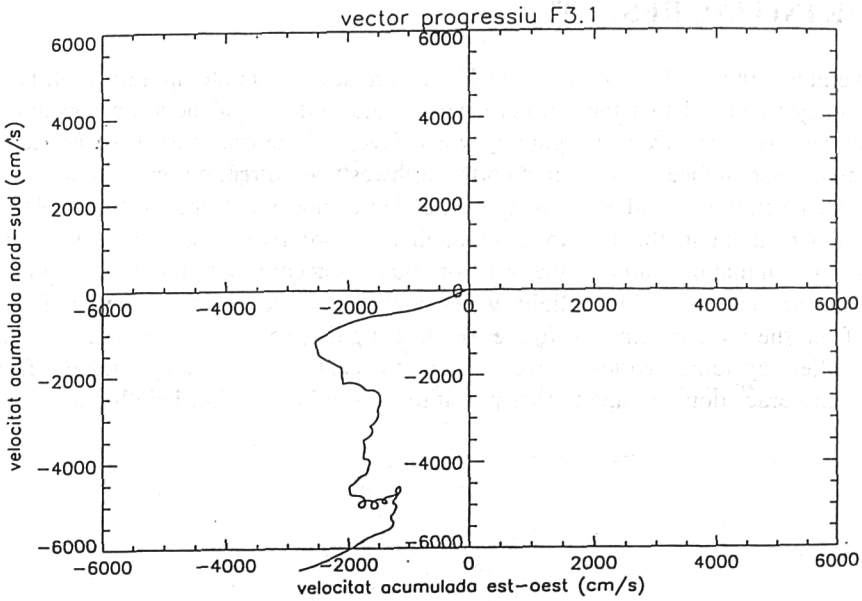


Figure 8: Progressive vector diagramme of time series of current measurements on 10m depth acquired at the offshore limits of the anticyclonic gyre on 300m bottom depth (November 1996 - February 1997)

Figure 9: LANDSAT/TM image of the FANS study area acquired in the November 1996 (infrared TM6 channel). The extension of the anticyclonic gyre can be inferred from the path of warm (reddish) gulf of Valencia waters and the eastward advection of the cool (bluish) Ebro river plume

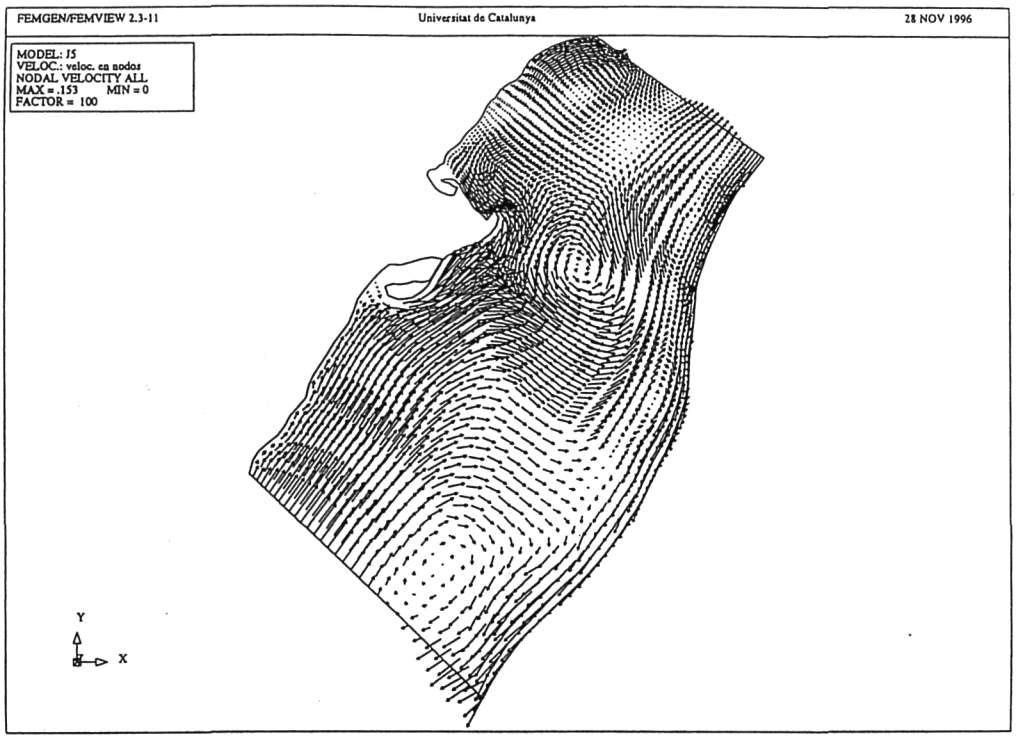


Figure 10: Model simulation of the 2DH mean circulation forced by channelled NW winds in the FANS study area under non-stratified conditions and assuming along-isobath southward flow on the open sea boundary

Preliminary numerical modelling results have indicated that the gulf of Valencia gyre might be forced by the frequent, intense channelled NW winds descending down the Ebro valley, which produce alongshelf wind stress variability and introduce negative vorticity south of the Ebro delta (see figure 10). Alternatively, this anticyclonic gyre might result from vorticity adjustment of the southward shelf/slope baroclinic jet related to the shelf widening (at the shelf widening zone, the shelf edge jet is forced to acquire positive relative -and potential- vorticity which has to be offset). On the other hand, the modelling work completed during the first project year suggests that the dispersion of the Ebro river plume is controlled by the shelf mesoscale circulation, on which both the slope dynamics and the local wind forcing play a very important role (see figure 11). It is suggested that the Ebro *narrow shelf* (characteristic shelf width of 40-50 km) might be *wide* enough so that the slope dynamics is not able to steer the shelf circulation completely.

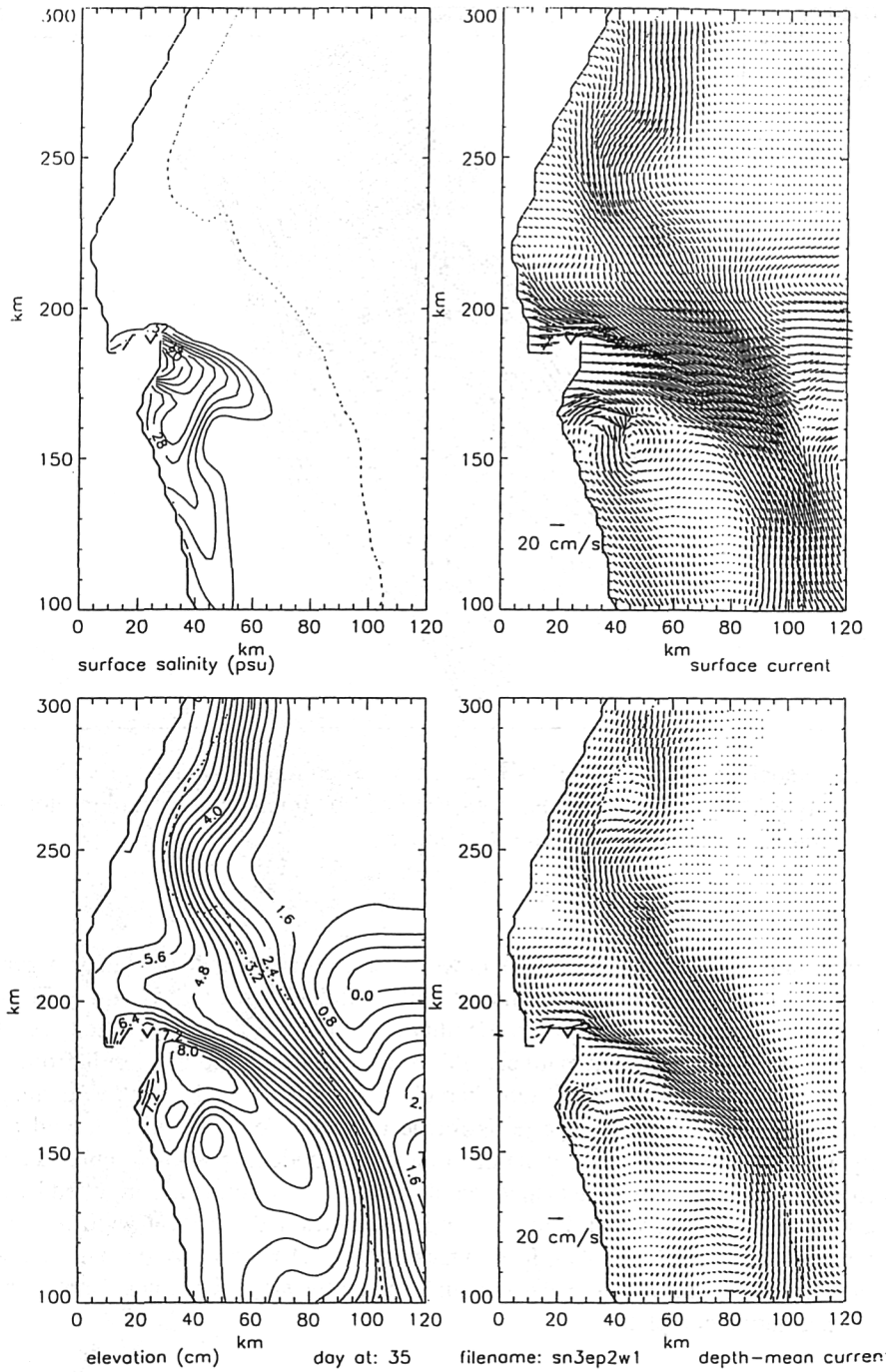


Figure 11: Modelled contours of surface salinity (ppt) and surface elevation (cm), and surface and deep circulation for the baroclinic case imposing an along shelf flow and channelled NW wind forcing

5. DISSEMINATION/EXPLOITATION

An alternative way to summarise the FANS project objectives is to consider their final user. For the coastal zone management community the FANS objectives are related to the assessment of sediment, nutrient and water fluxes in a region such as the Ebro delta and surrounding shelf. For the scientific community the FANS objectives are related to the nearshore, shelf and slope mutual interactions and couplings. All this requires, dissemination and exploitation.

The FANS internal dissemination/exploitation refers to the dissemination and exploitation of knowledge, tools, results, etc. between different disciplines and different country teams. From the dissemination standpoint this has required well structured field campaigns (figure 12 illustrates a "distorted" tripod and the FANS "flag") together with a well organised field data base and data fluxes. Most of this structuring comes from the kick-off-meeting and the subsequent plenary meetings every six months. Additionally several smaller meetings to discuss particular aspects of the field campaigns or data organisation have also been organised.

The internal dissemination also depends critically on a well defined sequence of model runs which minimises the purposeless duplication of modeling efforts and maximises the complementarity between simulation runs. This internal dissemination and structuring of model runs has also been greatly enhanced by the external "advicing" performed by Prof. O. Madsen from MIT who also represents a link with the USA scientific community interested in these topics.

From an exploitation standpoint FANS has proved to be an effective "one way" project to transfer results from hydrodynamicists to sediment/morphodynamicists and to nutrientologists. No feed-back links are foreseen within the project duration. In the same manner and from an internal exploitation standpoint, FANS has represented a two way interaction between the field teams, the numerical modeling teams and the satellite imagery teams.

From a dissemination standpoint the first and most important activity is the collection of FANS publications and communications which after one and a half years of project duration appear summarised in table 1.

Journals Publications	11
Communications	19

Table 1. FANS publications and communications.

This item represents the highest level and more permanent dissemination action of FANS. In this same line it is worthwhile mentioning that there is an agreement with Continental Shelf Research to publish a special number dealing with FANS topics. The full papers should be ready by mid 1999 and will be co-edited by A. Davies and A. Sanchez-Arcilla.

From a less specialised standpoint, but addressed also at communities of experts, there has been three sessions dealing with deltaic systems and deltaic vulnerability and in which the FANS methodology and preliminary findings have been presented. The first session on

deltaic systems took place during a workshop dealing with the "Fragility of Mediterranean Ecosystems" (Vilanova, March 1997) in which the cases of the Ebro and the Nile were presented in front of a community of experts, including representatives from the European Union, the Southern Mediterranean countries and the Commission of the European Communities.

The second session on deltaic vulnerability was included in an advanced study course on coastal vulnerability, supported by the Environment and Climate Programme of the European Union and which will take place in Vilanova in July 1997.

The third session took place during the LOICZ Open Science Meeting in the Netherlands (1997). FANS was also presented in the Euroconference "Oceanography and CZ Management" (Sant Feliu de Guixols, Spain, 1997) and will be also discussed in the World Deltas Symposium (New Orleans, USA, 1997).

From a more general standpoint and addressed to the overall society, there have been brief summaries of the FANS project in two public TV channels: i) the environment within the lunch time news of TV3 (2/1/97) and ii) lunch time news of TV1 (2/4/97).

The FANS project and its practical applications have also been described in a number of local news papers.

The potential exploitation of the FANS project is best represented by the "FANS Club of End-users" described in table 2.

Country (alphabetic order)	**FANS researchers acting as "promoter" and "contact"**	**Selected "end-users"**
France	Philippe Fraunié UTV	*Mr. François Rueda*, Direction du Service Maritime et de Navigation du Languedoc Roussillon
The Netherlands	Marcel J.F. Stive DH	*Dr. J.P.M. Mulder*, Rijkswaterstaat *Dr. J.J. Verburgh*, Shell
Norway	Bjorn Gjevik UiO	*Dr. Lars Petter*, Norwegian Meteorological Institute
Spain	Agustín S.-Arcilla UPC	*Mr. Francisco Montoya*, Ministry of Environment *Mrs. Teresa Moya*, Ebre-Institute, Generalitat of Catalunya
U.K.	John Simpson UW	*Dr. John Scott*, Defence Research Establishment

Table 2. "Club of FANS End-users".

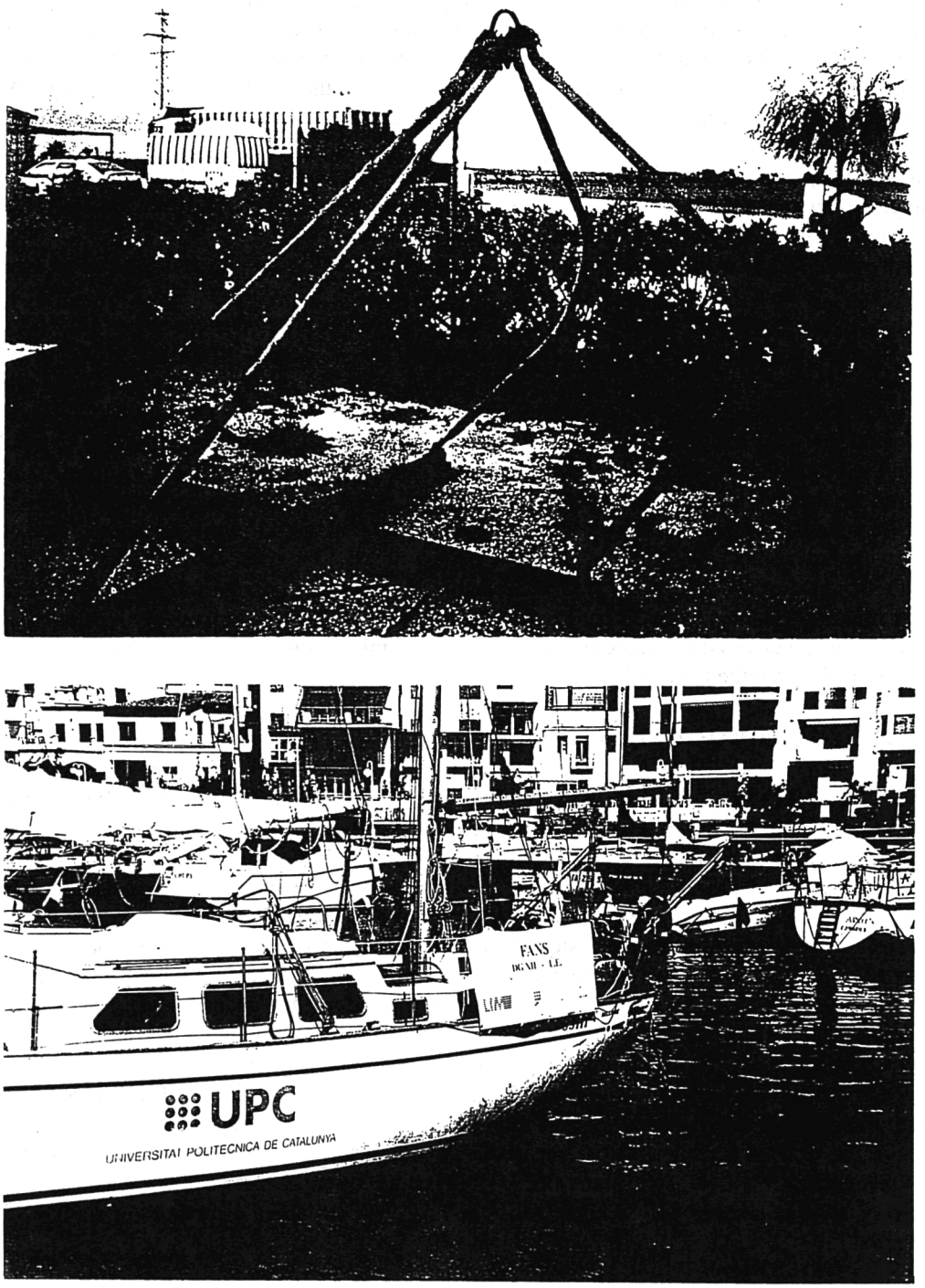


Figure 12: Two photographs of the FANS field effort showing a distorted tripod -by a medium wave storm- and one of the small support ships used in the project, displaying the FANS "flag"

It is worthwhile mentioning that there has been two recent additions to this Club of FANS End-users. The first one consists in establishing links between the FANS and the PACE MAST-III projects around the topic of shore face morphodynamics. With respect to this same topic a link has been established (through PACE) with the ONR-funded STRATFORM project in which the European Union capabilities are displayed.

Additional potential exploitation activities can be represented by a divulgative summary - prepared by the project co-ordinator- of FANS objectives addressed to the coastal zone managers, users and other interested bodies. This includes:

i. characterisation of climatic drivings and oceanographic responses at a variety of time scales (from daily to monthly),
ii. improving or starting the assessment of sediment and nutrient balances for an integrated deltaic management. This should be beneficial to assess: coastal fringe survival (via the sediment feeding through the shore face), water quality and fisheries in the nearshore and shelf areas (via circulation and plume dispersion studies, including the "shore" boundary condition for circulation and mixing and sensitivity to driving factors), impacts of gas and oil exploitation in subsidence rates and shore face morphology (via the long time scales sedimentary dynamics in the inner shelf), and impact of an accidental spill of e.g. pesticides from the river mouth (via river mouth processes and plume dispersion studies and simulations).

A final potential benefit of the FANS project is the support for validated models runs to evaluate impacts on coastal zones, rather than pure generation of numerical results. This should mean a clear added value for coastal zone administrations, users and consulting firms (so far, mainly for the Ebro delta area).

6. ACKNOWLEDGEMENTS

The FANS MAST-III project is supported by the EC MAST Research Programme, Directorate General for Science Research and Development, under Contract No. MAS3-CT95-0037-DG12, ESCY. FANS is also benefitting from the support of the Spanish science agency (CICYT-CITMAR) through parallel research projects which are being used to finance ship time and a more in depth study of the river mouth processes (in cooperation with the University of Valencia, the University of Barcelona and the CSIC). The FANS project has also benefitted from the use of the French research vessel Tethys-II, obtained through the FANS French partners. A number of additional field equipment (not included in the FANS original project) has been also contributed by the Proudman Oceanographic Laboratory, the University of Wales, The Generalitat de Catalunya and the CEEPYC-CEDEX. This support, together with the generous contributions from all FANS partners and other Spanish institutions (Ebro river authority, electrical and telephone companies and the International Centre for Coastal Resources Research (CIRC), which has financed the participation of a number of ex-USSR research institutions whose contribution to the field effort has proved very valuable indeed) is duly acknowledged and can be considered a measure of the FANS "impact".

TITLE: Surf and Swash Zone Mechanics
(project **SASME**)

CONTRACT NO: MAST3-CT97-0081

COORDINATOR:

Jørgen Fredsøe
Danish Hydraulic Institute (**DHI**)
Agern Allé 5
DK-2970 Hørsholm, Denmark
Tel: +45 45769555, Fax +45 45762567
e-mail: jf@dhi.dk

PARTNER AND CONTACT PERSONS:

Ida Brøker
Danish Hydraulic Institute (**DHI**)
Agern Allé 5
DK-2970 Hørsholm
Denmark
Tel: +45 45769555, Fax: +45 45762567
e-mail: ibh@dhi.dk

Nick Dodd
HR Wallingford (**HR**)
Coastal Group
Howbery Park
Wallingford
OXON OX10 8BA
UK
Tel: +44 1491-835381, Fax: +44 1491-825539
e-mail: nxd@hrwallingford.co.uk

Dano Roelvink
Delft Hydraulics (**DH**)
P.O. Box 177
2600 MH Delft
The Netherlands
Tel: +31 15 285 8585, Fax: +31 15-285 8582
e-mail: Dano.Roelvink@wldelft.nl

Denis Aelbrecht
Laboratoire National d'Hydraulique (**LNH**)
EDF-LNH
6, Quai Watier
B.P. 49
78401 Chatou Cedex
France
Tel: +33 130-877412, Fax: +33 130-878086
e-mail: Denis.Aelbrecht@der.edfgdf.fr

Hans Dette
Leichtweiss Institut für Wasserbau (**LWI**)
Institut für Hydromechanik und
Küsteningenieurwesen
P.O.B. 3329
Beethovenstrasse 51A
D - 38106 Braunschweig
Germany
Tel: +49 531-391-3930, Fax: +49 531-391-8217
e-mail: H.Dette@tu-bs.de

Rolf Deigaard
Technical University of Denmark (**DTU**)
Department of Hydrodynamics and Water Resources
(ISVA), Building 115
DK-2800 Lyngby
Denmark
Tel: +45 45251422, Fax: +45 45936328
e-mail: rd@isva.dtu.dk

Jan van de Graaff
Delft University of Technology (**DUT**)
Dept. Of Civil Engineering
Hydraulic and Offshore Engrg. Division
P.O. Box 5048
Stevinweg 1
2628 CN Delft
The Netherlands
Tel: +31 15-278 4846, Fax: +31 15-278 5124
e-mail: J.vandeGraaff@ct.tudelft.nl

Vicente Iranzo
Universitat Politecnica de Catalunya (**UPC**)
Dept. Fisica Aplicada
Modul B5, Campus Nord UPC
E-08034 Barcelona
Spain
Tel: +34 3-4017 985, Fax:+34 3 4016 090
e-mail: iranzo@benard.upc.es

D. Howell Peregrine
University of Bristol (**BrU**)
School of Mathematics
University Walk
Bristol BS8 1TW
England
Tel: +44 117-928 7971, Fax: +44 117-928 7999
e-mail: D.H.Peregrine@bristol.ac.uk

Marco Petti
University of Florence (**UFl**)
Dept. of Civil Engineering
Via di S. Marta 3
50139 Firenze
Italy
Tel: +39 55-4796 321, Fax: +39 55-495 333
e-mail: Petti@ingfi1.ing.unifi.it

Paul A. D. Bird
University of Plymouth (**UPl**)
Faculty of Technology
School of Civil and Structural Engineering
Palace Court
Palace Street
Plymouth
Devon PL1 2DE
UK
Tel: +44 1752-232534, Fax: +44 1752 232627
e-mail: pbird@plymouth.ac.uk

Clive Greated
The University of Edinburgh (**UEDIN**)
Fluid Dynamics Unit
Dept.of Physics and Astronomy
Kings Building
Mayfield Road
Edinburgh EH9 3JZ
UK
Tel: +44 131-650-5232, Fax: +44 131-650-5220
e-mail: C.A.Greated@ed.ac.uk

Inigo J. Losada
Universidad de Cantabria (**UCa**)
Ocean & Coastal Research Group
E.T.S .I. de Caminos, Canales y Puertos
Av. de los Castros s/n
39005 Santander
Spain
Tel: +34 42-201810, Fax: +34 42- 201860
e-mail: inigo@puerhp1.unican.es

SURF AND SWASH ZONE MECHANICS (SASME)

J. FREDSØE

Danish Hydraulic Institute
Agern Allé 5
DK-2970 Hørsholm
Denmark

NICK DODD

HR Wallingford
Coastal Group
Howbery Park
Wallingford
OXON OX10 8BA
UK

DANO ROELVINK

Delft Hydraulics
P.O. Box 177
2600 MH Delft
The Netherlands

CLIVE GREATED

The University of Edinburgh
Fluid Dynamics Unit
Dept. of Physics and Astronomy
Kings Buildings, Mayfield Road
Edinburgh EH9 3JZ
UK

ROLF DEIGAARD

Technical University of Denmark
Department of Hydrodynamics and
Water Resources (ISVA)
Building 115
DK-2800 Lyngby
Denmark

SUMMARY

This MAST project started on 1 October 1997, and runs for 3 years. The total costs is estimated to be 2.895.000 ECU of which the EU contribution will be 1.810.000 ECU. The main aims of the project are described, and the work plan is summarized. No results are yet available from the project.

1. INTRODUCTION

The objective of the present project is to investigate the physical processes which take place in the surf zone on a coast with and without coastal structures.

The project shall lead to a significantly improved description of the cross-shore and longshore sediment transport, which mainly occurs within the surf zone.

The SASME project is divided into two interlinked parts:
I. Surf and swash zone hydrodynamics and sediment transport, and
II. Surf and swash zone morphology.

The surf and swash zone hydrodynamics and sediment transport will concentrate on the behaviour of breaking and broken waves, their generation of small and large scale turbulence, and the resulting sediment transport.

The morphological study will focus on the bed behaviour in the surf/swash zone which includes bed-instabilities; formation of bars and their behaviour (like erosion and accretion in 2 horizontal dimensions; non-uniformities in the alongshore direction due to rip currents).

The far field impact of coastal structures will be investigated: the effect of the modifications of wave, current and sediment transport fields by the structures. The project will thus address important aspects of the function of the coastal structures. The project will not treat the three-dimensional near-field hydrodynamics and sediment transport around structures that are associated with local scour phenomena.

In terms of practical outcome, the project is expected to produce significant improvements in "medium" term modelling, which is necessary for the development of longer term prediction methods. In addition, improvements at a fundamental level will yield a basis for developments of transport and mixing models for quantities other than sediments in the surf and swash zones, plus some results of wider significance, for example in relation to breaking waves in deep water and their significance for air-sea exchange and mixing.

2. DESCRIPTION OF THE INDIVIDUAL PROJECTS

SASME is divided into the following four main projects which each has a project leader and an assistant project leader. The 4 projects are:

1. Breaking/broken waves in surf/swash zone. Project leader: Rolf Deigaard, DTU.
   Assisting pl: Clive Greated.

2. Vertical structure of motion and associated sediment transport plus morphological modelling of coastal profiles. Project leader: Clive Greated, UEDIN.
   Assisting pl: Rolf Deigaard.

3. Horizontal structure of motion plus area-modelling. Project leader: Nick Dodd, HR.
   Assisting pl: Dano Roelvink, DH.

4. Structure-seabed interaction. Project leader: Dano Roelvink, DH.
   Assisting pl: Ida Brøker, DHI.

Project 1: Breaking and broken waves in the surf and swash zone.

This project deals with waves just before they break, the processes af wave breaking and the further propagation as broken waves to the limits of the run-up in the swash zone. This project is led by Rolf Deigaard (DTU). The study treats plane as well as barred beaches and aspects of

hydrodynamics and sediment transport. The research will include analysis of field data, analysis of physical processes, mathematical modelling and laboratory experiments. The lab experiments will be concentrated on tests in wave flumes, applying a wide range of instrumentation, such as: wave guages, pressure transducers, Micro Flow meters, image analysis of floating particles and Laser Doppler Anemometry.

Breaking and broken waves are investigated by analysis of field experiments with wave propagation over barred coastal profiles. The measurements have been specifically aimed at improving the physical understanding of breaking processes, energy dissipation and the transformation of the wave energy spectrum across the coastal profile. Breaking conditions for waves in groups and under conditions with partial reflection will be investigated in order to identify differences in the breaking criteria for regular waves and for irregular waves.

Swash zone conditions will be investigated by laboratory experiments and by numerical modelling. The experiments will comprise regular and irregular waves over an impermeable plane, sloping beach with smooth and rough surfaces. Further experiments will be carried out with a porous beach in order to study the set-up, set-down, mean flow and the water tabel variations. Analytical and numerical solutions will be validated on the experimental data. The swash zone as a boundary condition for wave period averaged models will be addressed in order to find suitable closure approximations to represent both the incoming bores and the swash motion, cf. Brocchini and Perigrine (1995). A three-dimensional model based on a weakly 3D solution to the non-linear shallow water equations will be investigated and applied to describe obliquely incident waves. The effect of bed friction will be investigated in the model and assessed from the experimental results.

Long waves and wave reflection will be studied by laboratory experiments and by mathemacal modelling. The experiments will be carried out for bicromatic short period waves and for irregular waves of varying groupiness. Plane sloping beaches and barred profiles will be applied. The interaction between long and short period waves and the role of (partial) reflection will be investigated. The distribution of wave reflection from different parts of the beach profile is to be determined. A state-of-the-art model for wave driven currents, shear instabilities, edge waves and surf beat will be developed. The model is two-dimensional and depth integrated, it averages out the short period waves, but resolves the time scale of wave groups. It is an extension of the one-dimensional model of Roelvink (1993).

The importance of long period wave for the sediment transport will be investigated by sediment transport models. The results from flume experiments with different coastal profiles will be used as basis for sediment transport calculations with existing transport formulae. An area of particular interest is the potential for long wave resonance between a bar and the shoreline. The physics of sediment transport in wave groups and the associated long period waves will be investigated by a model for the turbulent boundary layer in the combined motion, and the role of low frequency waves for the development of the cross-shore morphology will be investigated.

Brocchini, M. and Perigrine, D. H. (1995): Flow properties of the swash zone. Proc. Coastal Dynamics '95. Gdynia, ASCE, pp. 221-232.

Roelvink, J. A. (1993): Surf Beat and its effect on cross-shore profiles. Ph.D. Thesis, Delft Univ. of Technology.

Project 2: Vertical structure of wave and breaker-induced motion and the associated sediment transport.

This project is concerned with the structure of wave-generated motions in the surf zone. It forcuses on the large scale vortices and turbulence generated by plunging breakers, nearbed wave boundary layer turbulence in the surf zone and the turbulence mechanisms that contribute to sediment transport. It is an integrated study involving numerical modelling, laboratory experiments and comparison with field data.

Erik Damgaard Christensen at the Danish Hydraulics Institute is developing a computer model, using a general Navier Stokes solver; a development of the Volume of Fluid technique. This can cope with overturning surfaces and is capable of tracing the complete wave breaking process on a beach. It has so far been used successfully for two-dimensional simulations on beaches of different slopes and is now being extended to three dimensions. Direct comparisons are being made with the experimental Particle Image Velocimetry (PIV) measurements being made by Narumon Emarat at Edinburgh.

At Delft hydraulics, Dirk-Jan R. Walstra is making further developments to the Delft Hydraulics' flow model (Delft3D-FLOW), paying special attention to the incorporation of roller effects and boundary layer schematisation. The model is initially to be tested against laboratory data obtained from the Delta Flume (LIP11D-experminent, Roelvink and Reniers, 1994). At a later date the performance of the Quasi-3D and full 3D formulations will be investigated and comparisons made with the LIP-shear experiments and other data as it becomes available from the MAST-projects (e.g. Coast3D).

At Bristol, Howell Peregrine is developing analytical techniques to study the mechanisms of the breaking process. The modelling for the plunging breaker type of flow initially has been to add a distribution of point vortices to their already available and highly accurate irrotational flow solver. Work is now in hand to make the connection between the plunging flow and the subsequent vortical motion using conserved quantities. Work is also in progress to extend the recent results of Brocchini and Peregrine (1997) on the modelling of strong turbulence at the free surface, with the eventual aim of obtaining rational models for spilling breakers.

At The University of Edinburgh Narumon Emarat and Clive Greated are performing a series of PIV flow mapping experiments in a wave flume to map the vortex and turbulence structure through the breaking process. These will be followed up by a larger scale series of tests at ISVA again using PIV flow mapping. The results will be used as input to a series of experiments to be carried out by Mutlu Sumer and Jørgen Fredsøe in the oscillating water tunnel at ISVA. In these experiments grids will be used to generate turbulence, representative of the structures produced by breaking. The flow and turbulence characteristics will be measures by LDA and the effect on the boundary layer will be studied. A a later stage, the PIV technique

will be used to study the motion of sediment particles below breakers.

Comparisons will be made, where possible, between the numerical and experimental results and data sets obtained by Hans Dette and colleagues at the Leichtweiss Institute. The near-shore profile behaviour has been studied over a medium term scale (3 years) at two field sites in the nontidal Baltic Sea (single and multiple bar area). For each measuring profile 4 wave guages were deployed. More than 100 data sets (raw and aggregated data) covering e.g. seasonal variability and the predominance of bar and surf zone breaking are being prepared, analysed and made available on CD-Rom for all MAST participants. Besides the water level and wave data, profile data will also be included. It is hoped that the data will contribute to the understanding of real life cases.

References:

Brocchini, M and Peregrine, D. H. (1998) "Strong turbulence at a free surface" Proc. Conf. on wind-over-wave couplings: perspectives and prospects, Inst. of Maths. and its Applications, eds. S.G. Sajjadi and N. Thomas, Oxford University Press.

Project 3: Horizontal Structure of Wave- and Breaker- Induced Motion and Area Modelling.

This part of the MAST3 project "Surf and swash zone mechanics" (SASME) concentrates on understanding and modelling both the structure of the horizontal (plan) mass and momentum budget in the surf and swash zone on the open coast, and the morphology in this region.

The work in this Task, led by Nick Dodd (HR), will focus on three particular aspects of the horizontal structure of the wave-induced hydro- and morphodynamics:

(1) Shear Waves

The aim is to develop a description and an understanding of the formation and evolution of shear waves, including their interaction with surf beat, edge waves, short (wind and swell) waves, an-d with complex beach topography. Such developments will lead to a better understanding of longshore current dynamics, and therefore of the propensity of these highly energetic motions to dominate mean surf zone motions and to affect the nearshore bathymetry and sediment budget. This work will benefit from developments in other parts of SASME such as on breaking and broken waves in the surf and swash zone and on the vertical structure.

HR and UPC will undertake work to describe the growth and evolution of shear waves.
UBr will take a different approach in studying shear waves as eddy motions.
DUT will investigate the effect of wave groups on shear waves.

(2) Rip Current Systems

The objective of this subtask is to understand rip current dynamics and associated sediment transport, and thereby to predict when rips may be expected to occur and their effect on the sediment transport budget. Also, different approaches to modelling will be investigated. The work on shear waves is likely to feed into this subtask, and results will be used in the complex beach topography subtask.

DHI and DTU will study rip channel formation on a barred coast using a numerical model, including their sensitivity to the presence of shear waves. DTU will also undertake an experimental investigation into the hydrodynamics associated with a rip channel. DH and HR will undertake numerical modelling of, respectively, a rip channel and a rip channel system.

(3) Complex Beach Topography

The main purpose is to improve the modelling of the morphological development of a natural beach over short time scales, and to get a better understanding of the significance of different beach processes. The work will use results from both other subtasks within this task as well as results from other tasks.

DHI and DTU will study the formation of rip channel systems as a stability problem.

They will also use a numerical model coupled with a phase-resolving sediment transport module to study the formation of rip channel systems.

UPC and HR will also take this approach, but focus more on the effect of manmade rhythmic systems (e.g. groynes) in initiating and / or controlling rip channels. DH will numerically model a rip channel and its development, and attempt to link modelling and monitoring techniques by means of data assimilation techniques. HR will use a numerical model to study the evolution of rip channel systems. LWI will analyze field data covering the formation of rip currents, channels and systems from the Baltic Sea coast.

One important end-product of this sub-task will be two or three review articles.

One will be on shear waves, a task led by Nick Dodd (HR).

Another will be on low-frequency motions (leader yet to be identified), and a third possible subject might be rip currents.

Project 4: Impact of structures on the near-shore morphology.

This task aims at understanding, modelling and describing the effects of various coastal structures on the nearshore morphology. The task is divided into two topics:

- modelling of the far field morphological evolution around structures, and
- review of the experience on implementation of coastal structures.

Modelling

The modelling applied to the role of structures will profit by developments and improvements carried out in other parts of SASME. The capabilities and limitations of the different modelling principles for different types of structures are analysed. The model results are used to analyse the flow, transport patterns and morphological development around the structure, to obtain a better understanding of the effect of the structures and of how a series of structures interacts.

DHI and DH will validate quasi-3D area models and compare with 2-D horizontal models and full 3-D models. The modelling of gradually varying sediment transport in a quasi 3-D model (lag effects) will be compared with the full 3-dimensional solution.

DUT will study the morphological behaviour of coasts with a series of (underwater) detached breakwaters, both by analysing laboratory data and by carrying out 2DH and Q3D simulations.

LNH will focus on simulating the development around a groin system by use of a full 3-dimensional modelling system. Tidal variations (water level and currents) will be included in the study. Special emphasis will be put on the effects of the 3-dimensional flow field in the lee of a groin.

Review of experience and modelling capabilities on implementation of structures.

The aim of this study is to provide clear guidelines on the use of coastal structure in coastline protection programmes. These guidelines will be based on a review of existing experience with structures, and on the results of the detailed modelling of the effects of structures during the SASME project. The guidelines are recognised as one of the most important end products of SASME and will be published both in a detailed report and as a review paper.

Structure of the task group

The activities of the task group will be focused on the following types of structures; per structure type, a coordinator has been assigned who will ensured that the various model studies carried out for the structure in question can be combined into a paper describing the most important processes, modelling techniques and practical guidelines. The structures considered are:

- offshore breakwaters and shore-attached offshore breakwaters
- submerged breakwaters
- groins
- harbour moles
- beach nourishments
- offshore nourishments

The final review paper and report, summarising the work related to all types of structures will be written by the members of the task group, with DUT og DH as most responsible partners.

INTERNET ADDRESS OF THE PROJECT

http://www.wldelft.nl/sasme.htm

TITLE: Prediction of Cohesive Sediment Transport and bed dynamics in estuaries and coastal zones with Integrated Numerical Simulation Models (project **COSINUS**)

CONTRACT NO: MAS3-CT97-0082

COORDINATOR:

Prof.dr. J. Berlamont, dr. E Toorman
Katholieke Universiteit Leuven
Hydraulics Laboratory
de Croylaan 2, B-3001 Heverlee, Belgium
Tel.no. (Fax): +32 16 32 1660 (1989)
E-mail: jean.berlamont@bwk.kuleuven.ac.be

PARTNERS:

Dr. F. Jakobsen
Danish Hydraulic Institute (DHI)
Agern Allé 5, DK-2970 Hørsholm, DK
Tel.no. (Fax): +45 45 179241 (762567)
E-mail : flj@dhi.dk

Dr. M. Mory
Université Jospeh Fourier, LEGI
BP 533, F-38041 Grenoble Cédex 9, F
Tel.no. (Fax): +33 47682 5060 (5001)
E-mail : Mathieu.Mory@hmg.inpg.fr

Dr. C. Le Normant
E.D.F., Lab. National d'Hydraulique (LNH)
6, Quai Watier, F-78400 Chatou, F
Tel.no. (Fax): +33 1 3087 7854 (8086)
E-mail : Catherine.le-normant@der.edfgdf.fr

Ir. H. Winterwerp
Delft Hydraulics
P. O. Box 177, NL-2600 MH Delft, NL
Tel.no. (Fax): +31 15 285 8813 (8710)
E-mail : han.winterwerp@wldelft.nl

Prof.dr. Z. Zielke, dr. M. Markofsky
Universität Hannover
Institut für Strömungsmechanik
Appelstrasse 9a, D-30167 Hannover, D
Tel.no. (Fax): +49 511 762 3776 (3777)
E-mail : mark@hydromech.uni-hannover.de

Dr. G.C. Sills
University of Oxford
Department of Engineering Science
Parks Road, Oxford OX1 3PJ, UK
Tel.no. (Fax): +44 1865 273 164 (907)
E-mail : Gilliane.Sills@eng.ox.ac.uk

Dr. C. Kranenburg
Technische Universiteit Delft (T.U.Delft)
P.O. Box 5048, NL-2600 GA Delft, NL
Tel.no. (Fax): +31 15 278 1971 (5975)
E-mail : c.kranenburg@ct.tudelft.nl

Dr. W. Roberts
H.R. Wallingford
Howbery Park, Wallingford OX10 8BA, UK
Tel.no. (Fax): +44 1491 83 5381 (2233)
E-mail : wr@hrwallingford.co.uk

Prof.dr. K. Dyer
University of Plymouth
Institute of Marine Studies
Plymouth PL 48AA, UK
Tel.no (Fax): +44 1752 232 420 (406)
E-mail : k.dyer@plymouth.ac.uk

PREDICTION OF COHESIVE SEDIMENT TRANSPORT AND BED DYNAMICS IN ESTUARIES AND COASTAL ZONES WITH INTEGRATED NUMERICAL SIMULATION MODELS COSINUS

JEAN E. BERLAMONT, ERIK A. TOORMAN

Katholieke Universiteit Leuven
Hydraulics Laboratory
de Croylaan 2, B-3001 Heverlee, Belgium

SUMMARY

Since the presently used models do not allow to simulate accurately the many different and interrelated cohesive sediment processes occurring in coastal and estuarine waters, there is a need for an integrated sediment transport management model in which all relevant physical processes are integrated.
COSINUS covers the theoretical, experimental and numerical study of the interaction of the processes which play a crucial role in the flocculation of sediment particles, the interaction between suspended sediment and turbulent flow, the generation and maintenance of concentrated near-bed suspensions (including lutocline formation) and the transition between fluid mud and the sediment bed. New integrated models will be set up and evaluated against both existing data and new laboratory and field experiments. The models will be used to parameterize the process descriptions to implement them in existing engineering system models. After testing, the improved system models will be applied to a few selected European estuaries to allow a quantitative assessment of the model performance. Evaluation of the large scale applications will lead to a feed-back to process module development and their parameterizations.

1. INTRODUCTION

The managing authorities of coastal waters and estuaries face a large number of problems related to cohesive sediment transport, sedimentation and erosion, such as: How to maintain safe navigable depths (at minimum cost) ? Where and how to dump dredged material ? How can the volume of wetlands be maintained or increased ? What will happen to the location of the turbidity maximum after constructing new harbour basins or deepening the navigation channels ? etc.

To answer these questions, one needs a model capable of simulating the many different and interrelated (cohesive) sediment processes occurring in coastal and estuarine waters, which can predict natural phenomena and the effects of human interference. Unfortunately, the presently used models are unable to produce reliable quantitative results due to too many simplifications. Progress in the understanding and the mathematical description of the

different processes and the increasing capacity and speed of modern computers opens new doors toward the operational use of much more detailed models.

Therefore, the goal of the COSINUS project (started on October 1, 1997) is to contribute to the development of an integrated sediment transport management model. "Integrated" refers to the integration of all relevant physical processes over the entire water column and the sediment bed and their interactions.

The project covers the theoretical, experimental and numerical study of the interaction of the processes which play a crucial role in: the flocculation of sediment particles, the interaction between suspended sediment and turbulent flow, the generation and persistence of concentrated near-bed suspensions (including lutocline formation) and the transition between fluid mud and the sediment bed. New integrated models will be set up and evaluated against experimental data. A field measurement campaign will be carried out to provide additional data to tune and validate the models. The models will be used to parameterize the process descriptions. These will be implemented in existing engineering system models. After testing, the improved system models will be applied to a few selected European estuaries to allow a quantitative assessment of the model performance. Both experimental and numerical data will be stored in a data base. The major deliverables of this project will be: well validated process modules and their parameterizations, a framework for integrated numerical simulations, guidelines for model calibration and a database for model validation. Exploitation of the results is achieved through their implementation in advisory studies for managerial authorities.

2. OBJECTIVES

The main objective of the research is ***to establish well validated physical and mathematical descriptions of the behaviour and fate of concentrated benthic suspensions (CBS) and their interaction with the water column and the sediment bed.***

After having identified the gaps in the present knowledge of cohesive sediment transport, the following sub-objectives have been formulated:

1. Select the most suitable model for the simulation of cohesive sediment-laden flow. Extend existing turbulence models to allow for the simulation of sediment-laden flow for a wide range of concentrations and turbulence intensities. Establish a formulation for the **turbulence damping** (buoyancy effect) and **turbulence generation** (internal wave turbulence production) in concentrated suspensions.
2. Establish a formulation for the floc formation from which the depositional flux and the resulting bed structure can be evaluated. Define the structural floc parameters that govern the rheological properties of the bed and of fluid mud. Develop a **floc model** which allows the calculation of the settling velocity of flocs in relation to turbulence, concentration, residence time and, if possible, organic content.
3. Establish a formulation for the **exchange of mass and momentum at the fluid mud/water interface,** unifying the concepts from **deposition, entrainment/erosion** and interface instabilities (internal waves). Understand why and **how benthic suspensions (CBS) can be generated** and maintained, and quantify the relevant processes.

4. Establish a formulation for the **development of erosion resistance (strength) in mud beds,** unifying the concepts from rheology, consolidation, liquefaction and fluidisation.

In order to make the modules applicable for integrated system models, aimed at large scale simulations, further sub-objectives are to:

5. Establish a data base to validate the models.
6. Establish parameterized forms of the above mentioned process models based on numerical and experimental data.
7. Establish guidelines to select and implement the proper model formulation.
8. Establish guidelines to carry out the necessary experiments in the laboratory as well as in the field for calibration of the models.
9. Establish general guidelines for engineers and managing authorities on how to set up the necessary field measurement campaigns to obtain the necessary initial and boundary conditions and the material parameters in order to validate or apply the integrated system models.

3. METHODOLOGY

The project is structured into six interacting Task Groups. Each of the first four sub-objectives is dealt with by one Task Group which aims at developing new process modules.

Task Group A on "Turbulence" will use 1D and 2D vertical (research) models, which solve the full hydrodynamic, turbulent energy and sediment mass conservation equations. One- and two-equation turbulence models will be used to test various semi-empirical relationships for the damping factor (i.e. the Schmidt number), the buoyancy and interparticle collision effect on the dissipation of turbulent energy and turbulence production by interfacial instabilities at lutoclines. Validation is done in close cooperation with Task Group C.

Task Group B on "Flocculation" will develop an advanced flocculation model to allow a more accurate estimation of the actual settling velocity of aggregate particles as a function of concentration, turbulent shear and time. A field campaign and laboratory experiments in oscillating grid tanks and (possibly) in open-channel shear flow will be carried out to obtain complete data sets to validate the model.

Task Group C on "Concentrated Benthic Suspension Dynamics" will study the conditions under which CBS can occur. Experiments will be carried out in open-channel flow and in a grid tank. Theories will be developed and tested by comparison with the experimental data and by numerical experiments, using the same models as for Task A.

Task Group D on "Bed Dynamics" will study the structural history of the saturated cohesive soil skeleton during consolidation, liquefaction and/or fluidisation conditions in order to obtain better estimates of the erosion strength. A generalized Biot model and an integral erosion/entrainment model will be used. Validation of the rheological closure equations will be done with data from settling column experiments and the literature. In-situ bed strength data will collected during the field campaign (Task B).

Task Group E on "Modelling" will parameterize the new process modules in order to obtain simple formulations which can be implemented into currently used (3D and 2DH) engineering system models. The performance of the improved models will be tested by application of the models to a schematic estuary, for which a 2DV solution with the detailed research model (used for Tasks A and C) is used as a reference. Various scenarios will be simulated. The system models be also be applied to three European estuaries. Evaluation of these large scale applications will lead to a feed-back to process module development and their parameterizations.

The data collected and/or generated by the various Task Groups (experimental data as well as data to set-up and calibrate the process modules and model applications), together with other relevant data from the literature, will be stored in a data base. The setup and maintenance of the data base is assigned to **Task Group F**.

RESULTS

Since the project started only about half a year ago, it is still too early to publish results. All information on the actual state of progress and publications can be found on the COSINUS home page http:/sun-hydr-01.bwk.kuleuven.ac.be/COSINUS/cosinus.html.

There is also a "CSRList" (Cohesive Sediments Research (moderated) "listserv" news and discussion group) for electronic distribution of information to the worldwide cohesive sediments research community. To subscribe mail "CSRList firstname lastname" to: listserv@cc1.kuleuven.ac.be.

TITLE: Coastal Study of Three-Dimensional Sand Transport Processes and Morphodynamics (Project COAST-3D)

CONTRACT NO: MAS3-CT97-0086

COORDINATOR:

Mr Richard Soulsby
Marine Sediments Group
HR Wallingford Ltd, Howbery Park
Wallingford, Oxfordshire
OX10 8BA, UK
Tel: +44 1491 822233
Fax: +44 1491 825743
Email: rls@hrwallingford.co.uk

PARTNERS:

Dr Piet Hoekstra
Department of Physical Geography
Institute for Marine and Atmospheric Research
Postbus 80.115, Heidelberglaan 2
NL-3508 TC Utrecht, NL
Tel: +31 30 2532753
Fax: +31 30 2540604
Email: p.hoekstra@frw.ruu.nl

Dr Rudolph Spanhoff
Ministerie van Verkeer en Waterstaat
Rijksinstituut voor Kust en Zee
Kortenaerkade 1, Den Haag
NL-2500 EX, NL
Tel: +31 70 3114230
Fax: +31 70 3114321
Email: rspanhoff@rikz.rws.minvenw.nl

Prof Dr Leo van Rijn
Delft Hydraulics
Marine and Coastal Management
PO Box 177
NL-2600 MH Delft, NL
Tel: +31 15 2858898
Fax: +31 15 2858710
Email: leo.vanrijn@wldelf.nl

Professor David Huntley
Institute of Marine Studies
University of Plymouth, Drake Circus
Plymouth, Devon
PL4 8AA, UK
Tel: +44 1752 232431
Fax: +44 1752 232406
Email: dhuntley@plymouth.ac.uk

Professor B O'Connor
The University of Liverpool
Department of Civil Engineering
PO Box 147
Liverpool
L69 3BX, UK
Tel: +44 151 794 5232
Fax: +44 151 794 5218
Email: ec09@liverpool.ac.uk

Dr Peter D Thorne
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead
Merseyside
L43 7RA, UK
Tel: +44 151 653 8633
Fax: +44 151 653 6269
Email: pdt@pol.ac.uk

Dr Franck Levoy
Universite de Caen, Laboratoir de Geologie Marine
Centre Regional D'Etudes Cotieres
BP 49, 54 Rue Du Dr Charcot
F-14530 Luc-Sur-Mer, F
Tel: +33 2 31 36 2222
Fax: +33 2 31 36 2220
Email: levoy@neptune.msh.unicaen.fr

Prof Dr Agustin Sanchez-Arcilla
Laboratori D'Enginyeria Maritima
Universistat Politecnica De Catalunya
C/ Gran Capita S/N, Campus Nord UPC
Mod D1, ES-08034, Barcelona, E
Tel: +34 3 2806400
Fax: +34 3 2806019
Email: arcilla@etseccpb.upc.es

Dr Jean Lanckneus
Marine Geological Assitance BVBA
Hundelgemse Steenweg 232
B-9820 Merelbeke
BE
Tel: +32 9 231 7355
Fax: +32 9 231 7355
Email: jean.lankneus@skynet.be

Dr Nicholas Cooper
The Environment Agency (Anglian Region)
Kingfisher House, Goldhay Way
Orton Goldhay, Peterborough
PE2 5ZR, UK
Tel: +44 1733 464411
Fax: +44 1733 464372
Email:

COASTAL STUDY OF THREE-DIMENSIONAL SAND TRANSPORT PROCESSES AND MORPHODYNAMICS

COAST-3D

R L SOULSBY

HR Wallingford, Howbery Park, Wallingford, OX10 8BA, UK

SUMMARY

The MAST-III RTD project COAST3D started in October 1997. A consortium of 11 partners including hydraulic laboratories, universities and national regulatory authorities from five EU states (UK, Netherlands, France, Spain and Belgium) will undertake this three-and-a-half year project. The project will make field measurements of waves, currents, sediment transport and morphodynamics at two contrasting sites. The results will be used to valid existing morphodynamic computational models, and lead to coastal zone management tools.

1. INTRODUCTION

Coastal management and engineering decisions rely increasingly heavily on predictions made by computational numerical models of hydrodynamic and sediment-dynamic processes and the resulting morphodynamic changes to the coastline and sea bed. Yet such models are rarely tested adequately against real data from coastal field measurements. This is largely because the many field experiments made to date have been designed to elucidate the physical processes rather than to evaluate numerical models. In addition, the most detailed data-sets are from North American sites, which are fundamentally different to European conditions. Evaluation of numerical models makes special requirements of the data, such as detailed measurement at the boundaries, and a dense spatial coverage of measurements within the modelled area. At the same time, improvements to numerical models are mainly made through improved understanding of the processes, so it is important to measure and interpret these also. The knowledge and models also need to be taken beyond the domain of the scientist, and put into a framework of guidelines and methodologies to be of direct value for coastal zone management.

Sandy coasts can be classified as 2-dimensional (uniform in the coastwise direction), 2.5-dimensional (as 2D, but with natural non-uniformities such as rip-channels), and 3-dimensional (with irregular features such as headlands and tidal inlets). One of the best ways of gaining insights into the complex 2- or 3-dimensional development and behaviour of sandy coastal systems is by simulating their structure, organisation and functioning by using numerical models. Nowadays, morphodynamic models especially have become important tools for coastal zone management to predict and evaluate the evolution in coastal morphology in response to environmental change and engineering works.

Numerical morphodynamic models are generally of two types: Coastal Profile (CP) Models, suitable for 2D coasts, and Coastal Area (CA) Models, suitable for 3D coasts, with certain variants of both being applicable to 2.5D coasts. The understanding and modelling of notionally 2D coasts is reasonably well advanced, but the question is being raised whether

any natural coast is sufficiently uniform to enable 2D modelling techniques to make successful predictions. Hence the focus is now turning to understanding the three-dimensional aspects.

2. OBJECTIVES

The purpose of the COAST3D project is

- to improve understanding of the physics of coastal sand transport and morphodynamics
- to remedy the present lack of validation data of sand transport and morphology suitable for testing numerical models of coastal processes
- to test a representative sample of numerical models for predicting coastal sand transport and morphodynamics against this data
- to develop validated modelling tools, and methodologies for their use, in a form suitable for coastal zone management

This will be achieved by making field measurements purpose-designed for numerical model evaluation, with adequate boundary conditions and a dense horizontal array of measurement points, in conditions typical of the European coastline. Previous coastal experiments in Europe and elsewhere have placed their main emphasis on hydrodynamics; an innovative feature of the present project is that the emphasis throughout is on sand transport and morphodynamics.

Another distinctive feature is that the focus is on non-uniform (3D) coasts, rather than on the relatively well understood (but possibly unrealistic) uniform 2D case. Experiments will be performed at two contrasting sites: a quasi-uniform (2.5D) stretch of the Dutch coastline, and a fully 3D site on the UK coast. This phased approach will allow both the process information and the performance of the numerical models to be more easily interpreted. Innovative techniques will be used in the experiments. Numerical modellers will work interactively with the experimenters, at the planning, experiment, and evaluation phases. Participants from national regulatory authorities will ensure that the project is focused on practical tools for coastal zone management.

Sites have been chosen in:

- the Netherlands for the 2.5D case, which is typical of the quasi-uniform sandy beaches dominated by breaker bars found on much of the coastlines of northeast France, Belgium, the Netherlands, western Germany, western Denmark, and eastern England.
- the UK for the 3D case, which is typical of the irregular coastlines featuring tidal inlets, river and estuary mouths, headlands, and coastal structures, often without breaker bars, found in western and southern Britain, Ireland, northern and western France, northern Spain, Portugal, and Norway.

A large proportion of the coastline of Europe falls into these two categories. The remainder comprise the micro-tidal coasts of the Mediterranean and the Baltic. These latter seas fall within the remit of the ongoing MAST-3 FANS project, based on an experiment in the

Mediterranean to measure water, sediment and nutrient fluxes in three domains: the nearshore, the shelf and the continental slope. Another complementary MAST-3 project, INDIA, will study the morphodynamic behaviour of tidal inlet entrances and adjacent coastlines at a site in Portugal. Links will be forged between COAST3D, INDIA and FANS, through the presence of common partners, so that a wide variety of different European environments will be covered by these three projects.

3. EXPERIMENTS

The first experiment will take place at Egmond on a quasi-uniform stretch of the Dutch coast (Fig.1), starting with a pilot experiment in spring 1998 followed by the main experiment in autumn 1998. Although the coastline and bathymetric contours appear on charts to be nearly straight, it is known from earlier work that the natural three-dimensionality produced by rip-channels intersecting a bar system has a major effect on the hydrodynamics and sediment dynamics of the coast. The site is regarded as "2.5–dimensional" as a result of these sedimentary non-uniformities, and the departures from 2-dimensionality are an important aspect of this experiment.

The second experiment, scheduled for 1999, will take place at Teignmouth on the south coast of England (Fig.2), where a rocky headland and a river mouth provide a strong three-dimensionality. A complicated re-curving spit is very active morphodynamically. This site, which additionally has a wide range of grain-sizes, will stretch the capabilities of present day coastal morphodynamic numerical models to their limits, and will provide a very exacting test of these and future models.

At each site a small number of permanent instruments will monitor conditions over at least 12 months. The main experimental work, however, will take place over an approximately 6 week period in the autumn (when beach conditions change most rapidly) at first the Dutch, and then the UK, site. The vast majority of the instruments are already owned by the partners, and will be deployed at both sites in succession, thereby making optimum use of the instruments, the logistics, the cooperative working practices, and the data management scheme. Instruments will be deployed in an array designed to meet the needs of numerical model evaluation, and to provide the more detailed process information. A pilot experiment of about two weeks duration will take place in the spring preceding each main experiment, to maximise the chances of success in the autumn.

The use of the innovative devices WESP and CRIS, which have been recently designed and constructed specifically for coastal experiments, is an important aspect of the implementation of the research programme. The WESP is a 10m high motorised tripod on wheels with a platform at the top supporting the engine and a cabin with facilities. Surveys can be conducted from the beach out to water depths of 6m in wave heights up to 2m (moderate storms). The WESP will tow a sledge (CRIS) carrying an intensive array of instruments wired in to the WESP cabin. This arrangement will ensure that the flow disturbance around the WESP does not influence the instruments.

The WESP is valuable for the collection of sand transport data, because it allows on-line measurements of short duration (30 min), and simultaneous collection of calibration samples by pumping systems. The availability of the WESP will allow a greater flexibility during the measurements by increasing the number of operational hours, by reducing ship time and the reaction time after an event and by deploying instruments at sites which are otherwise

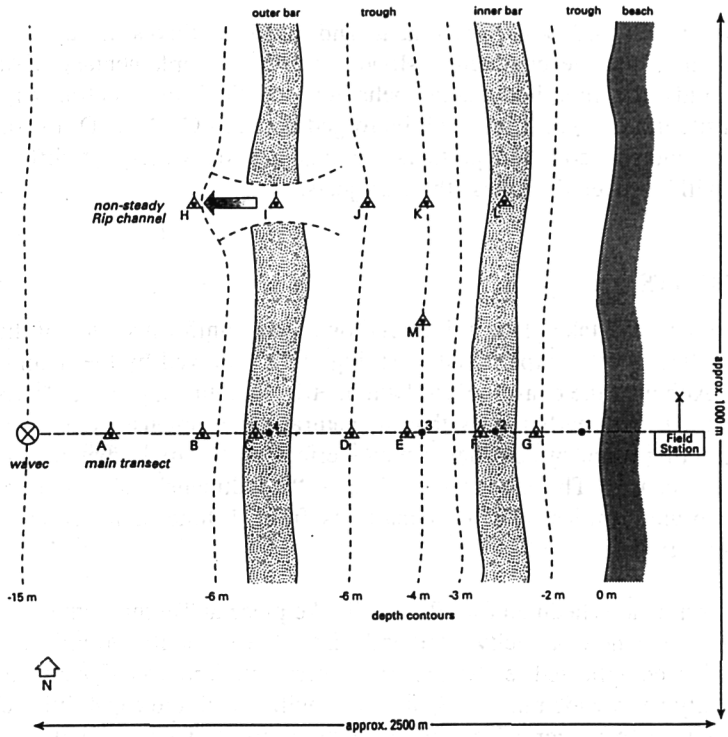


Figure 1. Schematic layout of instruments for Egmond experiment

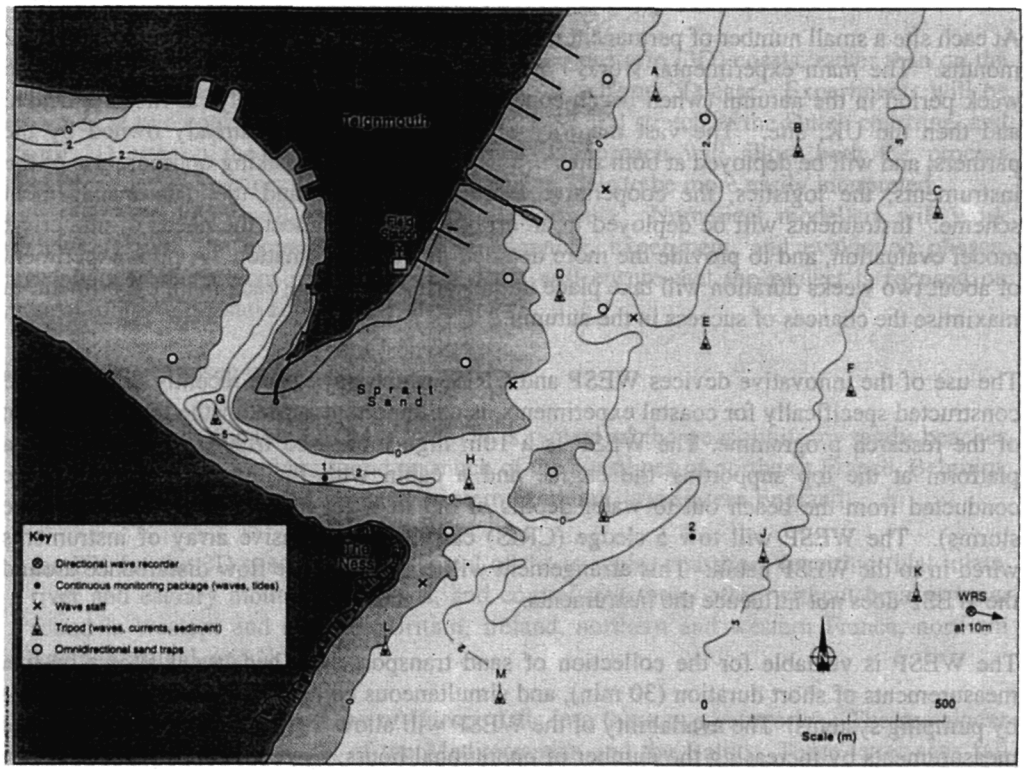


Figure 2. Schematic layout of instruments for Teignmouth experiment

difficult to reach. The WESP will be used for measuring the 3-dimensional bathymetry of the nearshore zone, for placing and relocating instruments and for taking samples. The WESP can be dismantled to be able to carry it to various sites in Europe.

A crucial aspect of the experiments is the large number of instruments which will be deployed. In many ways this is what distinguishes COAST3D from previous field campaigns, and makes the resulting data-set of so much value for evaluating numerical models. Most of the instruments are already owned and used by the participants, and in many cases have been specially developed by them.

4. MODELLING

A representative selection of numerical models of coastal hydrodynamics, sediment dynamics, and morphodynamics developed by the partners will be used at various stages throughout the project, most particularly for:

- preliminary runs to aid the design of the experiment. The models will be set up for the study area and run with representative inputs. Areas with strong spatial variations of the modelled parameters (waves, currents, sediment transport), and those areas where the models markedly disagree among themselves, will be identified for intensive instrumentation

- on-site modelling at a "modellers' week" midway through each experiment. Deficiencies in the experimental set-up can be remedied for the remainder of the experiment, and initial indications of the performance of the models obtained. The modellers' weeks will be open to modellers from outside the project to participate

- evaluation of the models after the full data validation, calibration and reduction. This will be the largest modelling effort, and will contribute towards the validation and accreditation of the models used.

The models used range from research models exploring the detailed physical processes (mainly at the universities) to fully operational models used routinely for consultancy applications (mainly at the hydraulic institutes).

Comparisons of the models with the data will be made in two distinct ways, by two distinct groups.

A diagnostic modelling group, made up of the university partners, will compare the measurements of individual physical processes with their representation by the models. It will identify: which models include the important processes, which of these give the best agreement with the data, how they can be improved, and how the improved algorithms can be included in the other models.

A practical modelling group, made up of the hydraulic institutes and regulatory authority partners, will test the overall capability of the models to reproduce the main trends in the data. They will address issues such as ease of setting up and driving the models, computational speed, stability and robustness, ease of plotting and interpreting results, as well as establishing an objective measure of "skill" in the models' performance against data. Best

features will be further improved and included in all the models. Further, the group will decide on recommended procedures for the use of numerical models in coastal applications, and embody these in guidelines for use in coastal zone management.

5. PROCESS INTERPRETATION

The use of the data to further the understanding of the processes taking place in the coastal zone is every bit as important as the use for model validation. Accordingly, the experiments have been designed to accommodate both uses of the data.

For the 2.5D experiment one of the major questions which will be addressed is the growth, development and migration of nearshore bars in the surfzone and its impact on the behaviour of the coast, as well as the role of rip channels on bar behaviour. In many surfzones nearshore bars are the main morphological phenomena and their behaviour is still only partly understood and forms a good test case for the models. To measure the different processes and parameters a main cross-shore array of instruments will be installed covering the entire shoreface from a depth of about 20 m to the high tide levels on the beach. A number of instruments will be mounted to one side of the main line, to quantify the effects of rip channels on longshore nonuniformity (Figure 1).

For the 3D experiment the main emphasis is on the variations in the measured parameters in the two horizontal dimensions, particularly identifying horizontal circulation patterns of currents and sediments. A wide range of depths is necessary to identify the differing processes which re-distribute sediment in offshore areas and in the surf-zone. Some emphasis on the vertical distributions is also necessary. To measure the different processes and parameters a main array of instruments will be installed along intersecting cross-shore and longshore transects as shown schematically in Figure 2. Instruments will be located at the offshore and lateral boundaries of the studied region, to provide boundary conditions for the numerical models.

In both cases, it must be emphasised that the layout of instruments in the figures are schematic, and the exact layout will be determined by consultation between all the partners at an early stage of the project, after initial runs of the numerical models have been made.

A number of instruments such as poles and WAVEC will be installed for a longer period of time to continuously record the boundary conditions at each site. Other instruments such as tripods and frames can be moved from one location to another and will be used on both sites. The greater part of these frames and tripods is in the possession of the different partners. These existing tripods though may need some adaptations. In addition, to further increase the spatial coverage and density of the measurements a number of new poles, tripods and frames has to be built prior to the experiments.

6. DATA MANAGEMENT AND AVAILABILITY

Good data management is a vital part of the project. A Data Management Group will oversee and specify:

- the synchronisation, record lengths and file formats of the logged data,
- the validation, calibration and basic analysis of the data,

- the design of a suitable data-base system,
- the storing of the data in the data-base,
- the public dissemination of the data through the Internet and CD-ROMs.

This will ensure uniformity of procedures between partners.

The data will be publicly available six months after the end of the project in two distinct forms:

(a) the complete data-set for study of physical processes,
(b) a condensed data-set of the basic variables for running and evaluating numerical models.

7. COASTAL ZONE MANAGEMENT

One of the most important products of the project is a set of tools and guidelines for practical coastal zone management (CZM). The production of these CZM tools will be guided particularly by the Rijkswaterstaat and Environment Agency partners, having regard to the following considerations.

Tools available to the coastal zone manager for solving problems are:

- data analysis
- measurement and monitoring
- (numerical) modelling.

Guidelines for using these tools should answer the following basic questions:

- WHEN to use,
- WHAT tools, and
- HOW to use these.

Answering the WHEN question first of all, requires an analysis of the CZM problem(s), leading to the definition of measurable:

- CZM objective(s), [eg maintenance of the coastline over a well defined length and for a well defined period of time],
- CZM parameter(s), [eg sand content of a well defined control volume],

and on this basis the definition of the most important

- temporal and spatial scale(s), and
- physical parameters.

Then, the answer to the question WHAT tools to use is depending on

- the availability of data,
- the possibilities for monitoring and measurements,
- the availability and (more important) the validity of numerical models, considering the spatial and temporal scales of interest.

Finally, the question HOW to use the tools may lead to guidelines for each individual tool, eg

- statistical analysis techniques (minimum data demands etc),
- monitoring and measurement schemes (parameters, instrumentation, frequency and spatial distribution, accuracy etc),
- methodology and procedures for applying individual numerical models.

For practical use however, it is just as important to develop guidelines on the combined use of the tools, answering:

- how to interpret measurement data,
- how to interpret model results, and
- how to draw conclusions in relation to the CZM problems.

8. CONCLUSIONS

The COAST3D project will

- make measurements at two contrasting sites, one typical of 2.5D and one of 3D conditions

- store the data in a properly managed data-base, and make them publicly available in two forms:

  (a) the complete data-set for study of physical processes, and

  (b) a condensed data-set of the basic variables needed for running numerical models, to provide definitive test-cases against which present and future models can be evaluated

- interpret the data to provide an increased understanding of the physical processes operating in the coastal zone

- make an evaluation of a representative sample of present-day European morphodynamic numerical models, in terms of both their ability to represent individual processes (diagnostic), and their overall usability and performance (practical)

- present the models and methods in a form suitable for coastal zone management, for example by providing a series of guidelines.

ACKNOWLEDGEMENTS

The COAST3D project is funded partly by the European Commission's research programme MAST under Contract Number MAS3-CT97-0086, and partly through national funding from the UK Ministry of Agriculture, Fisheries and Food under research project FD0803, the UK Environment Agency, and the Netherlands Rijkswaterstaat.

TITLE: INDIA: Inlet Dynamics Initiative: Algarve

CONTRACT NO: MAS3-CT97-0106

COORDINATOR:
Professor B A O'Connor
Department of Civil Engineering, University of Liverpool, Brownlow Street, Liverpool L69 3BX, UK.
Tel.no. (Fax): +44 151 794 5232(5218)
E-mail: price@liv.ac.uk.

PARTNERS:

Drs J J Williams/M T Jones (BODC)
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead, L43 7RA
Tel.no. (Fax) +44 151 653 8633(6269)
E-mail: jjw@wpo.nerc.ac.uk

Professor A J Sarmento
Instituto Superior Tecnico
Av Rovisco Pais 1
Lisbon, Portugal
Tel.no.(Fax) +351 1841 7405(7398)
E-mail: sarmento@hidro1.ist.utl.pt

Dr H Howa
Universite Bordeaux
Department de Geologie/Oceanographie
Avenue des Facultes
33404 Talence, Cedex
Aquitaine, France
Tel.no.(Fax): +33 05 5684 8849(0848)
E-mail: howa@geocean.u-bordeaux.fr

Dr R B Aurora
Instituto Hidrografico
Rua das Trinas 49
Lisbon, Portugal
Tel.no. +35 11 39 55 119
Fax.no.+35 11 39 60 515

Ing A Silva
Hidromod, Taguspark
Nucleo Central 349
Oeiras 2780, Portugal
Tel.no.(Fax): +35 11 421 1272
E-mail: hidromod@taguspark.pt

Professor J M A Dias
Universidade do Algarve
Campus de Gambelas
8000 Faro, Algarve, Portugal
Tel.no. +35 1 89 800900
Fax.no. +35 189 818353
E-mail: jdias@mozart.si.ualg.pt

Professor M Collins
The University of Southampton
Department of Oceanography
Highfield, Southampton SO17 1BJ
Tel.no. +44 1703 592 786
Fax.no. +44 1703 593059
E-mail: mbc@soc.soton.ac.uk

Dr S M Arens
University of Amsterdam
Faculty of Environmental Sciences
Nienwe Prinsengracht 130
Amsterdam, Noord Holland, Netherlands
Tel.no.(Fax) +31 20 525 7421(7431)
E-mail: s.m.arens@frw.uva.nl

Professor F Seabra-Santos
Universidade de Coimbra
Instituto do Mar, Largo D Diniz
Coimbra, Portugal
Tel.no.(Fax): + 351 39 410 678
E-mail: fseabra@gemini.ci.uc.pt

Professor D Huntley
The University of Plymouth
Drake Circus, Plymouth
Devon, PL4 8AA
Tel.no. (Fax) + 44 1752 232 431 (406)
E-mail: dhuntley@plymouth.ac.uk

INLET DYNAMICS INITIATIVE: ALGARVE (INDIA)

B.A. O'CONNOR[1], J.J. WILLIAMS[2], J.M.A. DIAS[3], G. VOULGARIS[4], M.A. DAVIDSON[5], S.M. ARENS[6], H. HOWA[7], A. SARMENTO[8]

1. Liverpool University, Dept.of Civil Engineering, Liverpool L69 3BX, UK.
2. Proudman Oceanographic Laboratory, Bidston, Birkenhead, L43 7RA, UK.
3. Universidade do Algarve,Campus de Gambelas, 8000 Faro, Algarve, Portugal.
4. University of Southampton, Dept. of Oceanography, Southampton, SO17 1BJ.
5. University of Plymouth, Inst. of Marine Studies, Plymouth, Devon, PL4 8AA.
6. University of Amsterdam, Faculty of Environmental Sciences, Nienwe Prinsengracht 130, Amsterdam, Noord-Holland, Netherlands.
7. Universite Bordeaux, Department de Geologie et Oceanographie, Avenue des Facultes, 33 404 Talence, Cedex, Aquitaine, France
8. MARETEC, Instituto Superior Tecnico, Av Rovisco Pais 1, Lisbon, Portugal.

SUMMARY

The multi-disciplinary, international Project INDIA is described along with details of the Project's aims and work plan. The main objective is to obtain an improved understanding of interactive coastal processes in relation to tidal inlet dynamics. The work started on the 1st November 1997 and involves the use of state-of-the-art field equipment, including remote sensing techniques and computer models of wave and current climates and bathymetric/topographic change. Fieldwork will centre around a natural inlet in the Ria Formosa barrier islands in the Algarve, Portugal but results will be extended to other situations through international partners from Australia, Poland, Korea and the USA as well as technical advisers from a number of EU companies.

1. INTRODUCTION

Tidal inlets occur widely throughout the world. They link together outer high energy coastal zones and inner, calmer, back-bay/lagoon areas. Natural inlets are dynamic features which move in the direction of net longshore sediment transport. If such movement is large, it can cause such a tortuous drainage route for water from the back-bay or lagoon that a new inlet is formed, leaving the original inlet channel to gradually infill with sediment. The dynamics of such processes, which are usually cyclic unless prevented by engineering works, are complex. Sediment is moved both up-and down-coast by wave action, and both on-and off-shore by wind action while the water movement through the inlet moves sediment both into and out of the back-bay/lagoon area to form flood/ebb deltas. Coastal bars formed by the ebb discharge also interfere with the incident wave climate and can produce difficult navigation conditions for ships using the back-bay/lagoon area. The movement of nutrients and

pollutants within the coastal zone and the back-bay/lagoon also becomes complex as old inlets close and new inlets are formed, thereby affecting other activities, such as fishing and tourism.
The effect of environmental change such as sea level rise on inlet stability is also far from clear. Any loss of protection for back-bay/lagoon activities, such as mariculture, port operations and tourism can have a major financial impact upon local communities. Any change in the cyclic movement of inlet location is also likely to affect coast protection measures. Suggestions for the use of different-sized dredged material to nourish local beaches presents difficulties for engineers planning coastal developments, since the by-passing of beach and seabed sediments is far from clear when an inlet is present.

While much work has been done in the past to answer particular inlet problems, such work has usually been small-scale and has followed an inlet-by inlet approach using standard field-based approaches. Little use has been made of computer models or remote sensing techniques nor has the multi-disciplinary nature of problems always been recognised. Rarely have all such elements been combined together. The present Project makes use of such a combined philosophy and builds upon earlier work completed by multi-disciplinary teams under the EU's MAST1 and MAST2 Programmes, O'Connor (1993, 1996). A new multi-disciplinary team has been assembled within the INDIA Project to study the problem of inlet dynamics.

The EU team has also been extended by including international members from Australia (Prof. M. Heron, Department of Physics, James Cook University); Korea (Dr H. Kim, Department of Civil Engineering, Kookmin University; Dr D Yum, the Korean Ocean Research and Development Institute (KORDI)); Poland (Dr L Kaczmarek, The Institute of Hydroengineering of the Polish Academy of Sciences (IBW/PAN)); and the USA (Dr G Howell, The Corps. of Engineers, Waterways Experimental Station (WES); Dr D Aubrey, Woods Hole Oceanographic Institute (WHOI)). In addition, a number of EU engineering companies are also acting as advisors including GEC-Marconi (Dr E. Pegram); Valeport Engineering (Mr C. Quartley); and Sir William Halcrow and Partners (Professor C. Fleming).

2. OBJECTIVES

The general objective of the INDIA Project is to obtain a better understanding of inlet processes and their prediction. Specific objectives are:-

(i) to understand complex interactions between wind and waves, tidal flow, sediment movement, including aeolian, and related phenomena which determine the morphodynamic behaviour and stability of tidal inlet entrances, flood/ebb deltas and adjacent coastlines and to develop methodologies by which processes can be incorporated into numerical models in order to predict change;
(ii) to understand and predict interactions between waves and tides at and adjacent to tidal inlets as well as the role played in inlet dynamics;
(iii) to understand and predict inlet bypassing processes; and

(iv) to understand back-bay and nearshore processes controlling the stability of inlets.

3. METHODOLOGIES

The understanding of inlet dynamics is to be obtained by a threefold approach. Firstly, observations over a two-three month period of wind/wave current climates; topographic and bathymetric change; and detailed flow and sediment transport processes at a number of points around and within a typical tidal inlet. Secondly, the use of a range of one, two and three-dimensional computer models to predict the spatial and temporal distribution of wave/current climates and both topographic and bathymetric change around the inlet as well as for "what-if" scenarios of changed mean sea level and wind/wave current climates. Thirdly, the intercomparsion of observed and computed results with data from other sites.

The fieldwork will involve state-of-the-art equipment such as radar (for surface currents and waves), acoustic (for suspended sediments), laser (for bathymetry) and video (for bathymetry and wave action) so as to enable observations during storms and, in the case of the video equipment, to allow longer-term observations of the inlet over the time scale of the Project. A temporary instrument bridge will also be used across the inlet so as to enable measurements during all-weather conditions. New sensors to study nearbed processes using particle-image approaches (PIV) will be developed and tested both in the field and in the laboratory as also will a new seabed/ beach crawler tractor (BSC). A large prototype-scale wave flume will also be used to test the response of field tripods and remote sensing sediment equipment to changing environmental conditions. Data collected from the field will also be used to calibrate and verify the various computer models used in the project.

The various field and computer observations will help to address the following research areas:-

(i) fundamental sediment transport mechanisms;
(ii) measured and predicted sediment transport rates;
(iii) mechanisms by which sediments by-pass inlets;
(iv) hydrodynamic properties of inlets;
(v) sediment transport mechanisms and rates through inlets;
(vi) modification of surface wave amplitude, form and direction by the flood and ebb tidal deltas and currents of the inlet and by the inlet itself;
(vii) the morphological evolution and present day dynamics of flood and ebb tidal deltas;
(viii) wave overwash processes and the contribution to the total sediment budget and to the morphological evolution of inlets;
(ix) aeolian sediment transport rates and contribution to the sediment budget;
(x) aeolian dune evolution; interactions between aeolian processes and the beach; and
(xi) hydrodynamic processes and sediment transport in the surf zone.

4. WORK PLAN

A small newly-dredged (October 1997), tidal inlet located at the western end of the Peninsula do Ancão in the Ria Formosa National Park (Algarve), Portugal has been selected for study. The field site encompasses a tidal lagoon, barrier islands, a narrow shelf and deep offshore water. The open ocean cost is subject to inshore waves with heights between 1-4m with periods between 6-16s. Tidal range at the site varies between 2-4m between Neaps and Springs. Sediment at the site is a clean sand of some 200 Tm mean size with transport predominantly from west to east. However, transport direction can be reversed by strong easterly winds known locally as the Levant, although they are less common. Medium to high air temperatures and low bio-mass production allows significant aeolian transport during storms.

Pictures of the site and further information can be obtained from the INDIA web site located at http://www.pol.ac.uk/jjw/INDIA.htlm.

The INDIA Project has a three-year timescale and work started on the 1st November 1997. In order to achieve the Project objectives, the research has been divided into four major work packages (WP) and a series of sub-work packages (SWP) as shown below:-

WP1	**Numerical modelling**
SWP1	2DH hydrodynamic lagoon model (LAGOON)
SWP2	Quasi-3D offshore model (3D-OFFSHORE)
SWP3	Wave models (WAM; RAY; 3D-WAVES)
SWP4	Quasi-3D hydrodynamics and sediments inlet model (3D-INLET)
SWP5	1DV hydrodynamics and sediments model (1D-W/C/S; 1D-SHEET)
SWP6	2DV surf/swash zone model (2D-SURF)
SWP7	2DV hydrodynamic bedform model (2D-BED)
SWP8	2DV aeolian transport model (2D-AEOLIAN)
WP2	**Fieldwork**
SWP9	Experimental preparation
SWP10	Field experiment logistics
SWP11	Lightweight instrument bridge and instrument support piles
SWP12	Remote sensing activities
SWP13	Offshore fieldwork
SWP14	Inlet and ebb/flood delta fieldwork
SWP15	Surf zone fieldwork
SWP16	Beach fieldwork
SWP17	Aeolian fieldwork
WP3	**Data analysis, investigation of processes, data management and data base**
SWP18	Data analysis
SWP19	Investigation and interpretation of processes
SWP20	Data management
WP4	Integration

As regards WP1, a range of models will be used with varying degrees of non-linear interaction. It is anticipated that the results will indicate the level of modelling complexity (to allow wave, currents and bathymetry to interact) required to predict observations of the inlet mouth and along adjacent coastlines. Results are also expected to guide future use of models for a range of engineering applications. The numerical models will also be used to:-

(i) understand and predict interactions between waves and tides in and adjacent to inlets;
(ii) understand mechanisms driving bypassing processes and predict morphology;
(iii) understand and predict hydrodynamic and sedimentary processes controlling inlet stability;
(iv) predict morphological response of an inlet system to changes in environmental conditions;
(v) aid in the design of field experiments through identification of important boundaries and in the initial quantification of significant gradients in processes;
(vi) extend through hindcast and forecast techniques both the temporal and spatial range of all hydrodynamic and sediment transport measurements obtained in the field;
(vii) aid in the interpretation of field data when spatial and temporal resolution of sensors limits understanding of processes;
(viii) help in the assessment of data quality; and
(ix) aid in assessment of how representative field data are of typical and extreme events.

As regards WP2, the sub-work packages cover activities of remote sensing; offshore measurements; nearshore measurements; beach measurements; aeolian measurements; and tidal inlet, delta and lagoon measurements.

A number of remote sensing instruments will be used in the INDIA Project to obtain data pertaining to bathymetry, tidal currents and waves over a wide study area encompassing the inlet, lagoon and offshore environments. These instruments will ensure acquisition of data at a spatial and temporal scale commensurate with the numerical models and will operate in conditions where conventional instrumentation frequently fails. An HF Radar system (OSCR) and a VHF Radar system (COSRAD) will be used to measure surface currents and waves every 20 minutes of the deployment. In addition, the VHF Radar system will provide information on surface roughness to aid numerical modelling of aeolian processes. The HR Radar will permit measurement of surface velocities in the tidal lagoon and at offshore locations up to a maximum distance of 40km from the transmission stations. The VHF Radar system will be deployed at the field site to measure in detail the surface currents and waves at and adjacent to the tidal inlet up to a maximum distance offshore of 2km. Remote video monitoring systems will be monitored on towers and used to monitor indirectly changes to nearshore and tidal inlet morphology. Snapshots and time exposures of the beach and breaking wave areas will be obtained every half hour of the deployment. Wave direction, height and period will be measured every half hour using a wave radar (X-Band) deployed at the field site. Detailed bathymetric survey

data of the inlet, ebb/flood deltas and adjacent intertidal and offshore areas will be obtained from rapid helicopter surveys conducted using Lidar. Owing to water clarity at the field site, resolution of bedforms within the deltas and the inlet will be possible using this technique. In addition, acoustic altimetry data will also be obtained using a local survey vessel. It is anticipated that surveys will be repeated twice during the experiment.

Aerial photographs of the field site will be obtained during the study in order to obtain additional information pertaining to inlet bedforms, inlet and shoreline position and dunes for integration into a geographical information system (GIS) to be assembled during the Project. In addition a series of aerial surveys of the entire field site and adjacent beaches and inlets will be conducted during the experimental period using a multi-spectral sensor deployed from a light aircraft (CASI). Sequential overflights with this instrument will provide useful information relating to changes in vegetation, suspended sediments, bedforms, ebb and flood delta structure and inlet morphology during the field campaign and will provide insight into complex interactions between waves, sediments and morphology at the inlet and in adjacent nearshore zones.

Measurements of offshore wind, wave direction, height and period and wind speed and direction will be obtained using meteorological and wave buoys. Tides, vertical profiles of current structure, turbulence and suspended sediment concentration will be measured using a multi-sensor mooring (PMP) at various offshore locations. Detailed near-bed measurements of turbulence, waves, suspended sediments and bedforms will be obtained at offshore locations using autonomous multi-sensor instrument platforms (BLISS).

Using a mobile beach and seabed crawler (BSC) and survey techniques, sequential measurements of nearshore morphology will be obtained along fixed transects, encompassing aeolian dunes and the beach, and extending out to beyond the surf zone at low water. Daily surveys will be conducted during the field campaign. The number of survey stations will be determined by local topographic gradients. Selected measurements of hydrodynamic conditions, suspended sediments and bedforms at selected locations in the surf zone will be obtained using sensors on the BSC. Extensive use will be made of automated fluorescent sediment tracing techniques to measure longshore and cross-shore sediment transport in situ. The existing detection system allows rapid sampling on a regular grid of sampling points at 1m intervals. Pilot studies on Peninsula do Ancão have confirmed the viability of this technique of monitoring longshore sediment transport. In combination with video monitoring techniques which will measure longshore currents, these studies will quantify longshore sediment transport along beaches adjacent to the inlet. These data will also be used to estimate the quantities of sediment intercepted by the inlet and by barrier island overwash and aeolian sediment transport processes.

In order to determine net volume changes of the beach, a number of shore-normal profiles encompassing the aeolian dunes, overwash areas and the beach will be surveyed at intervals sufficient to resolve morphological change in the system. Four principal survey transects will be located on beaches either side of the inlet. These

data will provide essential ground truth information for video image calibration and interpretation and will enable the estimation of a major element in the total sediment budget of the inlet system.

Meteorological measurements will be obtained using an automatic weather station for the aeolian work. Wind profile characteristics (wind speed, direction and air stability) will be measured over the beach and dune profile. Aeolian sand transport will be measured using saliphones and sand traps placed in a cross-section. Transport rates will be linked to volume change by means of daily measurements of erosion pins (ablation rods) and by survey. These will be installed to withstand overwash events. Surface roughness will be estimated from wind velocity data and from VHF Radar data. In vegetated areas, vegetation characteristics will be examined to estimate the surface roughness. These measurements will provide the following input parameters for the aeolian modelling activities: a series of reference wind speeds for air flow; roughness information, plant characteristics, density and FAI index; physical characteristics of the sediments; beach and dune profile characteristics; and water level.

Measurements of tidal propagation through the inlet and lagoon channels will be measured using pressure-temperature loggers (PTL). Hydrodynamic and suspended sediment data will be obtained at locations across the tidal inlet from the lightweight instrument bridge. Tides, vertical current structure, turbulence and suspended sediment concentration will be measured in the inlet by deploying turbulence sensors, acoustic sensors and a multi-sensor instrument package (PMP) from the bridge for a specified measurement period at regular intervals and from various locations above the bed. A pump sampler will also aid instrument calibration and determine the vertical distribution of sediment grain size. In addition, the bridge structure will also enable rapid acoustic surveys of inlet depth and thereby permit the study of bedform migration through the inlet. Acquisition of all data from the various instruments in the inlet will be synchronised and will be coincident with periods of data acquisition at offshore locations.

WP3 is intended to integrate activities of modelling, fieldwork, and data archiving within the Project. WP4 extends the integration to other existing and previous inlet dynamics studies and also makes use of the international partners in the Project.

5. MANAGEMENT

In order to help with the organisation of a complex twenty institute Project, use is made of four management committees drawn from the scientific partners within the Project as well as its industrial advisors. A Scientific Steering Committee (SSC) helps with long term Project goals including documentation and exploitation of Project results; a Numerical Modelling Committee (NMC) address progress on particular SWPs; a Fieldwork Management Committee (FMC) assists with progress on site planning and design of experiments; and a Data Management Committee (DMC) organises the formatting and archiving of data. Interaction between partners

is encouraged by regular progress meetings, details of which are available from the INDIA web site.

6. REFERENCES

O'Connor, B.A., (1993). Circulation and sediment transport on sand banks in European shelf seas: The LSB Project. In: MAST Days and EUROMAR Market, (eds.) Barthel, K-G., Bohle-Carbonell, M., Fragakis, C. and Weydert, M., Commission of the EC, Brussels, 1993, 1, 171-191.

O'Connor, B.A., (1996). CSTAB Handbook and Final Report, Rep. No. CE/05/96, Department of Civil Engineering, University of Liverpool, September 1996.

TITLE: Sediment Transport Modelling in Marine Coastal Environments (Project SEDMOC)

CONTRACT NO: MAS3-CT97-0115

COORDINATOR:
Prof. Dr. L.C. van Rijn
Marine Coastal Management
Delft Hydraulics
Delft, P.O. Box 177
The Netherlands
Tel: +31 15 285 85 85
Fax: +31 15 285 85 82
Email: leo.vanrijn@wldelft.nl

PARTNERS:

Dr J. Zyserman
Danish Hydraulic Institute
Agern Alle 5
2970 Hoersholm
Denmark
Tel: +45 45 76 95 55
Fax: +45 45 76 25 67
Email: jaz@dhi.dk

Dr J. van de Graaff
Delft University of Technology
Fac. of Civil Engineering
P.O.Box 5048, Stevinweg 1
2628 CN, Delft, The Netherlands
Tel: +31 15 278 48 46
Fax: +31 15 278 51 24
Email: j.vandegraaff@ct.tudelft.nl

Mr J. S. Damgaard
HR Wallingford LTD
Howbery Park
OX10 8BA
Oxfordshire, UK
Tel: +44 1491 82 24 65
Fax: +44 1491 82 57 43
Email: jsd@hrwallingford.co.uk

Prof. F. Seabra-Santos
Inst. do Mar, Univ. de Coimbra
Largo D. Diniz
3049 Coimbra
Coimbra, Centro, Portugal
Tel: +351 39 41 06 98
Fax: +351 39 41 06 78
Email: fseabra@gemini.ci.uc.pt

Prof. J. Fredsoe
Technival Univ. of Denmark
Department of Civil Engineering
Dep. of Hydrodyn. and Water Res.
Building 115, Lyngby, DK-2800
Denmark
Tel: +45 45 88 48 29
Fax: +45 45 93 28 60
Email: fredsoe@isva.dtu.dk

Mrs. C. Villaret
Electricite de France-LNH
B.P. 9
Quai Watier 6, Chatou, 78401
Ile de France
France
Tel: +33 1 30 87 83 28
Fax: +33 1 30 87 80 86
Email: catherine.villaret@der.edfgdf.fr

Prof. D. Myrhaug
Norwegian Univ. of Science and Technology
Marine Technology Centre
Otto Nielsen vei 10
Trondheim, N-7043, Norway
Tel: +47 73 59 55 27
Fax: +47 73 59 55 28
Email: dagmyr@marin.ntnu.no

Dr A. Davies
Univ. College of North Wales
Marine Science Laboratories
Menai Bridge, LL59 5EY
Anglesey, UK
Tel: +44 1248 38 28 84
Fax: +44 1248 71 63 67
Email: Oss062@sos.bangor.ac.uk

Dr G. Vittori
Inst. di Idraulica
Via Montallegro 1
Genova 16145, Liguria
Italy
Tel: +39 10 35 32 470
Fax: +39 10 35 32 546
Email: vittori@idra.unige.it

Dr J. Ribberink
Univ. of Twente
Fac. of Technology and Management
Drienerlolaan 5, Enschede 7500EE
The Netherlands
Tel: +31 53 489 27 67
Fax: +31 53 486 25 11
Email: j.s.ribberink@sms.utwente.nl

Prof. K.J. Eidsvik
Foundation for Scien. and Indust. Res.
Civil Eng., Dep. Coast. and Ocean Eng.
Klaebuveien 153
Trondheim, N-7034, Norway
Tel: +47 73 59 45 25
Fax: +47 73 59 45 35
Email: karl.eidsvik@bygg.ntnu.no

Dr C. Greated
Univ. of Edinburgh
Dep. of Physics and Astronomy
King's Building, Mayfield Road
Edinburgh, EH9 3JZ, Lothian, UK
Tel: +44 131 650 52 32
Fax: +44 131 650 52 20
Email: c.a.greated@ed.ac.uk

Dr P. Nielsen
Univ. of Queensland
Dep. of Civil engineering
Brisbane 4072, Queensland
Australia
Tel: +61 7 3365 3510
Fax: +61 7 3365 4599
Email: nielsen@uq_civil.civil.uq.oz.au

SEDIMENT TRANSPORT MODELLING IN MARINE COASTAL ENVIRONMENTS

SEDMOC

L.C. van RIJN

Delft Hydraulics, Delft, The Netherlands

SUMMARY

The quantification of sand transport rates in the marine coastal environment is a key element in the prediction of sea bed changes, coastline evolution and the morphological impact of human interference. Large gaps still remain in our knowledge of sediment transport processes, and a continuing need exists for an improvement in our understanding leading ultimately to reliable, well-validated, practical modelling systems. The main objectives of the project are therefore: to increase knowledge of the physical processes involved in transport of non-cohesive sediment (sand) under the influence of waves and currents; to develop improved predictive mathematical models for the quantitative description of sediment transport processes; and to deliver simplified sand transport models for use in coastal engineering practice.
The research will be concentrated on three main topics: A. Near-bed sediment transport processes; B. Suspended load processes; and C. Engineering sand transport formulations. Topics A and B will be concerned with sediment transport by waves and currents in both the sheet flow and rippled bed regimes, including the effects of sediment size gradation, of bed slope, and of various fluid-sediment-bedform interactions. These topics will be studied through a combination of innovative experimental work in the laboratory and mathematical model development. Topic C will involve the application of the results of these sophisticated research models in real life situations, and the development of practical integrated sand transport models for use by the coastal engineering community.

1. INTRODUCTION

The state of the marine environment is a matter of concern for several countries within the European Union. An important aspect of this is the future evolution of the coastline, where uncertainty arises both from the morphological impacts of human interference (e.g. beach nourishment and coastal protection schemes), and also the expected future rise in sea-level and associated climatic variations. These changes may gradually alter patterns of waves and currents and, hence, the sediment transport pathways in coastal areas. In the medium- and long-term, such changes may profoundly influence the stability of the shoreline itself, with all that this entails for the security and livelihoods of the large proportion of the population living near the coast.
The practical solution of real-life, coastal engineering problems in the short- and medium-term necessarily involves site-specific studies, often including the acquisition of field data. However, great expense is involved in carrying out field studies and, in recent years, increasing emphasis has been placed on the development of computer-based, coastal sediment transport and morphological modelling systems. Such models are generally capable of representing the surface waves and currents in a coastal area with considerable accuracy. However, the same

claim cannot be made for their prediction of net sediment transport rates, due largely to our presently incomplete understanding of detailed transport processes. Clearly, if morphological models are to make realistic predictions of shoreline evolution in the medium- and long-term, they must be based on accurate parameterizations of local sediment transport (i.e. point by point through the study area) in the short-term. The development of large-scale modelling systems therefore requires complementary studies of detailed physical processes.

2. OBJECTIVES

The general objective of the present project SEDMOC (SEDMOC = SEDiment transport MOdelling in marine Coastal environments) is to fill gaps in our existing knowledge of transport processes of non-cohesive sediments in the marine coastal environment, and to find suitable parameterizations of those processes which will lead to improvements in existing operational (large-scale) morphological models. In practice, due to the wide regional spread of expertise in the field of sediment transport, this can best be achieved by a joint-European approach to basic research and development.
To this end, detailed physical process models of differing complexity will be improved, intercompared and validated in relation to experimental data from the laboratory and the field; new laboratory experiments will be performed to investigate physical parameter ranges in which uncertainty presently exists; and existing field data will be analysed to ensure that the project is focussed on relevant practical problems. The detailed process studies will provide great scope for innovative work, and will help to reduce the present high degree of empiricism in the field of sediment transport. The core work of the project will involve parameterization of the theoretical and experimental results in order to produce simplified sediment transport predictors, based on sound physical arguments. Emphasis will be placed on strategies for the practical application of the results in conditions which may include, for example, a spectrum of irregular waves combined with a current profile over an irregularly undulating bed comprising a mixture of sediments, and practical approaches will be developed to predict sediment transport in the long-term for given 'wave climate' statistics.

Thus, the project will have a general character, not focussing on a particular set of physical conditions or on a pre-defined geographical site, and the deliverables will be applicable in a variety of coastal environments, including wave- or current-dominated, offshore or nearshore areas.

3. RESEARCH TOPICS

A balance will be established between 'basic research of physical processes', including experimental research and mathematical modelling, and the 'development of practical engineering formulations'. This balance will be achieved, in the first place, through the composition of the research team which includes leading European experts in (i) experimental sediment transport research (laboratory/field), (ii) theoretical fluid/sediment mechanics, and (iii) engineering field applications.

The research will be focussed on local sand transport modelling in the coastal zone and is summarized in terms of the following **topics**:

A. Near-bed sediment transport processes

Bed load transport in the sheet flow and rippled bed regimes, for steady and unsteady flow (due to waves): effects of sediment size gradation and sloping beds, prediction of hydraulic roughness of mobile beds (including sand ripple formation).

B. Suspended load processes

Suspended load transport above plane and rippled beds, for steady and unsteady flow (due to waves): formulation of bottom boundary conditions and also sediment mixing coefficient for suspension layer (including convective entrainment, vortex shedding), effects of sediment size gradation, sediment-induced stratification, turbulence damping, hindered settling.

C. Engineering sand transport formulations

Application of sophisticated research models in practical situations, development of practical integrated sand transport models (via parameterization of research model results), intercomparison and validation of practical transport models.

4. METHODOLOGY

The classical distinction between near-bed (bed load) and suspended load transport is used as the starting point for the definition of detailed objectives and tasks. However, this distinction is rather artificial and, in practice, Topics A and B are designed to achieve a complete and consistent description of processes throughout the water column. For example, the results obtained for the near-bed layer in Topic A will be used to determine improved bottom boundary conditions for the suspension layer in Topic B.

Topic A: Near-bed sediment transport processes

The objective of Topic A is to develop soundly-based physical arguments for near-bed sediment transport processes, which allow an extension of our existing knowledge to cases in which: (i) the bed comprises a mixture of grain sizes, (ii) the bed is sloping and, most importantly, (iii) the flow includes an unsteady component (due to waves).

In the first place, the requirement is for modelling systems which provide an accurate description of the vertical profiles of both horizontal velocity and sediment concentration from the stationary grain level to the top of the sheet flow layer, in both steady and unsteady flow conditions. The bed load transport rate can then be obtained from the resulting vertical profile of sediment flux. Finally, by running suitable models over parameter ranges of practical importance, engineering formulations can be developed (see Topic C). To this end, two lines of research will be followed in Topic A: (i) experimental laboratory research to guide the development of new conceptual models and to fill gaps in presently available datasets; and (ii) numerical and analytical modelling of boundary layer interaction processes through the bed load layer.

Topic B: Suspended load processes

The objective of Topic B is to explore physical phenomena in the suspension layer and, using parameterizations of the results obtained in Topic A, to define new, soundly based, bottom boundary conditions for the suspension layer (including near-bed convective effects).

Starting with a sufficiently refined description of the local hydrodynamics, including for example wave-induced currents and wave irregularity, improved models of suspension processes will be developed. These will be verified using results from new laboratory experiments designed to fill gaps in our existing knowledge, and will then be parameterized as part of the practical modelling work in Topic C.

Again, the general requirement is for models which provide an accurate, consistent description of the vertical profiles of both velocity and sediment concentration from the top of the sheet flow layer up into the suspension layer, in both steady and unsteady flow conditions. To this end, the same two lines of research will be followed as in Topic A, namely (i) experimental laboratory research and (ii) numerical and analytical modelling.

Topic C: Engineering sand transport formulations

In Topic C, a common effort will focus on the development and validation of practical, simplified models for bed load and suspended load transport for use in conditions of importance in coastal engineering practice. To a greater or lesser extent, all of the work carried out in Topics A and B will be directed towards this common objective, and all of the partners will make a full contribution to Topic C.

5. DATA MANAGEMENT

An existing database (set up in MAST1/2) will be updated and extended by the addition of new data from the proposed experimental research contributions. The present database contains more than 20 validated laboratory and field datasets and is considered as an important source of information for sediment transport modellers. The database will be updated when new data become available. Updated versions of the database will be send to the modellers regularly during the project. The final version will be available after the project.

Datasets generated within the project will be made available according to the Code on Data management in MastIII Projects.

The data management plan for the sand transport experiments is as follows:

- partners involved in experimental work are responsible for data collection, data analysis, data validation (quality checking), presentation of all data in reports and in data files, completion of data base forms (including an abstract of the experimental conditions) supplied by data management leader,
- the data management leader is responsible for the design and maintenance of a common database (including data base forms), selection of key data from the data report and data files of individual partners, banking of selected data in a common database, publication and distribution of data base results to partners.

6. EXPLOITATION AND DISSIMINATION

The main deliverables of the project, viz. agreed well-validated sediment transport models for classes of marine coastal zone environments and conditions, will be designed to be directly applied by coastal engineers, coastal zone managers, consultants, physical geographers and geologists. An increased understanding of the physics controlling sediment transport process in the coastal zone is important in relation to the application of appropriate sand transport models in the above-mentioned real world problems. In this respect the other main deliverable of SEDMOC, i.e. a reference document on sediment tranport modelling, will be of direct use.

The participation in SEDMOC of the leading European (hydraulics) laboratories in SEDMOC is important. This will ensure a direct coupling between research and consultancy, through the implementation of the results of the project in relevant engineering tools. In addition, potential users are not only part of the SEDMOC group itself, but are also very closely linked with other users in their organizations.

The exploitation strategy will be implemented in an exploitation plan, which will be defined during the early stages of the project, and then maintained, by the exploitation manager, who will be responsible for: WWW Home page, invitations to end-users and researchers from outside project to attend workshops, project description (handout), etc.

There will be an open research policy within SEDMOC. Exchange and dissemination of results will be stimulated and realized through: making relevant data available (data-management), using common test cases for model validation, stimulating the publication of results in (joint) scientific reports and journals, stimulating the presentation and publication of results at international conferences, stimulating transfer of knowledge through the task groups, organizing two workshops per year in order to stimulate the discussion of research progress among the participants, inviting other researchers to the workshops, for example experts in certain research areas, PhD. students (financed by other sources), and external users of the SEDMOC deliverables (drawn from the coastal engineering community), the involvement of the participating institutes in national research networks, which will give rise to further dissemination of knowledge.
The following target/user groups are identified: national and regional coastal and sea authorities, harbour/port authorities, consulting engineering firms (coastal engineers), european hydraulic laboratories, universities: faculties of civil engineering (hydraulic engineering), physical geography, oceanography, geology, consultants within dredging firms, offshore oil industry, contractors.

ACKNOWLEDGEMENTS

The SEDMOC project is funded partly by the European Commission's research programme MAST under Contract Number MAS3-CT97-0115, and partly through national funding from various institutes and organisations.

II.1.2 Structure and dynamics of shelf ecosystems

TITLE: Biogas transfer in estuaries (BIOGEST, http://www.ulg.ac.be/oceanbio/biogest/)
CONTRACT NO: ENV4-CT96-0213

COORDINATOR: Michel FRANKIGNOULLE
Université de Liège
Mécanique des Fluides Géophysiques
Unité d'Océanographie Chimique, Bâtiment B5
B 4000 Sart Tilman, Belgique

PARTNERS:
2- Université Libre de Bruxelles, Roland WOLLAST
Laboratoire d'Océanographie Chimique
Campus de la plaine, CP 208, Boulevard du triomphe
B 1050 Bruxelles, Belgique
3- Nederlands Instituut voor Oecologisch Onderzoek, Jack MIDDELBURG
Centre for Estuarine and Coastal Ecology
Vierstraat 28, NL-4401 EA Yerseke, The Netherlands
4- Centre des faibles radioactivités, Ba Cuong NGUYEN
CE Saclay, Laboratoire de Modélisation du Climat et de l'Environnement
Bâtiment 709, Orme des Mérisiers
F-91191 Gif-sur-Yvette , France
Sub-contractor: University of Crete
5- Plymouth Marine Laboratory, Cliff LAW
Prospect place, West Hoe,
Plymouth PL13DH, United Kingdom
6- Universidade de Aveiro, Armando da Costa DUARTE
Departemento de quimica
PT 3800 Aveiro, Portugal
7- Université de Bordeaux 1, Henri ETCHEBER
Departement de Géologie et Océanographie, URA CNRS 197
Avenue des Facultés
F 33405 Talence Cedex, France
8- Institut fur Biogeochemie und Meereschemie (IfBM), Walter MICHAELIS
Universität Hamburg
Bundesstr. 55, 21046 Hamburg, Federal Republic of Germany.
9- Aalborg Universitet, Niels IVERSEN
Sohngnardsholmsvej 57, DK-Aalborg, Denmark
10- Instituto de Investigaçao das Pescas e do Mar, Graça CABECADAS
Avenida de Brasilia, PT 1400 Lisboa, Portugal
11- Université de Pau et des Pays de l'Adour, Olivier DONARD
Laboratoire de chimie Bio-Inorganique et Environnement,
Ep Cnrs 132, Hélioparc Bâtiment De Vinci
2 Avenue du président Angot, 64000 Pau, France
12- Nederlands Instituut voor Onderzoek der Zee, Wim HELDER
Department of Chemical Oceanography P.O. Box 59
NL 1790 AB Den Burg, Texel, The Netherlands

BIOGAS TRANSFER IN ESTUARIES

Michel Frankignoulle[1], Sizenado Nogueira Abreu[6], Gwenaël Abril[1], David Amouroux[11], Stéphane de Beer[2], Alberto Borges[1], Isabelle Bourge[1], Maria Jose Brogueira[10], Graça Cabeçadas[10], Christine Canon[1], Antonio M. Correia[10], Hein de Wilde[12], Bruno Delille[1], Nikolai Delling[8], Olivier Donnard[11], Armando da Costa Duarte[7], Valdemar I. Esteves[7], Henri Etcheber[6], Anne Flensborg[9], Wim Helder[12], Jens Hefter[8], Hans de Heij[12], Niels Iversen[9], Giorgos Kouvarakis[13], Cliff Law[5], Emmanuelle Lemaire[6], Emile Libert[1], Roger Ling[5], Michèle Lojiens[2], Nikolas Mihalopoulos[13], Walter Michaelis[8], Jack Middelburg[3], Joppe Nieuwenhuize[3], Ba Cong Nguyen[4], Marta Nogueira[10], Christophe Peycheran[11], Jean Sciare[4], Richard Seifert[8], Tristan Sjoberg[5], Chun Mao Tseng[11], Peter Verhostad[8], Ronald Visser[12], Rutger de Wit[6] & Roland Wollast[2].

[1]Université de Liège, [2]Université Libre de Bruxelles, [3]Nederlands Instituut voor Oecologisch Onderzoek, [4]Centre des faibles radioactivités, [5]Plymouth Marine Laboratory, [6]Universidade de Aveiro, [7]Université de Bordeaux 1, [8]Universität Hamburg, [9]Aalborg Universitet, [10]Instituto de Investigaçao das Pescas e do Mar, [11]Université de Pau et des Pays de l'Adour, [12]Nederlands Instituut voor Onderzoek der Zee, [13]University of Crete.

INTRODUCTION

Estuaries are obligate pathways for the transfer of dissolved and particulate material from the continent to the marine system through rivers. They are extremely dynamic systems usually characterized by strong physico-chemical gradients, enhanced biological activity (both heterotrophic and autotrophic) and intense sedimentation and resuspension.
Profound changes are observed in the speciation of organic and inorganic compounds in response to these factors, particularly in the European estuaries of the North Atlantic system which are additionally subject to macro-tidal conditions. The strong tidal regime of these estuaries leads to an increased residence time of the fresh water in the estuarine mixing zone and the generation of a turbidity maximum, often associated with an oxygen-depleted zone within which various anaerobic processes may be stimulated. In addition, European estuaries are are supporting major population centers within their catchment area. As a result they are subject to intense anthropogenic disturbances reflected in elevated loadings of detrital organic matter, nutrients and toxic trace elements. Most of these features increase the potential for biogenic gas production within estuaries.
Intense respiration of detrital organic matter produces large quantities of dissolved CO_2, inducing partial pressures exceeding 1000 ppm in estuarine water and generating very high CO_2 fluxes to the atmosphere. The elevated nutrient loading enhances N_2O production within the estuary, via denitrification in the oxygen deplete zone and nitrification of ammonia when aerobic conditions are restored. The photo-production of CO in surface water is stimulated by terrestrially-derived dissolved organic matter. Anoxic sediments in the region of the turbidity maximum enhance H_2S and CH_4 production and methylation of various metals, with subsequent diffusion to the water column and volatilization. On the other hand, high primary production may occur either by photosynthesis when turbidity allows sufficient light penetration and chemo-autotroph processes, for example by nitrifying bacteria. The eutrophic conditions are also highly favorable for the production of DMS and COS.

OBJECTIVES

In spite of their potential importance in biogas emissions, very little is known about estuaries and their atmospheric coupling. On a global scale, estuaries may act as a significant source of these gases and their importance should be better investigated. The four objectives of this proposal are:

1- to determine the distribution of biogases affecting climate and atmospheric chemistry in surface water of European estuaries.

2- to evaluate the atmospheric biogases fluxes in European estuaries and their impact on the global budget.

3- to understand the major biological processes which are responsible for biogases distribution.

4- to develop a predictive biogeochemical model which can be used to relate biogases emission to organic matter and nutrients loadings.

We have therefore determined the distribution, in estuarine waters, of biogases liable to have major environmental consequences : CO_2, CH_4, CO, Non methane Hydrocarbons, N_2O, NH_3, DMS, COS, volatile halogenated organic compounds and biogenic volatile metals (objective 1).

A conclusive quantification of net estuarine and coastal emissions of greenhouse gases, can only be achieved by accurate measurements with high spatial and temporal coverage. The investigated estuaries are the Elbe, the Ems, the Rhine, the Thames, the Scheldt, the Loire, the Gironde, the Douro and the Sado (figure 1). Among these nine estuaries, three have been selected for intensive seasonal coverage : the Rhine, the Scheldt and the Gironde. These three estuaries are well representative of the diversity of European estuaries, both from the point of view of drainage basin type and importance (including size and water flow). The six other estuaries will be visited to check their general outlines. By the end of the project, we will be able to propose an estimate of gas emissions from major European estuaries (objective 2).

The following parameters and processes related to the biogas distributions are also measured: nutrients, organic and inorganic carbon, oxygen, respiration, primary production, atmospheric and sediment exchanges (objective 3).

Measurements of trace gas emissions and the study of underlying processes should allow us to relate atmospheric fluxes to the carbon and nitrogen loadings. Therefore, the effect of future changes in loadings on the emission of trace gases from estuarine and adjacent coastal areas could be estimated. Thanks to the diversity of the studied estuaries, the conclusions generate by this project could be applied to other similar sites in the world. Moreover, the model that will be developed will provide a decision tool for future environmental policy (objective 4).

WORK PLAN

The ultimate goal of BIOGEST is to understand biogases distribution in European estuaries as a function of both natural processes and human pressure. European coastlines and estuaries

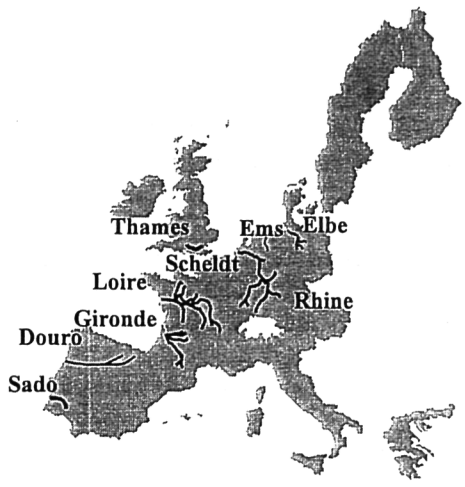


Figure 1: Investigated estuaries within BIOGEST

are characterized by a wide variety of conditions that leads to two major considerations: i) the overall understanding requires a large range of investigations and, ii) the understanding of the system could be extrapolated to other parts of the world.

Because it is not possible on a 3-years project basis to investigate all European estuaries, we have selected nine of them that are well representative of the European diversity: the **Elbe** (DE, North Sea), the **Rhine** (NL, North Sea), the **Ems-Dollard** (NL/DE, North Sea), the **Thames** (UK, North Sea), the Western **Scheldt** (NL/BE, North Sea), The **Loire** (FR, Gulf of Biscay), the **Gironde** (FR, Gulf of Biscay), the **Douro** (PT, Atlantic Ocean) and the **Sado** (PT, Atlantic Ocean). Table 2 summarizes the main features of those estuaries and shows that the choice of the Rhine , the Scheldt and the Gironde as sites for intensive studies is appropriate to investigated estuarine diversity taking into account major estuarine processes. The Rhine is characterized by the highest water flow which induces small residence time of water in the estuarine region (days, near Rotterdam). On the opposite, the Scheldt is characterized by a relatively small water flow and associated long residence time of water (2-3 months, near Antwerpen). As a result, the Rhine is well-oxygenated and N-species are dominated by nitrate, while the Scheldt displays anoxic conditions and N-species in river water are dominated by ammonium. The Gironde is characterized by a different geological drainage basin and exhibits an intermediate behaviour. The six other selected estuaries offer an interesting range of conditions, from both natural and human pressure points of view.

The project is divided into four parts, including three work packages (see also figure 2):

- *1. Intercalibration.* Throughout the project, some parameters and processes are regularly measured by different partners in different areas. will be achieved using certified standards so that the results obtained will be directly comparable with measurements in other part of the world and will contribute directly to the global databases.

Table 1: BIOGEST parameters & processes (repartition of tasks)			
Biogases	**Partners**	**Parameters**	**Partners**
CO_2	1-2-10	S, t°, SPM, O_2	1-2-3-10-12
CH_4	3-8-9-12	DIC/PIC	1-2-3-10
CO	5	DOC/POC	2-3-7-8-10
Non CH_4 hydrocarbons	8	NO_3, NO_2, NH_4 PO_4, SiO_2,	2-3-6-10-12
N_2O	3-9-12	Chlorophyll, Phaeopigment	1-2-7-10
NH_3	2-6	$\delta^{13}C$ & $\delta^{15}N$	3
S-gases	4		
Volat. Halog. Org.	8		
Volat. Metals	11		
Processes			
Respiration	1-2-7		
Primary production	2-7		
Atmospheric fluxes	1-3-4-5-8-9-11-12		
Fluxes from sediments	9-12		
CH_4 oxidation	9-12		

- *2. Workpackage 1: Intensive studies.* Processes (respiration and primary production) and conditions (e.g. organic carbon and nutrients loadings) responsible for biogases production and fate display strong seasonal variations. In order to assess this seasonal pattern, three estuaries have been selected and will be sites of at least one cruise per season. This workpackage is needed to obtain a comprehensive understanding of the processes influencing biogases in estuaries and the seasonal variation of their fluxes to the atmosphere.

Table 2 : BIOGEST selected estuaries and their main features									
	Intensive studies			**Short studies**					
	Rhine	**Scheldt**	**Gironde**	**Elbe**	**Ems**	**Thames**	**Loire**	**Douro**	**Sado**
Area	**224**	**22**	**85**	**146**	**12.7**	**15**	**121**	**98**	**7.6**
Disch.	**69.4**	**3.8**	**21.4**	**23.7**	**2.5**	**2.1**	**27**	**20.5**	**0.3-1.3**
Tide	**2-3**	**2-5**	**3-5**	**2-4**	**2-3**	**3-5**	**3-6**	**1-3**	**1-3.5**

Area in 10^3 km^2, discharge in $km^3.year^{-1}$, tidal range in m.

- *3. Workpackage 2: Short studies.* To be able to propose a budget for biogases emission valid for Europe, but also to take into account estuarine diversity, six other estuaries will be visited during single cruises. This workpackage is needed to give to the project and related results broad dimension.

- *4. Workpackage 3: Modelling.* Results obtained from workpackages 1 and 2 will be used to develop a coupled hydrodynamical/biogeochemical model which will allow to predict estuarine response to changes in human pressure on those environments. This workpackage is also needed to extrapolate conclusions yielded by workpackages 1 and 2 to other estuaries. Workpackage 3 will serve as a decision tool for future environmental policy.

RESULTS

The total number of cruises to be carried out within the project is 19 (12 for intensive studies, 6 for the others, and an extra-cruise on the Thames thanks to a ship opportunity). Since the beginning of the project (May 1996), 14 cruises have already been achieved. These field experiments are basically divided into two types of sampling:

- discrete sampling at typically 15 stations through the salinity gradient (from salinity 0 to ~30, by step of 2.5). Table 3 shows that 238 stations have been sampled so far. All the parameters and most of the processes are measured at these stations.

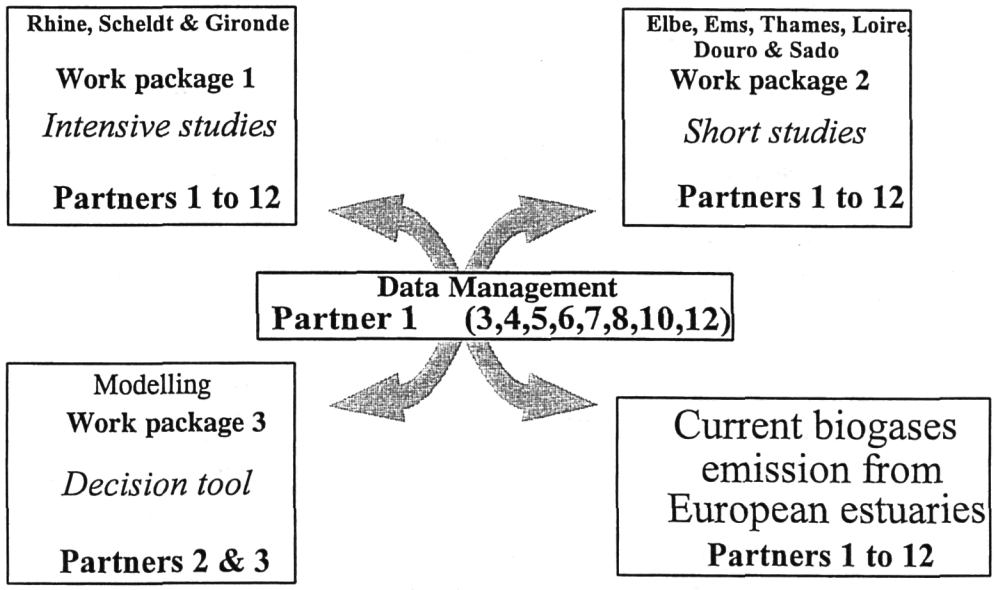


Figure 2: BIOGEST workpackages and partners involvement overview.

- underway sampling during all the cruises for biogases which can be determined using the equilibrator technique, as well as basic parameters (salinity, temperature, oxygen). More than 550 hours of underway measurements in the 14 visited estuaries have been carried out so far.

Table 3: BIOGEST cruises carried out so far (2/98) with number of discrete sampling stations (n) and partners participation

Cruises	Dates	n	1	2	3	4	5	6	7	8	9	10	11	12
Elbe	Apr 97	21	X	X	X	X			X	X				
Ems	Jul 97	13	X	X	X	X			X	X	X			X
Rhine 1	Oct 97	21	X	X	X				X				X	X
Rhine 2	Jul 97	14	X	X	X	X	X		X	X	X		X	X
Rhine 3	Nov 97	17	X	X	X		X		X	X			X	X
Scheldt 1	Jul 96	17	X	X	X	X	X	X	X	X	X	X	X	X
Scheldt 2	Dec 96	18	X	X		X	X	X	X	X	X		X	X
Thames	Sep96	20	X	X				X						
Gironde 1	Oct 96	19	X	X	X			X	X		X	X	X	
Gironde 2	Jun 97	15	X	X	X	X	X	X	X	X	X	X	X	X
Gironde 3	Sep 97	18	X			X			X	X	X		X	X
Gironde 4	Feb 98	17	X		X		X		X		X	X	X	
Douro	Sep 97	13	X	X	X		X	X				X		X
Sado	Sep 97	15	X	X	X		X	X			X	X		X
14		238	14	12	11	7	8	7	11	8	9	6	9	10

As shown in table 3, most of the work performed during the two first years of the project consists in field data acquisition. Our results indicate that the studied biogases are often highly over-saturated with respect to the atmosphere in all estuaries, with a frequent maximum at low salinity. Estuaries are thus a potential important sources of biogases. The distribution of biogases often depends on parameters and intricate processes evaluated during the cruises. It is thus of prime importance to allow efficient exchange of data between partners. An Internet web page has been developed at the early beginning of the project (http://www.ulg.ac.be/oceanbio/biogest/) where general informations are provided, as well as restricted access to BIOGEST database.

FINAL CONCLUSIONS

Scientific, economic and social impacts from BIOGEST are basically linked to the project objectives. Biogases emission from estuaries will be correlated to the human induced loadings of organic matter and nutrients, which are responsible for processes generating gases. The predictive model that will be developed from field data can be considered as a decision tool which could be used for a better environmental management. As an example, most estuaries are characterized by an important sewage load which is responsible for severe environmental changes. Eutrophication is also a drastic problem in adjacent coastal areas. The proposed model could be used to predict future environmental benefits from an improved regulation of nutrients and sewage loading. This project as a whole will aid to get a better understanding of environmental consequences of human activity on estuaries and its major achievements will be of use to evaluate other similar sites in the world (figure3).

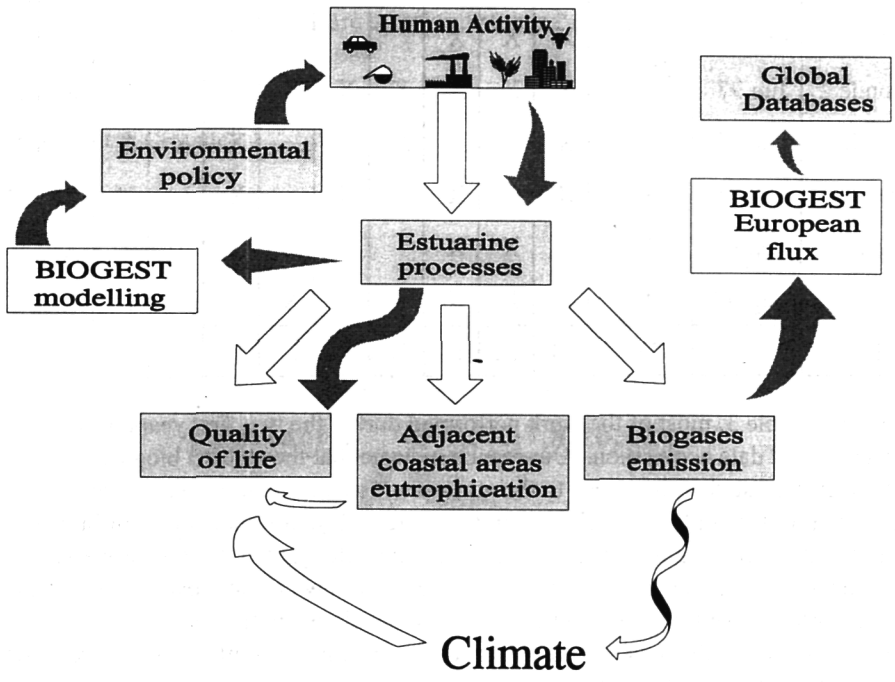


Figure 3: Human activity impact in estuarine environment and BIOGEST related topics (grey arrows).

BIOGEST PUBLICATIONS

Papers

- J. J. Middelburg and J. Nieuwenhuize. Carbon and nitrogen stable isotopes in suspended matter and sediments from the Schelde Estuary. In press in Marine Chemistry.
ELOISE Contribution n°025
- C. Pecheyran, D.Amouroux, O.F.X. Donard. 1998. Field determination of volatile selenium species at ultra trace levels in environmental waters by on-line purging, cryofocussing and detection by atomic fluorescence spectroscopy. In press in Journal of Analytical Atomic Spectrometry.
ELOISE Contribution n°026
- L. Cabecadas, M.J. Brogueira and G. Cabecadas. 1996. Phytoplankton around Cape Espichel (Portugal). Sartgerme (Turkey), Proceedings of the International Workshop on MED & BlackSea ICZM, 2-5 November 1996.
- C. Pecheyran, C.R.Quetel, F.M. Martin Lecuyer, O.F.X.Donard. Simultaneous determination of volatile metal (Pb, Hg, Sn, In, Ga) and non-metal species (Se, P, As) in different atmospheres by cryofocusing and detection by ICP/MS. Submitted.
- C.M.Tseng, A. De Diego, H. Pinaly, D.Amouroux, O.F.X.Donard. Automatic derivatization, cryofocusing and gas chromatography coupled to atomic absorption detection for rapid on-line mercury species determination in environmental samples. Submitted.
- D.Amouroux, E.Tessier, C. Pécheyran, O.F.X.Donard. Sampling and probing volatile metal(loid) species in natural waters after in-situ purge and cryogenic trapping followed by ICP/MS determination. Submitted.
- M. Frankignoulle and R. Biondo. A new design of carbon dioxide equilibrator with a fast response time. Submitted.
- A. Borges and M. Frankignoulle. Meso- and macro scale variations of the partial pressure of CO_2 in surface seawater along the Belgian and Dutch coasts. Submitted.
- J.-P. Gattuso, M. Frankignoulle and R. Wollast. Carbon and carbonate metabolism in coastal aquatic ecosystems. Submitted.

Oral presentations

- M. Frankignoulle. 1997. Biogas transfer in estuaries (BIOGEST). European Geophysical Society, XII General assembly, Vienna, Austria, 21-25 April 1997.
- R. Wollast, M. Loijens, M. Frankignoulle and C. Canon. 1997. Influence of enhanced biological activity on air-water CO_2 exchange in the Scheldt estuary. European Geophysical Society, XII General assembly, Vienna, Austria, 21-25 April 1997.
- G. Abril, P. Buat-Menard, J. Castel, H. Etcheber, J.C. Relexans and M. Frankignoulle. 1997. The Gironde estuary : a major heterotrophic system. European Geophysical Society, XII General assembly, Vienna, Austria, 21-25 April 1997.
- M. Frankignoulle. D. Amouroux, G. Cabeçadas, H. de Wilde, O. Donnard, A. C. Duarte, H. Etcheber, W. Helder, N. Iversen, C. Law, M. Lojiens, W. Michaelis, J. Middelburg, B.C. Nguyen, R. Seifert & R. Wollast. 1997. Biogas transfer in estuaries. Greenhouse gases and impacts on the Climate System : The status of research in Europe, Orvieto, Italy, 10-13 November 1997.
- M. Frankignoulle. D. Amouroux, G. Cabeçadas, H. de Wilde, O. Donnard, A. C. Duarte, H. Etcheber, W. Helder, N. Iversen, C. Law, M. Lojiens, W. Michaelis, J. Middelburg, B.C. Nguyen, R. Seifert & R. Wollast. 1997. Biogas transfer in estuaries. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.

- Regnier, P. and R. Wollast. 1997. A reaction-transport model of carbon and nitrogen species in the scheldt estuary. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- P. Herman, C. Heip, F. Meysman, J. Middelburg, K. Soetaert and J. Wijsman. 1997. Approaches To coupling of benthic and pelagic coastal ecosystems models. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- D. Amouroux, C. Pécheyran, H. Pinaly, O.F.X. Donard and G. Abril. 1997. Occurrence of natural and anthropogenic volatile metal and metalloid compounds in estuarine environments. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- H.P.J. de Wilde and W. Helder. 1997. Methane and nitrous oxide in estuaries. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- D. Amouroux, C. Pécheyran, H.Pinaly, O.F.X.Donard. 1997. Occurrence of natural and anthropogenic volatile metal and metalloid compounds in estuarine environments. Rimouski (Canada), 5th International Symposium on Model Estuaries, 21-23 May 1997.
- A.DeDiego, C.M.Tseng, D.Amouroux, O.F.X.Donard. 1997. Cryogenic techniques for speciation analysis. Nice (France), 5th Dauville Conference on Analytical Sciences, June 1997.
- D. Amouroux, O.F.X. Donard. 1997. Sampling and probing volatile metal(loid) species in coastal and marine environment : Air-sea gaseous exchanges. Brest (France), Workshop on marine analytical chemistry for monitoring and oceanographic research, 17-19 November 1997.
- D. Amouroux, E. Tessier, O.F.X. Donard. 1998. Volatile organotin compounds in coastal waters related to methylation pathways in contaminated aquatic sediments. Zurich (Switzerland), Workshop on organotin compounds in the environment, 29-30 January 1998.

Poster presentations.

- M. Frankignoulle, I. Bourge & C. Canon. 1997. Air-sea co_2 fluxes in european estuaries. Greenhouse gases and impacts on the Climate System : The status of research in Europe, Orvieto, Italy, 10-13 November 1997.
- C. Canon and M. Frankignoulle. 1997. Heterotrophic bacterial activity in european estuaries. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- J. J. Middelburg and J. Nieuwenhuize. 1997. Carbon and nitrogen stable isotopes in suspended matter from three major European Estuaries. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- J. Sciare, B.C. Nguyen and N. Mihalopoulos. 1997. Biogenic sulfur compounds emissions from european estuaries. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- C. Law and T. Sjoberg. 1997. Carbon monoxide in the Scheldt estuary. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- E. Lemaire, G. Abril, R. De Wit and H. Etcheber. 1997. Pigments and carotenoïds in surface waters from European estuaries. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- S. N. Abreu and A.C. Duarte. 1997. Nutrient gradients as function of salinity observed at Schelde in summer and winter conditions. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.

- R. Seifert and W. Michaelis. 1997. Dissolved organic carbon and light hydrocarbons in the Scheldt Estuary: First results. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- N. Iversen. 1997. Methane concentration, methane oxidation and methane emission measured in the Scheldt and the Gironde estuaries. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- G. Cabeçadas and M. J. Brogueira. 1997. Environmental conditions in two european estuaries: the northern Scheldt and the southern Sado. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- C.M. Tseng, A. De Diego, D. Amouroux, O.F.X. Donard and H. Etcheber. 1997. Critical accuracy evaluation of methyl-mercury from aquatic sediments by microwave assisted acid leaching : influence of the geochemical composition. First Annual Scientific ELOISE Conference, 21-23 May 1997, Arcachon, France.
- C.Pécheyran, D.Amouroux, B.Lalère, O.F.X.Donard. 1997. Determination of volatile metal species in the atmosphere and natural waters by cryogenic trapping - gas chromatography and Ar/He/O2 mixed plasma ICP/MS. Gent (Belgique), 1997 European Winter Conference on Plasma Spectrochemistry, 12-17 January 1997.
- C.M. Tseng, A. De Diego, D. Amouroux, O.F.X. Donard. 1997. Critical accuracy evaluation of methyl-mercury from aquatic sediments by microwave assisted acid leaching : influence of the geochemical composition. Rimouski (Canada), 5th International Symposium on Model Estuaries, 21-23 May 1997.
- D. Amouroux, C. Pécheyran, C.M. Tseng, H. Pinaly, O.F.X. Donard. 1997. Occurrence of natural and anthropogenic volatile metal and metalloid compounds (Hg, Pb, Se, Sn) in estuarine environments. Berkeley (USA), 4th International Conference on the Biogeochemistry of Trace Elements, 25-29 June 1997.
- C.M. Tseng, D. Amouroux, O.F.X. Donard. 1997. New extraction techniques for mercury speciation in estuarine environments. Workshop on marine analytical chemistry for monitoring and oceanographic research, 17-19 November 1997.

TITLE: ENVIRONMENTAL CYCLING OF SELECTED PERSISTENT ORGANIC POLLUTANTS (POPs) IN THE BALTIC REGION

CONTRACT NO: ENV4-CT96-0214

COORDINATOR: Jozef M. Pacyna
Norwegian Institute for Air Research
P.O. Box 100
2007 Kjeller, Norway

PARTNERS: Swedish Environmental Research Institute (IVL),
P.O.Box 47086, S-40258 GÖTEBORG, SWEDEN.

National Environmental Research Institute (NERI),
P.O.Box 358, DK-4000 ROSKILDE, DENMARK

University of Jyväskylä (UJ), P.O.Box 35,
FI-40351 JYVÄSKYLÄ, FINLAND

Daimler-Benz Aerospace - Dornier (DOR),
D-88039 FRIEDRICHSHAFEN, GERMANY

Institute for Ecology of Industrial Areas (IEIA),
6. Kossutha Str., PL-40832 KATOWICE, POLAND

Universita´ Degli Studi di Milano (UNIMI)
via Ravasi 2, I-21100 VARESE VA, ITALY

Stockholm University (SU), Department of Zoology,
S-10691 STOCKHOLM, SWEDEN

Technical University of Gdansk (TUG), Department of Chemistry, 11/12 Narutowicza Street,
PL-80-952 GDANSK, POLAND

ENVIRONMENTAL CYCLING OF SELECTED PERSISTENT ORGANIC POLLUTANTS (POPs) IN THE BALTIC REGION

JOZEF M. PACYNA[1], KNUT BREIVIK[1], ELISABETH G. PACYNA[1], FRANK WANIA[1], EVA BRORSTRÖM-LUNDEN[2], ERIK RUNGE[3], JAAKKO PAASIVIRTA[4], SEIJA SINKKONEN[4], JÖRG MÜNCH, JANINA FUDALA[6], DAVIDE CALAMARI[7], ANTONIO DI GUARDO[7], DAG BROMAN[8], JACEK NAMIESNIK[9]

[1]Norwegian Institute for Air Research, Kjeller, Norway; [2]Swedish Environmental Research Institute, Göteborg, Sweden; [3]National Environmental Research Institute, Roskilde, Denmark; [4]University of Jyväskylä, Jyväskylä, Finland; [5]Daimler-Benz Aerospace - Dornier, Friedrichshafen, Germany; [6]Institute for Ecology of Industrial Areas, Katowice, Poland; [7]Universita` Degli Studi di Milano, Varese Va, Italy; [8]Stockholm University, Stockholm, Sweden; [9]Technical University of Gdansk, Gdansk, Poland.

1. INTRODUCTION

During the last decade several studies have been carried out aiming at the improvement of our knowledge on the behavior of persistent organic pollutants (POPs) in the environment. Evidence has been found that many of these compounds create serious problems due to their toxicity, persistence, and bio-accumulation in various environmental compartments (e.g. Pacyna et al., 1993).

Major emphasis in the studies carried out so far has been placed on the following subjects:

- identification and quantification of POPs in environmental samples,
- emissions sources of POPs,
- major pathways of POPs through the environmental compartments,
- environmental and health effects and the degree of public health concern associated with POPs, and
- technical and other measures to reduce the levels of POPs in the environment.

Recently the results of the above mentioned studies have been reviewed in connection with the UN Economic Commission for Europe (ECE) Task Force on Persistent Organic Pollutants. It was pointed out that the most of POPs are anthropogenic in origin, some are widely used, and then released to the environment in large quantities. They have long environmental half-lives, resulting in continued increases in the global storage of POPs in the environment. Being often semi-volatile, POPs can be transported through ecosystems and travel distances on a local to global scale with the

atmosphere as a primary transport medium. Water streams are also considered as important transport medium for some POPs. For many POPs there is a systematic migration to cooler latitudes. Finally, a number of bioaccumulative POPs produce a broad range of immunilogical, reproductive, developmental, behavioral, and carcinogenic effects. Similar conclusions have been reached in North America from studies in the Great Waters region, e.g. the studies carried out for the U.S. Congress.

Although some initial work has been done in order to understand the fate, behavior, and effects of POPs, much less information is available on environmental cycling (migration) of these compounds through various environmental media. The major reason for this deficiency in our knowledge is related to a lack of detailed information on emissions of POPs and the parameters affecting their migration through the environment under various meteorological, chemical and physical conditions.

Recently a feasibility study has been carried out with support from the Nordic Council of Ministers (NMR) to review information on cycling of POPs in the regional environment. The main goal of this study was to review information on levels of POPs in various compartments of the environment, describe tools which can be used to simulate POP cycling on regional and global scale, and assess the environmental effects of POPs. Major conclusion of the project was that although very incomplete, the information on emissions and concentration levels available in the Nordic countries can be used in a simple multicompartment mass balance models to quantitatively describe and possibly predict the regional fate of selected POPs in the Nordic countries. It was also concluded that further improvement of our knowledge on the POP cycling is possible and a set of recommendations was defined in this connection. These recommendations called for obtaining more accurate and complete information on environmental inputs of POPs, broader and more complete basis of environmental data of the POP concentration levels in various compartments, and further improvement of models describing the migration of POPs through the environment.

2. OBJECTIVES

The overall goal of the *"POPCYCLING-BALTIC"* project is to develop a comprehensive, multicompartmental model to study the fate and behavior of POPs in the Baltic Sea environment.

The following POPs have been selected:

- hexachlorocyclohexanes (HCHs),
- selected polychlorinated biphenyls (PCBs),
- hexachlorobenzene (HCB),
- dichloro-diphenyl-dichloroethane (DDE),
- benzo(a)pyrene (B(a)P), and
- selected dibenzodioxins and dibenzofurans.

Specific objectives of the project are to:

- develop, evaluate, and use a non-steady state multimedia mass balance model that describes the fate of selected POPs in the Baltic Sea environment, in order to:

  --examine physical, chemical, and biological processes resulting in the migration of POPs through the individual environmental compartments,
  --describe meteorological, chemical, physical, anf biological parameters affecting the mobility of POPs in the environment,
  --assess the relative importance and absolute magnitude of various chemical inputs to the Baltic Sea, namely autochthonous sources vs. advective import, atmospheric vs. riverine sources, and old vs. new sources (i.e. environmental reservoirs vs. current emissions),
  --describe and possibly explain observed spatial patterns and temporal trends in the fluxes, concentrations, and relative compositions of various POPs within the Baltic Sea environment,
  --evaluate the relative importance of degradation, sediment burial, export in the atmosphere and outflow to the North Sea as loss mechanisms of POPs from the Baltic Sea,

- review information on present emissions and fluxes of the studied POPs to air, soil and water in the Baltic region and assess the emission input from surrounding regions within and outside Europe,

- assess historical emissions within and outside the study region for the last 2 decades,

- develop an emission data base for modeling purposes,

- complete and update existing data base of levels of POPs in the countries around the Baltic Sea and use these data for verification of model results, and

- prepare a set of recommendations with respect to the exposure and risk assessment for POPs in the Baltic Sea region.

3. WORKPLAN

The project is being carried out within three working groups concentrating on:

- emissions,
- compartmental modeling, and
- environmental data base.

3.1. Emission working group

The overall task of the emission working group (Task No. 1 of the project) is the elaboration of present and past emissions of POPs to the environment.

In order to obtain this task the emission working group has collected information on releases of the studied compounds to air, water, and soils. In the case of missing

information, an estimate of emissions is being performed on the basis of emission factors and production/consumption statistics. Information on present and past emission emissions are sought.

The collection of information on sources of POPs is carried out through interactions with national authorities in countries within the study region, in other European countries, and international programs studying regional emissions of POPs and their long-range transport. These programs include:

- the INPUT program within the Oslo and Paris (OSPAR) Convention, studying transport of various pollutants to the North Sea, and
- the European Soil and Sea Quality due to Atmospheric Deposition (ESQUAD) program in the Netherlands.

Information on emissions/releases and emission factors/emission rates for studied POPs has been sought from the following international organizations:

- the UN ECE Task Force on Emission Inventories,
- the World Agrochemical Data Bank,
- the International Register for Potentially Toxic Chemicals of the UN Environmental Program (IRPTC/UNEP), and
- the Food and Agriculture Organization (FAO).

An emission data base has been established on the basis of collected information and emission estimates within the project. The data base are structured along the major source categories agreed between the European Union program CORINAR and EMEP. The data base comprises information on sources (type and location), amount of activity, and amount of emitted POPs to the environment.

GIS will be used to store the information on location and magnitude of POP discharges in the Baltic Sea region and to obtain information on spatial distribution of POP releases in the study region.

3.2. Model working group

The overall task of the model working group of the project (Task No.2) is the development, application, and verification of migration model.

The information on emissions/releases of POPs, available from the emission working group of the project, is being applied in a non-steady-state multi-compartmental mass balance model based on the fugacity approach. Differences between urban and industrial centres and remote areas within one region are modeled by "nesting" small near-source compartments within the overall compartments representing a region. Among the processes included are interbasin mixing, wet and dry deposition, diffusive exchange across the air-water and air-soil interphase, diffusive and particle-mediated sediment-water exchange, vertical exchange in Baltic Proper, and POP degradation processes. Fish concentrations will be estimated by using the calculated water and sediment concentrations as input to existing fish uptake and food chain models.

Four major aspects related to the POPs fate are studied with the help of the model:

- seasonal cycling of POPs,
- environmental gradients of POPs,
- sea-air interactions, and
- long-term changes of POPs.

The following activities have been carried out:

- segmentation and parameterisation of the modeled environment,
- description and formalisation of the processes included in the model,
- formulation of the mathematical core of the model (differential mass balance equations) and derivation of the numerical and algebraic solutions,
- writing of the computer program (source code writing, debugging, designing user-friendly interface, etc,),
- selection of physico-chemical property data and estimation of environmental degradation half-lives as inputs for the model,
- writing the model documentation (help manual, description of model structure and use),
- performing the model simulations, and
- evaluation and comparison of model results with observed chemical fate.

GIS is being applied to the data on the environmental parameters which influence the fate of POPs, such as climatological parameters (temperatures, precipitation, sea ice cover, etc), water characteristics (e.g. concentration of suspended solids, primary productivity), and soil and sediment properties (mean depth, organic carbon content). These data will be used to obtain realistic environmental input values for the model calculations.

GIS is also being used to present the simulated model results, e.g. concentrations, fluxes, etc.

The final version of the model will be written in a manner that it could be used by non-experts on a Personal Computer (PC).

The model results will be verified through the comparison with measurement data available from the environmental data base of the project.

3.3. Environmental data base working group.

The development of environmental data base is the major task of this working group (Task No. 3 of the project). The environmental data base has a simple organization of the data allowing for the listing, sorting, and searching of data according to time, geographical area, sample matrix, and type of a compound. The development of a complex and sophisticated hierarchical structure is not planned.

The data base contains information on:

- congener and/or isomer specific concentrations of POPs,

- sample matrix,
- site,
- date,
- descriptors about data quality,
- information on detection limits, and missing data, and
- origin and reference of the cited data.

The final task of the project (Task No.4) is elaboration of the project recommendations with focus on exposure and risk assessment for POPs in the Baltic Sea region.

GIS will be used to tie together the results of the work on emissions/releases of POPs (Task 1), multimedia model (Task 2) and environmental data base (Task 3). This combined information will be used to elaborate a set of recommendations which will concentrate on the exposure and risk assessment for POPs in the Baltic Sea area. Through GIS the collected information will be displayed in an intuitive and easily comprehensible manner.

4. RESULTS

The project is scheduled for 3 years starting in June 1996. The following results have been obtained within various Working Groups during the first year of the project.

Working Group on Emissions:

1. Preparation of an emission factor guidebook for POPs studied within the project.
2. Elaboration of various sets of POP emission data for the reference years at the beginning of the 1980´s (mostly 1982) and at the beginning of the 1990´s.
3. Preparation of a spatial distribution of emission data for 1980´s within the EMEP grid system of 150 km by 150 km.

Working Group on Modeling:

1. Development of an integrated methodological approach to account for spatial variability in the context of compartmental chemical fate models.
2. Compartmentalisation of the Baltic Sea environment within the POPCYCLING model, i.e. definition of a system boundary, system components, and the spatial sub-division of the system components.
3. Description and formulation of contaminant fate processes in the POPCYCLING model.

Working group on Environmental Data Base:

1. Preparation of the environmental data base structure including the following matrixes: air, atmospheric deposition, marine environment (water, sediment fluxes, surface sediment), biota (mussels, code, herring), terrestrial environment (vegetation, soil), and rivers and lakes.
2. Preparation of the preliminary data set within the above mentioned structure.

3. Elaboration of quality assurance / quality control procedures for the data collected within the project.

5. FINAL CONCLUSIONS

Final conclusions will be prepared during the final year of the project performance.

TITLE: INTEGRATED MANAGEMENT METHODS: MONITORING ENVIRONMENTAL CHANGE IN COASTAL DUNE ECOSYSTEMS

CONTRACT NO: ENV4-CT960215

CO-ORDINATOR: ALLAN WILLIAMS Dr. Prof., Faculty of Applied Science, Bath Spa University College, Newton Park, Bath, BA2 9BN, United Kingdom. Fax: +44 1225 875 776, Tel: +44 1225 875 452, E-mail: A.T.Williams@bathspa.ac.uk

PARTNERS:

J.M. Alveirinho-Dias, Dr. Prof., Unidade de Ciencias e Tecnologias dos Recursos Aquaticos, Universidade do Algarve, 8000 Faro, Portugal. Fax: +351 89818353, Tel: +351 936404737, E-mail: jdias@si.ualg.pt

A.R. Pereira, Dr. Prof., Centro de Estudos Geograficos, Universidade de Lisboa, Portugal

F. Garcia-Novo, Dr.Prof. departmento de Biologia Vegetal y Ecologia, Universidad de Sevilla, Auda Reina Mercedes S/N Apartado 1095, Sevilla, 4180, Andalucia, Spain. Fax: +34 54626308, Tel: +34 54557060.

B. Hallegouet, Dr. Faculte des Lettres Victor Segalen, Universite de Bretagne Occidentale, Departement de Geographie, 20 Rue Duquesne, BP 814, 29285 Brest Cedex, France. Fax: +33 298016390, Tel: +33 298016877

C. Meur-Ferec, Dr., departement de Geographie, Universite du Littoral, Departement de Geographie, 2 chaussee des Darses, 59140, Dunkerque, France. Fax +33 28661569, Tel: +33 28237480, E-mail: meur@univ-littoral.Fr

M. Bonazountas, Dr. National Technical University of Athens, Greece, E-mail: bonazoun@central.ntua.gr

INTEGRATED MANAGEMENT METHODS : MONITORING ENVIRONMENTAL CHANGE IN COASTAL DUNE ECOSYSTEMS

A. T. Williams

Faculty of Applied Science, Bath Spa University College, Newton Park, Bath, BA2 9BN, United Kingdom. Fax +44 1225 875 776, Tel: +44 1225 875 452, E-mail: A.T.Williams@bathspa.ac.uk

SUMMARY

Current practice to date in dune management does not often embrace the potential advances that present day academic thought has produced *i.e.* there is a strong lag effect between the state-of-the-art knowledge and its implementation on the ground. The checklist system employed in this project is a new functional tool which will enable managers, on a European scale, to quantify and assess their systems both spatially and temporally so that any adverse trend can be observed in its infancy and appropriate measures taken. A European assessment of dune vulnerability will enable managers and researchers alike to access information on a continental scale. The checklist was originally designed for use in northern European dunes and requires amendments to make it universally applicable in the European context. Furthermore, since the ecological diversity of a sand dune system is a fundamental facet of overall dune health it is important that it should be an integral part of the dune checklist. To this end a series of vegetation surveys have been carried out to establish the links between ecological diversity, dune vulnerability and human interference. Although the checklist is simple to use and offers considerable savings in time and effort over less organised methods, especially when applied to a limited area or a small number of sites, it is field-based and therefore very time consuming for monitoring dune vulnerability at the regional or national scale. In contrast, aerial survey using small format digital cameras is a relatively inexpensive way of surveying long tracts of coastline in a short time. Many of the features laboriously recorded in the field-based checklist can be identified from digital images and current work suggests that over 70 % of the features identified on the check list can be correctly identified from digital images. The final deliverable of this project will be a sand dune GIS which will provide the end user with a decision support tool capable of addressing transboundary issues related to information and data dissemination.

1. INTRODUCTION

Sand dunes are an important natural phenomenon which provide a cost effective, ecologically sound means of natural front rank protection to shore lines. They play an important role in regulating coastal ground water (Louisse & Van der Meulen, 1991), and they provide a habitat for a rich community of highly specialised plant and animal species (Carter, 1991). Sand dune systems are particularly vulnerable to anthropogenic erosion and many of the dune systems in Europe are under threat from a wide variety of different pressures, such as, urbanisation, agriculture, leisure facilities e.g. golf courses and holiday developments. The major impact is thought to be as a result of recreational use of dunes which destroys the vegetation, exposing

the sand to aeolian and marine attack causing the loss of large areas of the dune system (Doody, 1982) but other types of anthropogenic forcings have also been shown to have a very significant impact on dunes vis-à-vis the two examples which follow. (1) The dune massif backing the cove of Croc Frehel, western Brittany, France, was stable with marram grass (*Ammophila arenaria*) covering the seaward zone and pine trees inland. Rapid degeneration followed the development of small scale camping on the dunes and foredune breaches grew into large scale blowouts which advanced inland (Bodere, *et. al.*, 1994). (2) In a study of the dune coasts of Brittany, Meur (1989) revealed that 450 000m3 of recorded sand extraction occurred from the dune system at Tronoen, western Brittany, between WW2 and 1978,(unlicensed removal may have increased this figure to 2 million m^3) reducing the system to a fragile vulnerable condition with only a narrow foredune remaining which is breached at frequent intervals allowing saltwater invasion of the relict sand quarries inland. Similar examples can be found throughout the dune coasts of Europe and in 1992, English Nature reported conclusively that more than half of the sand dunes in the UK were moving landward and that most of the remainder were stationary rather than growing seaward.

Public pressure on coastal zones around the world has increased dramatically in the last 50 years with an estimated 40% of the population of the earth now living at or near the coast (Carter, 1988) and in some regions which have experienced an explosion of international tourism the problem is particularly acute, for example, with an estimated 147 million international visitors per annum, the Mediterranean plays host to some 33% of the world's tourism industry (Mediterranee Economique CEFI, 1993). Even though tourism has an enormous economic potential, it influences the environment profoundly, and uncontrolled visitor pressure is considered to be the main factor effecting change at coastal sand dune sites. The steady impingement on dune coasts may endanger recreational development and ultimately may put the very survival of tourism at risk. It is now almost universally recognised that there is a real need to determine the way ecosystems function and how they can support and tolerate human use so that sustainable management can be approached. This has led Walker (1990) to suggest that with respect to the coastal zone, policy makers and managers require holistic techniques of data collection and analyses to enable them to cope with the large and growing population pressure at the coast. This is particularly relevant to coastal sand dunes since it is now recognised that such systems are especially vulnerable to anthropogenic erosion and many are in a critical phase for survival.

Whilst studies of numerous dune sites have clearly documented the features, processes and stages of dune degradation (Arens, 1996, Nordstrom *et al*, 1990, Louisse & Van der Meulen, 1991), the regional extent and rates of such environmental change are less well known. Up until the 1980's the basic concept applied to dune processes was that of a steady state equilibrium system. It is only in the past 15 years that analysis of dune ecosystems has concentrated upon the idea of non equilibrium systems. Research has concentrated on distinctly separate aspects of the physical sciences e.g. geomorphology, biology, ecology and hydrology and a large proportion of the literature in this field has been concerned with microprocess studies. Little attempt has been made either to integrate disciplines or to analyse quantitatively the holistic nature and time evolution of the whole dune system. Sherman and Bauer (1993, p414) have argued that 'it remains a daunting prospect to develop the appropriately parameterized process based numerical model' of the beach dune interaction. Even where some predictive morpho-dynamic models of the beach-dune erosion system exists, management of the latter remains an increasingly difficult task.

Checklists are common to many disciplines giving a structured approach to data collection and analysis. Repeated application of such a procedure with its continual analysis and refinement of data can be easily incorporated into an iterative model of problem solving which involves successive phases of conceptual thinking, field testing, evaluation and modification to achieve a final verified approach. In the context of dune management the approach must encapsulate perspectives from a variety of different disciplines include geography, geology, geomorphology, ecology and conservation so that planning and management of human activities at the coast may be integrated with the natural processes at work there (Carter, 1988; English Nature, 1992). Appraisal of dune environment parameters is vital for strategy formulation and given the complexity of coastal dunes it is self evident that managers should consider as many parameters as possible. Moreover, management practices aimed at dune restoration are relatively well understood, but management intervention to prevent or control dune degradation is often haphazard, under funded, sometimes too late and often expensive. In response to these deficiencies, a checklist has been developed which incorporates both objective and subjective judgments which allows management strategies to reflect harmony between qualitative and quantitative variables. The checklist is a structured and systematic procedure which summarises the present condition of a coastal dune through assessment of five major categories, these are; site and dune morphology, condition of the beach, surface character of the seaward 200m, pressure of use and protection measures. In pilot studies in the north of Europe it was found that the checklist delivered consistent results, enabling dune managers to identify spatial and temporal variations in the vulnerability of dune sites, significantly enhancing the strategic decision making process [Davies *et. al.* 1995] even when used by managers from different disciplines, whilst for southern European dunes the results of a pilot study (Alveirinho-Dias *et. al.*, 1994) suggest that some of the parameters such as beach replenishment, protection works, storminess and climate need to be reconsidered or added. Although the original checklist has provided a significant contribution to the collection and analysis of data for the dune manager, it was developed by and large by geomorphologists and has paid scant regard to the ecological dimension of sand dune ecosystems and a substantial part of this project aims to modify the checklist thereby addressing this deficiency.

The presence of vegetation is an integral part of dune formation and development because it impedes the free flow of sediment laden air causing the sand to be trapped allowing accumulation and dune building. Dune vegetation is physiologically and morphologically adapted to the extreme conditions imposed by a maritime environment e.g. most dune species are salt tolerant, are able to respond positively to sand accumulation and are able to avoid desiccation (Ranwell & Boar, 1986). As with any ecosystem there is a natural succession of vegetation types from pioneer species through intermediate to climax species and the loss of species through both natural and anthropogenic forcings leads to a loss in diversity which in turn can lead to a reduction of the resilience of a dune system. Sand dune vegetation can be assigned to three distinct morphofunctional types: foredune vegetation, secondary dune vegetation and inland vegetation. The first group is composed of species mainly associated with foredune habitats and consists of summer annuals and perennials. The physiological and morphological adaptations of these species in response to various maritime stresses include leaf adaptations such as pubescence, succulence and reinforced cuticle as well as root modifications such as thick spreading underground storage organs and root networks, the ability to survive burial by sand and seawater dispersal of seeds. Species clustered in the second group are related to secondary dune distribution and are perennial species with leaf morphological adaptations and to coastal climatic stress and a well developed underground root system. The third group is characterised by a diverse set of floristic elements and is

composed of forbs with rosette, tuft, or creeping forms and small graminoids. They belong to either inland dunes or non coastal habitats with sheltered conditions and are small annuals that mostly possess thin and soft leaves and a shallow hemispheric root system or one geotropic tap root.

Although the checklist is simple to use and offers considerable savings in time and effort over less organised methods, especially when applied to a limited area or a small number of sites, it is field-based and therefore very time consuming for monitoring dune vulnerability at the regional or national scale. In contrast, aerial survey using small format digital cameras is a relatively inexpensive way of surveying long tracts of coastline in a short time (Koh & Edwards, 1996 (a)). Many of the features laboriously recorded in the field-based checklist can be identified from digital images, including the area of the dune field, the extent (and often type) of vegetation cover - or conversely, the extent of bare sand, as well as elements such as path networks, blowouts, and breaches in the dune front. Indeed, current work suggests that over 70 % of the features identified on the check list can be correctly identified from digital images (Edwards *et. al.* 1996). In addition, much of the image data can be quantified, providing the opportunity to develop truly objective methods of assessment, and with repeat surveys, the opportunity to monitor change through time.

2. OBJECTIVES

Objective 1
To develop an integrated management tool via an innovative checklist system for European dune systems (Atlantic and Mediterranean). This will indicate and evaluate dune ecosystems vulnerability both on spatial and temporal scales.
Objective 2
To test a new remote image processing procedure as a dune management tool, and to integrate data, where appropriate, into the checklist procedures.
Objective 3
To select a small number of sites to examine how human activity affects the vegetation structure and vulnerability.
Objective 4
To assess the effectiveness of dune management strategies, and establish a data base/ GIS for the dune manager.

3. WORKPLAN

Site Description
The project area, indicated in figure 2 by heavy line type, was chosen to represent a wide variety of the dune types and conditions occurring in western Europe and includes dune sites in south-west Spain, south and west Portugal, west, north-west and Mediterranean France, south-west England and south-west Wales and type sites in Greece.

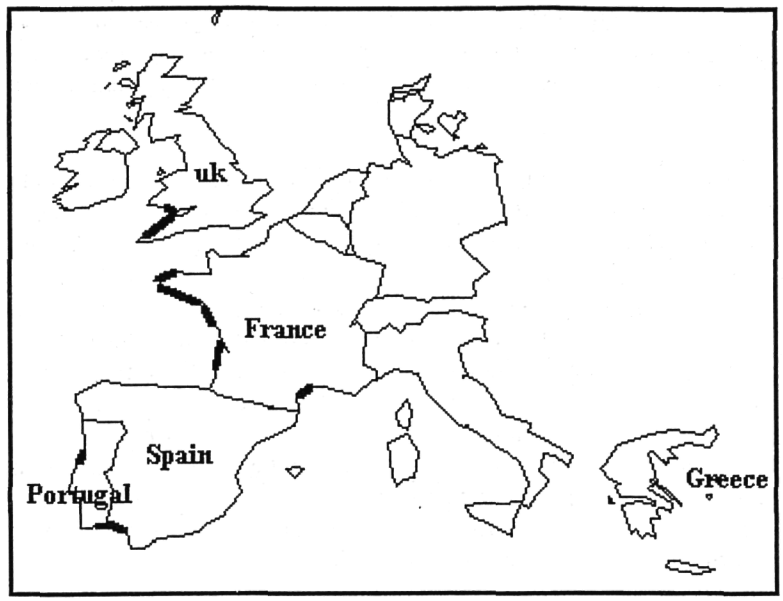


Figure 1. Outline of the project area

The Checklist

The original checklist was applied at chosen sites in each of the regions of the project area to provide a working sample of data. Detailed accounts (including parameter itemisation) of the checklist can be found in several publications including, Alveirinho Dias *et. al.*, (1994), Bodere *et. al.*, (1994), and Davies *et. al.*, (1995). Four characteristics of the checklist give a vulnerability index, (VI), A - site and dune morphology, B - beach condition, C - seaward character of the seaward 200m of the dune and D - pressure of use on the system. In essence each parameter is associated with a five point sliding scale grading from zero to four. Summation of all raw data expressed as a percentage of the total available allows a VI to be calculated. A fifth section rates the protection measures currently in force. A ratio of VI : PM between 0.8 and 1.3 indicates equilibrium in a dune system; values greater than 1.3 indicate that the system is negatively out of equilibrium i.e. the system is highly vulnerable, whereas values below 0.8 indicate that the system is out of equilibrium in the positive sense i.e. protection measures are more than adequate.

In Portugal a number of sites were selected which cover a wide variety of system types and forcings including natural phenomena such as aeolian and marine pressures, and human induced pressures such as tourism and fisheries. The Cacela beach / dune systems and the Ancao beach / dune systems on the south coast form part of the Ria Formosa barrier island which is a very high energy, dynamic region with a high human impact. These sites are currently being monitored through profiling to assess the effectiveness of dredging the lagoon, the spoil of which is used for ridge reconstruction. The impact of these management techniques on recently dredged channels and adjacent dune systems is being monitored. The Mira beach/dune system on the west coast is part of a complex more than 50km in length extending from Barra de Aveiro to Quiaios and is dominated by a high energy wave regime.

Tourist pressure is relatively low but traditional fishery activities exert a destructive impact on the dune system. The checklist was applied to these dune sites in winter and summer conditions. An alternative checklist has also been developed to determine system vulnerability which assesses resilience on three levels and takes into account the level of degradation and management measures required.

A further development of the checklist involves the use of planograms using maps, oblique and vertical air photographs to describe dune sites which will provide a single reference basis for the definition of dune descriptors so that managers have access to rapid and consistent methods of assessing dune condition.

Vegetation Survey

The loss of ecological diversity on sand dunes is a serious condition which can exert a significant influence on the overall health of a dune system. The absence of an assessment of the ecological status of dune systems in the original checklist is seen as a deficiency which must be addressed and in response to this, a series of vegetation surveys have been designed to identify the key elements which impact on the ecological vulnerability of a dune system and to investigate the relationship between vegetation response and coastal dune condition.

A survey of dune vegetation on 30 foredunes in the S.W. Iberian peninsula was undertaken to investigate the association of structural and functional characteristics of the vegetation. The sites were selected according to different dynamics and management strategies. It was assumed that geomorphological similarity in coastal foredunes leads to a standard habitat type which in turn leads to similarities in vegetation form and functionality. The dynamics of the foredune can then be inferred from the prevailing plant associations. The survey was carried out between October 1996 and March 1997. Abundance values were estimated using species relative cover in 250 m^2 plots. Functional and morphological characteristics of the species found were assessed; these were species persistence, leaf characteristics, vegetation height, presence of underground reserve organs, underground organ characteristics, ability to tolerate or avoid sand burial, and seawater dispersal. The data were analysed by polythematic divisive classification (TWINSPAN) to identify groups of species with similar traits. Plant Morphofunctional Types [PMFTs] were assigned to all species recorded and the vegetation was described in terms of PMFTs for the 30 sites.

The same sites were also assessed using the original checklist and the vulnerability index [VI] for each site was recorded. Foredunes were considered highly vulnerable when the VI was higher than 0.5. The species richness was recorded using a nested sampling method where four levels of area : 0.25, 2.5, 25, and 250 m^2 were identified within a 62.5 x 4 m plot in order to determine the composition and pattern of species accumulation in the vegetation. From these data, species / area curves were plotted to describe the pattern of diversity increase with area.

Digital Imaging Survey

The Airborne Digital Photographic System developed at Bath Spa University College comprises 3 principal components: The digital cameras (Kodak DCS 420 Digital Science), the mounting plate, and the intervalometer to manage the framing sequence. The assembly is self contained, transportable and can be easily mounted in a light aircraft. The system has been described fully by Koh & Edwards, (1996(a)). A major new development is the inclusion of the Kodak DCS 460 CIR Digital Science camera. This differs from the DCS 420 camera in

the array size of the CCD. Whereas the DCS 420 has an array size of 1524 [H] by 1012 [V] the DCS 460 has an array size of 3060 [H] by 2036 [V] giving a photocoverage four times larger than that of the DCS 420. This configuration produces a 24 bit colour image of 18.6 Mb whereas the DCS 420 produces a 24 bit colour image of 4.6 Mb. In addition, the DCS 460 colour infrared camera has been designed to integrate information on the spatial position of the camera at point of image capture into the image data file. This information is in the format of a standard NMEA sentence derived from Global Positioning Systems. Increased accuracies of the camera position can be achieved using real time differential global positioning (Koh & Edwards, 1996(b)).

An airborne digital imaging system [ADPS] was used to acquire aerial images of selected sand dune sites in Europe. Several modifications and improvements have been made to the ADPS during the course of the project and a rigorous methodology for mission planning and operation of the system has been developed. A flight track planner has been developed which can be used either on a palm top computer or on a PC. This is used to calculate flight line heading, flight line separation, aircraft altitude, required survey ground speed, framing rate, number of images per line, flying time, the total number of images and the number of PCMCIA cards required for each survey. A technique for flight track navigation has been developed using GPS whereby waypoints and aircraft altitude from the planner were input to the GPS and routes were identified, enabling the GPS to automatically compute the navigation information for use in flight. The onboard GPS was set to log in kinematic mode to obtain aircraft positional data during the survey and since both the GPS data and the image data are tagged with a time code, a positional fix was obtained for each image frame. A new development which integrates GPS positional data with image data to give 'centre of image location' for each frame is already on trial at time of going to press. GPS has also been used in real-time differential mode and in post-processed differential mode in the field, to collect position and attribute data. This data will be used for an evaluation of real-time v post processed data for dune managers.

To date there have been three aerial survey missions using the ADPS. The surveys were planned so that dune vegetation would be at a vigorous stage of growth and therefore able to provide good contrast with bare areas in the images:

June 1996, France

An imaging campaign was successfully accomplished which delivered colour infrared digital images, with a pixel resolution of 35 cm, of dune sites along the western coast of France from Arcachon to Cherbourg.

April 1997, Spain and Portugal

Colour infrared digital images with a pixel resolution of 40 cm were acquired at selected dune sites along the south coast of Spain from the mouth of the Rio Guadalquivir in the Donana National Park to the border with Portugal, along the south coast of Portugal from the border with Spain to Albufeira along the western coast of France from Arcachon to Cherbourg.

May 1997 France and U.K

Colour infrared digital images with a pixel resolution of 40 cm were acquired at selected dune sites along the south west coast of England from Land's end to Ilfracombe and along the south coast of Wales from Ogmore by Sea to Port Talbot.

A GIS is currently under development for the Cacela dune system, to integrate topo-hydrographic data, acquired before and after intervention, with the dune profile data acquired recently. This will enable volumetric and morphological changes to be detected.

4. SUMMARY OF RESULTS

Application of the checklist to dune sites in U K and the western coast of France has been shown to give consistent results. In the west and south of Portugal some of the parameters were found to be inappropriate e.g. 'wet slacks' and 'rabbit population'. Regeneration of dune vegetation, depending on climate conditions, is slower than in northern European dunes and nearshore topography has not been considered. Several modifications to the checklist which will improve its accuracy have been proposed as a direct result of these trials.

In Portugal it was shown that in the winter time there was a greater destruction of the dune by natural physical forces whereas there is increased visitor pressure in the summer. The dune sites in the Ria Formosa area are more vulnerable than those on the west coast.

Habitat heterogeneity within the foredunes caused by dynamics of the system and human interference allows the three different morphofunctional types to coexist in the same geomorphological unit under the same climatic conditions. Where foredunes are dominated by depositional processes or annual alteration of erosion / deposition the vegetation is characterised by a higher proportion of foredune type species. Increasing proportions of secondary species occur where foredunes are either eroding or stationary. A high proportion of inland type species is indicative of stable foredunes. It is postulated that the relative proportions of the three different morphofunctional types could be used as an indicator of the foredune dynamics.

Species / area curves illustrate how the number of species increases as the sampled area increases. Not all species / area curves have the same shape and so these curves can be used to compare the rate of species density increase with area amongst sites. When diversity (richness) and increase in diversity are plotted against VI there is a spatial segregation of both parameters depending on the degree of vulnerability. High vulnerability is related to low species density in $1m^2$ and to high rates of increase in diversity. The effect of increasing dune vulnerability on the pattern of foredune species accumulation can be used as a measure of the degree of disturbance within the foredune habitat.

As a result of these vegetation surveys a new section has been added into the checklist which can assess the vegetation status of the dune system to give a more complete analysis of the degree of vulnerability of the dune.

Preliminary results of the image processing suggest that digital imaging can be used to assess around 70% of the checklist elements. These include: areas of vegetation units, areas of bare sand, total path lengths, presence / absence of management features such as fencing, boardwalks, planting schemes, siting of amenities such as camp sites, car parks, beach shops / toilets etc., as well as giving an overview of developments adjacent to the dune sites which could impact on visitor pressure to the dunes. The images have yet to be used in a time series analysis but such an analysis could provide information related to vegetation and morphological change.

Analysis of the digital images of dune sites from four of the six locations is now in progress and a very small sample of these are shown below. One fundamental expression of human impact on dune sites is the development of access paths linking car parks to the beach. In extreme cases, the paths allow vehicle access to the dunes with parking and allied activities such as camping on the dunes themselves. Aerial photography gives an unparalleled opportunity to quantitatively assess the path network density in the dune field, and their relation to public access features such as the road network, car parks and holiday facilities such as hotels and camp sites. Figure 2 shows the regional variation of path development across the project area.

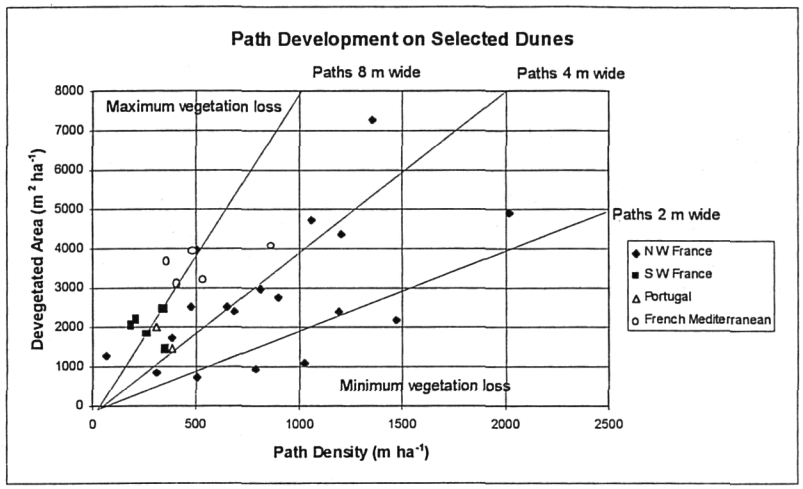


Figure 2 Relationship between path density and devegetated area of the dune at 4 regions in the project area

In general path densities in N W France are relatively high, but the majority of paths are narrow. There is considerable contrast with the situation in Mediterranean France where the path density is towards the lower end of the scale, but where path widths are extremely wide, reflecting severe public pressure on these often narrow dune sites. These contrast with sites from S W France, where the path density is relatively low, reflecting widely spaced, controlled beach access points, with heavy pedestrian traffic to the seaward edge of the dunes. The paths in these cases are wide, but the collateral damage indicated by devegetation is relatively small.

Similar regional influences can be detected when area of vegetation loss within the dunes is considered. In this process, the area of the dune field is determined in the digital image, as is the extent of the vegetation cover in the defined dune field. The vegetation cover in undisturbed areas of the dunes is also separately tested, thus determining a vegetation cover baseline to enable comparison between dune sites. For example, at some sites where dune accretion is very rapid, there has not been time for vegetation to completely colonise newly deposited sand, and the vegetation cover is incomplete. A simple weighting factor can be derived from testing of these undisturbed areas, thus allowing for the sparser vegetation cover in recently deposited dune fields. Likewise, a weighting factor which accounts for vegetation response to climate regime could be applied enabling comparison of dunes throughout the

European littoral. Preliminary observations of the devegetation of dune sites are included in Figure 3, and these suggest that regional differences in human impact on dune sites can be detected.

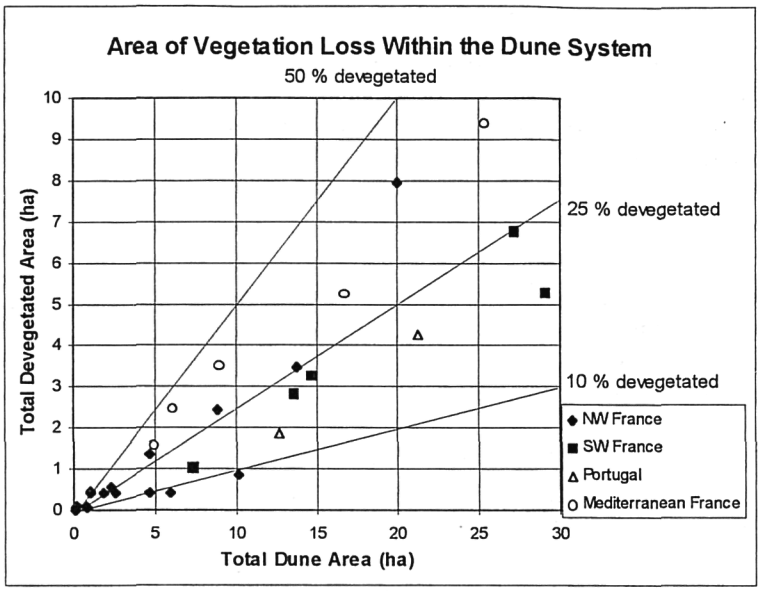


Figure 3. area of vegetation loss within the dune system at 4 regions in the project area

As a group, the Mediterranean dunes sampled are highly devegetated, whereas dunes sampled in S W France and Portugal are relatively undamaged. Dunes sampled in N W France show considerable variation, and some small dune sites are highly degraded. In all four regional variants, the degree of devegetation is highly dependent on management policy in relation to pressure of use.

Further research and development on the ADPS has enabled calibration of the cameras, trial of a new camera with a larger array size and the collection of data for evaluation of the camera's potential to provide data for the derivation of digital elevation models.

5. PRELIMINARY CONCLUSIONS

The checklist provides the dune manager with a management tool which is simple to use and easy to analyse. It can be operated by managers from numerous different backgrounds and with minor modifications is applicable in the Pan-European context. The inclusion of an ecological diversity section in the checklist enhances its ability to give a complete picture of dune vulnerability.

Aerial digital photography is a cost effective way of providing an archive of colour infrared photographs which can perform a useful role in the assessment of sand dune vulnerability for integrated coastal zone management.

The use of differential Global Positioning Systems for rapid environmental mapping greatly reduces the lead times in the development of information for decision support roles and is an indispensable tool for air survey navigation for digital imaging campaigns.

ACKNOWLEDGEMENTS

This work was supported by the European Commission Environment and Climate Research Programme, contract number ENV4-CT960215 in the framework of ELOISE.

The author would like to acknowledge Eastman Kodak, and in particular the Aerial Imaging Group and the Digital Imaging Group, for providing a Kodak DCS 460 CIR Digital Science Camera for field trials in May 1997 and Trevor Miller at Eastman Kodak Ltd. UK for facilitating this trial.

REFERENCES

Alveirinho-Dias, J.M., Curr, R.F.H., Davies, P., Pereira, A. R., Williams, A.T., 1994, Dune Vulnerability and Management: Portugal and North West Europe. Littoral 94, Eds: Soares de Carvalho, G. and Veloso Gomes, F., Instituto de Hidraulica e Recursos Hidricos, Universidade do Porto, Portugal pp 837-848.

Arens, S. M., 1996, Sediment dynamics of a coastal foredune at Schiermonnikoog, The Netherlands. Studies in European Coastal Management. Edited by P.S. Jones, M.G. Healy and A.T. Williams, Samara Publishing Limited, Cardigan, U.K. pp 137-146.

Bodere, J-Cl., Cribb, R., Curr, R.F.H., Davies, P., Hallegouet, B., Meur, C., Piriou, N., Williams A.T., & Yoni, C. 1994, Vulnerabilite des dunes littorale: Mise au point d'une method d'evaluation. In Defense des cotes ou protection de l'espaces littoral. Ed: Moissec, A., Cahiers Nantais. No. 41-42, URA 904, CNRS, Commission sur l'Environnement cotier de l'UGI. pp 197-201

Carter R.W.G., 1991, Near Future Sea Level Impacts on Coastal Dune Landscapes. Landscape Ecology, 6 1/2 29-39

Davies P., Curr R.F.H., Williams A.T., 1995. Dune management strategies: a semi-quantitative assessment of the interrelationship between coastal dune vulnerability and protection measures. Coastal Management and Habitat Conservation, edited by Salmon A.P, Berends P., Bonazountas M. EUCC, Leiden, Netherlands. pp 313-331.

Doody P., 1982, The Conservation of Sand Dunes. Nature Conservancy Council.

Edwards, E., Koh, A., Curr, R. & Williams, A.T, 1996. Aerial Digital Photography: A Management Tool for Sand Dunes, ICZM in the Mediterranean & Black Sea: Immediate Needs for Research, Education - Training, & Implementation, Proceedings of the International Workshop 2-5 November 1996, Sarigerme, Turkey, pp 171-185.

English Nature 1992, Coastal Zone Conservation - English Nature's Rationale, Objectives and Practical Recommendations.

Garcia-Mora, M.R., Gallego-Fernandez, J.B., Garcia-Novo, F., 1997, plant Morphofunctional Classification. A tool for Assessing Foredune Conditions. Conference Proceedings Coastlines '97, Naples, Italy, July 1997.

Koh, A. & Edwards, E., (a) 1996. Integrating GPS Data with Fly-on-demand Digital Imagery for Coastal Zone Management, AGI 96 Conference Proceedings, Geographic Information Towards the Next Millennium, Association for Geographic Information, 6.1.1 - 6.1.5, ISBN 1-874-05-924-1.

Koh, A., & Edwards E., (b) 1996, Differential Global Positioning Systems for Coastal Zone Management. ICZM in the Mediterranean and Black Sea: Immediate needs for Research, Education - Training and Implementation. pp 187-200..

Louisse C.J., and Van der Meulen F., 1991, Future Coastal Defence in the Netherlands: Strategies for Protection and Sustainable Development. Journal of Coastal Research 4 1027-1041

Mediterranee Economique: Premier Rapport sur la situationdes Pays Riverans au debut des annes 90 -CEFI-Economica- 1992, in Tabet-Aoul E. H,1995.

Meur, C., 1989, La Dune Bordiere de Tronoenau droit des carrieres de sable. Etude Morphologique et Propositions d'Amenagements. Unpublished D.E.A. de Geomorphologie, Universite de Bretagne Occidentale, Brest, 114p

Nordstrom, K., Psuty, N. and Carter, R. W. G., 1990, Coastal Dunes: Form and Process John Wiley and Sons, Chichester, U.K. 387 pp

Ranwell D. and Boar R., 1986 Coastal Dune Management Guide Institute of Terrestrial Ecology.

Sherman, D.J. and Bauer, B.O., 1993, Dynamics of Beach Systems, Progress in Physical Geography, 413-417.

Walker H.J., 1990, Nature, Humans and the Coastal Zone, International Journal of Social Education, 5 50-62

TITLE: **ECOFLAT**

CONTRACT NO: **ENV4-CT96-0216**

COORDINATOR:
Carlo H.R. Heip / Peter M.J. Herman
Netherlands Institute of Ecology
P.b. 140, 4400 AC Yerseke, The Netherlands
Heip@cemo.nioo.knaw.nl, Herman@cemo.nioo.knaw.nl
tel +31/113.577.445
fax +31/113.573.616

PARTNERS:

Jean-Louis Reyss, Sabine Schmidt
Centre des faibles radioactivités; (CFR)
Avenue de la Terrasse, F-91191 Gif-sur-Yvette , France
sabine.schmidt@cfr.cnrs-gif.fr
Phone: + 33 169 823535, Fax: + 33 169 823568

John Widdows, Mary Brinsley, Peter Salkeld
Plymouth Marine Laboratory (PML)
Prospect Place, West Hoe, Plymouth PL13DH, UK
j.widdows@pml.ac.uk
Phone: + 44 1752 633100, Fax: + 44 1752 633101

Marcel Marchand, Pauline Thoolen
Delft Hydraulics (WL)
Rotterdamseweg 185, NL-2600 MH Delft, The Netherlands
marcel.marchand@nsld.wldelft.nl
Phone: +31 15 569353, Fax: +31 15 619674

Harm Verbeek, Fred Twisk, Richard Eertman
Rijksinstituut voor Kust en Zee (RIKZ)
P.O. Box 8039, NL-4330 EA Middelburg, The Netherlands
R.H.M.eertman@rikz.rws.minvenw.nl
Phone: +31 11 8672230 Fax: +31 11 8616500

Magda Vincx, Maaike Steyaert, Tom Moens, Wim Vyverman, Ilse Hamels, Koenraad Muylaert
Universiteit Gent (UG)
Ledeganckstraat 35, B-9000 Gent, Belgium
magda.vincx@rug.ac.be
Phone: +32 92 645210 Fax: +32 92 645344

Patric Meire, Tom Ysebaert
Instituut voor Natuurbehoud (IN)
Kliniekstraat 25, B-1070 Brussel, Belgium
patrick.meire@instnat.be
Phone: +32 2 5581811 Fax: +32 2 5581805

Patrick Holligan, Catherine Lucas
Southampton University - Dept. of Oceanography (SUDO)
Southampton Oceanography Centre, European Way, Southampton SO14 3ZH, UK
Catherine.H.Lucas@soc.soton.ac.uk
Phone: +44 1703 596270 Fax: +44 1703 593059

PROJECT HOMEPAGE: **http://www.nioo.knaw.nl/cemo/ecoflat/ecoflat.htm**

ECOFLAT: THE ECO-METABOLISM OF AN ESTUARINE TIDAL FLAT

PETER M.J. HERMAN, CARLO H.R. HEIP

Netherlands Institute of Ecology, Yerseke, The Netherlands

1. INTRODUCTION

Estuaries in general tend to be heterotrophic systems (Heip et al., 1995), in which metabolism is partially driven by land-derived organic material and nutrients. In shallow estuaries a considerable part of this metabolism occurs in the sediments, and the pathways, the characteristic time scales and eventual fate of organic matter and nutrients in sediment metabolism are different from those in pelagic metabolism. Benthic-pelagic exchanges modify the transport and transformation of land-derived organic material and nutrients.

Tidal flats are important components of macro- and mesotidal estuaries and coastal systems all over the world. They are complex macromorphological structures, shaped in close relation to hydrodynamic factors in the estuary. A single tidal flat can consist of a series of habitats ranging from small sand dunes and megaripples to extensive flat muddy areas and may be inhabited by very different biological communities. Since they can occupy more than half of the total estuarine surface, tidal flats have a significant role in the metabolic processes and material fluxes within the estuary, especially in the degradation and transformation of organic material either advected or produced *in situ*. Understanding the ecological role of tidal flats in the functioning of the estuarine ecosystem is therefore a central question in the study of land-sea interactions.

Previous research on tidal flats has largely been descriptive; it has generally not adopted a multidisciplinary approach which is necessary to examine the complex interactions between physical, chemical and biological processes that are characteristic of the behaviour of tidal flats as geomorphologic and metabolic systems. Thus there exists a large literature on purely sedimentological (e.g. Dyer, 1986, Reineck & Singh, 1980) and purely biological and ecological problems (e.g. Reise, 1985), whereas very few multidisciplinary studies have been undertaken. In current ecological models of estuaries tidal flats are either absent or only present in mass balances on a gross temporal and spatial scale not corresponding to the scales at which the ecological processes actually take place. The lack of mechanistic understanding and representation of the processes limits the predictive capabilities of the models under scenarios relevant to the many ecological problems facing estuarine ecology: eutrophication, human interference with the hydrography, global change and loss of biodiversity.

Many important processes regulating eco-metabolism and material fluxes in estuarine environments have characteristic time scales of only a few hours. The tidal cycle causes

current velocities and water levels to change from zero to their maximum over about six hours. As a consequence, the intertidal sediment surface changes two times a day from a sediment-water interface to a sediment-atmosphere interface with associated shifts in the biogeochemical processes. Spatially, the scales of interest to the processes of carbon and nutrient exchanges range from a few mm (vertically), over a few cm (the scale of stream ripples, important for microdistribution of algae, microbial organisms, detritus, meiofauna) to a few tens of m (the scale of gradients in sediment composition and texture relevant to macrobenthos).

There exists a considerable gap between the small scales at which the processes operate and are measured, and the large scales (estuarine scale, regional scale) at which the environmental problems are posed. ECOFLAT tries to bridge this gap by explicitly studying the small scale processes and by integrating them in mathematical process models. From these models the ecological variables relevant to estuarine management and to extrapolation on a regional scale should become easier to predict, because based on a better mechanistic understanding. In the process studies, emphasis is placed on the study of the carbon and nutrient cycling within the flats and to the dynamics of carbon and nutrient exchange between the flat and the surrounding estuarine ecosystem.

2. OBJECTIVES

The objectives of ECOFLAT can be summarised in the following points:

1. A multidisciplinary study of processes important for the carbon and nutrient cycling within a tidal flat ecosystem, and between the tidal flat system and the estuary. Integrated measurements performed at the appropriate scales for the processes of interest.

2. Development of predictive mathematical models describing the processes and relating them to the main forcing factors for the tidal flat system.

3. Bridging the gap between the scales at which the processes operate and are measured, and the ecological target values for environmental management and prediction of the ecological consequences of global change.

3. WORKPLAN

The project is organised around a number of joint intensive field measurement campaigns, tailored to the small time and spatial scales central in the scientific topics to be studied. These campaigns involve all partners and last for one spring/neap tide cycle. The first four of these campaigns have been held at the Molenplaat tidal flat in the Westerschelde (S.W. Netherlands). A final intensive field campaign will be executed the Dutch Wadden Sea. This campaign is specifically addressing the problem of validation of predictions.

The measurements and modelling are organised in a number of work packages. The first work package addresses the problems of quantifying benthic-pelagic exchange in tidal flats. In the second work package, the microbial food chain in intertidal sediments is studied. The last work packages integrates the acquired knowledge in detailed process models, and in upscaling models to the scale of the estuary.

Work package 1. Benthic-pelagic exchange in tidal flats.

In order to predict the dynamics of sedimentation/resuspension processes in relation to physical factors a detailed hydrodynamic model has been constructed for the tidal flat under study. Current velocity patterns will be related to sediment composition; they are also important determinants for the biological community composition in the benthos. The availability of a good hydrodynamic model for the tidal flat is essential for the project as a whole, since hydrodynamics and related variables (e.g. sediment composition) provide a crucial link between estuary-wide environmental changes and the microscale processes on a tidal flat.

The project will unite different research groups in a conjoint approach to study whatever tracers of erosion / deposition processes are available. The study of specific composition of algae in the water column and on the sediments will, when complemented with studies of rates of growth in both environments, provide an estimate of exchange rates between the two groups of algae. At the ECOFLAT study site(s) the net loss of benthic microalgal biomass to the water column will be estimated over an annual cycle, taking into account the effects of variations in the sedimentary environment.

The joint study of depth distributions in the sediment of Chlorophyll-a and its degradation products on the one hand, and different radionuclides on the other hand will provide information on several aspects of benthic-pelagic exchange. The natural radionuclides 234Th ($t1/2 = 24.1$ days) and 210Pb ($t1/2 = 22.2$ yr) are produced continuously by uranium and radon decay in the water column and completely scavenged onto particles within one or two days. The excess 234Th or 210Pb sedimentary inventories indicate lateral resuspension / sedimentation processes resulting in net deposition. The simultaneous use of Chl-a and 234Th as tracers for reactive particle dynamics provides a very powerful technique since they have similar decay constants, yet distinctly different input functions (seasonal versus more or less constant). Excess 234Th and Chl-a versus depth profiles can be used to quantify particle reworking by applying transport-reaction/decay models. Similarly, excess 210Pb profiles can be used not only to determine bioturbation rates, but also sediment accumulation rates over decadal time scales. These excess 210Pb-based estimates can be compared with those based on the artificial radionuclides 137Cs ($t1/2 = 30$ yr) and 134Cs ($t1/2 = 2.05$ yr) that have distinct input functions (nuclear weapon testing, Chernobyl) rather than a semi-continuous input like 234Th and 210Pb. The cosmogenic radionuclide 7Be ($t1/2 = 53.3$ days) is mainly supplied by atmospheric deposition. 7Be profiles can be used to determine particle movement due to bioturbation and net accumulation, yet over a time scale of months. The combined use of Chl-a, 234Th, 210Pb, 137/134Cs and 7Be provides us (1) with tracers for transport of particles between sites (inventory studies) and (2) with estimates of rates of bioturbation and net sediment accumulation at a certain site, over time scales that vary from days (Chl-a, 234Th, 7Be) to years (210Pb, 137Cs).

By the deployment of annular flume measurements, the bulk organic material in the sediment will be separated into fractions resuspending at different current velocities. Annular flume measurements with different current velocities will quantify the erodability of the sediment as influenced by the biota. Annular flumes will be used to study the relationship between current pattern and ecophysiological responses of the benthic suspension feeders during a tidal cycle, a spring-neap tide cycle and at different locations with different current patterns. In

conjunction with the annular flume measurements, continuous recording of seston quality over a spring-neap tide cycle will be executed.

From the relationship between current patterns and animal physiology on the one hand, and from a hydrodynamical model of the currents over the flat on the other hand, we will model the optimal sites for suspension feeder occurrence. The model output will be compared with an existing mapping on the same tidal flat. The outcome of the modelling will be used as a basis for upscaling from the small scale processes to the estuarine scale

Work package 2. The benthic microbial food web in an intertidal flat system.

In comparison with pelagic primary production, the primary production by microphytobenthos is relatively understudied. Nevertheless, this primary production may constitute an important fraction of the total primary production in shallow tidal estuaries. A number of differences between planktonic and microphytobenthic primary production make the study of the latter an interesting, but difficult topic. The occurrence of microphytobenthos on sediment particles precludes the direct application of methods in use for measuring planktonic primary production. Different methods ($^{14}CO_2$ incubation, O_2 microelectrodes, fluorescence measurements, in situ ^{13}C labelling) will be applied. Apart from methodological difficulties, however, the factors limiting primary production by microphytobenthos may be of a fundamentally different nature than those for phytoplankton. The total biomass of microphytobenthos, expressed per unit area, can be of the same order of magnitude as that of phytoplankton. The viable biomass occurs in the top few mm of the sediment only, whereas planktonic biomass may be distributed over several meters of water. Consequently, the transport of substrates necessary for primary production to the places of high biomass and high production is an essential factor limiting microphytobenthic production. This applies both to nutrients and to inorganic carbon. Although the bulk contents of nutrients in sediments usually amply suffice for the production of microphytobenthos, local needs in the very limited volume in the upper mm of the sediment may be so high that diffusion limits the availability of nutrients. Due to limitation of the supply of inorganic carbon from the sediment the pH may rise considerably and in turn limit primary production by physiological stress. Possible supply of carbon dioxide from the air further complicates the picture. The vertical movements of microphytobenthos through the top mm's of the sediment may be an adaptation to the transport limitation of production substrates. This movement may be a prime reason for the excretion of extracellular polymeric substances (EPS), which play an important role in the stabilisation of intertidal sediments. Detailed, short-term modelling and observational studies are needed to unravel the relationships between the different substrate limitations and the possible adaptations of the organisms.

Unravelling the intricate relationships between benthic biology and biogeochemical processes in sediments is a complicated scientific challenge. This project aims at providing some of the data needed to reconcile both paradigms. It will be needed to translate the concepts used in geochemical approaches into biologically known organisms and their activities and to translate biological measurements (species abundance and biomass, production figures, grazing and predator-prey interactions) into geochemically meaningful parameters.

'Bacteria' are among the most prominent of the geochemical metaphors that need translation into biologically measurable variables. 'Bacteria', in the context of early diagenesis theory, stands for the biological actors leading to degradation of organic matter, reoxidation of

reduced substances, absorption of inorganic nutrients etc.. From a biological point of view, these processes are mediated through a complex of organisms, the sediment microbial loop, consisting of far more than bacteria alone. It is generally accepted that microheterotrophs, meiofauna and macrofauna (deposit feeders) have intense interactions with the bacteria in the sediment. How, and how much, these interactions modify the bacterial activity or abundance, however, is less well known. Many of the interactions are poorly quantified, and the sensitivity of the overall result (e.g. the overall organic matter degradation rate) to the complexity and the magnitude of the interactions is not well studied. 'Classical' benthic categories such as meiofauna or macrofauna do not correspond to functional groups, since within these categories 'internal' predation may be an important process. For example, in estuarine nematode communities, predators (on other meiofauna) usually constitute a significant portion of the total biomass. A rather complete inventory of the (qualitative) feeding behaviour within the groups would be needed to assess the error introduced by treating them as black boxes. For macrofaunal species in estuaries, qualitative descriptions of feeding behaviour are more or less available. For meiofauna, the picture is far from complete. Much more research on microheterotrophs is needed before the possible internal links can be specified.

We hypothesise that the interactions between bacteria, detritus and the higher organisms feeding directly on them are of prime importance for system functioning. There has been much discussion on the question whether metazoan benthic animals feed directly on detritus or feed mainly on bacteria. Current opinion holds that direct feeding on detritus is needed for the energy balance of the metazoans. It is also thought that feeding rates on bacteria are too weak to affect bacterial biomass or activity greatly. While data for macrofauna provide good evidence for this statement, data on meiofauna and microheterotrophs are too scarce to be convincing. Quantification of the rates is therefore needed. These studies are fraught with technical and methodological difficulties. The project will focus on meiobenthos, where the chances of success are thought to be largest.

Work package 3. Integrative mathematical modelling

The biogeochemical study of organic matter transfer and mineralisation in intertidal sediments is challenged by a number of difficulties, mainly related to the specification of the upper boundary processes. It has been shown in model studies that a different vertical distribution of mineralizable carbon results from two basically opposed assumptions on the upper boundary condition: an imposed upper flux condition vs. an imposed upper concentration condition. The first condition is usually adopted for deep sea sediments. In intertidal sediments the imposed upper concentration condition may be a better approximation of reality.

A second complication in the specification of the upper boundary conditions is the fact that, within a tidal cycle, an intertidal flat changes state between an aquatic and a semi-terrestrial environment. During ebb tide a three-phase interaction (solid substances, interstitial water and air) must be considered for volatile species, while exchanges for non-volatile species are blocked. During flood tide exchanges at the upper boundary for all chemical species are possible in a two-phase interaction of water and solids.

Primary producers are the third complication for the upper boundary specification. Intertidal sediments show (at day time) simultaneous production and consumption of organic matter and, inversely, simultaneous consumption and production of inorganic nutrients.

A further complication for the early diagenesis approach is the problem of advective exchange of pore-waters. The interstitial water in coarse sediments on the flats is drained during ebb tide, resulting in much faster exchanges of solutes than can be effectuated through diffusion.

Within the present project, it is our aim to extend the 'classical' early diagenesis modelling to take into account the different complications posed by intertidal sediments. We will construct and analyse different theoretical early diagenesis models in which the typical intertidal upper boundary conditions are represented, and evaluate the relative importance of the different factors.

Within the project, this early diagenesis model will also serve as an integrating tool for observations on the benthic biology, physical and biological transport process measurements, and geochemical observations. The measurements on erosion / deposition processes (work package I), on the benthic actors in primary production and mineralisation (work package II), will be completed with measurements of depth concentration profiles of oxygen, carbonate species, sulphides, silicate, nutrients, organic carbon, redox potential and pH over tidal cycles and over spring/neap tide cycles. Together these measurements will constrain the outcomes of the early diagenesis modelling.

A major objective of the project is bridging the gap between the large-scale environmental problems (estuarine management, global change) and the small scales at which the actual biological and biogeochemical processes take place and are measured. The scale difference in itself poses a problem, but associated to it is the problem that the variables of interest are at a different level. For estuarine management problems related to hydrographical changes, eutrophication, toxic pollution or other anthropogenic stress, it is of prime importance to be able to evaluate the effects of human interference on politically and socially important target variables, e.g. diversity and biomass of macrobenthic assemblages, wintering bird populations, sea mammals, aesthetic value of the landscape, etc.. Moreover, in the context of global change, there is a need for the deduction of gross rates of material transfer, production and consumption from a basic typology of the estuary. We take the point of view that prediction of large-scale effects and rates should be rooted in a mechanistic understanding of the processes actually taking place in the estuary. It is no trivial task to extrapolate rates and processes from a single tidal flat to effects on target variables at the scale of the estuary.

A prerequisite for the upscaling is that a correct relationship be found between the most important driving factors and the ecological processes within the system. In the present project, the process models for benthic dynamics are forced by hydrodynamics on the one hand, and by concentrations of ecological variables (organic material, nutrients, suspended solids,..) in the water column on the other hand. The (time) dynamic nature of the diagenetic and process models make them fit, in principle, for inclusion in a general ecosystem model that generates this external forcing. The ecosystem model MOSES and the existing hydrodynamic models for the Westerschelde will be used for this purpose. From the ecological model (which provides forcing with respect to organic material and nutrients) and the hydrodynamic model (providing forcing with respect to sediment composition, stability, current regime, erosion / deposition processes) predictions will be made on the spatial and temporal distribution of macrobenthic animals in the estuary. Macrobenthic animals are an important ecological target variable for environmental management in themselves. Moreover, they are a key variable in the assessment of the potential of the estuary for wintering birds.

Not only biomass values of the macrofauna, but also the composition of the fauna, its distribution with respect to depth in the sediment and with respect to exposure time of the flat area are important variables for the birds.

Extensive data sets on the macrobenthos are available. Validation will therefore also be achieved by comparing predictions based on hydrodynamics and on the general ecosystem model with a data base of observations on macrobenthos and sediment texture in the estuary. This will be used as a test of the validity and appropriateness of the current estuarine habitat classification for predicting macrobenthos characteristics and carrying capacity for wintering birds.

4. RESULTS

In the first 1.5 years of the project, four intensive two-week campaigns at the Molenplaat (Westerschelde) have been performed. This has resulted in a wealth of samples and data, that have not yet been fully worked up. In what follows we will give some examples of measurement and model results. We stress that a more complete analysis of these results has to be performed in the coming year.

A 2D (XY) hydrodynamic model with a spatial resolution of a few decametres has been constructed for the wide area around the tidal flat. This model has been calibrated on water height measurements at different stations. One of the relevant outcomes of the hydrodynamic modelling is a map of bottom shear stress on the flat (Figure 1). The model is also used to calculate transport of different sediment fractions and of organic matter, and will serve as a basis for the modelling of optimal sites for filter feeding on the flat. The latter is to be compared with the mapping of the benthic fauna (Figure 2), that shows clear spatial correlations with the bottom shear stress and the sediment composition.

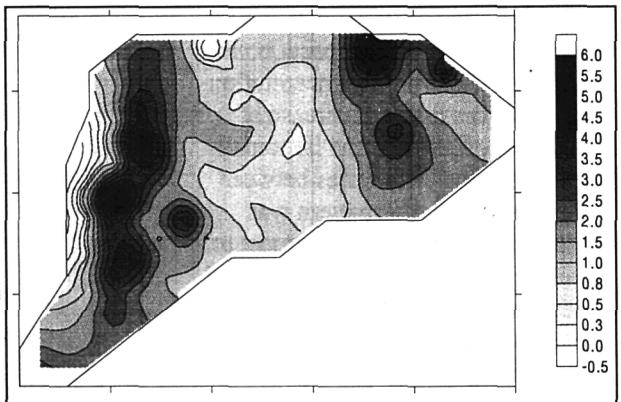


Figure 1. Bottom shear stress (Pa) as calculated from the hydrodynamic model for the Molenplaat, Westerschelde. (Thoolen, unpublished)

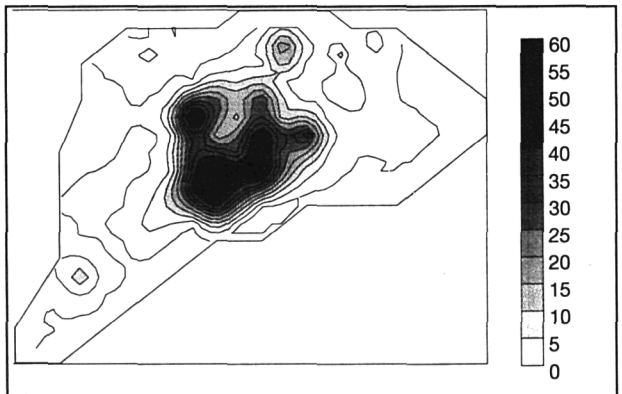


Figure 2. Spatial distribution of macrobenthic filter feeding biomass (g AFDW m^{-2}) at the Molenplaat, Westerschelde (Herman, unpublished)

The annular flume measurements (J. Widdows, unpublished results) have stressed the importance of the biological community in the determination of the erodability of the sediment. The high density of microphytobenthos during the spring campaign almost doubled the critical erosion velocity, compared to the late summer / autumn campaign when microphytobenthos was much scarcer. This seasonal biological effect was stronger than the difference between sites, due to hydrodynamics.

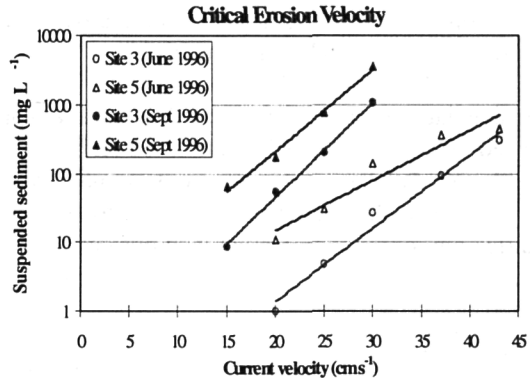


Figure 3. Seasonal changes in sediment stability on the Molenplaat tidal flat (Widdows, unpublished). Critical erosion velocity (u_{crit}) for a threshold of 100mg SPM l^{-1} increased from 17 to 31 cm s^{-1} at site 5 (edge of tidal flat) and from 22 to 37 cm s^{-1} at site 3 (centre).

Seston and chlorophyll dynamics in the water column at high tide (Figure 4) showed a very distinct pattern. At the top the tidal current speed, both seston and chlorophyll concentration peaked, with a distinct increase of concentration towards the bottom. Although some differences between sites were found, this pattern was quite common. It shows that most of the chlorophyll in the water is related to resuspension / sedimentation cycles. It is most probable, therefore, that microphytobenthos constitutes the most important part of the food of benthic suspension feeder. This hypothesis is further investigated through species identification of the algae in the samples. The occurrence of resuspended algae in the water column at all sites does not imply that resuspension is equally strong everywhere. *In situ* labelling experiments with ^{13}C have shown that a much larger fraction of the algae is swept away by the tide at the sandy sites than at the most muddy site (where most of the filter feeders occur). Most probably, there is a continuous transport by reuspension and sedimentation of microphytobenthos production from the sandy to the muddy sites.

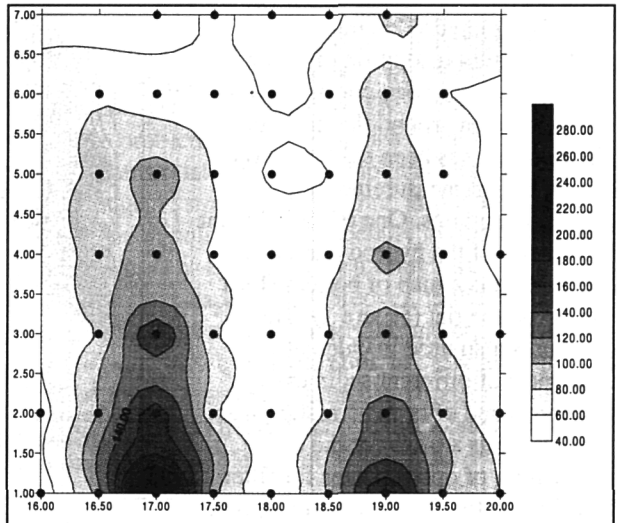


Figure 4. SPM concentration (mg.l^{-1}) in the water column (vertical axis: height) over time (horizontal axis) (Herman, unpublished)

The counting of natural radionuclides in the sediment column is hampered by the low activity in these sediments. The top sediment layers display traces of seasonal cycles in deposition, that correlate to patterns in chlorophyll a concentration. However, detailed long-lasting counting must confirm the first results.

The activity of benthic filter feeders, mainly *Cerastoderma edule* and *Mya arenaria*, has been monitored continuously during the field campaigns, using the naturally occurring quantity and quality of the seston. The measurements indicate the general importance of the quality of the seston, which is a complicated function of the differential erosion/sedimentation characteristics of organic and inorganic particles. These data will be used in the modelling of suitability of parts of the tidal flat for the occurrence of benthic filter feeders.

In the second work package, considerable effort has been put into the analysis of the composition, biomass and activity of the microphytobenthos on the tidal flat. Gross oxygen production, measured with glass microelectrodes, and ^{14}C uptake, were used to estimate the input of organic matter by microphytobenthos. Significant differences appeared in the oxygen and carbon production among the stations. The discrepancies between oxygen and carbon results are an indication of limitation in nutrients or inorganic carbon at some stations. An *in situ* labeling experiment using ^{13}C will hopefully lead to an independent estimate of primary production, which is less influenced by experimental conditions. However, lab measurements are still ongoing.

The meiofauna species composition and depth distribution have been determined at the five selected sites on the flat. Conspicuous differences in the meiofauna depth distribution were found between the sites. These were related to the grain size distributions and to the productivity of the microphytobenthos in the surface layer. Additional information is being collected on autotrophic (flagellates, diatoms, cyanobacteria) and heterotrophic (ciliates, flagellates, amoebas) microbenthos. Species composition, depth distribution and biomass of this group is studied at the same sites where meiobenthos is sampled. Biodiversity of this group can be extremely high, and very different between the sandy station 4 and the muddy station 2 (Figure 5).

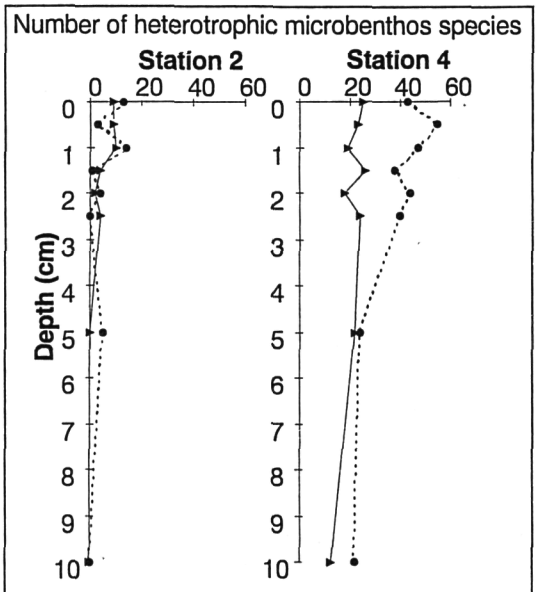


Figure 5. Species diversity in the microbenthos as a function of depth into the sediment at the sandy station 4 and the muddy station 2. Data of Hamels (unpublished).

For the estimation of grazing rate by meiofauna, several approaches have been taken. By sampling in the field at very small (1.25 cm^2) scales, it has been tested whether a better correlation between meiofauna density, bacteria and microphytobenthos could be obtained than at a coarser scale. Spatial correlation could be interpreted as indicating a causal relation between these variables. However, no consistent correlations could be demonstrated. In a second approach, methodological evaluations have been made of the techniques for studying grazing rates with radioactive tracers. Large flaws, due to fixation of organisms, have been detected. A new methodology compensating for these errors has been established for future work. Finally, a methodology is being worked out to estimate meiofauna grazing rates during the *in situ* labelling experiments with ^{13}C.

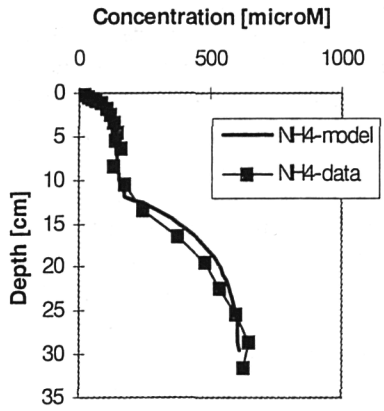


Figure 6. Prediction of the diagenetic model for the Skagerrak data of Canfield et al. (1993): ammonium profile. (Meysman, unpublished)

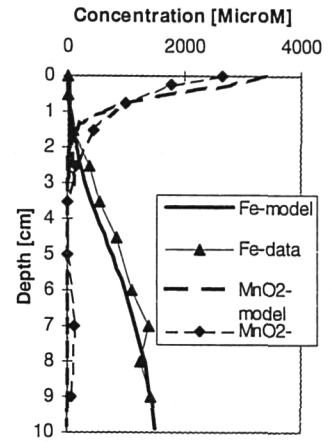


Figure 7 Prediction of the diagenetic model for the Skagerrak data of Canfield et al. (1993): manganese and iron oxide profiles. (Meysman, unpublished)

A mathematical model for early diagenesis in intertidal sediments has been formulated and coded in a computer program. This model is prepared to contain primary production formulations. For this purpose, it contains many reactions, important for modelling pH profiles in sediments. The combination of slow chemical and micobiological reactions with the fast equilibrium reactions in acid-base pairs has necessitated the development of a new numerical technique for the solution of algebraic-differential equations. This technique is now fully tested and working properly. The model's parameters are currently being validated using published concentration profiles of subtidal sediment. (see Figures 6 and 7 for a comparison with Skagerrak data published by Canfield et al. (1993). In a later stage, it will be applied to the profiles obtained at the Molenplaat.

These pore water profiles have been obtained in 1996 by the use of pore water peepers. Results show the importance of iron and manganese cycles, at least at the more silty sites. The profiles also show evidence of important pore water ventilation by animal activity. Whole-core incubations for oxygen consumption and CO_2 production have been performed. Oxic and anoxic incubations of sediments sampled at different depths have indicated no difference in mineralisation rate under the two regimes. These mineralisation rates differ considerably between stations, and correlate well with direct measurements of CO_2 production by the sediment at low tide.

For the upscaling from local processes to prediction of macrobenthic distributions at the estuarine scale, a general framework has been established. This so-called habitat evaluation procedure relies on the proper definition of the characteristics of the habitat and the system on the one hand, and of the species' preference for certain levels of these characteristics on the other hand. Predictions are based on the combination of both sets of parameters. In the coming years, the currently developed system will be completed by extensive data analyses aimed at improving the parameter values.

5. FINAL CONCLUSIONS

In the ECOFLAT project, the approach to the problem of predicting the spatio-temporal distribution of benthic communities and their anticipated future change, hinges mostly on a better understanding of the functional relationships between the different components of the benthic system on a tidal flat, and the surrounding pelagic ecosystem. The measurements, experiments and observations made will allow us to unravel and model several important aspects of these functional relationships. At present, we have mostly collected and analysed our field data and worked out the modelling methodology. We hope to achieve a much deeper analysis of the results in the coming year of the project.

6. REFERENCES

Canfield, D.E., B. Thamdrup and J.W. Hansen. 1993. The anaerobic degradation of organic matter in Danish coastal sediments: iron reduction, manganese reduction, and sulfate reduction. *Geochim. Cosmochim. Acta* 57: 3867-3883.

Dyer, K. 1986. Coastal and estuarine sediment dynamics. J. Wiley & Sons, Chichester. 358 pp.

Heip, C.H.R., N.K. Goosen, P.M.J. Herman, J. Kromkamp, J.J. Middelburg & K. Soetaert. *in press*. Production and consumption of biological particles in temperate tidal estuaries. *Oceanogr. Mar. Biol. Ann. Rev.*, 1995.

Reineck & Singh. 1980. Depositional sedimentary environments. Springer, Berlin. 594 pp.

Reise, K. 1985. Tidal flat ecology: an experimental approach to species interactions. Springer, Berlin. 191 pp.

TOROS (TINTO ODIEL RIVERS OCEAN STUDY)

CONTRACT NO: ENV4-CT96-0217

COORDINATOR: Dr Françoise ELBAZ-POULICHET
UMR Géofluides, Bassins, Eau
CNRS-ORSTOM-Université Montpellier II
CC57
F-34095 MONTPELLIER cedex
FRANCE

PARTNERS:

Partner 2
Dr Jose BORREGO FLORES
GSA
University of Huelva
Campus de la Frontera
21819 HUELVA
Spain

Partner 3
Mrs. Maria Jesus GUTIERREZ DE LA CAMARA
INTA
Carretera Torrejon-Ajalvir km.4
28850 TORREJON DE ARDOZ/ MADRID
Spain

Partner 4
Pr. Mario CHICA-OLMO
Research Group "Geostatistics, Remote sensing and GIS"
AVDA. Fuentenueva S/N
18071 GRANADA
Spain

Partner 5
Dr. Nicholas Hugh MORLEY
University of Southampton-Department of Oceanography
Southampton Oceanography Center
Waterside Campus
European Way
SO14 3ZH SOUTHAMPTON
United Kingdom

Partner 6
Dr. Eric ACHTERBERG
University of Plymouth-Department of Environmental Sciences
Drake Circus
PL4 8AA PLYMOUTH
United Kingdom

Partner 7
Dr. Jean-Marie BECKERS
Universit_ de Liège-Geohydrodynamics and Environmental Research (GHER)
Sart Tilman B5
B-4000 LIEGE
Belgium

Partner 8
Dr. Antonio CRUZADO
CSIC/CEAB
Cami de Santa Barbara S/N
17300 BLANES
Spain

BIOGEOCHEMISTRY OF AN ACIDIC AND METAL-RICH RIVER-ESTUARY SYSTEM: RIO TINTO AND ODIEL, RIA HUELVA AND GULF OF CADIZ, SOUTH-WEST SPAIN

Françoise ELBAZ-POULICHET[1], Eric ACHTERBERG[2], Jean-Marie BECKERS[3], Jose BORREGO[4], Charlotte BRAUNGARDT[2], Mario CHICA-OLMO[5], Antonio CRUZADO[6], Maria GUTIERREZ de la CAMARA[7], Marc LEBLANC[1], Juan A. MORALES[8], Eduardo de MIGUEL[7], Nicholas H. MORLEY[8], P. NOMERANGE[3]

[1] UMR Géofluides, Bassins, Eau. CNRS-ORSTOM-Université MONTPELLIER II. CC57. F-34095 MONTPELLIER cedex, France.
[2] University of Plymouth-Department of Environmental Sciences. Drake Circus. PL4 8AA PLYMOUTH. United Kingdom
[3] Université de Liège-Geohydrodynamics and Environmental Research (GHER). Sart Tilman B5, B-4000 LIEGE, Belgium.
[4] GSA, University of Huelva, Campus de la Frontera, 21819 HUELVA, Spain
[5] Research Group "Geostatistics, Remote sensing and GIS", AVDA. Fuentenueva S/N, 18071 GRANADA, Spain
[6] CSIC/CEAB, Cami de Santa Barbara S/N, 17300 BLANES, Spain
[7] INTA, Carretera Torrejon-Ajalvir km.428850 MADRID, Spain
[8] University of Southampton-Department of Oceanography, Southampton Oceanography Center, SO14 3ZH SOUTHAMPTON, United Kingdom

1. INTRODUCTION

Dissolved trace metal concentrations in the surface waters of the Mediterranean Sea have been reported to be higher than those in other surface ocean waters (e.g. Boyle et al, 1985). A flow of trace metal enriched water through the Strait of Gibraltar into the Western Mediterranean has been observed in several studies (van Geen et al., 1988; Morley and Burton, 1992). The sources of trace metals to the waters flowing into the Mediterranean have not been clearly identified (van Geen et al., 1991). North Atlantic Surface Water (NASW) is generally depleted in trace metals. Van Geen et al. (1991) have suggested that metal enrichment of NASW occurs on the Spanish Shelf as a result of upwelling of metals originating from a diagenetic shelf sediment source, and perhaps also as a result of a 'metal trap' mechanism driven by an estuarine-type circulation pattern and biological production along the Iberian coast. An alternative for the high trace metal concentrations observed Spanish Shelf Water involves rivers draining the South Iberian Pyrite belt (SW Spain, S Portugal).

The Tinto and Odiel rivers (Fig.1) are comparatively small (83 and 128 km respectively) and have an annual average discharge of 15 m^3s^{-1}, ranging seasonally from 1 - 100 m^3s^{-1}, and drain possibly the largest sulphide mineralisation area in the world (Strauss et al., 1977).

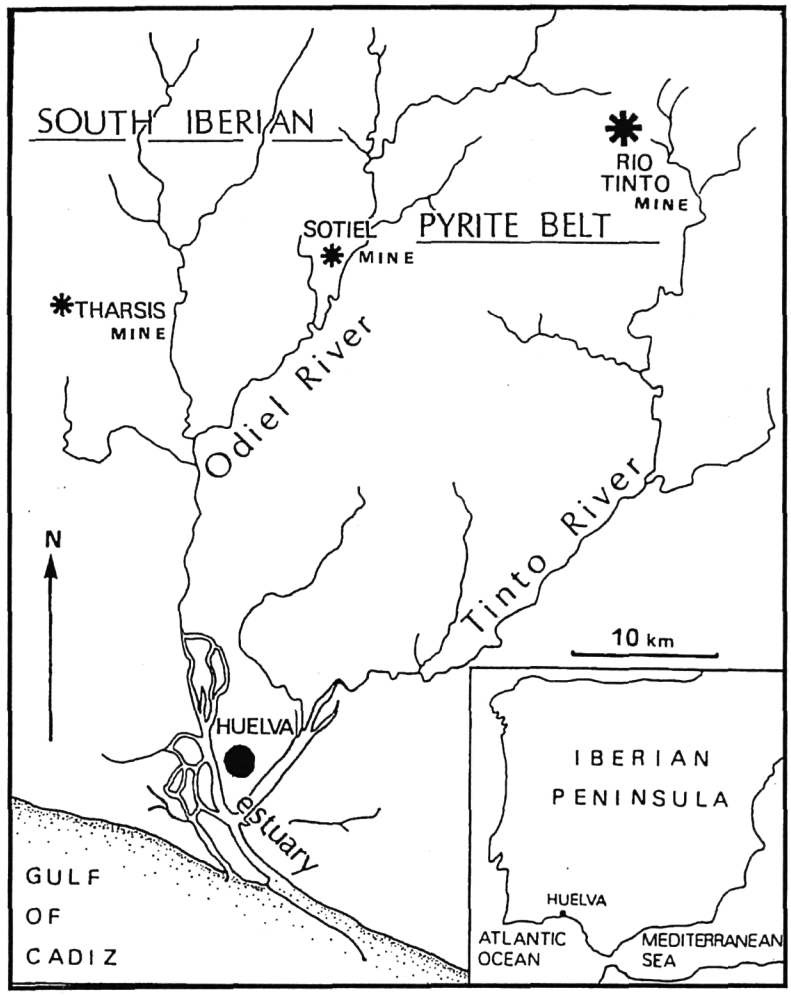


Fig.1: Map of study area

The Rio Tinto Massif sulphide deposit is estimated to contain about 1 Gt of sulphides, a large part of which has been exposed since the late Miocene (22 Ma.) and consequently has suffered from strong weathering, producing a metal enriched gossan (Strauss et al, 1977). This predominantly Zn-Cu-Pb mineralisation includes traces of Cd, Ag and Au

and has been worked since Phoenician and Roman times (Rothenberg et al, 1980), leaving a legacy of enormous quantities of wastes and slags.

The estuarine zones of both rivers are sites of major industrial activity including phosphate-based fertiliser plants (processing imported apatite and leaving large waste deposits of phosphogypsum), a pyrite roasting plant, a Cu smelting plant and a paper mill which processes eucalyptus wood from local sources. Furthermore, the industrial area includes oil refineries and other chemical industries, which are situated on the east bank of the outer estuary, downstream of the confluence of the Rio Tinto with the Rio Odiel. As a consequence of acid mine drainage, industrial inputs and run-off from the phosphogypsum deposits, the rivers Tinto and Odiel are highly acidic (see Fig.2).

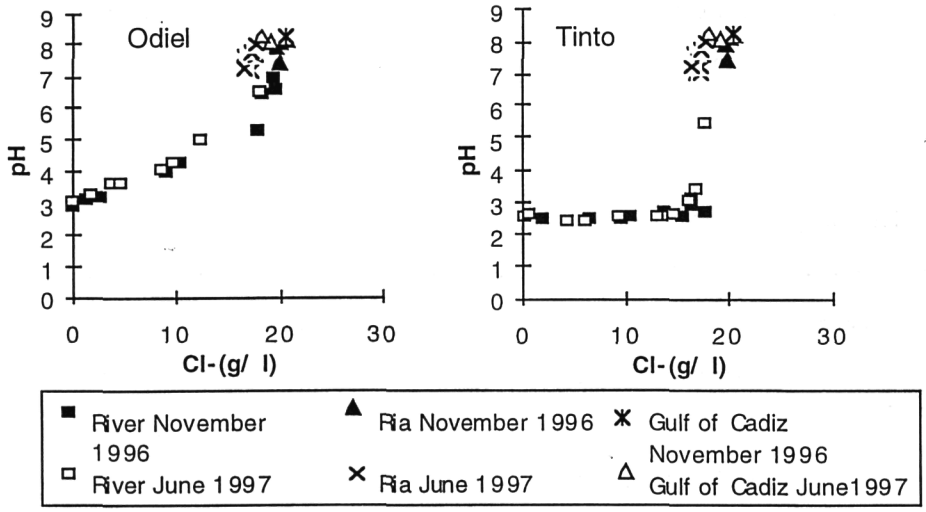


Fig.2: pH versus chloride concentration in the Odiel and Tinto rivers and Huelva estuary (Ria)

Previous studies (e.g. Cabrera et a.l, 1992; Campos, 1991; Nelson and Lamothe, 1993; Elbaz-Poulichet and Leblanc, 1996) have shown extremely high metal concentrations in the acidic waters and estuarine sediments. However, little information is available on the metal loads, metal speciation and temporal and spatial variability of trace metal concentrations in these rivers and their common estuary.

2. OBJECTIVES

The aims of TOROS project are:

1) To quantify the of metal fluxes discharged by the Tinto and Odiel rivers into the Gulf of Cadiz, and investigation of the estuarine processes which modify these metal fluxes during the extreme increase in pH encountered in this system (pH 2-8).

2) To study the fate of metals in the Gulf of Cadiz with respect to early diagenesis, hydrodynamics and biological activity occurring in this coastal sea.

3) To record effects of human activities on the local environment through historical times, from ancient mining (Phoenician, Roman) to present

3.WORKPLAN

Subtasks have been defined and are presented in the following table, along with the involvement of the different partners. In order to fulfil our aims and objectives, 4 cruises on the rivers, the estuary and the coastal waters of the Gulf of Cadiz have been scheduled during different seasons.

1) Metal biogeochemistry

The workplan includes discrete collection of water, suspended matter, sediments and interstitial water samples. The samples are be analysed in the laboratory for the determination of total metal concentrations (Cd, Cu, Ni, Co, Cr, Pb, Zn, As, Fe, Mn). High-resolution ship-board measurements of dissolved trace metal in estuarine and coastal surface waters are undertaken using automated voltammetry. In addition, studies of temporal variation of trace metals during tidal cycles are undertaken using automated voltammetric instrumentation.

The metal distribution in dated (C-14 and Pb-210) sediment cores from the estuary will be determined, in conjunction with sedimentological features of the cores. The cores represent an integrated picture of the mine inputs over a large time scale (ca 6000 years).

2) Biological processes

Nutrient (phosphate, nitrate species and silica) and chlorophyll concentrations, and phytoplankton species are analysed on a seasonal basis in the river, estuary and coastal waters of the Gulf of Cadiz.

3) Hydrology and sedimentology

In order to obtain a better understanding of the biogeochemical processes controlling the trace metal distribution and behaviour in this study area, and to provide water flow data for contaminant flux calculations, a considerable quantity of supporting information is required. The main characteristics that are investigated in the river and estuarine system include major ion concentrations, water and sediment discharge, sedimentation rates and mineralogy.

4) Modelling

As the necessary basis for understanding the fate and fluxes of trace metals in the Gulf of Cadiz, the hydrodynamics of this coastal system are modelled. The hydrodynamic model focuses mainly on the circulation of water in this coastal sea, but is modified to incorporate the data obtained for trace metals, nutrients and primary productivity. Remote sensing techniques are used to track the path of the estuarine plume during the sampling periods.

5) Data management and dissemination

A geostatistical treatment of all the data is performed and a GIS data base has been created, which will assist in data exchange and data availability. A web page has been set up at the start of the project in order to ensure a proper dissemination of the information within the TOROS project and with anyone interested in the project.

Partners / Subtasks	1	2	3	4	5	6	7	8
Trace metal biogeochemistry								
Freshwater/Seawater interface								
distribution	X					X		
speciation						X		
Sediment/Water interface								
early diagenesis					X			
Past and present fluxes to sediments	X	X						
Distribution in the waters of the Gulf of Cadiz					X	X		
Hydrology								
Major element concentrations		X						
Water discharge		X						
Sedimentology								
Sedimentation rates		X						
Mineralogy		X						
Biological Processes								
Nutrients								X
Primary Production								X
Modelling								
Hydrodynamic of the Gulf of Cadiz							X	
Trace metal or primary production							X	X
Remote sensing			X	X				
Data management								
GIS data base				X				
Geostatistic processing				X				

Table 1: List of subtasks and involved partners

Partner 1: University of Montpellier II, Partner 2: University of Huelva, Partner 3: INTA, Partner 4: University of Granada, Partner 5: University of Southampton, Partner 6: University of Plymouth, Partner 7: University of Liège, Partner 8: CEAB)

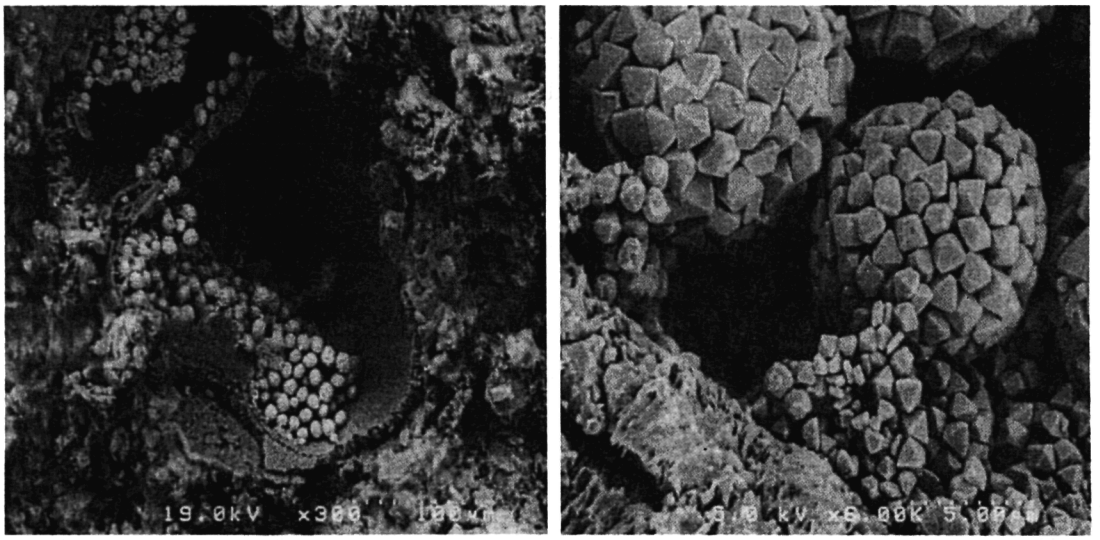
4. MAIN ACHIEVEMENTS TO DATE

Main achievements to date concern the hydrodynamical model, the biology and the metal geochemistry. In this paper we will mainly focus on the trace metal biogeochemistry.

1) History of metal mobilisation

In order to record the effects of human activities through historical times, a deep sediment core has been collected in the upper Tinto mixing zone. This core includes all the

quaternary deposits. Preliminary mineralogical observations show an important detrital input of pyrite grains (5-10%) in the most recent sediments, which can most likely be related to mining activities from the XIXth and XXth centuries. On the other hand, neo-formation of pyrite is occurring in deeper sediments where aggregates of pyritospheres are observed on organic-rich detritus such as mollusc shells, plant fragments (Fig. 3). Investigation into pyrite is important as Fe sulfide is expected to play an important role in storage of metals in the sediments. The samples are now being analysed for C-14 and metals in order to trace the variations of metal input from mining activities during the last two millenia.



(a) (b)

Fig.3: SEM pictures of pyrite neoformations in the sediments of the Rio Tinto estuary in relation with organic matter. (a) Within a shell. (b) Magnification of a pyritosphere

2) Metal behaviour in the dissolved phase of the mixing zone:

In November 1996 and June 1997 dissolved metal concentrations were extremely high in the Odiel and Tinto rivers when compared with other European river systems (Table2).

river	Cd	Cu	Fe	Zn	Pb	As
Gironde (1, 2, 3,4)	0.35-0.52	13	139	18	0.26	13
Loire (4, 5)	0.25				0.39-0.89	
Seine (6, 7)	0.35	32	40	105	1.4	
Rhone (8, 9)	0.27	35	232	20	0.42	
Tinto (TOROS)	2617	448000	12000000	890000	5555	29253
Odiel (TOROS)	868	137000	734000	418000	307	369

Table 2: Dissolved metal concentrations (nM) in the largest French rivers and in the Tinto and Odiel rivers. Data for the Tinto and Odiel rivers may vary on a seasonal basis. Data presented in this table refer to the November 1996 survey. 1) Kraepiel et al., 1987; 2) Elbaz-Poulichet et al., 1987; 3) Seyler, 1985; 4) Elbaz-Poulichet, 1988; 5) Boutier et al., 1993; 6) Chiffoleau et al., 1994; 7) Huang and Mouchel, 1994; 8) Elbaz-Poulichet et al., 1996; 9) Guieu et al., 1993.

Higher metal concentrations were observed during the November survey compared with the June survey. During both surveys all the metals (Mn, Al, Zn, Cd, Cu), with the exception of U and As, showed a close correlation with Mn and Fe (see Fig. 4). A slight removal of dissolved metal was observed in the mixing zone of the Odiel, whilst a clear mobilisation of metals occurred during the early stage of mixing in the Tinto (Fig. 5).

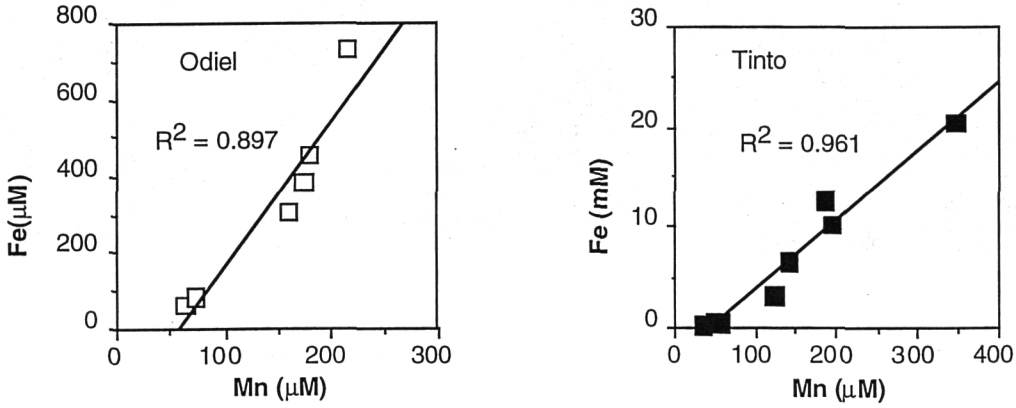


Fig. 4: Example of metal correlations observed in the Tinto and Odiel mixing zone. Similar relation were observed for Al, Zn, Cd, Cu and Ni

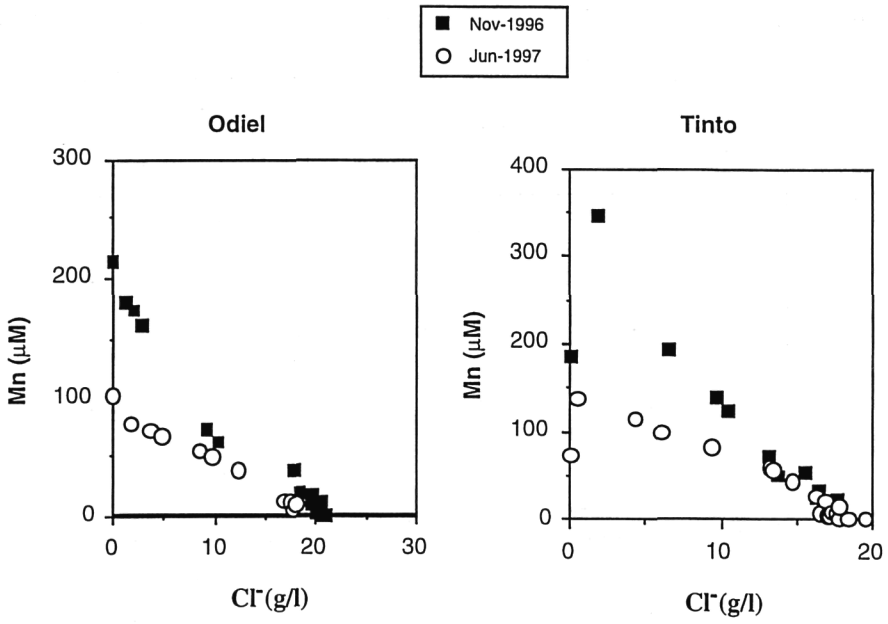


Fig. 5: Mn vs Cl in the Odiel and Tinto mixing zone. Similar relations were observed for Fe, Al, Zn, Cd, Cu and Ni.

A source for dissolved U was apparent in the mixing zone of the Rio Tinto (Fig. 6). The most likely input source for U is formed by run-off from phosphogypsum deposits along the northern bank of the Rio Tinto. Furthermore, a sink for dissolved U was observed in the Odiel mixing zone.

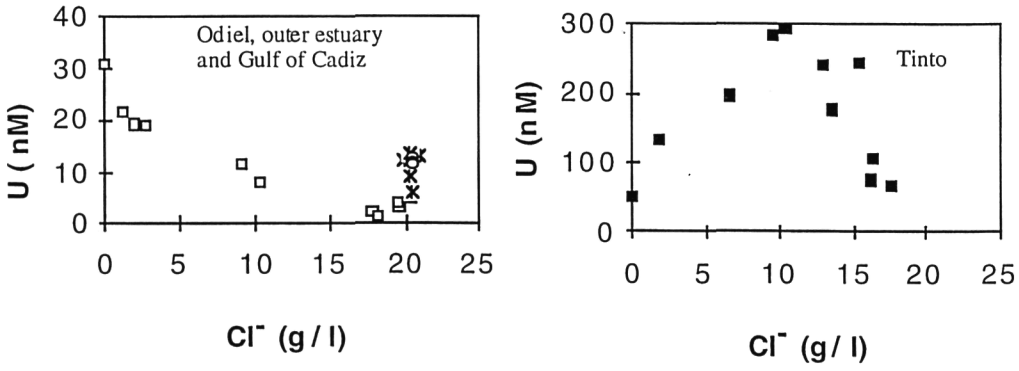


Fig.6: U vs Cl in the Odiel and Tinto mixing zones.

In the Tinto mixing zone, total dissolved As showed a contrasting behaviour (Fig.7) depending on the season and/or on the hydrology. In November, As was mainly supplied to

the estuarine zone by the river and its behaviour was correlated with Fe and Mn. However, the dissolved As distribution in June suggested the presence of an intra-estuarine source.

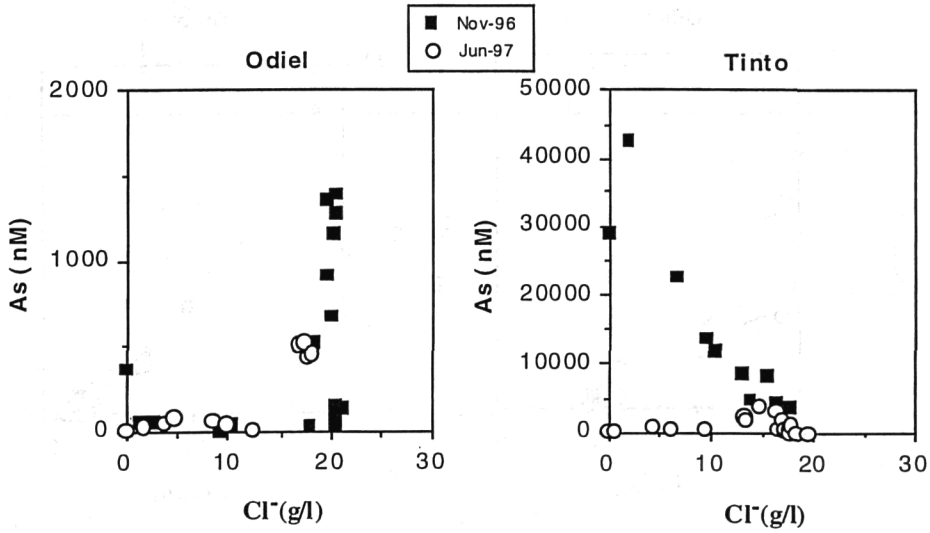
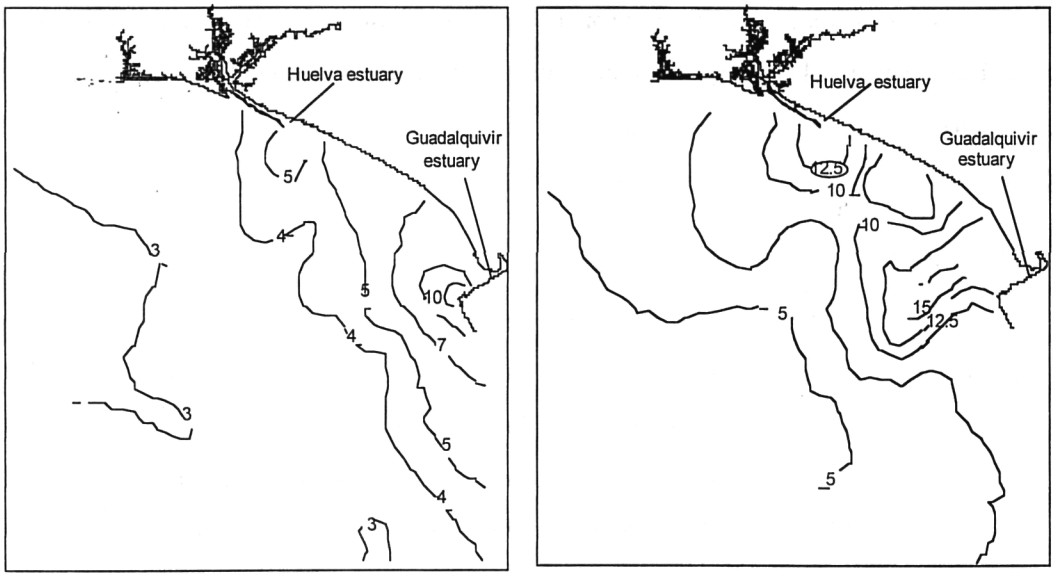


Fig.7: As vs Cl in the Odiel and Tinto mixing zones.

In the Odiel river, As distribution was characterised by a strong increase in concentrations in the lower mixingzone, a phenomenon which can possibly be attributed to direct industrial effluent inputs from fertiliser plants, copper smelting and pyrite processing industries situated in this area and/or to the entrainment of As enriched Tinto waters into the Odiel river. The next two surveys which are planned for 1998 are intended to assist us with the assessment of the importance of the temporal variability in metal concentrations, which does not appear to be directly related to the fresh water discharges by the Rio Tinto and Odiel.

3) Metal concentrations in the Gulf of Cadiz

Discrete samples were collected in the Gulf of Cadiz in November 1996. In June 1997, continuous underway sampling and automated voltammetric metal analysis were carried out on-board ship, resulting in about 250 on-line measurements of dissolved Cu and Ni in the surface waters. Distributions of total dissolved Cu and Ni concentrations in surface waters of the Gulf of Cadiz are shown in Fig. 8, in the form of contour plots. These metal distribution data have not been corrected for tidal movement yet.



(a) (b)

Figure 8: Distribution of total dissolved Ni (a) and Cu (b) in surface waters of the Gulf of Cadiz, June 1997.

Enhanced metal levels were observed around the mouths of the Huelva (15 nM Cu, 5 nM Ni) and the Guadalquivir (20 nM Cu, 15 nM Ni) estuaries. Metal concentrations decreased with increasing distance from the coast to levels below 5 nM Cu and 3 nM Ni at the sea-ward limit of the sampling area. This decrease can be explained by the mixing of metal-polluted estuarine with more pristine North Atlantic waters, which typically have surface water concentrations of 1 - 1.5 nM Cu and 1.8 - 2.5 nM Ni (Morley et al., 1993; Landing et al., 1995). The difference between the enrichment of Cu (ca. 3 - 5 times) and Ni (ca. 1 - 2 times) in the outer Gulf of Cadiz, calculated with respect to typical off-shore concentrations for the Atlantic Ocean, is most likely the result of a strong enrichment of Cu and the absence of Ni enrichment in the geology of the Iberian Pyrite Belt. Dissolved metal concentrations measured during this survey are comparable to those published by van Geen *et al.* (1991), who reported typical dissolved concentrations over the Spanish shelf in the region of 6.6 nmol kg^{-1} Cu and 3.4 nmol kg^{-1} Ni, and levels of 8 - 21 nmol kg^{-1} Cu and 3 - 6 nmol kg^{-1} Ni some 40 km to the south-west of the Guadalquivir estuary.

Further studies will be focusing on the detailed investigation of fluxes and variability in Huelva estuary metal discharges and the spatial development of the metal plume in the Gulf of Cadiz.

4) Interdisciplinary modelling:

The GHER 3D model has been improved by adding the possibility to include a nested model into a larger scale model. For the TOROS project, this means that we have now a model with a 4km resolution covering the Gulf of Cadiz and the Alboran sea. Into this region, a model with 1.3 km was nested, with a coverage which corresponds to the June cruise of the TOROS project. The nesting procedure relies on a two way nesting technique, designed to extract boundary conditions for the fine scale model from the coarse grid model by interpolating parabolically the fields at the open boundary of the fine scale model. This interpolation is done such that the sum over the fine grid cells covered by a large cell is identical to the large cell content. Experiments with an academic test case in which a frontal system is perturbed showed that to obtain a robust method, one should use a nesting on temperature and salinity values rather than on heat and salt fluxes. Though this does not conserve heat and salt between the fine model and the large model, it behaves dynamically correctly. For biological tracers however, fluxes can be used for the nesting procedure, with the advantage of an explicit conservation of the tracers. After testing this method in the academic situation, where it proved to be robust enough and computationally efficient, the system was applied to the real case of the Gulf of Cadiz. Here some care was taken so that the two topographies (the one in the large scale model and the one in the fine scale model) were coherent. Then the model setup was done by using monthly averaged climatologies for the open boundary conditions in the western and eastern boundaries, as well as for sea surface temperature and salinity values. First, monthly averaged wind stresses were used to force the model initialised with January climatology. After one year of simulation, the nesting was implemented by interpolating the large grid results into the fine model. First results indicate robust results concerning the inflow of Atlantic waters into the Mediterranean sea (the Alboran sea gyre is always well represented) and the outflow of deep Mediterranean waters into the Atlantic. The current offshore of the Rio Odiel and Rio Tinto is mostly directed

towards the Gibraltar strait, whereas the central part of the Gulf of Cadiz exhibits some variability in the model results. If this variability is related to the dynamics of the region or simply to the adjustment of the system to the initial condition has to be clarified. Indeed, the deeper regions of the Gulf of Cadiz were almost void of hydrographic data, so that the initial density fields may be too far from a climatological situation. Presently, the study is to be extended by replacing the climatological atmospheric forcings by ECMWF daily data, by coupling the 5 state variable biological model to the nested version and by making a sensitivity analysis of the average model results on tidal movements excluded up to now.

5. CONCLUSIONS

This study is the first multidisciplinary approach intended to investigate the extreme trace metal enrichment, which occurs in the Huelva river and estuarine system and continental shelf waters of the Gulf of Cadiz. The preliminary results show highly acidic, and metal enriched waters discharged by the Huelva estuary into the Gulf of Cadiz. Metal pollution is the result of mine drainage in the upper catchment and industrial inputs into the lower catchment of the system. Dissolved Fe and pH appear to be the geochemical master variables in this system. The strong tidal influences on the estuary, with a strong seasonal variation in freshwater discharges result in a high temporal and spatial variation in metal concentrations. Improved knowledge concerning the key processes controlling metal concentrations in the system is required to allow predictions on the effect remedial actions will have on this system.

Gulf of Cadiz Water (GCW) has a distinct identity with enhanced metal levels, and may provide up to 20% of the inflow into the Mediterranean. The TOROS project complements the MAST III targeted program on Canary-Azores-Alboran Sea-Strait of Gibraltar (CANIGO). An important aim of CANIGO includes the evaluation of biogeochemical fluxes through the Gibraltar Straits. In the coming year, metal and nutrient data obtained during the TOROS surveys will be included in the hydrodynamical model developed in the framework of TOROS, by the group at the University of Liege. The data will be used for model validation and metal concentrations measured at the Strait of Gibraltar in the framework of CANIGO will be compared with those computed using the model.

The environmental situation in the Tinto area has important socio-economic implications for the population in the region. The legacy of the mining activities has resulted in large amounts of waste materials and severe soil degradation. Run-off of acid mine drainage from mining areas has contaminated fish and shellfish and has jeopardised water intake for agricultural and potable water purposes. The rehabilitation of the Rio Tinto mining area and its surface waters is therefore an important issue. An improved scientific understanding of the physico-chemical processes influencing the water quality in the mining area is therefore important for decisions on rehabilitation measures to be decided on by policy makers. The TOROS project will provide valuable information to assist in the rehabilitation project and in subsequent water pollution management programmes. This aspect of water resource and coastal zone management is important in south European regions and especially in the province of Huelva which suffers from chronic lack of water to cover agricultural and health needs. Furthermore, the results of this study will be used for the estimation of the impact of the Huelva system on trace metals inputs into the Western Mediterranean basin.

TOROS web page: http://carpanta.ugr.es/toros.html

REFERENCES

BOUTIER, B, CHIFFOLEAU, J.F., AUGER, D. AND TRUQUET, I., 1993. Influence of the Loire river on dissolved Pb and Cd concentrations in costal waters of Brittany. Est. Coast. Shelf Sci., 36, 133-145.

BOYLE E., CHAPNICK, S., BAI X., AND SPIVACK, A., 1985. Trace metal enrichments in the Mediterranean Sea. Earth Planet. Sci. Lett., 74, 405-419.

CABRERA, F., CONDE, B. AND FLORES, V. 1992. Heavy metals in the surface sediments of the tidal river Tinto (SW Spain). Fresenius Environ. Bull., 1, 400-405.

CAMPOS, J.M., 1991. Contamination por metales en los sedimentos de los rios Tinto y Odiel. Ph-D thesis. University of Sevilla.

CHIFFOLEAU, J.F., COSSA, D., AUGER, D. AND TRUQUET, I., 1994. Trace metal distribution, partition and fluxes in the Seine estuary (France) i low discharge regime. Mar. Chem., 47, 145-158.

ELBAZ-POULICHET, F. AND LEBLANC, M., 1996. Transfert de métaux d'une province minière à l'océan par les fleuves acides (Rio Tinto, Espagne), C.R, Acad. Sci. Paris; t.322, série II a, 1047-1052.

ELBAZ-POULICHET, F., 1988. Apports fluviatiles et estuariens de Pb, Cd, Cu a l'ocean, comparaison avec l'apport atmosphérique. These de Doctorat d'Etat, Université de Paris VI, 288pp.

ELBAZ-POULICHET, F., GARNIER, J.M., GUAN, D.M., MARTIN, J.M., AND THOMAS A.J., 1996. The conservative behaviour of trace metals (Cd, Cu, Ni and Pb) and As in the surface plume of stratified estauries. example of the Rhone river (France). Est. Coast. Shelf. Sci., 42, 289-310.

ELBAZ-POULICHET, F., MARTIN, J.M., HUANG, W.W.AND ZHU, J.X., 1997. Dissolved Cd behaviour in some selected French and Chinese estuaries, Consequences on Cd supply to the ocean. Mar., Chem 22, 125-136.

GUIEU, C., ZHANG, J., THOMAS, A., MARTIN, J.M. AND BRUN-COTTAN, J.C., 1993. Significance of the atmospheric fallout on the upper layer water chemistry of the northwestern Mediterranean Sea. Journal of Atmospheric Chemistry, 17, 45-60.

HUANG, W.W.AND MOUCHEL, J.M., 1994. Concentrations totales et formes chimiques des metaux dissous dans la Seine. Rapport 1994/III, Piren Seine, GDR Analyse et modelisation des systemes fluviaux anthropises.

KRAEPIEL, A., CHIFFOLEAU, J.F, MARTIN, J.M. AND MOREL, F.M.N., 1997. Geochemistry of trace metals in the Gironde estuary, Geochim. Cosmochim. Acta, 70, 1421-1436.

LANDING, W.M., CUTTER, G.A., DALZIEL, J.A., FLEGAL, A.R., POWELL, R., T SCHMIDT, D. SHILLER, A, STATHAM, P., WESTERLUND S. AND RESING, J. 1995. Analytical intercomparison results from the 1990 Intergovernmental Oceanographic Commission open-ocean baseline survey for trace metals: Atlantic Ocean. Mar. Chem., 49, 253-265.

MORLEY, N. AND BURTON, J., 1992. In Water Pollution Research Report Series of the Environmental Programme of the CEC, n°30, 111-117.

MORLEY, N.H. STATHAM, P.J. AND BURTON, J.D, 1993. Dissolved trace metals in the southwestern Indian Ocean. Deep-Sea Research I, 40, 1043-1063.

NELSON, C.H. AND LAMOTHE, P.J., 1993. Heavy metal anomalies in the Tinto and Odiel river and estuary system, Spain. Estuaries, 16, 495-511.

ROTHENBERG, B., AND BLANCO FREIJERO, A., 1980. In Scientific studies in early mining and extractive metallurgy, Craddock, P, eds, British Museum Occasion, 20.

SEYLER, P., 1985. Formes chimiques et comportement de l'As en milieu estuarien. Thèse de Doctorat, Université de Paris VI, 194pp.

STRAUSS, C.K., MADEL, AND FERNANDEZ, A., , 1977. in: 3time and strata bound ore deposits, Klemm D. and Schneider, H. eds, Springer Verlag, Berlin, 55-93.

VAN GEEN A., ROSENER, P., AND E.A., BOYLE, 1988. Entrainment of trace metal-enriched Atlantic shelf-water in the inflow to the Mediterranean Sea. Nature, 331, 423-426.

VAN GEEN, A., ADKINS, J.F., BOYLE, E.A., NELSON, C.H. AND A. PALANQUES, 1997. A 120-yr record of widespread contamination from mining of the Iberian pyrite belt. Geology, 25, 291-294.

VAN GEEN. A., BOYLE, E.A., AND W., MOORE, 1991. Trace metal enrichments in waters of the Gulf of Cadiz, Spain. Geochim., Cosmochim., Acta, 55, 2173-2191.

TITLE: ROLE OF BUFFERING CAPACITIES IN STABILISING COASTAL LAGOON ECOSYSTEMS (« ROBUST »)

CONTRACT N°: ENV4-CT96-0218 (Environment & Climate)

CO-ORDINATOR: Dr. Rutger DE WIT,

Laboratoire d'Océanographie Biologique. UMR 5805 Environnements et Paléoenvironnements Océaniques, Université Bordeaux 1 & CNRS, 2 rue Jolyet, F-33120 ARCACHON, Aquitaine, France

PARTNERS:

Dr. Marc TROUSSELLIER, Laboratoire d'Hydrobiologie Marine, Université Montpellier II & CNRS URA 1355, Place E. Bataillon, F-34060 MONTPELLIER, France

Dr. Lucas J. STAL, Center for Estuarine and Coastal Ecology, Netherlands Institute of Ecology, PO Box 140, NL-4400 AC YERSEKE, The Netherlands

Dr. Hans VAN GEMERDEN, Dept of Microbiology, University of Groningen, PO Box 14, Kerklaan 30, NL-9751 NN HAREN, The Netherlands

Prof. Ireneo FERRARI & Dr. Pierluigi VIAROLI, Dipartimento Scienze Ambientali, Università di Parma, Università di Parma, Viala della Scienze, I-43100 PARMA, Italy

Prof. Remigio ROSSI & Prof. Victor U. CECCHERELLI, Dipart. Biologia Evolutiva, Università di Ferrara, Via L. Borsari 46, I-44100 FERRARA, Italy

Prof. Rodney A. HERBERT, Dept of Bological Sciences, University of Dundee, GB-DUNDEE DD1 4HN, Scotland, United Kingdom

Prof. Francisco RODRÍGUEZ-VALERA, Departamento de Ciencias y Tecnología, Universidad Miquel Hernández, ALICANTE, Communidad Autonoma de Valencia, Spain

Dr. Bente Aa. LOMSTEIN, Dept of Microbial Ecology, Institute of Biological Sciences, University of Aarhus, Building 540, Ny Munkegade, DK-8000 AARHUS C, Denmark

THE ROLE OF BUFFERING CAPACITIES IN STABILISING COASTAL LAGOON ECOSYSTEMS (« ROBUST »)

RUTGER DE WIT[1)], LUCAS J. STAL[2)], BENTE AA. LOMSTEIN[3)], RODNEY A. HERBERT[4)], MARC TROUSSELLIER[5)], HANS VAN GEMERDEN[6)], PIERLUIGI VIAROLI[7)], VICTOR U. CECCHERELLI[8)] & FRANCISCO RODRÍGUEZ-VALERA[9)]

[1]UMR EPOC 5805, Université Bordeaux 1 & CNRS, Arcachon, France, [2]Center for Estuarine and Coastal Ecology, N.I.O.O., Yerseke, The Netherlands, [3]University of Aarhus, Aarhus, Denmark, [4]University of Dundee, Dundee, U.K [5]Université Montpellier II & CNRS URA 1355 [6]University of Groningen, Groningen, The Netherlands, [7]Università di Parma, Parma, Italy, [8]Università di Ferrara, Ferrara, Italy [9]Universidad Miquel Hernández, Alicante, Spain

1. SUMMARY

This project focuses on identifying, describing and defining the biotic and abiotic processes in coastal lagoons that act as buffers against environmental change induced by external forcing. These mechanisms provide stability and robustness, but when their capacities are exceeded they give rise to non-linear responses. Non-linear behaviour of coastal ecosystems has been recognised as a major reason why such changes are difficult to predict. Buffering capacities need to be restored on an appropriate timescale in order to provide the long-term sustainability and economic, social and scientific value of these unique ecosystems.

This project involves mechanistic studies and requires a multi-disciplinary approach involving microbiologists, marine biologists (algologists and zoologists), biogeochemists, and system ecologists. This study focuses on the following processes that are related to buffering capacities: 1) role of sediment oxygenation in rooted phanerogam communities and microbial processes in the rhizosphere; 2) primary production of plant and algal biomass as a mechanism for countering the effects of nutrient load; 3) the iron redox system in the sediment and its role as trap for toxic hydrogen sulphide and sequestering phosphate; 4) the rates and pathways of benthic mineralisation of organic carbon, nitrogen and phosphorus compounds, and how they are regulated by the quality, quantity, availability and sedimentary depth distribution of organic matter inputs as well as how they determine nutrient fluxes across the sediment water-interface.

A major component is directed to the study of processes associated with rooted phanerogam communities which are characteristic of healthy, but only relatively stable coastal lagoon ecosystems. Special emphasis is focused on the meadows of the small seagrass species *Zostera noltii* Hornem. in the Bassin d'Arcachon (South-West France). This is compared with analogous processes occurring in macroalgal and cyanobacterial dominated systems where the buffering capacity has been exceeded as a consequence of eutrophication, contamination or physical factors. The work content is organised in four work packages: 1) field measurements on annual time-scales, 2) detailed and intensive field measurements during joint field campaigns in the Bassin d'Arcachon to study processes that occur on short time scales, 3) mesocosm experiments to evaluate the effect of forcing factors, and 4) laboratory experimentation to study the ecophysiology of individual microbial species and the interactions occurring amongst physiologically dissimilar populations.

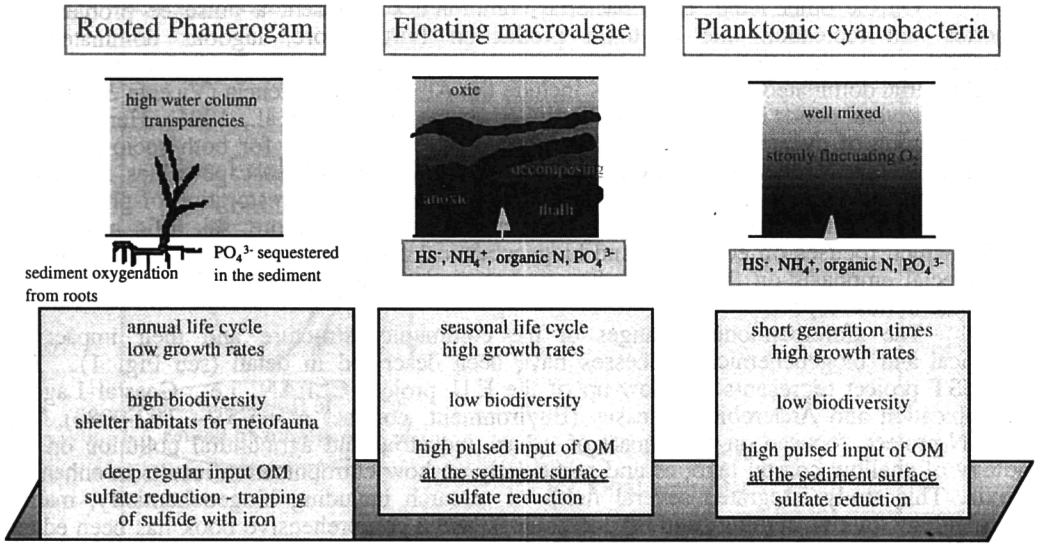


Fig. 1: Some major ecological and biogeochemical processes in shallow coastal lagoons characterised by three different primary producer communities (OM = organic matter)

2. INTRODUCTION

Environmental change due to external forcing is difficult to predict in coastal systems, due to the problems of non-linear responses (Cadée et al., 1994). Well documented important non-linear responses of coastal lagoons subject to pollution/eutrophication include abrupt historical shifts of the plant communities from original rooted phanerogams (*Zostera*, *Ruppia*) to communities dominated by floating macroalgae (*Ulva*, *Monostroma*, *Enteromorpha*, *Gracillaria*) or planktonic cyanobacterial blooms. Concomitantly, drastic changes occur with respect to biogeochemical flows and cycles. Rooted phanerogam communities represent healthy ecosystems, with low annual fluctuations of biomass, high macroorganism biodiversity, high water column transparencies, complex trophic relationships, efficient sediment oxygenation and slow rates of internal recycling (Sand Jensen and Borum, 1991; Caumette et al., 1996).

There has been a world-wide decline of seagrass meadows, particularly also in European intertidal areas and lagoon systems from Denmark to the Mediterranean. Fortunately, Arcachon Bay (S.W. France), which is a macrotidal lagoon (155 km^2) on the Atlantic coast, has maintained the nowadays most extensive seagrass meadows of the small species *Zostera noltii* Hornem. in Western Europe (covering 70 km^2 of the intertidal flats). This outstanding environment has also important values for wildfowl, i.e., 40,000 Brent geese (*Branta bernicla bernicla*) overwinter in this area and forage on the seagrass meadows. It has been included in the « Zone of Special Protection » according to the E.C. directive (AN01), and has been selected for the European coastal zone management demonstration project TERRA which is supported by the E.C. DG XI, DG XIV, and DG XVI (European Commission, 1997).

In contrast, floating macroalgal communities represent strongly fluctuating biomasses, with a peak which correlates well with the level of nitrogen inputs (Piriou & Ménasguen, 1992; Chapelle et al., 1994). These systems exhibit shortened food-chains, high rates of internal recycling (Sand-Jensen and Borum, 1991, Viaroli et al., 1997) and are susceptible to dystrophic crises during warm periods, which in several cases occur annually (Caumette, 1986; Izzo and Hull, 1991; Sfriso et al., 1992; Viaroli et al., 1992, 1993). Macroalgal blooming is a particular nuisance in Bretagne (France), French Mediterranean lagoons and Italian lagoons in the Po delta (Adriatic coast). In order to ameliorate the symptoms of dystrophic crisis, many regional and local authorities in Western Europe currently harvest algal biomass and even engage expensive oxygenation of lagoon water.

On the other hand, cyanobacterial communities represent a nuisance problem for fisheries and recreation due to toxin production Furthermore, lagoons dominated by cyanobacteria are characterised by a low macroorganism biodiversity. Particular examples of cyanobacterial dominated coastal lagoons include the Albufera de Valencia (Vicente & Miracle, 1992) and several ponds in the Italian Valli di Comacchio (Sorokin et al., 1996). Hence, large-scale blooming of cyanobacteria and macroalgae must be prevented for both socio-economic reasons as well as for the conservation of biodiversity and land- and seascape values. A positive measure constitute the development of policies for conservation and restoration of phanerogam communities within the frame of coastal zone management. Therefore, scientific research is needed which focuses on ecological and biogeochemical processes in shallow coastal lagoons with special emphasis on the role of the primary producer communities. ROBUST aims to contribute in this respect.

The aforementioned changes of the community structure and their impact on ecological and biogeochemical processes have been described in detail (see Fig. 1). The ROBUST project represents a follow-up of the E.U project CLEAN, i.e., Coastal Lagoon Eutrophication and Anaerobic processes (Environment, contract n° EV5V-CT92-0080). The CLEAN project focused on the impact of urban, industrial and agricultural pollution on the biology of shallow coastal lagoons and particularly on how eutrophication results in enhanced anoxia. This study integrated several fields of research including biogeochemistry, marine microbiology, marine algology and marine zoology and a comprehensive book has been edited by Professors Pierre Caumette, Rodney A. Herbert and the late Dr. Jacques Castel (Caumette et al., 1996). As a result of the data obtained in the CLEAN project we developed new concepts which would allow more detailed mechanistic studies to be undertaken. The aim is to increase our understanding of stability and succession phenomena in coastal lagoons.

We recognise that it is possible to identify biological, biogeochemical and geochemical processes within coastal lagoon systems which act as buffers against environmental change. Our objective is to identify, describe and define these biotic and abiotic components of internal processes with their interrelationships and how they act as buffers against environmental change. We think that buffering processes are a major reason for non-linear behaviour of coastal lagoon ecosystems. Sudden drastic changes of community structures occur whence the buffering capacity is exceeded; hence, buffering capacities can be quantified and as a mechanistically defined concept it facilitates experimental studies. This concept can however be related to holistically defined concepts, i.e., buffering capacities provide « local stability » and the « resilience » of ecosystems is related to efficient recycling or regeneration of buffering capacities. These concepts are depicted in Fig. 2, which also shows our working hypothesis for the community shifts in shallow coastal lagoons upon nitrogen loading. It seems that forcing with phosphorus gives rise to succession towards blooming cyanobacteria, but this has been unsufficiently documented so far.

We address this field of research by mechanistic studies requiring a multi-disciplinary approach involving microbiologists, marine biologists (algologists and zoologist), biogeochemists, and system ecologists. Although no ecosystem modellers directly participate in ROBUST, we recognise the importance of this discipline and we have established links with ecosystem modellers particularly Professor Christian of the University of East Carolina (U.S.A.) and by our participation in the ELOISE thematic group 3 on modelling and data management.

Buffering capacities thus contribute to resistance and stability of ecosystems. They give rise to time delays and slowing down of biogeochemical processes, thereby circumventing the impact of pulsed phenomena and catastrophic events. However, buffering capacities need to be restored on an appropriate time-scale to provide long-term sustainability. Therefore, the concept of buffering capacities may prove to be operational and useful for coastal zone management. Firstly, one can envisage a situation of an apparently healthy seagrass community close to a saturation of its buffering capacities and therefore susceptible to sudden undesirable changes. Scientific research will help to reveal the relevant parameters behind saturation of buffering capacities and this must be translated in indices that are useful for coastal zone managers. Improved predictability will help to anticipate and thus to interfere, mitigate or

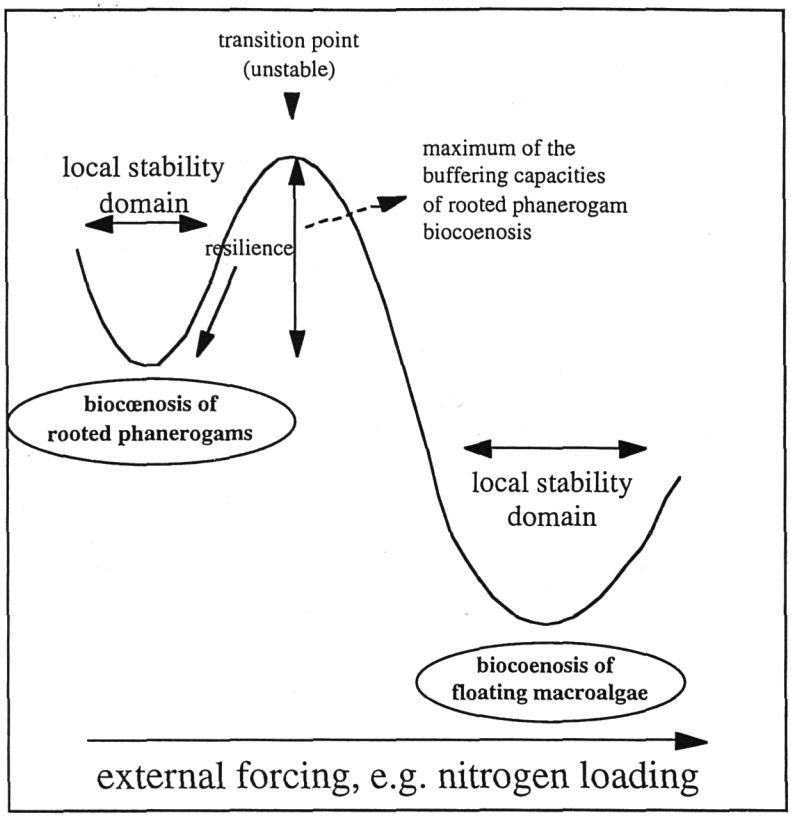


Fig. 2 Conceptual scheme of an ecosystem trajectory in a shallow coastal lagoon ecosystem subject to external forcing e.g. increased nitrogen inputs. The pristine biocoenosis of rooted phanerogams present a certain resistance towards change of community structure, which is characterised by the so-called « local stability domain ». Once the threshold forcing level has been surpassed (transition point) the community becomes unstable and the original biocoenosis will be replaced by floating macroalgae which occupy a new local stability domain « degraded state ». The distance « upslope » to the transition point represents the buffering capacities of the biocoenosis, which are maximal in the « valley » of its local stability domain. Hence, buffering capacities can be saturated to a certain extent in particular ecosystems. Resilience is a measure of the speed of return to the original « valley » and can be related to the speed of regeneration or restoration of buffering capacities.

counteract before catastrophic events take place. Secondly, the recognition of the importance of buffering capacities and their restoration and regeneration processes is most important for designing strategies for the restoration of seagrass habitats. Thus, it will not be sufficient only to plant rooted phanerogams in shallow coastal lagoons, rather should one also restore the hydrological and biogeochemical sedimentary environment to ensure the long-term sustainability of the restored biotopes.

3. OBJECTIVES

The proposal "ROle of BUffering capacities in STabilising coastal lagoon ecosystems" has the following objectives:

1- To identify, describe and define the biotic and abiotic components of internal processes and their interrelationships in coastal lagoon systems which act as buffers against environmental change induced by external forcing.
2- Once described and defined, the objective is to quantify the "buffering capacity" and, consequently, to determine the threshold levels of external forcing processes, above which they have a major impact on community structure and biogeochemical flows.
3- To study the potential and occurrence of mechanisms that represent natural recycling and restoration of "buffering capacities" on different time scale's (including studies of diel and tidal cycles as well as seasonal variations).
4- To perform mechanistic studies to elucidate interactions among organisms, which belong to different taxonomic and ecological functional groups, and their abiotic environment, in order to achieve understanding of buffering capacities that occur at the community level.

The project very actively contributes to the thematic network ELOISE. We participate strongly to the thematic working groups 2 and 3, i.e. « Ecosystem structure and functioning and human impacts » and « Modelling and data management », respectively. To a lesser extent we contribute in thematic group 1 « Global change and biogeochemical cycles ». The University of Bordeaux as co-ordinator of the ROBUST project has organised the first annual scientific ELOISE conference which took place 21-23 May 1997 in Arcachon (France).

4. WORKPLAN

The choice of the lagoons has been based on their importance with respect to the objectives of the study and according to criteria's of availability of scientific background information and sampling logistics (proximity of a partners laboratory). Thus, the Bassin d'Arcachon and the Sacca di Goro, have been chosen as the major field sites:

1) Bassin d'Arcachon (Atlantic coast, S.W. France) as an example of rooted phanerogam communities. This lagoon represents the most extensive intertidal meadows of the seagrass *Zostera noltii* in Western Europe (70 km^2). This environment is characterised by a strong tidal activity which ensures regular mixing of the water body. The Marine Station in Arcachon provides laboratory facilities, lodgement for researchers and students and a 12 m research vessel, which allows to organise joint field campaigns every year.
2) Sacca di Goro (Adriatic coast, Po delta, Italy) as an example of an intermediate hypertrophic lagoon in which rooted phanerogams (mainly *Ruppia*) had been displaced by *Gracillaria* and *Ulva*. Water exchange is limited in comparison to Arcachon.

Occasionally, specific studies have been performed in artificial fish-ponds in Certes (Audenge, S.W. France), Etang du Prévost (Palavas, S. France), the S'Ena Arrubia (Sardinia, Italy), Valli Smarlacca and Valli di Comacchio (N.E. Italy). The fish-ponds in Certes and the Valli Smarlacca represent systems dominated by the rooted phanerogam *Ruppia cirrhosa* Petanga, whilst several ponds in the Valli di Comacchio offer the opportunity to study systems dominated by cyanobacteria. In the frame of our project we focus on the following key-issues:

i- The importance of benthic processes

Sediments are an extremely important component of shallow marine environments, as particulate organic matter (POM) is concentrated 10,000 to 100,000 fold in the sediment relative to seawater. Consequently, coastal lagoon sediments fuel intensive biogeochemical activity including the mineralisation of organic matter. Aerobic mineralisation in the sediment is limited by the oxygen supply which is regulated by 1) the diffusive flux through the sediment water

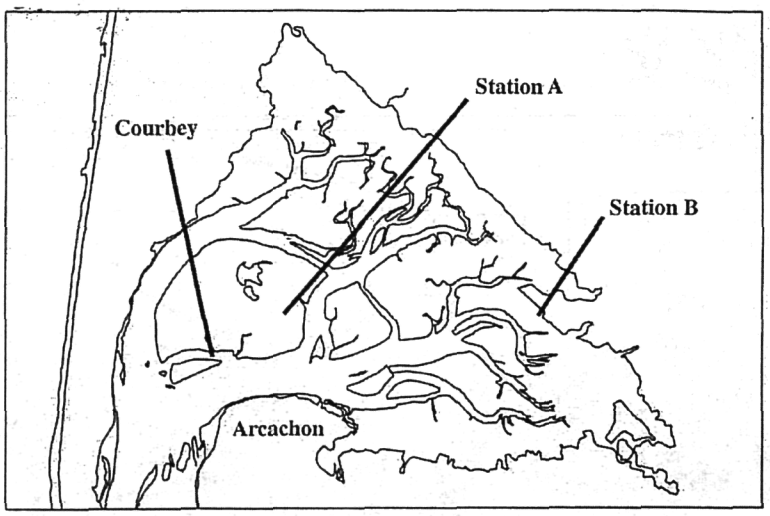


Fig. 3: Map of « Le Bassin d'Arcachon » located on the S.W. coast of France. The ROBUST sampling stations A and B correspond to intertidal *Zostera noltii* meadows. Occasionally, studies have been performed at the subtidal station in the « Chenal du Courbey », which is a tidal channel.

interface, 2) direct supply from plant roots and 3) burrowing and pumping activities of the benthic infauna. Therefore, rooted plants and benthic infauna have a major impact on sediment oxygenation and act as a buffer against oxygen deficiency. Nevertheless, anaerobic mineralisation often accounts for more than 50 % of the organic matter mineralisation in coastal marine ecosystems (Jørgensen, 1982, 1989). Sulphate is the key electron acceptor in anaerobic respiration in coastal environments. This compound is converted by the sulphate-reducing bacteria into sulphide which is a toxic for all living organisms. Only organisms belonging to a limited number of taxonomic groups, principally prokaryotes, can tolerate this compound to a certain degree. Hence, environmental problems due to discharge and run-off of organic and inorganic nutrients are often manifested by enhanced sulphate reduction and release of toxic sulphide in the ecosystem, which affects biodiversity for obvious reasons. We evaluate the toxicity of sulphide of the key fauna species *Acartia tonsa* , *Mysochra pontica.* (copepods), and *Mythilus* sp., *Scapharca inaequivalis* and *Venus Gallina.* On the other hand, the potential of microbial reoxidation of sulphide by chemotrophs and phototrophs is assayed at various sites to study ecosystem resilience towards increased rates of sulphate reduction.

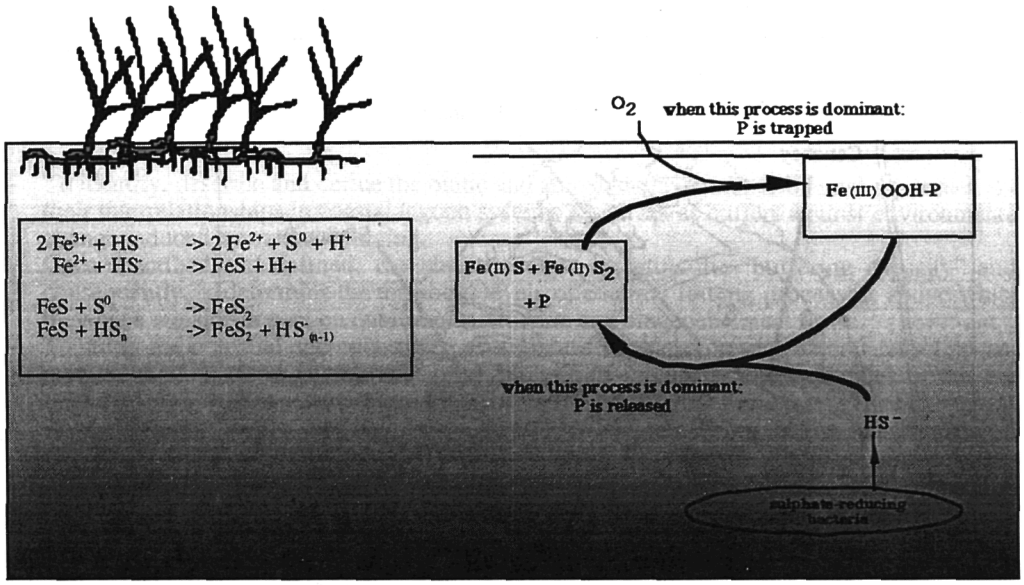


Fig. 4: Biogeochemical role of iron as a buffer: chemical reactions leading to trap of sulphide (left hand panel) and redox-cycling of iron compounds in relation to phosphate mobilisation/immobilisation (right-hand panel).

ii- Role of the iron redox system in the sediment

Several mechanisms exist by which sulphide can be removed, those which trap it contribute to the buffering capacity of an ecosystem. Ecologically the most important example of sulphide trapping is iron (see Fig. 3): ferric iron (Fe^{3+}) can be reduced to ferrous iron (Fe^{2+}) by sulphide (H_2S) to form zero-valence sulphur (S^0), and the ferrous iron formed then can combine with another sulphide atom to form ferrous sulphide (FeS). Furthermore, pyrite (FeS_2) can be formed by the reaction of FeS with elemental sulphur (Berner, 1984) or by the rapid reaction of FeS with polysulphides (Luther, 1991). At high oxygen tension, FeS is oxidised through an abiotic reaction, whilst microbial oxidation processes may be important at low oxygen tension or under anaerobic conditions. The different iron and sulphur pools in the sediment are monitored (e.g., Giordani et al., 1996, 1997; Stal et al., 1996).

Ferric iron hydroxide also efficiently sequesters phosphate in the sediment. This may be a mechanism whereby phytoplankton productivity remains limited, thus ensuring water column transparencies. However, the Fe-bound phosphorus may be released under reducing conditions (see Fig. 4). Bartoli et al. (1996) have indeed observed that phosphate was released into the water column during anoxic events during the summer months in heavily loaded Sacca di Goro. Alternatively, phosphorus can be bound by calcium to form apetites. One of our main hypothesis to be tested during the project is whether iron-rich ecosystems are indeed better buffered than iron-poor systems against eutrophication and pollution stress.

iii- Nitrogen cycling

The best known aspects of the nitrogen cycle concern the rates of dinitrogen fixation, mineralisation (ammonium production), dissimilatory nitrate reduction (ammonium production), nitrification and denitrification. The organic material released from plant roots directly stimulates bacterial sulphate reduction and nitrogen fixation (Welsh et al., 1996, 1997). The occurrence of heterotrophic nitrogen fixation in the rhizosphere of eelgrasses seems to be a ubiquitous phenomenon in these ecosystems (McRoy et al., 1973; Capone & Budin, 1982; O'Donohue et al., 1991), suggesting that these systems have evolved under nitrogen limiting conditions. Nitrification and denitrification occur around the oxycline in the oxic and anoxic layers, respectively. The close coupling of these processes ensure an efficient elimination of nitrogen (as N_2) from the system (Blackburn et al., 1994). However, the process of nitrification enters

in competition with the assimilation of ammonium by growing plants. By contrast, storage of N in plant material can be regarded as a temporal buffering capacity. Therefore, we gather detailed information on the temporal variations of nitrification, denitrification and uptake and storage of N by plants. In this respect, we have established strong research links with the ELOISE project NICE (NItrogen Cycling in Estuaries, supported by E.C.-DG XII MAST-3).

The pool of dissolved organic nitrogen (DON) is not well characterised despite DON having been known and measured during the past 25 years in marine environments. Thus, 70-80 % of the DON pool in sea water and sediments consists of unidentified compounds (Antia et al., 1991). The identified components of the DON pool, comprise polypeptides, other amino compounds, nucleic acids and urea (Lomstein et al., 1997; Sloth et al., 1995). Few measurements exist with respect to the efflux of DON from the sediment surface: in some cases DON efflux was only of minor importance with respect to inorganic nitrogen (Hopkinson, 1987), while other studies showed that DON represented a substantial amount of the nitrogen efflux (Enoksson, 1993; Boucher and Boucher-Rodoni, 1988; Hansen and Blackburn, 1991, 1992a,b; Lomstein and Blackburn, 1992; Lomstein et al., 1989; Hansen et al., 1993), which, especially, appears to be the case during periods of deposition of organic matter directly on the sediment surface. Mathematical modelling indicates that the intensity and pathways of the benthic nitrogen cycle are determined by the quantity, quality of degradable POM (i.e., its N-content), and its depth distribution (Blackburn & Blackburn, 1993a, b). However, these model predictions still need to be validated by experimental observations, which are proposed in this project.

iv- Prokaryotic biodiversity

The study places emphasis on mechanisms of buffering processes during periods of environmental stress, which have not been well characterised. Conversely, the effects of environmental stress on macrofauna biodiversity have been well-documented, although the effects on prokaryotic communities are less well understood. Recently molecular methods have been developed which enable determination of prokaryotic biodiversity in environmental samples. During the CLEAN project it was found that the biodiversity of eukaryotes and prokaryotes did not always show parallel changes (Benlloch et al., 1995, 1996). Therefore, more attention is paid to microbial biodiversity and we attempt to establish relationships with the metabolic reactivity of the system and a possible role as a buffering factor.

v- Role and habitats of meiofauna

The stands of primary producers also have a strong impact on the processes in the water column, for example, the large thalli of *Ulva* act as a physical barrier separating the water column into two distinct layers: an uppermost actively photosynthesising layer which is well oxygenated or over-saturated, and a lower reduced layer containing decaying thalli. A major question to be addressed concerns to what extent rooted seagrasses and macroalgae provide habitat diversity for the meiofauna, thus contributing to species biodiversity and whether some habitats may provide shelter during adverse conditions, e.g. during periods of algal and plant biomass decomposition. Special attention is paid to shelter around seagrass roots, related to their oxygen release (Colangelo et al. 1996). Such sheltered habitats represent buffering capacities that allow populations to survive during adverse periods. Meiofaunal communities from these environments need to be compared with those of reduced sediments.

Since the publication of Fenchel & Riedl's study of the sulphide biome in 1970, studies have been performed on the meiofaunal community of reduced sediments, which were originally thought to be devoid of life. The authors showed that the sulphide biome supported a distinct fauna which they postulated was adapted at the physiological level to the anoxic environment. Boaden & Platt (1971) coined the term "thiobios" to describe the biome of sulphide rich zones. It was suggested that the sulphide biome would contain at least some primary faunal elements of the oldest biosystems on earth (Fenchel & Riedl, 1970). This concept was later strongly criticised (Reise & Ax, 1979). However, it is now clear that some meiofauna are able to live in reduced sulphide containing environments (see review by Giere, 1993). There is evidence that not only protozoans, but also some metazoan meiobenthos can survive for long periods of time under anoxic conditions. Furthermore, many thiobiotic animals can tolerate H_2S. Adaptations against the deleterious effects of sulphide include production of sulphur-containing granules, or production of insoluble precipitates and iron binding of reduced

sulphur in the tissues (Giere, 1992). The project involves the study of sulphide toxicity in meiofaunal and macrofaunal species from both the *Zostera* habitat and highly reduced sediments.

The close-up above mentioned processes that provide buffering capacities to coastal lagoons do occur over very different spatial and temporal scales. Therefore, this study requires a spectrum of methods including field work to document in situ processes, mesocosm experiments where the effects of external forcing on short-time scales can be evaluated, and laboratory experiments to study the relevant physiology of individual species or the interactions between species in defined mixed populations. Buffering capacities include storage of nutrients in plant biomass, which have a life cycle on a annual or seasonal bases. In contrast, microbiological and biogeochemical processes may respond on very short time scales. As a result, field work studies need to operate on different temporal levels. Rather than separating the efforts according to traditional scientific disciplines, the work packages have been organised as a function of the logistics and time scale of the research requirements. Thus, scientists from the various disciplines cooperate and work as an integrated group. All the work-packages contribute to achieve the main objectives. The different work packages are listed below and are co-ordinated by one participant (name in parentheses):

1 Demography of primary producers in Sacca di Goro and the Bassin d'Arcachon, and the seasonal variations of detritus production and sediment/water column biogeochemistry (Rutger de Wit).

2 Detailed field work during field campaigns, focusing on detailed studies with a response time-scale of one to two weeks (Lucas J. Stal).
Studies have been focused on the dynamics of sulphate reduction - sulphide oxidation, on speciation of phosphorus and its availability on short time scales, on detailed descriptions of meiofaunal densities and taxonomic composition along gradients from the phytal habitat to non-vegetated patches etc.

3 Mesocosm experiments (Bente Aa. Lomstein)
The degradation of seagrass (*Zostera marina*) roots and of macroalgal thalli (*Monostroma* sp.) has been studied using small well-controlled continuous flow systems at the University of Aarhus (Denmark). Six Plexiglas continuous flow-through chambers (25x25x14 cm) were filled with homogenised sieved marine sediment (10 cm) and amended with seagrass roots (at 4 cm depth in the sediment) or with *Monostroma* thalli (on the sediment surface). Chambers were thermostated, the water column was continuously flushed with artificial sea water (5 $ml.min^{-1}$), which allowed to monitor sediment-water exchange in a precise way. Unamended chambers served as controls. Mesocosm facilities at the Marine Station in Aracachon has allowed to incubate sediment cores with living *Zostera noltii* plants in flow-through systems under different environmental conditions.

4 Laboratory experimentation (Rodney A. Herbert)
These systems are employed for the isolation of bacteria, physiological studies and studies of feeding selectivity and meiofauna in laboratory systems (*Acartia tonsa*, *Mysochra pontica*). A major advantage of laboratory systems is the degree of control of physico-chemical parameters that can be achieved. This enables individual parameters to be changed in an ordered and controlled manner and to measure their impact.

5. RESULTS

During the last two years we have accumulated a wealth of data on different aspects of buffering capacities in shallow coastal lagoon ecosystems. We are however still working on the analysis and interpretation of these data which will be published in peer-reviewed international journals. This way our work is submitted to the critical review of independent scientists which is a garantee of high quality. As a consequence it is still premature to disseminate the results in a detailed way and the results presented here can only be preliminary and general.

The Bassin d'Arcachon is still an outstanding environment which still harbours the nowadays largest meadows of the seagrass species *Zostera noltii* Hornem. (70 km^2) in Western Europe. Nevertheless, a critical evaluation of nutrient loading through the tributaries has shown that nitrogen inputs continue to rise, while phosphorus loadings have drastically decreased since the early 1980's after the implementation of urban wastewater treatment schemes. Consequently, the system receives fresh water with molar N/P ratios far above the Redfield ratio (data courtesy of IFREMER, Arcachon and l'Agence de l'eau Adour-Garonne). Prokaryotic nitrogen metabolism provides a buffer against external nitrogen loading. Using mesocosms, we found that experimental nitrate additions to the water column in seagrass beds resulted in a shift from a net N gain to a net N loss for the sediment. This was due to reduced N_2 fixation and increased denitrification rates, but these bacterial-driven fluxes were low in comparison to the nitrogen assimilation rates by standing plant biomass.

The living *Zostera noltii* plants establish strong links with the bacteria in the rhizosphere (Welsh et al., 1997). The rhizomes and roots of this phanerogam present a habitat for sulphate-reducing and nitrogen fixing bacteria (Finster et al., submitted).

Because heterotrophic bacteria have much lower C/N ratios than detritic plant material, its mineralisation creates a demand of mineral N. In microcosm experiments we have shown that additions of *Zostera marina* roots to sediments resulted in increased bacterial ammonium assimilation rates thus making inorganic nitrogen less available for plant growth. Hence, the effect is a reduction of the effect of external N-loading (Lomstein et al., in prep).

We have found that high iron availability in the sediment (50 - 100 $\mu mol.cm^{-3}$) buffers efficiently against increased biogenic sulphide production related to increased eutrophication (see also Giordani et al., 1996, Stal et al., 1996). Free sulphide is rarely detected in Arcachon Bay sediments and only in deep sediment layers where its impact on flora and fauna is quite limited (Schaub and Van Gemerden, 1996).

A new device, the biological oxygen and sulphide monitor (BOSM) has been developed for measuring the reoxidation of sulphide by abiotic processes and chemotrophic bacteria in sediment slurries under both aerobic and anaerobic conditions (Heijs et al., in prep).

Table 1: Typical sedimentary phosphate concentrations at ROBUST station A (Ile aux Oiseaux) in the Bassin d'Arcachon (values in $\mu mol.cm^{-3}$)

	Zostera noltii vegetated spot	non-vegetated spot
porewater + $MgCl_2$ (1 M) exchangeable phosphate	0.037	0.041
Fe-bound phosphate (extracted by 0.1 M NaOH)	0.033	0.027
Ca-bound phosphate (extracted by 0.5 M HCl)	4.43	7.00
Organic phosphate	5.86	0.53
Total phosphate	10.3	7.67

In contrast, it appears that iron is less important for sequestering phosphate. Table 1 shows some typical phosphate concentrations in *Zostera noltii* vegetated and in non-vegetated sites at ROBUST station A. Iron-bound phosphate represents less than 1 % of total phosphate. A major fraction is bound to calcium (e.g., calcium hydroxy apatites), which is related to the very high total Ca content of 45 $\mu mol.cm^{-3}$. Mobilisation of calcium bound phosphorus is stimulated by protons and organic acids formed by fermentation processes; this might play a role in reducing sediments (Stal et al., 1986). Organic phosphate was a major fraction in the vegetated site (57 %) and less important at the non-vegetated site (7 %). Hence, plant biomass and detritus represent a major temporal sink for phosphorus and we are currently studying the remineralisation of organic phosphorus and the importance of bacterial phosphatases in this

process. Interestingly, alkaline phosphatase activities were very low at the non-vegetated site and higher, albeit patchily distributed, at the vegetated site. On average per cm^{-3}, vegetated sites yielded 4 to 5 times more culturable viable bacteria showing phosphatase activity than non-vegetated sites.

Finally we found that the *Zostera noltii* meadows supports a habitat for a diverse gastropod and copepod fauna. The copepod fauna comprises both species specialised to live on the *Zostera* leaves as well as strictly meiobenthic species. Sulphide tolerance of the dominant benthic copepod species *Mysochra pontica* is intermediate between those found for species from sandy sediments and those found for typical thiobenthic representatives from euxinic sediments.

The Sacca di Goro contrast with Arcachon Bay by a more limited tidal flushing and by nitrogen inputs per unit area exceeding by a factor of ca. 6. Important blooms occur of *Gracillaria* sp. and *Ulva* sp. and dystrophic crises occur on an annual basis. Very high concentrations of iron occur (200-500 $\mu mol.cm^{-3}$) in the sediment. In general the vulnerability of a lagoon can be described by the seasonal changes in the HS^- - FeS - FeS_2 system. Surprisingly, the total ratio of acid volatile sulphides to Fe(II), which is an indication of the saturation of the sedimentary iron buffer to sulphide, was always below 1. In a similar lagoon, i.e. the Etang de Prévost it was found that this ratio approached 1 (saturation value) during the dystrophic crises in the summer months. However, despite the apparent excess of reactive iron in the sediments of the Sacca di Goro, free sulphides were still detected in the pore water, indicating that a large proportion of the measured reactive iron was unavailable to buffer against sulphide release (Giordani et al., 1997). The reason for this phenomenon still need to be identified. On the other hand, dystrophic crises in the Sacca di Goro are stimulated by the fact that sulphide is directly produced in the water column during the degradation of the algal biomass (Viaroli et al., 1996). The fact that algal biomass is mineralised in the water column in contrast to the within sediment degradation of seagrass roots (representing ca. 50 % of seagrass detritus) is most important from the biogeochemical point of view and both processes have been simulated in mesocosm experiments.

In Italy we work in close co-operation with potential end-users, i.e., the Amministrazione Provenciale di Ferrara. Therefore, we have developed methods to use as indices for determining the susceptibility of lagoons to oxygen deficiency and dystrophic crises. Based on a comparison of six sheltered coastal lagoon ecosystems we propose a classification. The classification criteria are based on a combination of different variables measured during the growth and decay phases of the dominant primary producers, i.e., net maximum community productivity (NP), dark respiration (DR) of oxygen, sediment oxygen demand (SOD), dark sulphide release from sediments (DSR), sediment acid volatile sulphide (AVS) and reducible iron. The classification based on NP, DR and DSR only provides coarse information allowing to rapidly asses the balance of community oxygen metabolism and the intensity of disturbance and/or resistance against dystrophy. The classification based on SOD/SRR and AVS/Fe gives more sensitive information on sediment buffering capacities, but is biased by the large spatial heterogeneity of the individual variables (Viaroli et al., in prep.).

ACKNOWLEDGEMENTS

ROBUST is a European Union research project, contributing in the ELOISE network supported by C.E.-DG XII « Environment & Climate » (Contract N° ENV4-CT96-218). We acknowledge the dedicated contributions of our coworkers and students who participate in the project: Françoise Truong, David T. Welsh, Rémy Guyoneaud, Stéphane Riou, Elvire Antajan, Pierre Caumette, Pierre-Jean Labourg, Claude Courties, Bartholomeus Schaub, Ute Wollenzien, Ab de Zwaan, Sander K. Heijs, Henk Jonkers, Marco Bartoli, Gianmarco Giordani, Roberta Azzoni, Monica Benatti, Francesca Cavicchini, Laura Tajé, Gessica Gorbi, Sandra Sei, Mariona Invidia, Antoni Bodini, Mimmo Cavalca, Giorgi Benassi, Ireneo Ferrari, Maria Antonia Colangelo, Alberto Guerrini, E.A. Fano, Pito L.G. Gatti, V. Gaiani, Remigio Rossi, Andrew Donelly, Josefa Antón, Silvía Gonzalez-Acinas, Ana Isabelle Anton, Ana Cifuentes, Kai Finster, Anne Turi Neubauer, Jesper Hansen & Anne-Grethe U. Jensen

REFERENCES

Antia N.J., Harrison P.J. & Oliveira L. (1991). The role of dissolved organic nitrogen in phytoplankton nutrition, cell biology and ecology. *Phycologia,* 30: 1-89.

Bartoli M., Cattadori M., Giordani G. & Viaroli P. (1996) Benthic oxygen respiration, ammonium and phosphorus regeneration in surficial sediments of the Sacca di Goro (Northern Italy) and two French coastal lagoons : a comparative study. *Hydrobiologia,* 329:143-159.

Benlloch S., Acinal S.G., Martinez-Murcia A.J. & Rodríguez-Valera F. (1996) Description of prokaryotic biodiversity along the salinity gradient of a multipond solar saltern by direct PCR amplification of 16S rDNA. *Hydrobiologia,* 329: 19-31.

Benlloch, S., Rodríguez-Valera, F., Martinez-Murcia, A.J. (1995) Bacterial diversity in two coastal lagoons deduced from 16S rDNA PCR amplification and partial sequencing. *FEMS Microbiol Ecol* 18, 267-280

Berner, R.A. (1984). Sedimentary pyrite formation: an uptdate.*Geochim. Cosmochim. Acta* 48, 605-615

Blackburn T.H. & Blackburn N.D. (1993a). Rates of microbial processes in the sediment. *Phil. Trans. R. Soc. Lond.* A. 344: 49-58.

Blackburn T.H. & Blackburn N.D. (1993b). A reaction diffusion model of C-N-S-O species in some Arctic sediments. *FEMS Microbiol. Ecol.*, 102: 197-205.

Blackburn T.H., Blackburn N.D., Jensen K. & Risgaard-Petersen N. (1994). Simulation model of the coupling between nitrification and denitrification in a freshwater sediment. *Appl. Environ. Microbiol.*, 60: 3089-3095.

Boaden P.J.S. & Platt H.M. (1971) Daily migration patterns in an intertidal meiobenthic community. *Thalassia Jugosl.*, 7: 1-12.

Boucher G. & Boucher-Rodoni R. (1988). *In situ* measurement of repiratory metabolism and nitrogen fluxes at the interface of oyster beds. *Mar. Ecol. Prog. Ser.*, 44: 229-238.

Capone D.G. & Budin J.M. (1982) Nitrogen fixation associated with rinsed roots and rhizomes of the eel grass *Zostera marina. Plant. Physiol.*, 70: 1601-1604.

Caumette P. (1986) Phototrophic sulfur bacteria and sulfate reducing bacteria causing red waters in a shallow brackish coastal lagoon (Prevost Lagoon, France). *FEMS Microbiol.-Ecol.*, 38:113-124.

Caumette P., Castel J. & Herbert R. (1996) (eds) Coastal lagoon eutrophication and anaerobic processes. Developments in Hydrobiology, 117, 253 pp. Kluwer, Dordrecht, also published as *Hydrobiology*, 329.

Chapelle A., Lazure P. & Ménesguen A. (1994) Modelling eutrophication events in a coastal ecosystem. Sensitivity analysis. *Estuar. Coast. Shelf Sci.*, 39: 529-548.

Colangelo M.A., Macri T. & Ceccherelli V.U. (1996) A field experiment on the effect of two types of sediment distrubance on the rate of recovery of a meiobenthic community in a eutrophicated lagoon. *Hydrobiologia* 329: 57-67.

Enoksson,V. (1993). Nutrient recycling by coastal sediments: effects of added algal material. *Mar. Ecol. Prog. Ser.*, 92: 245-254.

European Commission (1997) Better Management of coastal resources. 47 pp, ECSC-EEC-EAEC, Brussels

Fenchel T. & Riedl R.J. (1970) The sulphide system : a new community underneath the oxidised layer of marine sand bottoms. *Mar. Biol.*, 7: 255-268.

Giere O. (1992) Benthic life in sulfidic zones of the sea-ecological and structural adaptations to a toxic environment. *Verh. Dtsch. Zool. Ges.*, 85: 77-93.

Giere O. (1993) Meiobenthology. The microscopic fauna in Aquatic sediments. Springer-Verlag, 328 pp.

Giordani G., Azzoni R., Bartoli M. & Viaroli P. (1997) Seasonal variations of sulphate reduction rates, sulphur pools and iron availability in the sediment of a dystrophic lagoon (sacco di Goro, Italy). *Water, air and Soil Pollution* 99: 363-371.

Giordani G., Bartoli M., Cattadori M. & Viaroli P. (1996) Sulphide release from anoxic sediments in relation to iron availability and organic matter recalcitrance and its effects on inorganic phosphorus recycling. *Hydrobiologia*, 329: 211-222.

Hansen, L.S. & Blackburn, T.H. (1991). Aerobic and anaerobic mineralization of organic material in marine sediment microcosms. *Mar. Ecol. Prog. Ser.* 75: 283-291.

Hansen, L.S. & Blackburn, T.H. (1992a). Mineralization budgets in sediment microcosms: effect of the infauna and anoxic conditions. *FEMS Microbiol. Ecol.* 102: 33-43.

Hansen, L.S. & Blackburn, T.H. (1992b). Effect of algal bloom deposition on sediment respiration and fluxes. *Mar. Biol.* 112: 147-152.

Hansen, L.S., Holmer, M. & Blackburn, T.H. (1993). Mineralization of organic nitrogen and carbon (fish food) added to anoxic sediment microcosms: role of sulfate reduction. *Mar. Ecol. Prog. Ser.* 102: 199-204.

Hopkinson Jr., C. S. (1987). Nutrient regeneration in shallow-water sediments of the estuarine plume region of the nearshore Georgia Bight, USA. *Mar. Biol.* 94: 127-142.

Izzo G. & Hull V. (1991) The anoxic crises in dystrophic processes of coastal lagoons: an energetic explanation. In : Rossi C. & Tiezzi E. (Eds) *Ecological Physical Chemistry*, Elsevier Sci. Pbls. Amsterdam, pp 559-572.

Jørgensen B.B. (1982) Mineralization of organic matter in the sea bed - the role of sulfate reduction. *Nature* 296, 643-645.

Jørgensen, B.B. (1989). Biogeochemistry of chemoautotrophic bacteria. In: *Autotrophic bacteria.* Schlegel, H.G. and Bowien, B. [eds.]. Science Tech Publishers, Madison, WI, Springer-Verlag.

Lomstein B. Aa., Jensen, A-G. U., Hansen, J.W., Andreasen, J.B., Hansen, L.S., Berntsen, J., Kunzendorf, H. (1997) Budgets of nitrogen and carbon cycling in the shallow water of Knebel Vig, Denmark *Aquatic Microb. Ecol.* 14, 69-80

Lomstein, B.Aa. & Blackburn, T.H. (1992). Sediment nitrogen cycling in Aarhus Bay, Denmark. The Danish Environmental Protection Agency, Copenhagen, pp. 1-74. English summary.

Lomstein, B.Aa., Blackburn, T.H. & Henriksen, K. (1989). Aspects of nitrogen and carbon cycling in the northern Bering shelf sediment. I. The significance of urea turnover in the mineralization of ammonium. *Mar. Ecol. Prog. Ser.* 57: 237-247.

Luther, G.W. (1991). Pyrithe synthesis via plysulphide compounds.*Geochim. Cosmochim. Acta* 55, 2839-2849

Mc Roy C.P., Goering J.J. & Chaney B. (1973). Nitrogen fixation associated with seagrasses. *Limnol. Oceanogr.*, 18: 998-1002.

O'Donohue M.J., Moriarty D.J.W. & Mac Rae I.C. (1991) Nitrogen fixation in sediments and the rhizosphere of the seagrass *Zostera capricorni Microbiol. Ecol.*, 22: 53-64.

Piriou J.Y. & Ménesguen A. (1992) Environmental factofs controlling the *Ulva* sp. blooms in Brittany (France). In: Colombo G., Ferrari I., Ceccherelli V.U. & Rossi R., (eds) *Marine Eutrophication and Population Dynamics*, 25th E.M.B.S. Olsen & Olsen, Fredensborg, pp 111-116.

Reise K. & Ax P. (1979) A meiofaunal "thiobios" limited to the anaerobic sulfide system of marine sand does not exist. *Mar. Biol.*, 4-54: 225-237.

Sand-Jensen K. & Borum J. (1991) Interactions among phytoplankton, periphyton and macrophytes in temperate freshwater and estuaries. *Aquatic Botany*, 41: 137-175.

Schaub, B. and Van Gemerden, H. Sulfur bacteria in sediments of two coastal ecosystems: the bassin d'Arcachon, south-west France. *Hydrobiologia*, 329: 199-210

Sfriso A., Pavoni B., Marcomini A. & Orio A.A. (1992) Macoalgae, nutrient cycles, and pollutants in the lagoon of Venice. *Estuaries*, 15: 517-528.

Sloth, N.P., Blackburn, T.H., Hansen, L.S., Risgaard-Petersen, N & Lomstein, B.Aa. (1995). Nitrogen cycling measurements in sediments with different organic loading. *Mar. Ecol. Prog. Ser.*, 116: 163-170.

Sorokin, Y.I., Dallocchio, F., Gelli, F. & Pregnolato, L. (1996). Phosphorus metabolism in anthropogenically transformed lagoon ecosystems: The Comacchio lagoons (Ferrara, Italy). *J. Sea Res.* 35, 243-250

Stal L.J., Behrens S.B., Villbrandt M., van Bergeijk S. (1996) The biogeochemistry of two eutrophic marine lagoons and its effect on microphytobenthic communities. *Hydrobiologia*, 329: 185-198.

Viaroli P., Bartoli M., Fumagalli I. & Giordani G. (1997) Relationship between benthic fluxes and macrophyte cover in a shallow brackish lagoon. *Water, Air and Soil Pollution*, 99: 533-540.

Viaroli P., Naldi M., Bondavalli C. & Bencivelli S. (1996) Growth of the seaweed *ulva rigida* C. Agardh in relation to biomass densities, internal nutrient pools and external nutrient supply in the Sacca di Goro lagoon (Northern Italy). Hydrobiologia 329: 93-103.

Viaroli P., Naldi M., Christian R.R. & Fumagalli J. (1993) The role of macroalgae and detritus in the nutrient cycles in a shallow-water dystrophic lagoon. *Verh. Internat. Verein. Limnol.*, 25: 1048-1051.

Viaroli P., Pugnetti A. & Ferrari I. (1992) *Ulva rigida* growth and decomposition processes and related effects on nitrogen and phosphorus cycles in a coastal lagoon (Sacca di Goro, Po River Delta). In: Colombo G., Ceccherelli V., Ferrari I. & Rossi R. (Eds) *Marine eutrophication and population dynamic*, Proc. 25th EMBS, Olsen & Olsen, Fredensborg, Denmark, pp 77-84.

Vicente, E. & Miracle, M.R. 1992. The coastal lagoon Albufera de Valencia: An ecosystem under stress. *Limnetica* 8, 87-100

Welsh D.T., Bourguès S., De Wit R. & Auby I. (1997) Effect of plant photosynthesis, carbon sources and ammonium availability on nitrogen fixation rates in the rhizosphere of *Zostera noltii*. *Aquatic Microbial Ecol.* 12, 285-290

Welsh D.T., Bourguès S., De Wit R. & Herbert R.A. (1996) Seasonal variations in nitrogen-fixation (acetylene reduction) and sulphate(reduction rates in the rhizosphere of *Zostera noltii* : nitrogen fixation by sulphate-reducing bacteria. *Mar. Biol.*, 125: 619-628.

TITLE : BIOGEOCHEMICAL INTERACTIONS BETWEEN THE DANUBE RIVER AND THE NORTHWESTERN BLACK SEA : **EROS-21**

CONTRACT N° : ENV4 CT96-0286
IC20-CT96-0065

COORDINATOR :

Dr Jean-Marie Martin
Joint Research Center-Environment Institute, I-21020 Ispra (Varese), Italy.
Tel: +39 332 789 601
Fax: +39 332 789 222
E-mail: jm.martin@jrc.it

PARTNERS :

WESTERN EUROPE :

Dr Christiane Lancelot
Universté Libre de Bruxelles
Groupe de Microbiologie des
Milieux Aquatiques (ULB-GMMA)
Bld du Triomphe, CP 221
B-1050 Brussels, Belgium.
Tel. : +322.650.59.88/89
Fax : +322.650.59.93
E-mail : lancelot@ulb.ac.be

Prof. Alain Saliot
Université Pierre et Marie Curie
Laboratoire de Physique et
Chimie Marine (LPCM)
Place Jussieu, 4
F-75252 Paris cedex 05, France.
Tel. : +33-1-44.27.48.79
Fax : +33-1-44.27.49.93
E-mail : saliot@ccr.jussieu.fr

Dr Pieter M.J. Herman
Netherlands Institute of Ecology
Centre for Estuarine and Coastal
Ecology (NIOO)
Korringaweg, 7, P.O. Box 140
NL-4401 AC Yerseke, The Netherlands
Tel. : +31-113-577.300
Fax : +31-113-573.616
E-mail : herman@cemo.nioo.knaw.nl

Prof. Venugopalan Ittekkot
Universität Hamburg
Institut für Biogeochemie und
Meereschemie (UH-IBMC)
Bundesstr. 55,.
D-20146 Hamburg, Germany
Tel. : +49-4041-234.992
Fax : +49-4041-236.347
E-mail : ittekkot@dkrz.de

Prof. Bernard Wehrli
Eidgenössische Anstalt für
Wasserversorgung, Swiss Federal Institute
for Environmental Science and Technology
Abwasserreinigung und Gewässerschutz
(EAWAG)
Ueberlandstrasse, 133,
CH-8600 Duebendorff, Switzerland.
Tel. : +414-349.21.17
Fax : +4141-349.21.68
E-mail : wehrli@eawag.ch

Dr Vittorio Barale
Joint Research Center Ispra (JRC EC)
Institute for Remote Sensing Applications
(SAI/ME) TP272
I-21020 Ispra (Varese), Italy.
Tel. : +39-332.78.92.74
Fax : +39-332-78.90.34
E-mail : vittorio.barale@jrc.it

Prof. Jacques. Nihoul
Université de Liège (ULg-GHER)
Geohydrodynamics & Environmental
Research Laboratory
Sart Tilman,
B5, B-4000 Liège, Belgium
Tel. : +32-4-366.33.50
Fax : +32-4-366.23.55
E-mail : j.nihoul@ulg.ac.be

Dr Gustave Cauwet
Centre National de la Recherche
Scientifique(CNRS-DR13)
Laboratoire Arago
Observatoire Océanologique B.P. 44
F-66651 Banyuls-sur-Mer, France.
Tel. : +33.4.68 88 73 56
Fax : +33.4. 68 88 59 46
E-mail : cauwet@arago.obs-banyuls.fr

Prof. Paul Tréguer
Institut Universitaire Européen de la Mer
(IUEM-Brest)
Université de Bretagne Occidentale
Technopole Brest-Iroise
Place Copernic
F-29280 Plouzané, France.
Tel. : +33 2 98 49 86 64
Fax : +33 2 98 49 86 45
E-mail : Paul.Treguer@univ-brest.fr

Dr Thomas Weisse
Max-Plank-Institute for Limnology (MPIL)
Abteilung Ökophysiologie
August-Thienememann Str., 2, PO. Box 165
D-24306 Plön, Germany.
Tel. :49-4522.763.255
Fax :49-4522. 763.310
E-mail : weisse@mpil-ploen.mpg.de

Dr Josette Garnier
Centre National de la Recherche
Scientifique (URA1367)
Circulations et Transports Hydriques
Continentaux
Université P. & M.Curie, Paris VI
Place Jussieu, 4
F-75252 Paris, France
Tel. : +33-1-44.27.70.27
Fax : +33-1-44.27.51.25
E-mail : jgarnier@biogeodis.jussieu.fr

Dr Hervé Claustre
Laboratoire de Physique et Chimie Marine
(LPCM)
BP 08, Quai de la Darse.
F-06238 Villefranche-sur-Mer, France
Tel. : +33 4 96 76 37 29
Fax : +33 4 96 76 37 39
E-mail : claustre@ccrv.obs-vlfr.fr

Dr Cécile Guieu
Laboratoire de Physique et Chimie Marine
(LPCM)
BP 08, Quai de la Darse
F-06238 Villefranche-sur-Mer, France.
Tel. : +33.4.93.76.37.24
Fax : +33.4.93.76.37.39
E-mail : guieu@obs-vlfr.fr

Dr Leo Goeyens
Vrije Universiteit Brussel (VUB-ANCH)
Dienst voor Analytische Chemie
Pleinlaan 2,
B-1050 Brussels, Belgium.
Tel. : +32 2 629.32.63
Fax : +32 2 629.32.74
E-mail : lgoeyens@vub.ac.be

EASTERN EUROPE :

Prof. Nicolae Panin
National Institute of Marine Geology and Geo-ecology (Geo-ECOMARE)
BP 34-51, Dimitrie Onciu Str, 23-25
RO-70318 Bucharest, Romania.
Tel. : +40-1-252 2594
Fax : +40-1-252 2594
E-mail : panin-geomar@rolink.iiruc.ro

Dr Alexandru Bologa
Romanian Marine Research Institute (RMRI - Constanta)
Department of Oceanography
Blvd. Mamaia, 300
RO-8700 Constanta 3, Romania.
Tel. : +40-41-64.32.88
Fax : +40-41-83.12.74
E-mail : abologa@alpha.rmri.ro

Dr Iliya Shterev
Institute of Oceanology IO-Varna -,
Bulgarian Academy of Sciences
Department of Marine Chemistry
P.O. Box 152
BG-9000 Varna, Bulgaria.
Tel. : +35 9.52.776698
Fax : +359.52.774256
office@iobas.io-bas.bg

Dr. Emil Stanev
University of Sofia - Faculty of Physics
Department of Meteorology & Geophysics (DMG)
5 James Bourchier Str.
BG-1126 Sofia, Bulgaria.
Tel : +359-2-625.62.89
Fax : +359-2-962.52.76
E-mail : stanev@phys.uni.sofia.bg

Prof. Michael Ivanov
Russian Academy of Sciences
Institute of Microbiology (IM-RAS) -
Laboratory of Microbial Biogeochemistry
Prospekt 60 - Letyia Oktjabrja, 7, bed 2
RU-117811 Moscow, Russia.
Tel. : +7-095-135.21.39
Fax : +7-095-135.65.30
E-mail : ivanov@imbran.msk.su

Prof. Gennady Polikarpov
Ukrainian Academy of Sciences
Institute of Biology of the Southern Seas (IBSS-Sevastopol)
2 Prospekt Nakhimova
UA-335011 Sevastopol, Ukraine.
Tel. : +380-0692-526629 /452120/241581
Fax : +7-0692-444477
E-mail : GGP@iur.sebastopol.ua

Prof. Yuvenaly Zaitsev
National Academy of Sciences of Ukraine
Institute of Biology of the Southern Seas
Odessa Branch (IBSS,Odessa),
37, Pushkinskaya Str
UA-270011 Odessa, Ukraine.
Tel. : +380-482-250 918
Fax : +380-482-250 918
E-mail : inbum@farlep.net

Prof. Erik Galimov
Vernadsky Institute of Geochemistry and Analytical Chemistry (VIGAC)
Geochemistry Department
Kosygin Str. 19
RU-11795 Moscow, Russia.
Tel. : +7-095-137.41.27
Fax : +7-095-938.20.54
E-mail : galimov@geokhi.msk.su

THE NORTHWESTERN BLACK SEA : A PILOT SITE TO UNDERSTAND THE COMPLEX INTERACTION BETWEEN HUMAN ACTIVITIES AND THE COASTAL ENVIRONMENT

Christiane Lancelot[1], Nicolae Panin[2], Jean-Marie Martin[3]

[1] Université Libre de Bruxelles, Groupe de Microbiologie des Milieux Aquatiques, Brussels, Belgium; [2] Romanian Center of Marine Geology and Geo-Ecology, Bucharest, Romania, [3] Joint Research Center, Environment Institute, Ispra, Italy

INTRODUCTION

Coastal ecosystems are important spawning and nursery grounds for marine organisms and are of great value for recreational activities. Coastal areas are also the recipient of increasing amounts of nutrients and contaminants from human activities, including industrial effluents, agricultural runoff, and municipal sewage. As a consequence, remarkable changes have been observed in coastal waters all around Europe during the last decades. The EROS (European River Ocean System) project is part of a long-term research to understand the biogeochemical processes and their alteration by human activity in the European coastal zone. The ultimate objective is to develop a mathematical model of the land-ocean system to be used as a scientific tool for reducing the degree of uncertainty within current coastal zone management decisions are taken in order to achieve sustainable development of coastal and land-locked ecosystems.

Since 1994, the EROS team is focusing its research to the lower reaches of the Danube and its delta along with the north-western Black Sea. The Black Sea, with its unique features, such as being the largest enclosed catchment basin receiving freshwater and sediment inputs from rivers draining half of Europe and parts of Asia, represents the ultimate example of deterioration of the coastal and marine environment in Europe. It was chosen as a pilot site to understand the complex interactions between human activities and the marine environment. The Black Sea ecosystem has indeed experienced several changes during the last decades, driven by human perturbations in the coastal ecosystem itself and in the drainage basins of

the rivers. Among these, the Danube river receiving the effluents from eight European countries is affecting the north-western Black Sea ecosystems and represents the most significant source of river-borne pollution flowing into the Black Sea.

Assessing and predicting the response of the Black Sea ecosystem to human perturbations is the ultimate objective of EROS 21, bringing together biologists, geochemists and physicists of Western, Eastern and Central Europe. More specifically, the project addresses the following questions : What would be the consequences of a reduction of the river input of nutrients for the eutrophication and the ecosystem structure of the north-western Black Sea ? What are the riverine sources, levels and fates of key organic/inorganic pollutants in the Black Sea environment ? What are likely to be the short- and long-term consequences of the regulation of river discharge for sediment erosion/transport/deposition and water stratification ?

PROJECT METHODOLOGY :

HISTORICAL DATA, FIELD RESEARCH AND MATHEMATICAL MODELLING

The complex interactions between the continental and marine coastal systems require definition and integration of the most natural and human-induced driving forces controlling the ecosystem variability. The EROS approach was to review existing data in the Danube drainage basin and the north-western Black Sea, conduct process-level studies under field and laboratory-controlled conditions and combine them with remotely sensed satellite data to develop and validate numerical models describing ecosystem and biogeochemical transformations along the aquatic continuum of the Danube - north-western Black Sea.. A number of field investigations were organised in the lower reaches of the Danube and its delta, at strategic coastal areas south of the Danube mouth to monitor the seasonal evolution of nutrients and algal blooms and in the north-western Black Sea. Two large expeditions were conducted in the Black Sea in summer 1995 and spring 1997 aboard the Ukrainian research vessel « Professor Vodyanitsky ». A total of 150 stations were sampled in the area of Danube influence along eutrophic-oligotrophic gradients as well as in the central basin. There a sediment trap was deployed from August 1995 to October 1996 to measure sedimentation rates and the nature and composition of sinking particles. Process-level studies were conducted on the rate of microbial degradation of organic matter both in the water

column and in the sediment. These experiments were combined with isotope measurements in an attempt to discriminate biodegradable organic matter of continental or marine origin. For the first time, investigations on the structure and functioning of the planktonic food-web were conducted in an integrated comprehensive way : studies of the relationship between phytoplankton communities and nutrient availability (N:P:Si) were combined with experimental investigation of the feeding ecology of key planktonic organisms (protozoa, copepods, *Noctiluca*) and of the gelatinous carnivores *Mnemiopsis* and *Aurelia*. The rate of sedimentation and the processes occurring within the sediments and at the water-sediment interface were studied as well. For the first time, a benthic lander was successfully used in the Black Sea to measure nutrient exchanges at the sediment-water interface. The knowledge gained is progressively integrated in a hierarchy of 'offline' coupled physical-biogeochemical models of different spatio-temporal and trophic resolution which describe biogeochemical transformations along the aquatic continuum from the Danube river over the north-western shelf to the central Black Sea basin as a function of meteorological forcing and human activities.

RESULTS

Sensitivity of the Black Sea ecosystem to human perturbations : phenomenological analysis and mathematical modelling of historical data

Since the early sixties noticeable and well-documented alterations have been observed at various trophic levels of the Black Sea ecosystem. In less than 30 years the Black Sea ecosystem has been evolving from a highly biodiverse ecosystem, characterised by rich biological resources to a low biodiversity ecosystem dominated by a dead-end gelatinous food-chain (e.g., Mee, 1992). During the late 1980's there was an almost total collapse of fisheries, which coincided with an unprecedented increase of the jellyfish *Aurelia* but also of the exotic combjelly *Mnemiopsis* unintentionally introduced in the Black Sea in the mid-1980's. At the time, it was thought that these carnivores - lacking predators and feeding on zooplankton, fish eggs and larvae - were dramatically reducing recruitment of fish to the adult stocks and were claimed responsible of the ecosystem destabilisation.

EROS re-analysis of existing data in combination with numerical experimentation making use of the conceptual mechanistic model BIOGEN developed in the scope of EROS (Van

Eeckhout and Lancelot, 1997), however, suggests that the successful development of the undesirable gelatinous carnivores results from a combination of human perturbations having occurred almost synchronously in the drainage basin of the Danube river and in the marine system: manipulation of hydrologic regimes of out-flowing rivers (Bondar, 1977), urban and industrial expansion and the intensive use of agricultural fertilisers (Bologa et al., 1984; Gomoiu, 1990), introduction of exotic species such as the gelatinous Ctenophore *Mnemiopsis* sp. (Vinogradov et al., 1989; Mutlu et al., 1994), selective and excessive fishing (Ivanov and Beverton, 1985; Stepnowski et al., 1993; Bingel et al., 1993; Gücü, 1997). Among these however, human-induced changes in the Danube watershed were the dominant driving force.

Human-induced changes in the river watershed conducted since the 1970's were dramatically modifying the quantitative and qualitative nutrient environment of the coastal phytoplankton, increasing nitrogen and phosphorus (due to cultural eutrophication) and lowering silicate (due to hydraulic management). This nutrient change was stimulating, after 1970, the development of numerous phytoplankton blooms during the summer period in this phosphorus-limited marine environment and generally, the phytoplankton community was dominated by non-diatom species some of them of little palatability for mesozooplankton. As an immediate response to increased primary production, large developments of herbivorous copepods and carnivorous predators (fishes) were first observed (Porumb, 1970). The higher fish availability led to an increase of fish catches and as a matter of consequence of the fishing pressure (Zaitsev, 1993, Gücü, 1997). By decreasing fish stocks, fishing pressure indirectly stimulated the development of the predatory gelatinous carnivores *Aurelia* and the alien *Mnemiopsis*, competing with the fish for copepods. This situation was accelerated in an explosive way due to the lack of known predators of these gelatinous carnivores and to their voracious feeding of fish eggs and larvae. Most of organic matter produced by primary producers was thus deviated to a trophic dead-end. The organic matter, derived from dead organisms further enhanced the development of bacterial populations with subsequent oxygen deficiency problems and increasing the bulk of organic matter reaching the sediment.

Present-day functioning of the Black Sea ecosystem : signs of improvement

Since 1995, however, some positive signs of coastal Black Sea ecosystem recovery were observed by the EROS project at different levels of the Black Sea ecosystem:

First of all, phosphorus and nitrogen loads have considerably decreased, but concentrations in the Danube river are still comparable to other polluted European rivers, such as the Rhine, Rhone and Po (Cociasu et al., 1997). However, budget calculations, based on the *in situ* measurements of phosphate benthic fluxes, indicate that sediments are contributing as much phosphate for coastal phytoplankton growth than Danube waters (Friedl et al., 1997).

As expected, no clear trend could be observed in the evolution of silicate concentrations in the Danube after the dramatic decrease that followed the building of the iron gates in 1972. A value of 100 μM is typical for dissolved silica in the Danube (Cociasu et al., 1997). Such a concentration is significantly lower than the average value of 175 μM characterising the world's rivers (van Bennekom and Salomon, 1980).

Inorganic contaminants as well were found to now reach concentrations similar to those recorded in the Mediterranean and Baltic Sea although historically extremely high levels of contaminants were reported for the north-western Black Sea. In contrast, the Danube river has been found to continue representing an important source of organic pollutants for the north-western Black Sea, especially for its northern mouth (Chilia Branch). The concentrations of petroleum hydrocarbons, organochlorine compounds and of the sewage marker trialkylamines were two orders of magnitude higher in the Danube mouth than in the open sea. The chemical composition of the organochlorine compounds revealed a recent increase in use of pesticides in the riparian countries. Their concentration level recorded was one order of magnitude higher than those reported for the Mediterranean Sea.

At the ecosystem level, some planktonic and benthic species considered to be extinct or very rare nowadays became again very common in the Black Sea. In the same direction, a slight recovery of the mussel (*Mytilus galloprovincialis*) populations was observed from 1995 to 1997. On the other hand, the abundance of the undesirable jellyfish has levelled out and the number of anchovy eggs and larvae has increased (Shiganova, 1997)

Incidentally these events are corresponding to the economical collapse which recently occurred in the Eastern and Central European countries. However, to which extent the

present-day catastrophic socio-economic situation induced such a rapid response of the coastal ecosystem cannot be assessed by a simple correlation between events. The complex interactions between the continental and marine systems require a more in-depth analysis of the natural science, social science and economic science interfaces.

CONCLUSION

Observational achievements already made by the EROS project indicate that the north-western Black Sea represents well a unique region where the effect of curative measures upon the quality of a given coastal ecosystem and its biological resources can be tested because of :

- the high sensitivity of the north-western Black Sea ecosystem to human disturbances, as demonstrated by historical records tracing the environmental and ecological changes over the past 30 years, and
- its rapid response to human-induced changes as suggested by the improvements recorded after the economical collapse faced by the Eastern and Central-Europe countries.

However, the complex interactions revealed between the continental and marine systems and between different human-induced activities superimposing on natural variability cannot be understood by simple correlation between events. The ongoing hierarchical development of coupled physical-mechanistic biogeochemical models developed in the scope of EROS for describing biogeochemical transformation and ecosystem change along the Danube river-Black Sea aquatic continuum in response to natural and human-induced perturbation will encompass this complexity. When validated it will constitute a valuable tool for answering the following environmental questions:

- What is the time needed for a given ecosystem to recover after a voluntary reduction of nutrient loads to the coastal area ?
- What is the buffering capacity of the ecosystem to nutrient reduction ?
- What is the synergy between human-induced changes such as eutrophication, overfishing and introduction of exotic species leading to ecosystem destabilisation ?

REFERENCES

Bingel F., Kideys A.E., Ozsoy E., Tugrul S., Basturk O. and Oguz T. (1993). Stock assessment studies for the Turkish Black Sea coast. NATO-TU Fisheries Final Report. Institute Of Marine Sciences. METU Içel Turkey 108p.

Bologa A.S., H.V. Skolka and Frangopol P.T. (1984). Annual cycle of planktonic primary productivity off the Romanian Black Sea coast. Marine Ecology-Progress Series 19:25-32.

Bondar, C. (1977). Changes in hydrological pattern induced by engineering works on the lower Danube. Hidrotecnica, 22(7):87-9 (in Romanian).

Cociasu, A., V. Diaconu, L. Popa, , I. Nae, L. Dorogan, V. Malciu. 1997. The nutrient stock of the Romanian shelf of the Black Sea during the last three decades. In : Ozsoy, E., Mikaelyan, A. (eds) Sensitivity of North Sea, Baltic Sea and Black Sea to anthropogenic and climatic changes. NATO-ASI Series, 49-64.

Friedl G., Ch. Dinkel, B. Wehrli (1997). Benthic fluxes of nutrients in the north-western Black Sea. Est. Coast. Shelf. Sc.

Gomoiu M.T. (1990). Marine eutrophication syndrome in the north-western part of the Black Sea. In: Vollenweider R.A., Marchetti R. and Viviani R (eds) Marine Coastal Eutrophication. Elsevier Publ. 683-703.

Gücü, A. (1997). Role played by fishing on the Black Sea ecosystem . In : Ozsoy, E., Mikaelyan, A. (eds) Sensitivity of North Sea, Baltic Sea and Black Sea to anthropogenic and climatic changes. NATO-ASI Series,149-162.

Ivanov L. and Beverton R.J.H. (1985). The fisheries resources of the Mediterranean. Part Two: Black Sea. G.F.C.M. Studies and Reviews No.60, Rome: FAO, 135p

Mee, L.D. (1992). The Black Sea in crisis: The need for concerted international action. Ambio, 21(3):278-286.

Mutlu E., Bingel F., Gücü A.C., Melnikov V.V., Niermann U., Ostr N.A. and Zaika V.E. (1994). Distribution of the new invader Mnemiopsis sp. and the resident Aurelia aurita and Pleurobrachia pileus populations in the Black Sea in the years 1991-1993. ICES J. Mar. Sci. (51): 407-421.

Niermann U., F. Bingel, A. Gorban, A.D. Gordina, A.C. Gücü, A.E. Kideys, A. Konsulov, G. Radu, A.A. Subbotin & V.E. Zaika. (1994). Distribution of anchovy eggs and larvae (Engraulis encrasicolus Cuv.) in the Black Sea in 1991 and 1992 in comparison to former surveys. ICES J. Mar. Sci. (51): 395-406.

Shiganova, T. (1997). Mnemiopsis leidyi abundance in the Black Sea and its impact on the pelagic community. In : Ozsoy, E., Mikaelyan, A. (eds) Sensitivity of North Sea, Baltic Sea and Black Sea to anthropogenic and climatic changes. NATO-ASI Series, 117-130

Sorokin, Y.I. (1983). The Black Sea. Ecosystems of the world. In P. H. KETCHUM (eds) : Estuaries and enclosed seas. 26: pp.253-291, Elsevier, Amsterdam.

Stepnowski A., Gücü A.C., and F. Bingel. (1993). Assessment of the pelagic fish resources in the southern Black Sea using echo integration and Dual-Beam processing. Archives of Acoustic, Polish Academy of Science Journal, 18 (1), pp. 83-104.

Tolmazin D. (1985). Economic impact of the riverine-estuarine environment of the USSR: The Black Sea basin. Geo. Jl, 11:137-152

van Bennekom, J., W. Salomon. (1980). River inputs to ocean systems. Joint copyright UNEP and UNESCO, 33-51

Van Eeckhout D. & Lancelot C., 1997. Modelling the functioning of the north-western Black Sea ecosystem from 1960 to present. In : Ozsoy, E., Mikaelyan, A. (eds) Sensitivity of North Sea, Baltic Sea and Black Sea to anthropogenic and climatic changes. NATO-ASI Series, pp 455-468.

Vinogradov, M.E. (1992). Long-term variability of the pelagic community structure in the open Black Sea. In : Problems of the Black Sea. International Conference on Problems of the Black Sea. International Conference. Sevastopol, Ukraine. November 10 - 15: 19-33.

Zaika, V.E. (1992). The ecosystem degradation is increasing. In : Problems of the Black Sea. International Conference on Problems of the Black Sea. International Conference. Sevastopol, Ukraine. November 10 - 15: 97-100.

TITLE:

European Salt Marsh Modelling (EUROSSAM)

CONTRACT N°:

ENV4-CT97-0436

COORDINATOR:

Prof. Jean-Claude Lefeuvre UNIVERSITE DE RENNES 1 UMR 6553 Laboratoire d'Evolution des Systèmes Naturels et Modifiés 35042 Rennes Cédex, FR	 Tel. 33 (0)2 99 28 61 42 Fax. 33 (0)2 99 28 14 58 e-mail lefeuvre@univ-rennes1.fr
Dr Eric Feunteun UNIVERSITE DE RENNES 1 UMR 6553 Laboratoire d'Evolution des Systèmes Naturels et Modifiés 35042 Rennes Cédex , FR	 Tel.: 33 (0)2 99 28 14 39 Fax.: 33 (0)2 99 28 14 58 e-mail: eric.feunteun@univ.rennes1.fr

PARTNERS

Dr. L. Boorman LaB COASTAL The Maylands Holywell Huntington CAMBS GB PE17 3TQ, UK	 Tel Fax: 44 1480 468 068 e-mail Laurie.Boorman@btinternet.com
Dr Willem VanDuin DLO – INSTITUTE FOR FORESTRY AND NATURE RESEARCH Dep.of Aquatic Ecology PO box 167, 1790 AD Den Burg, NL	 Tel.: 31 222 369702 fax: 31 222 319265 e-mail : w.vduin@ibn.dlo.nl
Prof. J.G. Ferreira IMAR – INSTITUTO DO MAR UNIVERSIDADE DE LISBOA 2825 Monte de Caparica, PT	 tel : 351 1 295 44 64 Fax.: 351 1 294 85 54 e-mail: jgferreira@compuserve.com
Prof. A. de Bettencourt IMAR UNIVERSIDADE DE EVORA Appartado 94 cargo dos Collegais 7000 Evora, PT	 Tel.: 351 66 740 823 Fax.: 351 66 294 93 e-mail
Prof. R. Neves INSTITUTO SUPERIOR TECNICO Avenida Rovisco Pais 1096 Lisboa Codex, PT	 Tel.: 351 1 841 73 98 Fax.: 351 1 8417398 e-mail: rneves@hidrol.ist.utl.pt
Prof M.J. Costa INSTITUTO DE OCEANOGRAFIA Rua Ernesto Vasconcelos Campo Grande 1700 Lisboa, PT	 Tel.: 351 1 750 00 78 Fax. 351 1 750 00 09 e-mail: zitasia@cc.fc.ul.pt
Dr. J.C. Salomon IFREMER Brest (FR) DEL / AO BP 70, 29 280 Plouzané ,FR	 Tel.: 33 (0)2 98 22 43 09 Fax: 33 (0)2 98 22 46 44 e-mail: j.salomon@ifremer.fr

MODELLING OF EUROPEAN SALT MARSHES FUNCTIONING : AN INDISPENSABLE APPROACH FOR A SUSTAINABLE MANAGEMENT OF THESE THREATENED ENVIRONMENTS

J-C. LEFEUVRE, E. FEUNTEUN, V. BOUCHARD
Université de Rennes I, UMR Ecobio, Laboratoire d'Evolution des Systèmes Naturels et Modifiés, 350420 Rennes Cédex, France.

INTRODUCTION

Saltmarshes constitute dynamic environments which present at once characteristics of both marine and terrestrial systems. They develop at the higher reaches of the intertidal range of flat and silted areas. Their creation and development are enabled if they are located in areas sufficiently protected against erosion by high energy waves to permit sedimentation (Vernberg, 1993). Such conditions occur behind spits, offshore bars and islands, in protected bays or on the shores of estuaries where river sediments deposit (Chapman, 1974). A progressive and more or less regular accretion occurs with a colonisation by saltmarsh vegetation.

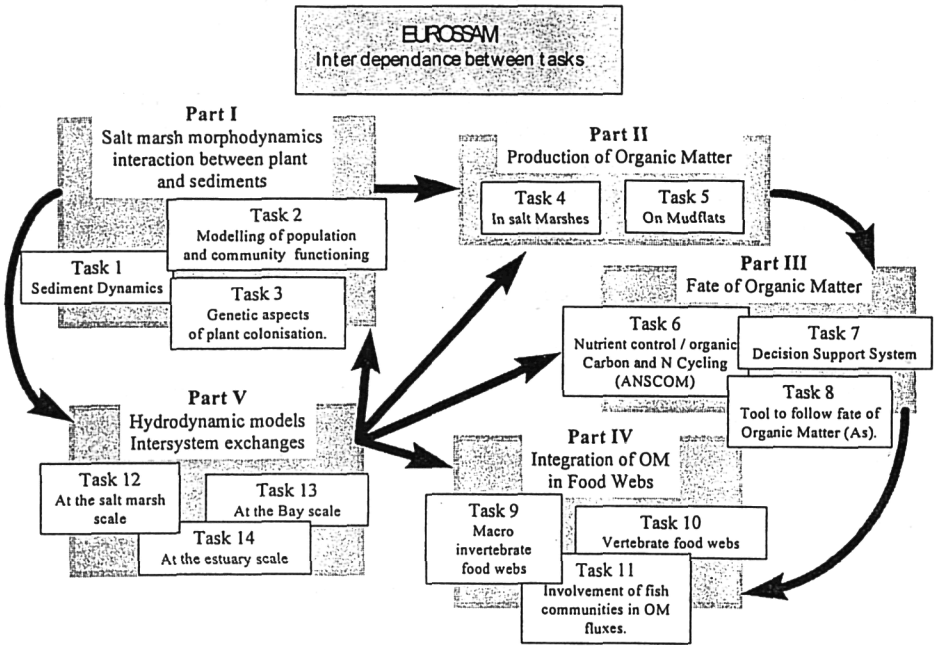
The primary production of most of these saltmarshes are among the most productive ecosystems of the world and the vegetation cover provides sheltered habitats for many organisms. Therefore they are assumed to play essential roles in the functioning of estuaries, bays and tidal flats. Consequently, they contribute significantly to the productivity of coastal waters including that of shellfish, crustaceans, fish and birds (i.e. waders and anseriforms). This assumption is sustained by the outwelling hypothesis successively developed by Teal (1962), Odum (1980), Dame *et al.* (1986) and Lefeuvre *et al.* (1996).

Intrinsic characteristics of saltmarshes confer them an effective role in flood, erosion and storm surges control. Moreover, they improve water quality by retaining pollutants, excess of nutrients, and diseases caused by micro-organisms. Some are grazed by cattle and sheep and produce meat with a special flavour, highly appreciated in several countries.

Despite such fundamental functions, saltmarshes are threatened within the European Community because of a range of natural and mainly anthropogenic factors. To enable the European Community to pursue a sustainable policy on the conservation of these marshes it was necessary to perform intensive research on their general functioning with a quantification of the various processes sustaining their productivity. So far, most of the studies were undertaken on compartments often artificially separated according to the research team's specialities. Generalisations to the global functioning of saltmarsh systems are made by theoretical, but not validated, assumptions linking different models.

Indeed until 1979, most European studies aimed at describing the functions of estuarine systems (primary and secondary productivity, trophic areas for terrestrial and aquatic species, nursery zones, *etc.*). However, the functional role of salt marshes towards coastal waters was not well understood (Wolff *et al.* 1979): in contrast to the United States there were few data

available on fluxes of organic matter. However, budget studies on a saltmarsh in the Wadden Sea showed import of Particulate Organic Carbon, (Wolff *et al.*, 1979; Dankers *et al* 1984). Which, in a first approach, seemed to contradict Odum's outwelling hypotheses stating that American saltmarshes export important quantities of organic matter towards coastal waters. This contradiction originated a range of studies on the functioning of other European saltmarshes in order to assess differences in functioning between North American and European saltmashes. This is why a project on comparative studies of saltmarsh processes are being performed within the Environment & Climate Programme of the European Community (contracts n° EV4V-0172F, and n° EV5V-CT92-0098).



These projects were carried out in four countries: The Netherlands, UK, Portugal and France. The results showed a large variability of primary production between sites (from 5 to 36 T DW OM y^{-1}). This variability is due *pro parte* i) to tide amplitudes (less than 3 m. in the Netherlands, almost 15 m. in Mont Saint Michel Bay in France), ii) to the location of marshes relative to the mean sea level, and iii) to plant community structure. There is also a great inter-annual variability of the primary production within sites. However, despite this high variability, the results we obtained, globally support Wolff and Dankers' findings, except in Mira Estuary (Portugal) (Lefeuvre *et al*, 1996). This project also strengthens more recent investigations of American scientists (Dame 1989) on the causes of variability and supports the marsh-estuarine theory (Dame *et al*, 1992; Dame, 1994). This theory states that saltmarshes tend to mature along a seawards - landwards gradient ; pioneer zones being located closest to the sea at the limit of mud flats and mature ones bordering the terrestrial systems. In estuaries the gradient is organised differently, probably due to the influence of fresh water : pioneering marshes developing upstream and mature marshes in downstream reaches influenced by marine waters. According to Dame (1994), evidence to date indicates that mature American systems export all materials, mid-aged systems import particulate materials and immature systems import all forms of materials. Regarding the strong contrasts between North American and European salt marshes, it is not sure that this fascinating theory

can provide for a clear vision of import-export budgets for the marshes of the western coast of Europe. Indeed, European processes are not quite the same because of the important tidal ranges in the sites under study. For instance, in the Mont Saint Michel's Bay (France), mature marshes tend to import macro-detritus such as dead leaves, plant debris *etc*, but these materials are processed by micro-organisms into particulate organic matter and dissolved nutrients which are exported by run-off waters.

Whatever the processes involved, there is a general evidence that these saltmarshes do function, more or less directly, as nutrient producers which enrich the coastal fringe and sustain the productivity of coastal marine biota. However, the relative contribution of the saltmarshes according to their maturity stage is still poorly understood and controversies on this subject are ongoing. Therefore, more attention has to be paid on the comprehension of the processes involved in the creation of saltmarshes from the pioneer zones to the most mature systems. Moreover, the extent of coastal marine waters enriched by these various types of saltmarshes is not accurately described yet. There is a crucial need to understand the processes underlying the organic matter fluxes between marshes and coastal waters, and to identify the extent of coastal waters whose functioning is influenced by the adjacent saltmarshes. This research topic has to be supported by the development of hydrodynamic and sedimentary models linked to biological and ecological process models.

In order to provide reliable and useful information for the sustainable management of these environments, it is also necessary to understand the interactions between human activities and the functioning of these saltmarshes and the coastal waters to which they are linked. This objective will be enabled by the development of a Decision Support System.

OBJECTIVES.

Following two previous EC funded projects on the functioning of European salt marsh ecosystems, the overall objective of the EUROSSAM project is to develop a policy and management tool for the conservation and restoration of salt marshes. In particular, the project will aim at:

1. The improvement and testing of a range of ecological processes and hydrodynamic models to predict the likely responses of various salt marsh ecosystems to environmental changes such as potential impacts of predicted rise of sea level or human activities on the functioning of salt marshes and on the fluxes of various nutrients between the salt marshes and adjacent marine coastal waters;
2. The calibration of the process models to specific conditions encountered in various European salt marshes;
3. The linkage of the process models with the hydrodynamic model in order to develop a decision support system (DSS) tool.

The project identifies four goals :

1. To investigate and model salt marshes in regard to the interactions between sedimentation or accretion of plants. This sub-project intends to develop a typology of pioneer salt marshes which will take into account population processes, genetic aspects of plant colonisation in pioneer littoral zones and the geomorphology of those wetlands. Models

will be constructed which allow to predict the behaviour of salt marsh ecosystems subject to environmental changes. For example, to predict the effects of a potential rise in sea level on plant communities and/or organic matter production (PART 1).

2. To develop a robust ecological model of processes taking place inside salt marshes and mudflats, including organic matter production and nutrient cycling within and between the vegetation and sediment compartments. The ecological salt marsh model will be developed in such a way that it will be easy to run different modules for each process (ANSCOM and DRAINMOD). This will render the model a strong research tool and make it flexible enough for using it in different geographically or functionally different marshes. The modelling objectives will be complemented by specific process studies needed to calibrate the model (PARTS 2 and 3).
3. To investigate the colonisation of mudflats and salt marshes by wildlife fauna and the integration of organic matter from these ecosystems in food webs. The study of animal communities, their involvement in food webs and in organic matter fluxes will provide supplementary information to the general understanding of the global functioning of coastal hydrosystems (PART 4).
4. To develop hydrodynamic models at 3 different scales: at the salt marsh, at the bay and at the estuary scale. In order to support the prediction of the functioning of the bay, the morphological dynamics of the salt marsh and the distribution of plant and animal communities will be investigated (PART 5).

The evaluation and testing of the above models as well as the marsh typology will both increase our understanding of the processes controlling the salt marsh ecosystem. They will highlight areas where the processes are not well understood, and where more detailed research is needed. The intention is to build a tool for management, rather than a research one, that will run on the fairly limited data sets likely to be available for most marshes.

TITLE: **Atmospheric Nitrogen Inputs into the Coastal Ecosystem (ANICE)**

CONTRACT NO: **ENV4-CT97-0526**

COORDINATOR:

Dr. G. de Leeuw
TNO Physics and Electronics Laboratory,
P.O. Box 96864, 2509 JG The Hague, The Netherlands

Phone: +31 70 374 0462
FAX: +31 70 374 0654;
email: deleeuw@fel.tno.nl

PARTNERS:

Dr. Heinke Schlünzen
Meteorologisches Institut
Zentrum für Meeres- und Klimaforschung
Universitaet Hamburg
Bundesstrasse 55, 20146 Hamburg, F.R.G.

Phone: +49 40 4123 5082
FAX: +49 40 4117 3350
email: schluenzen@dkrz.de

Dr. Michael Schulz
Institut für Anorganische und Angewandte Chemie
Universitaet Hamburg
Martin-Luther-King Platz 6, 20146
Hamburg, F.R.G.

Phone: +49 40 4123 4095
FAX: +49 40 4123 2893
email: michael.schulz@dkrz.de

Dr. Gerald Geernaert
National Environmental Research Institute
Roskilde, DK 4000 Denmark

Phone: +45 46 30 1101
FAX: +45 46 30 1214
email: glg@dmu.dk

Dr. Lise Lotte Geernaert-Sorensen
Risø National Laboratory
Roskilde, DK 4000, Denmark

phone: +45 46 77 5015
FAX: +45 46 75 5619
email: lotte.geern@risoe.dk

Dr. Tim Jickels
School of Environmental Sciences
University of East Anglia
Norwich NR4 7TJ, Norfolk, GB

phone: +44 160 359 3117
FAX: +44 160 350 7719
email: T.Jickells@uea.ac.uk

ATMOSPHERIC NITROGEN INPUTS INTO THE COASTAL ECOSYSTEM (ANICE)

GERRIT DE LEEUW
TNO Physics and Electronics Laboratory,
P.O. Box 96864, 2509 JG The Hague, The Netherlands

Phone: +31 70 374 0462; FAX: +31 70 374 0654;
email: deleeuw@fel.tno.nl

SUMMARY

The study on Atmospheric Nitrogen Inputs into the Coastal Ecosystem (ANICE) is focused on the improvement of models describing atmospheric transport and transformation of nitrogen compounds. Model tools are needed for mapping of the nitrogen load and for studies of the impacts of different regulations of anthropogenic emissions. The Southern North Sea is taken here as the prototype. ANICE is a mixture of modeling efforts and experiments. The latter are needed both to improve and to test the models. The study involves two intensive field experiments (IOP) with measurements at a coastal site, on a research platform and during the second IOP also on a ship, as well as from a long-term observational period involving automated sampling. Remote sensing techniques will be used as a tool.

1. INTRODUCTION

The contribution of atmospheric inputs to coastal eutrophication problems is now beginning to be recognised in a number of areas around the world [Paerl, 1995]. The ANICE project (ANICE = Atmospheric Nitrogen Inputs into the Coastal Ecosystem), is focused on atmospheric inputs of nitrogen compounds (HNO_3, NO_3^-, NH_3 and NH_4^+) into the sea and the governing processes that are specific for coastal areas. The Southern North Sea will be studied as a prototype. Because the processes are described by physical equations and chemical reactions, as opposed to empirical relations, the results can also be applied to other regional seas like the Mediterranean, the North Atlantic continental shelf area and the Baltic.

ANICE is a combination of experimental and modeling work, involving a close collaboration between experimentalists and modelers. An interesting feature of the ANICE project is the use of two complementary models, ACDEP [Hertel et al., 1995] and METRAS [Schluenzen, 1990], with different scales, different mixing schemes and different initialisations. ACDEP will be used to calculate air mass trajectories (96 hours backward) based on EMEP meteorology, and to provide the 'large' scale lateral boundary conditions for calculations with METRAS in the coastal model domain where most measurements are taken. Finally, ACDEP will be used to estimate atmospheric inputs of nitrogen to the total North Sea, while METRAS enables detailed studies of the coastal area. The combined modeling effort is expected to lead to a major improvement of the final result, i.e. an estimate of atmospheric inputs into the North Sea, that can be used in effect studies. The impact of atmospheric nitrogen on coastal ecosystems will be assessed.

Extensive experimental work is planned to validate the models, assess the model results and, in particular, improve the models by taking into account coastal processes that not only affect

inputs of atmospheric nitrogen in coastal regions, but also in open sea. Experimental data will be used in the model runs.

2. OBJECTIVES

The overall aim of the ANICE project is to improve the accuracy and performance of model tools that estimate atmospheric nitrogen deposition into the sea. The model domain is the southern part of the North Sea. Special emphasis will be on the chemical and physical processes governing the transformation of nitrogen compounds and their deposition into coastal waters.

The specific objectives of ANICE are:

- To understand how the physical processes in the coastal region affect the atmospheric input of nitrogen compounds in the sea, to use these to provide a better parameterisation for the transport-chemistry models, and to assess errors due to assumptions that do not strictly apply in coastal environments.

- Construction of a non-linear multi-process surface layer model of governing physical processes related to the growing wave field, accelerating wind field, and integrated along-trajectory fluxes

- Understand the effect of heterogeneous processes on the deposition of nitrogen compounds into the sea, parameterise the effects and implement them in the transport-chemistry models.

- To use both a Lagrangian and a Eulerian model to improve the calculation of the nitrogen input into the North Sea.

- Development and application of new techniques that can be used for continuous sampling to provide inputs for a better assessment of the nitrogen inputs into the North Sea.

- Assessment of the impact of atmospheric nitrogen on coastal ecosystems.

- Establish a model tool for assessment of N-load reduction strategies.

3. ANICE EXPERIMENTS

ANICE involves two intensive field experiments (IOP) with measurements at a coastal site, on a research platform and during the second IOP also on a ship, as well as a long-term observational period involving automated sampling. Remote sensing techniques will be used as a tool.

During the long-term observations, measurements will be made of aerosol size distributions, aerosol chemical composition, and concentrations of relevant gases. Automatic rain samplers will be deployed on a ferry for one year. Major ions, pH and conductivity will be measured in the rain samples to obtain an accurate estimate of the wet deposition contribution at several locations across the North Sea. The results will be compared with model simulations using both the 'standard' inputs and the measured rain rates as inputs.

Intensive observational periods will be conducted in June 1998 and in the summer of 1999, each during a period of three weeks. The IOPs involve a coastal station in the UK, a research platform (Meetpost Noordwijk, or MPN) at 9 km from the Dutch coast, and during the second IOP also a ship sampling upwind or downwind from either of these two stations. During each IOP, single level concentrations of both HNO_3 and NH_3 will be measured at all stations. Also other relevant gases, aerosol chemical composition and aerosol particle size distribution, and a suite of meteorological and oceanographic parameters will be measured. The first IOP will focus on HNO_3/NO_3^- relations , while during the second IOP the emphasis will be on processes related to NH_3.

Meetpost Noordwijk (MPN) is a research tower in the North Sea (45° 16' 25.9" N; 04° 17' 45.8" E), at 9 km from the Dutch coast near Noordwijk. The tower is equipped with booms at the west and the north sides of the tower, which allow for unperturbed turbulence measurements. The boom heights are adjustable.

MPN will be used for measurements of fluxes of HNO_3 and NH_3 using the eddy accumulation technique. Aerosol particle size distributions, size segregated aerosol composition, filter samples and rain water samples will be analysed for the major ion components. Together, these data allow for determination of the scavenging of HNO_3 and NH_3 by heterogeneous or homogeneous reactions. Fluxes of momentum, heat and water vapour will be measured using micro-meteorological methods.

The UK coastal site is at the Weyborne Observatory in North Norfolk, immediately on the coast of Northeast Norfolk. Size segregated aerosols and rainwater will be sampled and analysed for major ions including nitrate, ammonium, nitrite and organic nitrogen. Selected samples collected at this site and elsewhere will also be analysed for stable nitrogen isotopes. The extension of ANICE to include organic nitrogen is important given the recent realisation that this important group of nitrogen compounds has often been neglected.

A ship will be used to sample gas concentrations, aerosol particle size distributions, aerosol chemical composition, micrometeorological fluxes and mean meteorological parameters, from very close to the shore out to open sea. Analyses of NH_x will be performed in the water column in horizontal profiles, supported by measurements of pH, salinity and chlorophyll concentration. Emphasis will be put on the near coastal areas upwind from the MPN to support the flux measurements on the tower with information on the spatial distribution of the concentration of NH_3 at the surface.

In clear sky conditions, aerosol optical depth will be retrieved from satellite data, to provide large-scale images of the aerosol density over the ANICE area. The boundary layer structure will be characterised with lidar.

4. MODELING

Two different transport chemistry models will be applied:

- The Lagrangian transport-chemistry model ACDEP will be used for a coarse gridded mapping of nitrogen depositions to the North Sea. The results will consist of dry and wet deposition of nitrogen gas phase compounds and dry and wet deposition of nitrogen in aerosol phase. All results having a 6 hours resolution. The calculations will be based on EMEP meteorological data, emission inventories for Denmark and Northern Germany and

the EMEP emission inventories for the rest of Europe. Furthermore, ACDEP will be used to calculate air mass trajectories and to initialise the North Sea meteorological and chemical properties.

- The Eulerian model METRAS will be used for detailed studies of coastal effects in the southern North Sea. The model calculates prognostically wind, temperature, humidity, cloud - and rainwater as well as concentrations of chemical species including chemical gas-phase and aerosol (sea-salt, fine particle nitrogen and sulphur species). Meteorological processes, deposition (dry and wet) as well as entrainment fluxes of nitrogen species and the characteristic time scales of the interacting processes will be simulated for the area under investigation for some experimental days with high resolution in space and time.

Heterogeneous processes are important for ANICE because of interactions involving nitric acid, nitrate, ammonia, ammonium and sea salt aerosols, and the formation of new particles through nucleation. Heterogeneous processes are modelled to include their effects in the transport-chemistry models.

The distribution of load with varying stratification will be treated by constructing a simple, non-linear model of all governing physical processes related to the growing wave field, accelerating wind field, and integrated along-trajectory fluxes. While momentum and heat can generally be regarded as "conservative quantities," gaseous nitrogen compounds are often so reactive that source and sink terms must be taken into account to evaluate their fluxes.

5. CONCLUSION

The ANICE project started on 1 February 1998 and has a duration of 3 years. The plans for the project have been outlined. Preparations have started for the intensive observations and the first IOP that will take place 8-26 June, 1998.

An attempt will be made to assess the impact of atmospheric nitrogen compounds on coastal ecosystems. This will involve consideration of both episodic and chronic nitrogen inputs and will be based on comparisons of phytoplankton nitrogen requirements, other external nitrogen inputs to the area of interest and the direct nitrogen fluxes provided by ANICE.

ACKNOWLEDGEMENTS

The ANICE project is supported by the European Commission EC DG XII, contract ENV4-CT97-0526, with additional support from the participants' institutes. MPN is owned and maintained by the Dutch Ministry of Public Works.

REFERENCES

- Hertel, O., Christensen, J., Runge, E.H., Asman, W.A.H., Berkowicz, R., Hovmand, M.F., and Hov, Ø., 1995. Development and Testing of a new variable scale model - ACDEP. *Atmospheric Environment*, **29**, 1267-1290.
- Paerl, H.W. Coastal eutrophication in relation to atmospheric nitrogen deposition: current perspectives. Ophelia, Vol. 41, 237-259, 1995.
- Schluenzen K.H. (1990): Numerical studies on the inland penetration of sea breeze fronts at a coastline with tidally flooded mudflats. Contr. Atmos. Phys., 63, 243-256.

BALTIC SEA CYANOBACTERIA (BASIC)

CONTRACT NO: **ENV4-CT97-0571**

COORDINATOR: Lucas J. STAL
NIOO-Centre of Estuarine and Coastal Ecology
P.O.Box 140, NL-4400 AC Yerseke, The Netherlands
Phone: +31 113 577497 Fax: +31 113 573616
e-mail: stal@cemo.nioo.knaw.nl

PARTNERS: Anthony E. WALSBY and Paul K. HAYES
School of Biological Sciences, University of Bristol
Woodland Road, Bristol, BS8 1UG, United Kingdom
Phone: +44 117 9287490 Fax: +44 117 9257374
e-mail: HayesPK@bsa.bristol.ac.uk

John R. GALLON
Biochemistry Research Group, University of Wales Swansea
Singleton Park, Swansea, SA2 8PP, United Kingdom
Phone: +44 1792 295376 Fax: +44 1792 295447
e-mail: j.r.gallon@swansea.ac.uk

Klaus von BROECKEL
Institut für Meereskunde, Department of Marine Planktology
Düsternbrooker Weg 20, D-24105 Kiel, Germany
Phone: +49 431 8802372 Fax: +49 431 8801569
e-mail: Klausb@sfb313.uni-kiel.de

Birgitta BERGMAN
Department of Botany, Stockholm University
S-10691 Stockholm, Sweden
Phone: +46 8 163751 Fax: +46 8 165525
e-mail: bergmanb@botan.su.se

A. Kaarina SIVONEN
Department of Applied Chemistry and Microbiology
P.O.Box 56, FIN-00014 University of Helsinki, Finland
Phone: +358 9 70859270 Fax: +358 9 70859322
e-mail: Kaarina.Sivonen@Helsinki.Fi

Patrizia B. ALBERTANO
University of Rome 'Tor Vergata', Department of Biology
Via della Ricerca scientifica, I-00133 Roma, Italy
Phone: +39 6 72594345 Fax: +39 6 2023500
e-mail: albertano@tovvx1.ccd.utovrm.it

DEVELOPMENT OF CYANOBACTERIAL BLOOMS IN THE BALTIC SEA

LUCAS J. STAL[1], PATRIZIA ALBERTANO[2], BIRGITTA BERGMAN[3], KLAUS VON BROECKEL[4], JOHN R. GALLON[5], PAUL K. HAYES[6], KAARINA SIVONEN[7], ANTHONY E. WALSBY[6]

[1]Netherlands Institute of Ecology, Centre of Estuarine and Coastal Ecology, Yerseke, The Netherlands; [2]University of Rome, 'Tor Vergata', Rome, Italy; [3]Stockholm University, Stockholm, Sweden; [4]Institut für Meeresforschung, Kiel, Germany; [5]University College of Wales, Swansea, UK; [6]University of Bristol, Bristol, UK; [7]University of Helsinki, Helsinki, Finland

SUMMARY

The Baltic Sea is a large brackish sea that in recent years experienced an increasing level of eutrophication. As a result of this nutrient input blooms of phytoplankton occur regularly. Of particular interest are blooms of cyanobacteria. These blooms occur during a relatively short period in summer but they have a patchy distribution. Until now it has proved to be difficult to predict where and when blooms of cyanobacteria will develop. An important part of these blooms consist of filamentous, heterocystous cyanobacteria. These organisms are diazotrophic and grow at the expense of atmospheric nitrogen, which is abundantly present. Their growth is therefore not limited by nitrogen. The diazotrophic cyanobacteria produce also gas vesicles that provide them with buoyancy. They occur in aggregates that float to the sea surface where they eventually form a dense scum. Not in the last place because many species are toxic, these blooms are considered a nuisance. Although the surface accumulations of the larger cyanobacteria are most conspicuous, they represent only a relative small portion of the cyanobacterial bloom. Up to 80% of the bloom may be composed of extremely small-sized picoplanktonic species and they may be responsible for a considerable part of the primary productivity in the Baltic Sea. However, the diazotrophic species may be responsible for up to 25% of the total nitrogen input in this sea. About 10% of the nitrogen fixed are transferred to the picoplankton.

1. INTRODUCTION

The Baltic Sea is the largest body of brackish water on Earth. It has a surface of 374,000 km^2, a mean depth of approximately 60 m and a maximum depth of 455 m (Kullenberg 1981). The Baltic Sea is subdivided into a number of areas: the Gulf of Bothnia in the northernmost part; the Gulf of Finland, bordered by Finland, Russia and Estonia; the Gulf of Riga; the Baltic Proper; the Gotland Sea; the Bornholm Sea and the Kiel Bight (Fig. 1). Tides are virtually absent in this sea. The Baltic Sea is connected to the North Sea via the narrow Öresund. Seawater of full salinity enters through this channel and is then partly mixed with the brackish water, which is diluted by fresh water from rivers, coastal run-off and rainfall. The large net freshwater supply shows weak seasonally variations. The salinity gradient ranges from 1-4 ppt, i.e. almost freshwater, in the most eastern and northern parts, to 7-8 ppt in the south. There are long residence times of water, salt and nutrients.

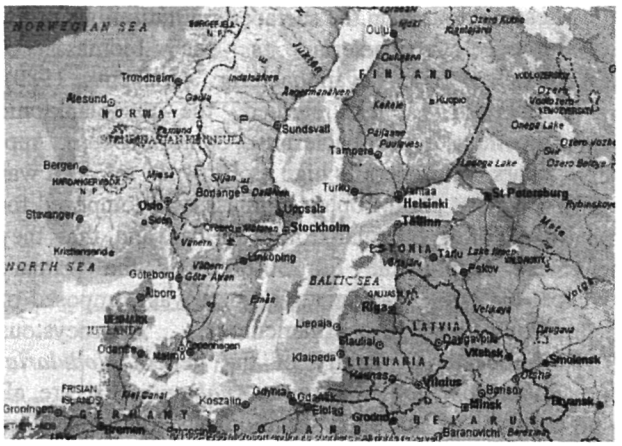


Fig. 1. The Baltic Sea (from Microsoft Encarta 97 World Atlas)

The water column in the Baltic Sea is vertically stratified by gradients of temperature and salinity (Fig. 2). The sill depth is above the halocline. The water does not freely mix but is separated into layers of increasing density. In summer a layer of warm water about 20 m deep floats on the colder layers below (thermocline); at greater depths of 60-90 m there is another layer of denser more saline water (halocline). In the Baltic Sea the large-scale circulation is weak.

The Baltic Sea experiences a high nutrient input via atmosphere (through rainfall and particulate deposition) and from the land (from rivers and run-off) (Larsson et al. 1985). There is a large input of humic substances and erosion causes strong redistribution of particles and nutrients. Nutrient inputs show therefore large regional gradients. Export and import to the ocean is small compared to internal sinks and load. Another important feature of the Baltic Sea is the strong coupling of benthic and pelagic systems.

The input of phosphate and nitrogen is particularly important (Granéli et al. 1990). In these nutrient gradients either nitrogen or phosphorus may limit primary productivity. Eutrophication in the Baltic Sea has led to mass occurrence ("blooms") of certain plankton, a well-studied phenomenon that can be predicted on the basis of nutrient dynamics. Spring blooms of planktonic diatoms develop when the ratio nitrogen:phosphorus is high (Niemi 1979, Conley and Johnstone 1995). However, a notable exception is the regular mass-occurrence of blooms of cyanobacteria (blue-green algae). Although blooms of cyanobacteria are well known from freshwater lakes, they are almost lacking in the marine environment, with the exception of the Baltic Sea and tropical oceans (Reynolds 1987, Capone et al. 1997, Walsby et al. 1997). Blooms of cyanobacteria may become so extensive that they can be seen from satellite photographs (Horstmann 1983). In recent years the extent of the blooms of cyanobacteria in the Baltic Sea has increased considerably, which has been attributed to an increasing eutrophication (Kahru et al. 1994).

The cyanobacterial blooms in the Baltic Sea are commonly diazotrophic; i.e. the organisms fix atmospheric nitrogen. Indeed, preliminary studies suggest that such blooms may account for 15-25% of the nitrogen input into the Baltic Sea. Nitrogen-fixing cyanobacteria are important components of water blooms in the Baltic Sea (Leppänen et al. 1988). Cyanobacterial blooms typically occur in summer but it has proved difficult to predict when and where they will develop as these blooms have an extremely patchy distribution (Kononen et al. 1996). Another property of these cyanobacteria is that they possess gas vesicles that provide them with buoyancy (Walsby et al. 1995). It was shown that during calm days these organisms float rapidly to the surface, where they experience optimal light conditions. The possible toxicity of these blooms is of great environmental concern (Sivonen et al. 1989).

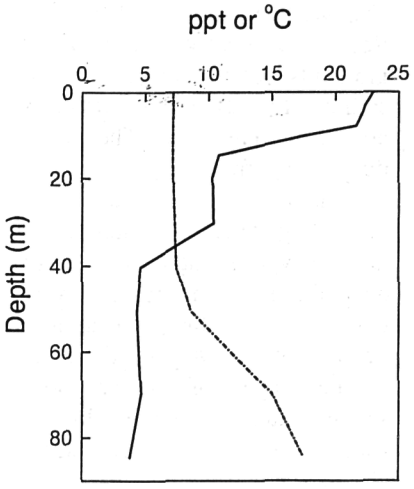


Fig. 2. Typical CTD depth profiles of temperature (solid line) and salinity (dotted line) in the Baltic Proper.

Less obvious than the surface accumul-ations of the larger cyanobacteria, is the biomass of picoplanktonic cyanobacteria (Jochem 1989). Although far less studied, the picoplanktonic unicellular cyanobacterium *Synechococcus* spp. occurs in numbers as high as $10^5 - 10^6$ mL^{-1}. It was found that phototrophic biomass was composed for 40-80% of picoplanktonic species and that they were responsible for 50-60% of the primary productivity. The remaining part was composed of colony-forming, filamentous, heterocystous cyanobacteria, mainly of the genera *Nodularia*, *Aphanizomenon* and some *Anabaena* that are all capable of nitrogen fixation and are therefore independent on combined sources of nitrogen (Fig. 3).

The objectives of this study include the assessment of the input of new nitrogen and carbon into the Baltic Sea and the identification of the factors that control these processes. In addition, predictions will be made with regard to the local risks caused by toxin production by blooms of cyanobacteria. An integrated model of photosynthesis, nitrogen fixation and toxin production for cyanobacterial waterblooms will be developed for this purpose. The factors that limit growth, photosynthesis and nitrogen fixation in filamentous and picoplanktonic cyanobacteria will be determined and related to the biodiversity of this community.

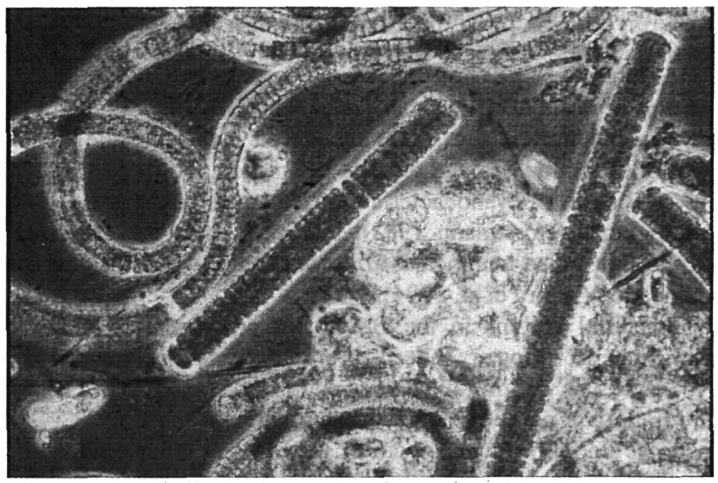


Fig. 3. Micrograph of coiled and straight trichomes of the diazotrophic cyanobacterium Nodularia. *Photo: LJ Stal, NIOO-CEMO Yerseke, The Netherlands*

2. RESULTS

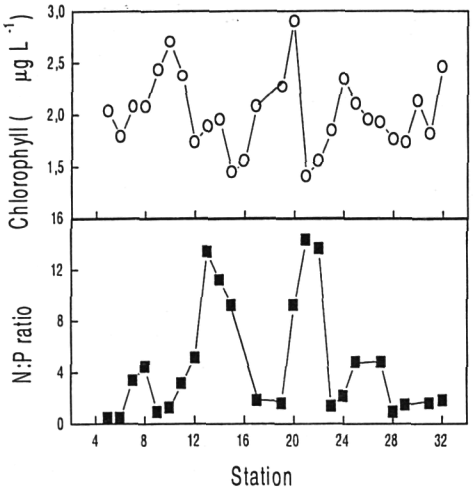


Fig. 4. Surface concentrations of chlorophyll a and ratios of nitrogen to phosphorus during a cruise track from the Bornholm Sea to the Gotland Sea from June 26 to July 3 1995. Data from A. Stuhr, Institut für Meeresforschung, Kiel.

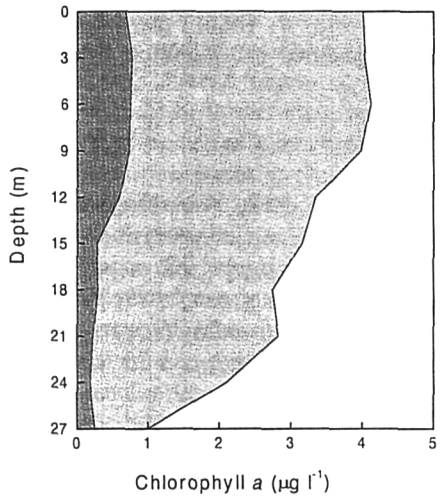


Fig. 5. Typical depth distribution of chlorophyll a in the >20 (m fraction (dark gray) and total chlorophyll a (light gray). Data from L.J. Stal, NIOO-CEMO, Yerseke, The Netherlands

2.1. Nutrients and biomass

The concentrations of nitrogen to phosphorus during a bloom of cyanobacteria in the Baltic Sea were always well below the Redfield ratio of 16 which indicated a relative nitrogen deficit (Fig. 4). This could be taken as evidence for the occurrence of nitrogen limitation. When comparing the patterns of chlorophyll a and the N:P ratios it seems that a high amount of phototrophic biomass coincides with a strong depletion of nitrogen. From this it is concluded that the phytoplankton effectively scavenges nitrogen from the water.

In Fig. 5 the depth distribution of chlorophyll *a* in two size fractions in the Baltic Sea is depicted. The fraction >20 µm contains all the larger diazotrophic cyanobacteria. These species also produce aggregates and the fast majority of this material is retained by a 100-µm plankton net. The fraction <20 µm is composed virtually exclusively of picoplanktonic cyanobacteria, smaller than 2 µm (results not shown). It is obvious that the phototrophic biomass is composed predominantly of picoplanktonic species. The amount of chlorophyll *a* in both fractions was greatest in the upper 12 m of the water column. The chlorophyll concentrations were also constant which was the result of mixing of this part of the water column. The higher amount of biomass of the diazotrophic cyanobacteria in the upper part of the water column reflects the possession gas vesicles by these organisms that make them buoyant. The picoplanktonic cyanobacteria do not possess gas vesicles but due to their small size their sinking rate is very low.

Table 1. The different size classes of phycobiliprotein containing picoplankton (≤3 μm) and their respective frequencies in the upper 20 m of the water column in the Baltic Proper (Middlebank) in July and August 1995. Data from Albertano et al. (1997).

	July		August	
Size class	Fraction (%)	Average size (μm)	Fraction (%)	Average size (μm)
I	26.9	0.40 ± 0.10	26.1	0.59 ± 0.12
II	46.7	0.78 ± 0.14	49.7	0.96 ± 0.13
III	26.4	1.35 ± 0.25	24.1	1.50 ± 0.24

The picoplanktonic community was composed of three clearly distinguishable size fractions (table1). The analysis of the picoplanktonic community was carried out twice, producing essentially the same results. Almost half of the community belonged to size class II, while the size classes I and III were about equal and comprised each about 25% of the total cell number. In July the size classes were about 0.4, 0.8 and 1.4 μm in diameter. In August the cells were somewhat bigger and measured 0.6, 1.0 and 1.5 μm. Although the difference was hardly significant, it was persistent. Conceivably, nutritional conditions were better in August than in July. Nutrient limitation normally results in a decrease of the cell size of these organisms (Raven 1986). A small size increases the surface : volume ratio and hence the affinity of the organism for nutrients.

Different strains of *Synechococcus* sp. from the Baltic Sea were isolated and are cultured in the laboratory. In culture, the cell size was significantly bigger than under natural conditions. This was most likely due to the high nutrient concentrations present in the culture medium. Interestingly, also the isolated strains of *Synechococcus* sp. could be placed in three groups on the basis of their color. The three groups of picoplankton were green (contained no phycoerythrin), red (contained phycoerythrin) and brown (both phycocyanin and phycoerythrin). It is tempting to assign the different pigmented picoplankton strains to the different size classes.

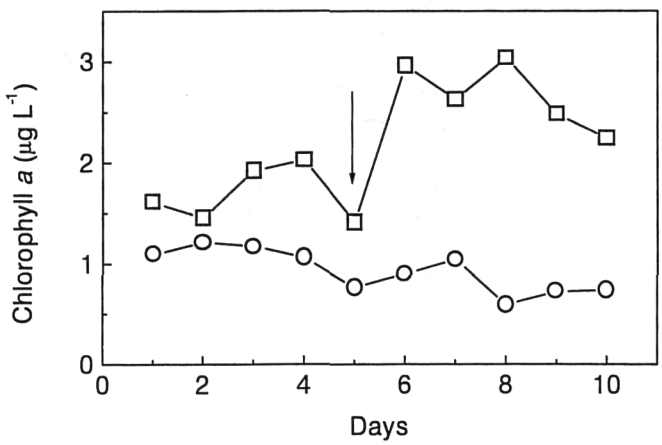


Fig. 6. Average chlorophyll a concentrations in the upper 18 m of the water column for the picoplankton fraction (squares) and the fraction >20 μm (circles) over 10 successive days. The arrow indicates a storm-mixing event. Data from LJ Stal, NIOO-CEMO, Yerseke, The Netherlands.

In Fig. 6 the results of chlorophyll *a* determinations during 10 successive days are shown. On day 5 a storm event occurred. The upper 18 m of the water column was sampled and the chlorophyll was determined in two size fractions. The fraction >20 μm contained the larger aggregate-forming diazotrophic cyanobacteria while the fraction < 20 μm predominantly consisted of picoplankton (< 2 μm).

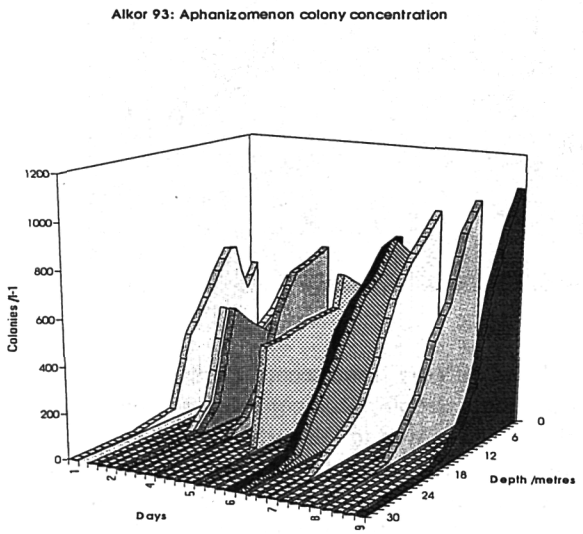


Fig. 7. Depth distribution of colonies of the heterocystous cyanobacterium Aphanizomenon *sp. during 9 successive days. Data from Walsby et al. (1997).*

From these chlorophyll data it can be clearly seen that immediately following the storm event at day 5 the chlorophyll related to the picoplankton doubled within one day. From culture experiments with *Synechococcus* sp. it is known that the maximum doubling time of this species is about 24 h. It was therefore concluded that before the storm event, the cells were growing slowly because of a nutrient limitation. The storm event caused a deep mixing which brought nutrient-rich water to the photic zone. The picoplankton responded to this by non-limiting growth for one generation after which nutrient-limited growth was re-established. The non-diazotrophic picoplankton was probably nitrogen-limited.

The larger diazotrophic species did not respond by an increase of growth rate. In the first place, the maximum growth rate of the diazotrophs is much lower than in the case of picoplankton and therefore a sudden increase in their biomass was not expected. Secondly, these species were not growing under a nitrogen limitation since they can fix dinitrogen (N_2), which was abundantly present. In fact, their biomass seemed to decrease after the storm event. It was possible that the deep mixing event caused a loss due to the collapse of gas vesicles. However, when considering the depth distribution of colonies of the diazotrophic, gas vacuolate species *Aphanizomenon*, an interesting response was observed (Fig. 7). On day 5 when the storm event occurred, the colonies were deeply mixed into the water column. The days after the storm were characterized by very calm weather. *Aphanizomenon* sp. possessed gas vesicles that provided them with buoyancy. From Fig. 7 it is clear that the colonies floated to the surface where they accumulated. Eventually, these surface accumulations became a dense scum (Fig. 8) that is notorious for the possible toxicity, the bad smell and the deterioration of water quality.

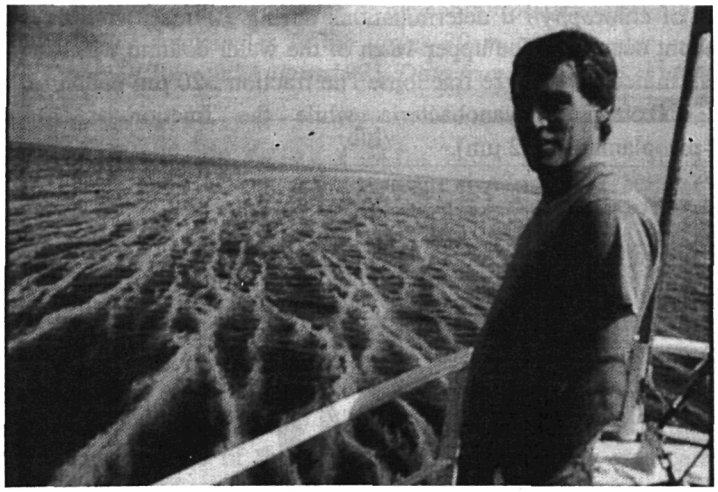


Fig. 8. Surface accumulations of blooms of cyanobacteria in the Baltic Sea. Photograph by M Meyerhöfer, IfM, Kiel, Germany.

2.2. Photosynthesis

In Fig. 9 a light versus photosynthesis curve recorded from a natural sample from the Baltic Sea is shown. This particular sample was collected at night, when large numbers of heterotrophic nanoflagellates had moved to the surface and were responsible for the high rate of respiration. In this case respiration equaled P_{max} and no net oxygen evolution was observed at any light intensity. Light-versus-photosynthesis curves were used to develop Excel spreadsheet models that allowed calculation and integration of photosynthesis at any time and at any depth in the water column. An example of the results of such calculation for the cyanobacterium *Aphanizomenon* is shown in Fig. 10. This graph shows that below a certain depth no oxygen exchange occurs because the biomass of *Aphanizomenon* is negligible. Towards the surface where the cyanobacterium is abundant but the light intensity is below the compensation point, net oxygen uptake occurs. At the surface, net oxygen evolution occurs during most of the day at maximum rate (P_{max}). Only during a short time at sunrise and sunset photosynthesis is not saturated. At midday, a little dip was observed, which is caused by photoinhibition at high light intensity.

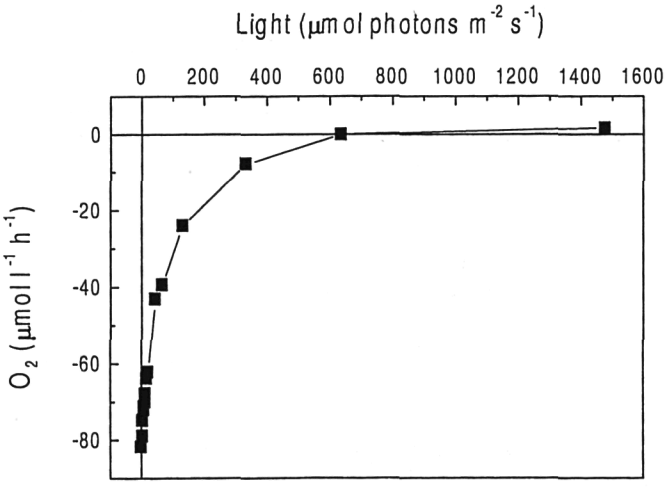


Fig 9. Light versus photosynthesis curve recorded from a natural sample from the Baltic Sea taken during the night when heterotrophic respiration equaled approximately P_{max}. Data from M Staal and LJ Stal, NIOO-CEMO, Yerseke, The Netherlands

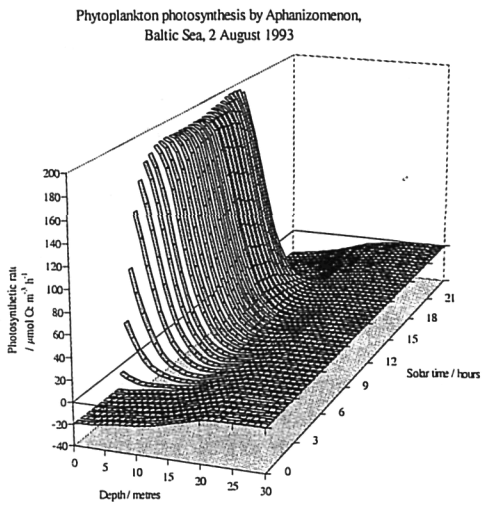


Fig. 10. Results of an Excel spreadsheet calculation of photosynthesis by Aphanizomenon *in the water column of the Baltic Sea over a 24 h period. Data from Walsby (1997a).*

The photosynthetic characteristics of cultures of cyanobacteria isolated from the Baltic Sea were also determined (table 2). The cultures investigated in this particular case showed some remarkable differences. The picoplanktonic *Synechococcus* spp. had a much lower maximum capacity for photosynthesis than the diazotrophic *Nodularia spumigena*. Relative to P_{max}, dark respiration was much lower in *N. spumigena*. The affinity for light (α) of this organism was average. The phycoerythrin-containing (red) *Synechococcus* sp. had a very high value of (α), whereas the phycoerythrin-less (green) *Synechococcus* sp. had a very low value. There is some evidence that the red species is more abundant at higher depth, whereas the green type occurs predominantly in the surface layers. The photosynthetic characteristics of the *Synechococcus* spp. are in agreement with such a distribution in the water column. The photosynthetic characteristics of *N. spumigena* are in agreement with the occurrence of this species close to the water surface and the fact that this organism has to devote a considerable part of its photosynthetic potential to nitrogen fixation.

Table 2. Photosynthetic characteristics of three key species of Baltic Sea planktonic cyanobacteria. Data from M. Staal and LJ Stal, NIOO-CEMO, Yerseke, The Netherlands

Organism	P_{max}	α	Respiration
Synechococcus sp. (red)	198	9.1	68
Synechococcus sp. (green)	119	0.3	15
Nodularia spumigena	649	4.0	49

2.3. Nitrogen fixation

The nitrogen-fixing cyanobacteria in the waterblooms of the Baltic Sea are of the heteroeystous type. Nitrogen fixation is extremely oxygen sensitive and is not compatible with oxygenic photosynthesis. Cyanobacteria therefore need special adaptations in order to be capable of diazotrophic growth (Canini et al. 1996). The heterocyst is a special differentiated cell that has lost its capacity of oxygenic photosynthesis and is the site of nitrogen fixation in these cyanobacteria. About 5% of the cells of *Nodularia* spp. differentiate into heterocysts. In some cyanobacteria the frequency of heterocysts can be as low as 1% (Albertano et al. 1996). This is also the case in *Aphanizomenon* sp. but this low heterocyst frequency normally does not affect the specific nitrogenase activity of these organisms (Janson et al. 1994).

The heterocyst contains photosystem I and is therefore capable of harvesting light and supply nitrogenase with energy. However, for the source of electrons, heterocysts depend on the vegetative cells, just as for the supply of acceptor molecules to assimilate the fixed nitrogen. For these reasons nitrogen fixation in heterocystous cyanobacteria is to a large extend light dependent. This is clearly seen in Fig. 11 where the 24 h variation of nitrogenase activity in a Baltic Sea cyanobacterial bloom is depicted. The highest nitrogenase activity was at noon, when the light intensity was highest. Nitrogenase activity, measured as acetylene reduction, amounted more than 25 μmol C_2H_2 reduced (mg Chl *a*)$^{-1}$ h^{-1} in this specific case. However, activities of over 40 μmol C_2H_2 reduced (mg Chl *a*)$^{-1}$ h^{-1} have been observed in the Baltic Sea. These activities are among the highest reported in literature. The light response curve of nitrogen fixation in the Baltic Sea is depicted in Fig. 12. This curve shows that nitrogenase saturates at the relatively low light intensity of about 600 μmol m^{-2} s^{-1}. At the highest light intensity nitrogenase activity seemed to be photoinhibited. Although nitrogenase activity was largely dependent on light, considerable nitrogen fixation occurred during the dark. The average dark activity that was measured on one occasion amounted 5.5 μmol C_2H_2 reduced (mg Chl *a*)$^{-1}$ h^{-1}. However, when samples were collected during the day and then assayed in the dark, nitrogenase activity almost doubled and amounted more than 10 μmol C_2H_2 reduced (mg Chl *a*)$^{-1}$ h^{-1}. This was evidently because the cells were charged in the light with products of photosynthesis.

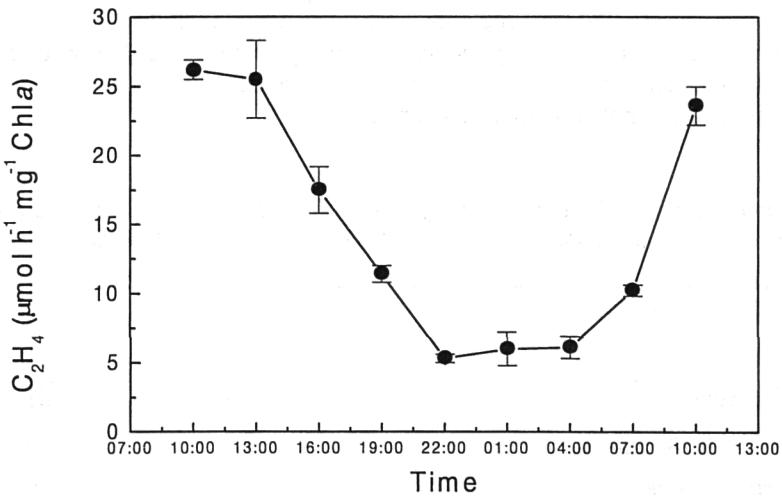


Fig. 11. Variation during 24 h period of nitrogenase activity in natural samples of a Baltic Sea waterbloom. Data from LJ Stal, NIOO-CEMO, Yerseke, The Netherlands.

In cultures isolated from the Baltic Sea species-specific differences were observed when comparing light and dark nitrogenase activity. When *Aphanizomenon* sp. was grown under an alternating 12-12 h light-dark cycle, the amount of nitrogen fixed during the dark was almost 25% of the total nitrogen fixed during 24 h. Under the same conditions *Nodularia spumigena* fixed more than 40% of the total nitrogen during the dark period.

Since diazotrophic cyanobacteria have basically an unlimited supply of nitrogen, their growth is certainly not limited by that nutrient. Preliminary investigations showed that phosphate is also not the limiting factor for photosynthesis, nitrogen fixation and growth in this group of cyanobacteria, but that iron appeared to be the limiting factor. The picoplankton is not capable of nitrogen fixation and it was shown that this group of organisms was nitrogen-limited. It was also demonstrated that the *Synechococcus* spp. grew at the expense of nitrogen fixed by the heterocystous cyanobacteria. About 10% of the nitrogen fixed by the diazotrophic cyanobacteria were thus transferred to the picoplankton.

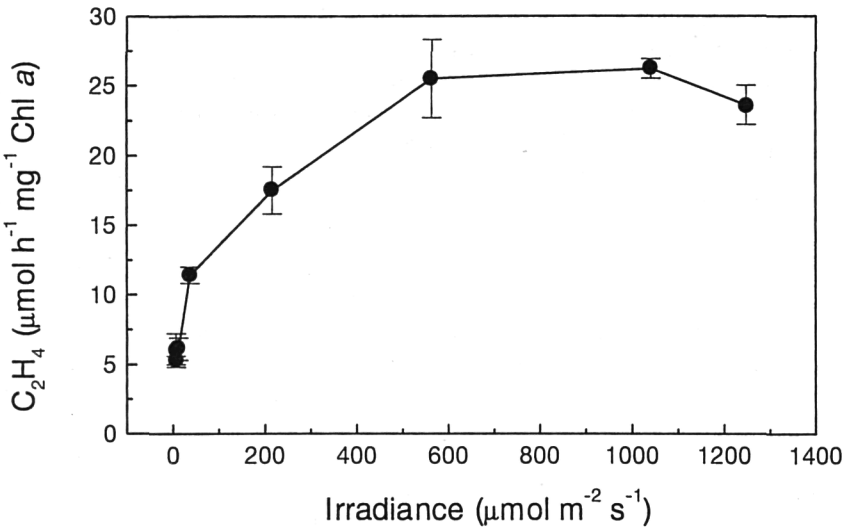


Fig. 12. Nitrogenase activity plotted versus light intensity. Data from LJ Stal, NIOO-CEMO, Yerseke, The Netherlands.

3. DISCUSSION

Blooms of cyanobacteria are virtually absent in the marine environment. A notable exception is the mass occurrence of blooms of the non-heterocystous cyanobacterium *Trichodesmium* spp. in the tropical ocean (Capone et al. 1997). This is also remarkable because *Trichodesmium* is a non-heterocystous, nitrogen-fixing cyanobacterium (Gallon et al. 1996). Heterocystous cyanobacteria are particularly rare in saline environments. Certain species occur as symbionts in planktonic diatoms while other species are sometimes found on rocky shores or tidal sediments. This scarcity of diazotrophic cyanobacteria is also remarkable because as a rule productivity in the sea is limited by nitrogen and nitrogen-fixing organisms would therefore be expected.

Blooms of heterocystous and non-heterocystous cyanobacteria are common in

freshwater environments. Fossil akinetes, resting stages of heterocystous cyanobacteria, have been discovered in the sediments of lakes and have been taken as evidence for eutrophication in the past (van Geel et al. 1996). The only saline environments in which blooms of heterocystous cyanobacteria occur are the Baltic Sea and the Peel-Harvey estuary, Australia, both eutrophic brackish water bodies (Huber 1986). It is not known why saline environments select against heterocystous cyanobacteria.

In the Baltic Sea, blooms of heterocystous cyanobacteria develop in summer when the water temperature has increased and, more importantly, when the N:P ratio is well below the Redfield value of 16. When this is the case it is generally assumed that algae are limited by nitrogen. However, heterocystous cyanobacteria are not likely to become nitrogen-limited because they have access to a virtually unlimited supply of atmospheric nitrogen (N_2). In order to be able to use N_2, it is also important that there is ample supply of phosphate. It was demonstrated that phosphate was not the limiting factor for the heterocystous cyanobacteria. Preliminary results of bioassays indicated that iron limited growth. Iron is an important element in components of photosynthetic and respiratory electron transport chains and in enzymes such as nitrogenase and superoxide dismutase. The latter enzyme may be involved in the protection of nitrogenase from oxygen inactivation (Canini et al, 1996). Iron limitation will therefore affect metabolism of heterocystous cyanobacteria in various ways.

The heterocystous cyanobacteria possess gas vesicles that make them buoyant. They also form aggregates that float to the surface of the sea and accumulate in dense scum. It was demonstrated that this buoyancy has a clear selective advantage for these cyanobacteria (Walsby et al. 1997). The notorious surface scum of the heterocystous cyanobacteria underestimate the total biomass of these organisms in the water column. Only a fraction of it is present in the surface scum. Even more important is the contribution of the picoplanktonic cyanobacteria that may represent as much as 80% of the total cyanobacterial biomass. This group of organisms can not fix nitrogen. It was shown that they grow under nitrogen limitation and that they depend on nitrogen fixed by the heterocystous cyanobacteria. Hence, the growth of picoplanktonic cyanobacteria depends directly on the nitrogen fixed by the heterocystous species.

The information obtained about the photosynthetic characteristics of the diazotrophic cyanobacteria and light attenuation in the water column was used to model the daily integral of photosynthesis (Walsby 1997b). It was shown that photosynthesis depended on the main depth of the phytoplankton community. The next step will be to include photosynthesis by picoplankton, nitrogen fixation and toxin production in such models.

ACKNOWLEDGMENTS

This research was carried out with financial support of the European Commission ENVIRONMENT AND CLIMATE program, contracts EV5V-CT94-0404 and ENV4-CT97-0571. The authors would like to thank the crew of FS 'Poseidon' and FS 'Alkor' and Drs. R. Boje and M. Grilli Caiola who were principal investigators in the first Baltic Sea project. The following persons are gratefully acknowledged for their contributions to the projects: E. Bachiddu, G. Barker, S.B. Behrens, E. Bolander, A. Canini, D. Di Somma, M. Epple, A. Evans, A. Heinänen, C.R. Hipkin, B. Ibelings, S. Janson, F. Jochem, A. Jones, N. Köhler, U. Kumitz, D. Leonardi, S. O'Mahony, M. Meyerhöfer, U. Rasmussen, A. Sletterink, C.J. Smith, J. Snoek, M. Staal, C. Starkerud, A. Stuhr, W. van Dok, M. Villbrandt, P. Visser, T.J. Walton.

REFERENCES

Albertano P, Di Somma D, Capucci E (1997) Cyanobacterial picoplankton from the Central Baltic Sea: cell size classification by image-analyzed fluorescence microscopy. Journal of Plankton Research 19: 1405-1416.

Albertano P, Di Somma D, Leonardi D, Canini A, Grilli Caiola M (1996) Cell structure of planktic cyanobacteria in the Baltic Sea. Algological Studies 83: 29-54.

Canini A, Albertano P, Leonardi D, Di Somma D, Grilli Caiola M (1996) Superoxide dismutase in cyanobacteria of the Baltic Sea. Algological Studies 83: 129-143.

Capone DG, Zehr JP, Paerl HW, Bergman B, Carpenter EJ (1997) *Trichodesmium*, a globally significant marine cyanobacterium. Science 276: 1221-1229.

Conley DJ, Johnstone RW (1995) Biogeochemistry of N, P and Si in Baltic Sea sediments: response to a simulated deposition of a spring diatom bloom. Marine Ecology - Progress Series 122: 265-276.

Gallon JR, Jones DA, Page TS (1996) *Trichodesmium*, the paradoxical diazotroph. Algological Studies 83: 215-243.

Granéli E, Wallström U, Larsson U, Granéli W, Elmgren R (1990) Nutrient limitation of primary production in the Baltic Sea area. Ambio 19: 142-151.

Horstmann U (1983) Distribution patterns of temperature and water colour in the Baltic Sea as recorded in satellite images: indicators for phytoplankton growth. Berichte Institut Meereskunde Kiel 106: 147-158.

Huber AL (1986) Nitrogen fixation by *Nodularia spumigena* Mertens (Cyanobacteriaceae). 1: Field studies and the contribution of blooms to the nitrogen budget of the Peel-Harvey estuary, Western Australia. Hydrobiologia 131: 193-203.

Janson S, Carpenter EJ, Bergman B (1994) Fine structure and immunolocalisation of proteins in *Aphanizomenon* sp. from the Baltic Sea. European Journal of Phycology 29: 203-211.

Jochem F (1989) Distribution and importance of autotrophic ultraplankton in a boreal inshore area (Kiel Bight, Western Baltic). Marine Ecology Progress Series 53: 153-168.

Kahru M, Horstmann U, Rud O (1994) Satellite detection of increased cyanobacterial blooms in the Baltic Sea: Natural fluctuation or ecosystem change? Ambio 23: 469-472.

Kononen K, Kuparinen J, Mäkela K, Laanemets J, Pavelson J, Nõmmann S (1996) Initiation of cyanobacterial blooms in a frontal region at the entrance to the Gulf of Finland, Baltic Sea. Limnology and Oceanography 41: 98-112.

Kullenberg G (1981) Physical Oceanography. In: Voipio A (ed) The Baltic Sea. Pp. 135-181, Elsevier Science Publishers, Amsterdam.

Larsson U, Elmgren R, Wulff F (1985) Eutrophication and the Baltic Sea: causes and consequences. Ambio 14: 9-14.

Leppänen J-M, Niemi A, Rinne I (1988) Nitrogen fixation of cyanobacteria (blue-green algae) and the nitrogen cycle of the Baltic Sea. Symbiosis 6: 181-194.

Niemi A (1979) Blue-green algal blooms and N:P ratio in the Baltic Sea. Acta Botanica Fennica 110: 57-61.

Reynolds CS (1987) Cyanobacterial water-blooms. Advances in Botanical Research 13: 67-143.

Raven JA (1986) Physiological consequences of extremely small size for autotrophic organisms in the sea. In: Platt T, Li WKW (eds) Photosynthetic Picoplankton. Can. Bull. Fish. Aquat. Sci. 214: 1-70.

Sivonen K, Kononen K, Carmichael WW, Dahlem AM, Rinehart KL, Kiviranta J, Niemela SI (1989) Occurrence of the hepatotoxic cyanobacterium Nodularia spumigena in the Baltic Sea and structure of the toxin. Applied and Environmental Microbiology 55: 1990-1995.

Van Geel B, Odgaard BV, Ralska-Jasiewiczowa M (1996) Cyanobacteria as indicators of phosphate eutrophication of lakes and pools in the past. Pact 50: 399-415.
Walsby AE (1997a) Numerical integration of phytoplankton photosynthesis through time and depth in a water column. New Phytologist 136: 189-209.
Walsby AE (1997b) Modeling the daily integral of photosynthesis by phytoplankton: its dependence on the main depth of the population. Hydrobiologia 349: 65-74.
Walsby AE, Hayes PK, Boje R (1995) The gas vesicles, buoyancy and vertical distribution of cyanobacteria in the Baltic Sea. European Journal of Phycology 30: 87-94.
Walsby AE, Hayes PK, Boje R, Stal LJ (1997) The selective advantage of buoyancy provided by gas vesicles for planktonic cyanobacteria in the Baltic Sea. New Phytologist 136: 407-417.

TITLE : INFLUENCE OF RISING SEA LEVEL ON ECOSYSTEM DYNAMICS OF SALT MARSHES (ISLED)

CONTRACT NO : ENV4 - CT97 - 0582

COORDINATOR : Dr. Thomas E. Cappenberg, Netherlands Institute of Ecology - Centre for Estuarine and Coastal Ecology, Korringaweg 7, POB 140, 4400 AC Yerseke, The Netherlands. Phone : 31-113-577455, FAX : 31-113-573616, e-mail : cappenberg@cemo.nioo.knaw.nl (NIOO)

PARTNERS : Prof. Dr. Raoul Lemeur, Laboratory of Plant Ecology, Faculty of Agricultural and Applied Biological Sciences, University of Ghent, Coupure Links 653, B-9000 Ghent, Belgium. Phone : 32-9-2646112, FAX 32-9-2244410, e-mail : Raoul.Lemeur@rug.as.be (RUG)

Dr. John Thomson, Challenger Division for Seafloor Processes, Southampton Oceanography Centre, Empress Dock, European Way, Southampton, SO14 3ZH, UK. Phone : 44-1703-596548, FAX : 44-1703-596554, e-mail : jth@soc.soton.ac.uk (SOC)

Prof.Dr.Erik Kristensen, Institute of Biology, Odense University, Campusvej 55, 5230 Odense M, Denmark. Phone : 45-6557-2754, FAX : 45-6593-0457, e-mail : ebk@biology.ou.dk (OU)

Dr. Bertrand Le Rouzic, Unite Mixte de Recherche 6553, Universite de Rennes, Av. G.Leclerc, Campus de Beaulieu, 35042 Rennes, France. Phone : 33-2-99-281403, FAX : 33-2-99-281617, e-mail: Bertrand.Le-rouzic@univ-rennes1.fr (MRU)

Dr. Barry Wyatt, Institute of Terrestrial Ecology, Monks Wood, Abbots Ripton, Huntingdon, PE17 2LS, UK. Phone : 44-1487-773381, FAX : 44-1487-773467, e-mail : b.wyatt@ite.ac.uk (ITE)

Prof.Dr. Maria Amelia Martins-Loucao, Departamento de Biologia Vegetal, Faculdade de Ciencias da Universidade de Lisboa, Campo Grande, Bloco C2, 1700 Lisbon, Portugal. Phone : 351-1-7573141, FAX : 351-1-7500048, e-mail : bmloucao@bio.fc.ul.pt (FFCUL)

INFLUENCE OF RISING SEA LEVEL ON ECOSYSTEM DYNAMICS OF SALT MARSHES (ISLED)

Thomas E. Cappenberg
Netherlands Institute of Ecology - Centre for Estuarine and Coastal Ecology, Korringaweg 7, POB 140, 4400 AC Yerseke, The Netherlands.

1. INTRODUCTION

Accelerated sea level rise as a result of the human impact on global climate change, has a dramatic impact on the coastal zone, in particular on ecosystems such as *salt marshes*, which are in one way or another dependent on the tidal movement of the sea. On the long term, salt marshes will only survive if they are able to maintain their elevation relative to mean sea level, otherwise they will be drowned. Without an adequate understanding of the nature, scale and extent of the counteracts to survive, future management and uses of these areas and resources will be extremely difficult. Although we have some understanding of how (i.e. in what direction) the morphology and ecology of the salt marshes will react to increased flooding frequency, we have only scanty information about their rate of response. This is primarily due to our incomplete characterisation of the temporal and spatial scales of the physical, chemical and biological processes involved.

In this project we will focus on identifying, describing and defining the abiotic and biotic processes in salt marsh ecosystems resulting from and counteracting the effect of increased inundation frequencies. These countereffects provide stability and robustness, but when their capacities are exceeded they give rise to non-linear responses. Non-linear behaviour of salt marsh ecosystems has been recognised as a major cause for unpredictable changes. This project involves mechanistic studies and requires a multi-disciplinary approach involving microbiologists, marine biologists, biogeochemists and system ecologists. It is multidisciplinary in its objectives and methods, with a high degree of interaction between the partners. The overall aim is to obtain a comprehensive insight into the dynamics of the system counteracting the effects of sea level rise, and will be integrated into mathematical models fit for future management and conservation of salt marshes.

Firstly, we will determine the historical and current rates of accretion and erosion for predicting the past development and future survival of marshes. We aim to study the ecophysiological processes that lead to changes in competitive abilities of tidal vegetation promoting enhanced trapping of detrital and organic material on the vegetated surface so that long-term changes in the pattern of flooding are counteracted.

Besides these long-term effects of accelerated sea level rise there are also short-term effects on the diversity, biomass, distribution and functional behaviour of salt marsh flora and fauna. The actual zonation pattern of the vegetation in tidal marshes depends on soil characteristics, biotic processes that govern the succession processes in the vegetation, but especially on the flooding frequency of the specific marsh area. The vegetation pattern in estuarine marshes is generally similar regardless of climatic conditions, though the actual constituent species within various zones depend on the specific climatic circumstances.. The lower marsh is usually dominated by a vegetation type of low diversity, (in North Western Europe dominated by *Spartina* species). In the higher parts of the marsh (relative to mean sea level) the vegetation is more diverse, with a more intricate relation between species, dependent on competition processes and differences in soil characteristics. In contrast to the vegetation pattern, the faunal diversity decreases with increasing intertidal height and in the uppermost dry zones the benthic fauna is composed of only one or two opportunistic species, but in very high abundance's. Mineral availability in combination with the aeration of the soil, the period during which plants are able to photosynthesise, and changes in the populations of soil dwelling macro- and micro-organisms (e.g. burrow dwelling invertebrates, nitrogen fixing bacteria, denitrification bacteria, mycorhizal fungi) may all result in differentiated changes in the growing potential and hence the competitive ability of the various plant species.

Accelerated sea level rise as a result of global warming is a relatively slow process and difficult to assess in a reasonable length of time. However, civil engineering activities in estuaries may influence the tidal pattern in estuaries and result in changing flooding frequency within a few years' time. In many estuaries in Europe dredging activities are regularly undertaken resulting in an increase in the tidal prism (intended to provide a better access to sea ports). The increase in the tidal prism has a direct effect on the flooding frequency of the adjacent tidal marshes. For example the Westerschelde Estuary, the entrance to the Belgian port of Antwerp, will undergo a *unique* major dredging operation within the next few years, starting in 1997. Hydrologists have calculated a resulting increase in the mean level of the high tide in the estuary of 5 - 10 cm at the Dutch - Belgian border. Even in the mouth of the estuary the increase of the mean high tide level will still be 2 cm. As a result, the vegetation of the higher areas of the salt marshes in the area is expected to become less diverse and approach the community structure as currently found in the lower parts of the marsh. Such effect will be noticeable within a couple of years from the start of the dredging operation. Although interesting in itself, the way by which the vegetation changes may be similar to the response to the expected global accelerated sea level rise and therefore enables us with a *natural analogue* to model the changes caused by long-term global change processes.

2. OBJECTIVES

The project Influence of rising Sea Level on Ecosystem Dynamics of salt marshes (ISLED) has the following goals :

1. To determine the influence of increased flooding frequency on the ecophysiology of tidal marsh plant species and to examine its influence on the activity of sediment micro-organisms in view of the availability of nutrients for the plants.
2. To examine the influence of increased flooding frequency on the infaunal invertebrate community and on bioturbation effects.
3. To study important microbial trophic interactions, including carbon mineralization, related to differences in inundation frequencies.
4. To evaluate the influence of increased flooding frequency on the sedimentation patterns, i.e. its accretion rates and to reconstruct the history of anthropogenic inputs in the studied marshes.
5. To develop a management model to conserve marsh ecosystems as a typical unique landscape in view of accelerated sea level rise.

3. WORKPLAN

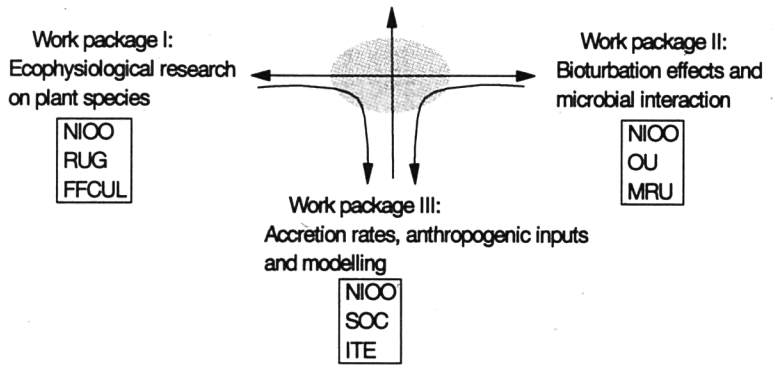
In this project *three different experimental levels* will be considered:

1. Field experiments. In joint field campaigns, twice a year, three marshes different in expected mean level of the high tide along a transect in the Westerschelde Estuary will be examined, and within one marsh a transect from the low- to high-intertidal zones will be sampled.
2. Large-scale mesocosms experiments, in which the expected inundation frequency can be manipulated to examine ecosystem processes under natural circumstances.
3. Pot- and sediment core experiments in the laboratory to examine individual selected processes.

The project will be organised around a number of joint intensive field measurement campaigns, tailored to the time and spatial scales central in the scientific topics to be studied. These campaigns will involve all partners and will be held in three marsh locations at the Westerschelde Estuary, different in effective impact of the intensive dredging operation in increase in flood level and expected inundation frequency. The campaigns will be organised when the growing season of the marsh vegetation will start (May/June) and when biomass is maximal (September/October) in each year of the project. Participation at these joint campaigns is mandatory for all teams; however, the actual duration of the visit will vary between 1 week and 1 month depending on the degree of participation and the type of field work. They will be preceded by a period of method development and intercalibration. Besides these joint field champaigns detailed studies will be set up in order to achieve the tasks of the project. All data from the field sites and the experimental set-ups will be integrated and extrapolated by the exploitation of remote sensing (Compact Airborne Spectrographic Imager) and a Geographic Information System (GIS). It will allow the integration of processes over space and time, and extrapolation of results to cover the effects of sea level rise on the whole system.

The project is divided into three Work Packages, in which the different Tasks for the various partners are given. Data management will be executed by NIOO in close co-operation with all participants and in line with the ELOISE rules. The general flow of information within the project is schematised in which the DATA CENTRE occupies a central role in the flow of information :

Long-term information for management and extrapolation



4. Results

Recently the project has been started and its Start-up Workshop has been held from 26 - 28 of March this year in NIOO-CEMO at Yerseke (The Netherlands). The first two field campaigns for 1998 has been scheduled from 15 - 26 of June and from 21 of September to 2 of October, in which for the latest period the first airborne remote sensing flight is planned.

EFFECTS OF CLIMATE INDUCED TEMPERATURE CHANGE ON MARINE COASTAL FISHES

Contract: ENV4-CT97-0596

Coordinator:

Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI)
Professor Dr. Hans-O. Poertner
Marine Biology/Ecological Physiology
Alfred-Wegener-Institute
Postfach 12 01 61
Columbusstrasse
DE-27568 Bremerhaven
Germany
Tel: ++49-471-4831-307
Fax: ++49-471-4831-149
hpoertner@awi-bremerhaven.de

Partners:

Universität Bremen (UHB)
Professor Dr. Wolf Arntz
Universität Bremen/Fachbereich 2/Meeresbiologie
Leobenerstrasse
DE-28359 Bremen
Germany
Tel.: ++49-421-218-1
Fax: ++49-421-218-4259

Univ. of Rome "La Sapienza" (UNISAP)
Professor Dr. Alfredo Colosimo
Dept. of Biochemical Sciences
Univ. of Rome "La Sapienza"
P.le A. Moro, 5 - 00185 Roma
Italy
Tel.: 0039-6-4450291
Fax: 0039-6-4440062
colosimo@axcasp.caspur.it
colosimo@icgeb.trieste.it

Department of Fisheries and Marine Biology, University of Bergen (UiB)
Prof. G. Nævdal
University of Bergen
Department of Fisheries and Marine Biology
Bergen High Technology Center
N-5020 Bergen
Norway
Tel.: ++47 55584401
Fax: ++47 55584450
gunnar.naevdal@ifm.uib.no

Zoological Institut, University of Bergen (ZI)
Prof. Ole Brix
Institute of Zoology/University of Bergen
Allegaten 41
N-5007 Bergen
Norway
Tel.: ++47 55583585
Fax: ++47 55589673
ole.brix@zoo.uib.no

Department of Biology, University of Antwerp (RUCA)
Dr. Ronny Blust
Department of Biology RUCA
University Centre of Antwerp
Groenenborglaan 177 U7
B-2020 Antwerpen
Belgium
Tel.: ++32-3-2180344
Fax.: ++32-3-2180497
blust@ruca.ua.ac.be

EFFECTS OF CLIMATE INDUCED TEMPERATURE CHANGE ON MARINE COASTAL FISHES

HANS-O. PÖRTNER[1], RONNY BLUST[5], OLE BRIX[4], ALFREDO COLOSIMO[3], RAINER KNUST[1], GUNNAR NÆVDAHL[4], FRANZ J. SARTORIS[2], BART DE WACHTER[5]

[1]Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany; [2]University of Bremen, Germany; [3]Dept. of Biochemical Sciences, Univ. of Rome, Italy; [4]University of Bergen, Norway; [5]Department of Biology, RUCA, Antwerpen, Belgium

Introduction

Changes in the earth's climate through warming of the atmosphere have been predicted and concomitant negative consequences in many marine ecosystems are expected. Although the impact of decadal-scale variations by the coupled ocean-atmosphere system on marine communities and populations has been well documented (Cushing, 1982; Beamish, 1995; Bakun, 1996), causal relationships are largely obscure. Temperature changes can affect, directly or indirectly, marine populations during all life stages. To analyse and interpret these effects a profound synthesized knowledge of ecological and physiological processes is required. Within the framework of the European initiative ELOISE (European Land Ocean Interaction Studies) a project was designed to further our understanding of the past and present impact of climate induced temperature changes on fish populations through the combination of retrospective studies, field data analysis, ecological and physiological experiments, genetical investigations and modelling. We have selected two model species characterized by northern and southern distribution limits in the North Atlantic: eelpout (*Zoarces viviparus*), as a typical non-migrating inhabitant of the coastal zone, with a k-selektive reproduction strategy (viviparous) and cod (*Gadus morhua*), as an typical inhabitant of continent shelf with a high importance for fisheries. Both species have a boreal distribution, the southernmost distribution limits are in the Wadden Sea of the southern North Sea (eelpout) and in the northern part of the Biscay (cod). Accordingly, populations of the two species have adapted to temperature regimes in a latitudinal cline.

A comparison between summer water temperature and abundance of *Zoarces viviparus* in the German Wadden Sea over the last 40 years, shows a distinct relationship between hot summer events and a high mortality (re-calculated from data of Ulleweit, 1995) and indicates the sensitivity of this species to temperature. For cod, the effect of temperature changes is not necessarily the same in all areas of distribution (Daan, 1994). Depending on the ambient temperature regime, these populations exhibit differing reactions to temperature changes. Those

dwelling in colder waters (Labrador, Greenland, Iceland and Barents Sea) seem to augment stock size, recruitment and growth rates when temperature is increasing whereas those in warmer regions (North Sea, Georges Bank, Newfoundland) do better at cooler periods. In the Arcto-Norwegian cod stock off N. Norway and in the Barents Sea, year classes of higher abundance were associated with high temperatures and a 20-fold range of year-class abundance at age 3 was recorded (Nakken, 1994). So, global warming might have opposite effects on cod populations on the northern and southern edges of their distribution. Also, temperature is responsible for most of the observed differences in growth (Brander, 1994). The effect is big enough to have significant consequences for assessment of the impact of climate change and also for short-term catch forecasts.

The physiological mechanisms underlying these patterns are incompletely understood. Therefore, the general objective of this project is to investigate the possible impact of climate induced temperature changes on the distribution and population dynamics of these two fish species by evaluating the effects of temperature regime at the physiological, genetic and ecological level. One way to predict how ecosystems will react to global warming, is to look at causal relationships between oceanographic data and natural in retrospective studies. Long-term data series of biological parameters are essential for retrospective analysis of climate impact on marine systems, however, they are scarce. Usually, data on commercially exploited fish species and long term series on coastal fish fauna provide the most complete information as fisheries data often have been recorded for decades and even centuries.

Ecological key processes which determine population structure and dynamics, are reproduction, recruitment, growth and mortality. The timing as well as the success of reproduction processes are strongly temperature sensitive. Examples can be found in different fish species: Most of the North Sea fishes spawn 1 to 2 months earlier in the western part, with higher temperatures in spring than in the German Bight or along the Danish coast (Lozan, 1990). Differences in abundance and growth rates of fish species in the shallow water of the Wadden Sea can be strongly related to differences in seasonal temperature periodicity (Fonds, 1983). This temperature trigger is apparently the same for different regions, which results in the shift of the spawning period along its geographical distribution.

Energy allocations to growth and reproduction are only possible after the requirements for physiological and biochemical homeostasis (maintenance) (Wieser, 1994) including the cost of swimmig and food consumption (Boutilier, 1998) are met. Throughout the latitudinal cline physiological acclimation of individuals or genetic adaptation of the population may occur (Hummel et al., 1997). Subtle changes in the energy budget result, consequently yielding changes in the condition, in biochemical constituents (energy reserve), and in the reproductive cycle, depending on the reallocation of energy reserves. Adaptation of the population is caused by an elimination of those genotypes that were not able to perform one of these subtle changes. A change in temperature will disturb these balances, ultimately leading to a significant shift in the distribution limits of a species.

Since poikilotherms lack mechanisms for physiological temperature regulation their body temperature is determined by the environment. Regulated physiological parameters like metabolic rate, acid-base status and cellular energy levels may display substantial changes before harmful effects occur (Pörtner, 1993; Pörtner & Grieshaber, 1993), and thus may be used as physiological parameters indicating critical temperature limits (Zielinski & Pörtner, 1996; Sommer et al., 1997; Pörtner et al., 1998). In this context it is also essential to determine whether the animals living at the distribution limits have reached the limits of their adaptational potential. This is an open field of study and the physiological and biochemical background of adaptability has not sufficiently been addressed. As a corollary, an important aspect is the determination of critical thresholds in the maintenance of balance between energy producing and energy consuming processes including a study of the key mechanisms underlying the general process of temperature acclimation and evolutionary adaptation (Cossins and Bowler, 1987; Pörtner et al., 1998).

Retrospective studies

The retrospective studies will provide us with historical information about relationships between meteorological, hydrographical, and fisheries data. Long time series (published and unpublished data) on the relative abundance of eelpout and cod and data on population dynamics will be re-analysed and compared with historical meteorological and hydrographical data to come to a basic understanding of the relevance of changing temperature regimes for the abundance, population dynamics and recruitment success of cod and eelpout. Seasonal periodicity of air and water temperature, wind dynamics as well as extreme events, like storms, ice winter and hot summers will be considered.

Ecological studies

The relationship between population parameters and climate condition will be measured by analysing growth rates and fecundity of specimen from different climate regions and by estimating the impact of temperature on growth under standardised condition. Growth rate and the gonosomatic development depends on the environmental condition. The limiting factor for growth and for the gonosomatic development is the metabolic energy available for these developmental processes. Field data on growth and fecundity from species sampled in different climatic regions will be collected to reveal the relationships between growth, fecundity and climatic conditions, like the summer period, minimum and maximum water temperatures and ice conditions. In addition maximal growth rates versus water temperature will be estimated in laboratory experiments under standardised condition (Fonds et al., 1989).

Physiological studies

Adjustment of critical temperatures. In order to understand the distribution limits of the selected species, the stress thresholds for temperature changes will be identified (Sommer et al., 1997; Zielinski & Pörtner, 1996; Pörtner et al., 1998) and interpreted in relation to the distribution of species. For the deeper understanding of the background of critical temperatures oxygen consumption values (Hop & Graham, 1995) together with potential changes in the acid-base status, the levels of intracellular high-energy phosphates and the actual energy available to ATP consuming mechanisms (quantified as the Gibbs free energy change of ATP hydrolysis; Pörtner et al., 1996) will provide information on the disturbance of the balance of energy production and consumption during environmental stress. Special emphasis will be given to the study of the adaptive modulation of energy partitioning between different physiological processes (Wieser, 1994; Thiel et al., 1996). Considering the high costs of protein synthesis (18 - 26% depending on organism and cell type, and even more during growth, Hawkins, 1991) the downregulation of protein synthesis appears as a general cost-saving response during energy limitations. Since anaerobic metabolism is known to depress protein synthesis and, in addition, anaerobiosis is observed once a critical temperatures is passed (Sommer et al., 1997) the capability to maintain protein synthesis might be crucial during long-term temperature stress. We will determine the temperature dependent costs of protein synthesis and identify the critical temperature limits for protein synthesis.

Haemoglobin oxygen transport. Oxygen is taken up via the gas exchange surface and is transported to fish tissues by the respiratory pigment, heamoglobin. Temperature not only has a direct effect on the oxygen binding properties of the pigment, but also indirectly influences transport by modifying the binding of ligands (protons, ions, anaerobic end products, organic phosphates, catecholamines). On top of this, temperature also has an effect on the levels of these ligands. In fish, reduced temperature sensitivity in the oxygen affinity of haemoglobins is often a direct result of the dissociation of ligands like protons and organic phosphates. The concentration of organic phosphates, levels of met-haemoglobin and other haematological parameters (like haematocrit) have not been studied in fish with different haemoglobin (Hb) types. Knowledge of other parameters which may influence Hb function (the intracellular environment) is also very important for evaluating the selective importance of protein polymorphisms (see also genetics). In our investigation we will mainly focus on the interaction of ligands and temperature. The temperature sensitivity will be quantified by thermodynamic analysis.

Protective mechanisms. In addition to physiological and biochemical mechanisms of acclimation and adaptation to temperature change, poikilotherms also rely on defense mechanisms against temperature induced damages. Two of these defense mechanisms will be

studied: signals that trigger migration in sedentary organisms and cellular defense strategies involving the production of stress proteins. Heat shock proteins (HSPs) are a major group of stress proteins, which protect the cellular apparatus against temperature stress. Although the cellular functioning of HSPs is still incompletely understood, some general hypotheses seem to emerge. All HSPs seem responsible for the regulation of protein homeostasis and in addition increased levels of HSPs protect the cell from protein denaturation during temperature stress. As a consequence of their protective function, HSPs also increase tolerance to extreme temperatures. Increased levels of HSPs, after an initial temperature stress, protect tissues from subsequent sublethal stress exposure which would normally result in structural damage (Brown et al., 1993). Increased levels of HSPs found during extended periods of environmental stress suggest an important role during long term adaptational processes (Sanders, 1993).

Genetic studies

The biological significance of genotypic variability in relation to its environmental performance is addressed by examining the relationship between genotype and physiological capacity. This variability is very different between species. Some species show polymorphisms in nearly 50% of their proteins/enzyme systems while other species hardly show any diversity. These protein polymorphisms may be explained as an adaptation to environmental changes (i.e. temperature, salinity etc.) or may be fundamental as 'genetic reserve' for further evolution. Selection at the limits of geographical distribution may be based on variability in adaptation which again depends on differences in functional properties. As a consequence, poikilotherms may respond to temperature changes with capacity adaptations which permit metabolic homeokinesis (constancy of metabolic activity). Animals which live in unstable environments frequently have a greater capacity for acclimation than animals that live in stable temperature environments.

The respiratory proteins have been used for decades for genetic typing of e.g. fish, and their functional properties have been extensively studied by biochemists and physiologist. On this background the respiratory pigments become ideal for investigating interrelated variabilities of genotype and function. Several investigations have so far demonstrated relationships between genotype and growth (Mork et al., 1984a, Nævdal et al., 1992) and between genotype and maturation (Mork et al., 1984b).

Modelling

The general aim of this task is to model the temperature sensitivity of marine species (*Gadus morhua* and *Zoarces viviparus*) at different hierarchical levels. This will be achieved by extensive use of the Recurrence Quantification Analysis (RQA) approach, usually applied in the study of time-series to discover subtle periodicities which baffle traditional Fourier methods. RQA shows useful whenever the variables of interest are time- (e.g. seasonal metabolic parameters) or space- (e.g. physico-chemical properties of the amino acid residues along a

protein's primary structure) dependent. The different hierarchical levels at which the temperature sensitivity of *Gadus morhua* and *Zoarces viviparus* will be modelled are the following: a) at a molecular level, by analysing the primary structures of Heat Shock Proteins and haemoglobins; b) at a species level by looking for the most significant species identifiers among physiological indicators of temperature-sensitivity; c) at a population level by trying to predict the influence of temperature and climatic changes on growth, distribution and population size on the basis of historical data. The synthesis of the data from the ecological, physiological and genetic tasks will allow for the modelling to proceed on the population level for a prediction of the distribution limits of fish species under changing temperature regimes.

References

Bakun, A. (1996) Patterns in the Ocean - Ocean Processes and marine population dynamics. California Sea Grant College System, La Jolla, 323 pp.

Beamish, R.J. (ed.) (1995) Climate change and northern fish populations. Can. Spec. Publ. Fish. Aquat. Sci. 121, 739 pp

Boutilier, R.G. (1998) Physiological ecology in cold ocean fisheries: a case study in Atlantic cod. In: Cold Ocean Physiology (Pörtner, H.O., R. Playle, eds.) Cambridge University Press, pp. 463-489.

Brander, K. (1994) Patterns of distribution, spawning, and growth in North Atlantic cod: the utility of interregional comparisons. ICES Marine Science Symposia 198: 406-413

Brown, M.A., Upender, R.P, Hightower L.E. & Renfro J.L. (1993) Thermoprotection of a functional epithelium: heat stress effects on transepithelial transport by flounder renal tubule in primary monolayer culture. Proc. Natl. Acad. Sci. U.S.A. 89, 3246

Cossins, A.R. & Bowler, K. (1987) Temperature biology of animals. Chapman and Hall, London, New York.

Cushing, D.H. (1982) Climate and Fisheries, Academic Press, London, 373 pp

Daan, N. (1994) Trends in North Atlantic cod stocks: a critical summary. ICES Marine Science Symposia 198: 406-413.

Fonds, M. (1983) The seasonal distribution of some fish species in the western Dutch Sea. In: W.J. Wolff, Ecology of the Wadden Sea 2. Part 5 , A.A. Balkema, Rotterdam, 1983, 139pp.

Fonds, M., Iedeme, A. and Puyl, P.V. (1989) Metabolism, food consumption, growth and food conversion of shorthorn (*Myoxocephalus scorpius*) and eelpout (*Zoarces viviparus*), ICES C.M. 1989/G31, 10pp.

Hawkins, A.J.S. (1991) Protein turnover: a functional appraisal. Funct. Ecol. 5, 222-233.

Hop, H., Graham, M. (1995) Respiration of juvenile Arctic cod (*Boreogadus saida*): effects of acclimation, temperature, and food intake. Polar Biol., 15, 359-367

Hummel, H., Sommer, A., Bogaards, R.H., Pörtner, H.O. (1997) Variation in genetic traits of the lugworm Arenicola marina: temperature related expression of mitochondrial allozymes? Mar. Ecol. Prog. Ser. 159: 189-195.

Lozan, J. (1990) Autökologische Untersuchungen über die Kliesche (*Limand limanda*) der Nordsee. Ver. Inst. Küsten- und Binnenfischerei, 101, Hamburg, 204pp.

Mork, J., Giskeødegard, R. & Sundnes, G. (1984) Population genetic studies in cod (*Gadus morhua* L.) by means of the haemoglobin polymorphism; observations in a Norwegian coastal population. Fisk. Dir. Skr. Ser. Hav.Unders. 17, 449-471

Mork, J., Giskeødegard, R. & Sundnes G. (1984) The haemoglobin polymorphisme in Atlantic cod (*Gadus morhua* L.); genotypic differences in somatic growth and in maturing age in natural populations. Flødevigens Rapportser. 1, 721-723

Nakken, O. (1994): Causes of trends and fluctuations in the Arcto-Norwegian cod stock. ICES Marine Science Symposia 198:406-413

Nævdal, G., Folkvord, A., Otterlei, E. & Thorkildsen, S. (1992) Growth rate related to genotype of O-group cod at three environmental temperatures. Sarsia 77, 71-73.

Pörtner, H.O. (1993) Multicompartmental analyses of acid-base and metabolic homeostasis during anaerobiosis: invertebrate and lower vertebrate examples. In: Surviving hypoxia: mechanisms of control and adaptation (eds Hochachka, P.W. *et al.*). CRC Press Inc., Boca Raton FL, U.S.A. pp. 139-156.

Pörtner, H.O., Grieshaber, M.K. (1993) Characteristics of the critical Po_2(s): gas exchange, metabolic rate and the mode of energy production. In: The vertebrate gas transport cascade: adaptations to environment and mode of life (ed. Bicudo, J.E.P.W.). CRC Press Inc., Boca Raton FL, U.S.A, pp. 330-357.

Pörtner, H.O., Finke, E. & Lee, P. G. (1996) Metabolic and energy correlates of intracellular pH in progressive fatique of squid (*L. brevis*) mantle muscle. Am. J. Physiol. 271, R1403-1414.

Pörtner, H.O., I. Hardewig, F.J. Sartoris, P. van Dijk (1998) Energetic aspects of cold adaptation: critical temperatures in metabolic, ionic and acid-base regulation? In: Cold Ocean Physiology (Pörtner, H.O., R. Playle, eds.) Cambridge University Press, pp. 88-120

Sanders, B.M., Martin, L.S., Nelson, W.G., Phelps, D.K. & Welch, W. (1991) Relationships between accumulation of a 60kDa stress protein and scope-for-growth in *Mytilus edulis* exposed to a range of copper concentrations. Mar. Environm. Res. 31, 81-97

Sommer, A., Klein, B. Pörtner, H.O. (1997) Temperature-induced anaerobiosis in two populations of the polychaete worm *Arenicola marina* (L.) J. Comp. Physiol. B167, 25-35

Thiel, H., Pörtner, H.O. & Arntz, W.E. (1996) Marine life at low temperatures - a comparison of polar and deep-sea characteristics. In: Deep-sea and extreme shallow-water habitats:

affinities and adaptations (eds. Uiblein, F., J. Ott and M. Stachowitsch) - Biosystematics and Ecology Series 11, pp. 183-219. Austrian Academy of Sciences, Vienna 1996

Ulleweit, J. (1995): Zur Ökologie zweier Standfischarten, der Aalmutter (*Zoarces viviparus*) und des Butterfisches (*Pholis gunnellus*) aus dem niedersächsischen Wattenmeer. Dipl. Thesis Universität Bremen 1995, 99pp.

Wieser, W. (1994) Cost of growth in cells and organisms: general rules and comparative aspects. Biol. Rev. 68,1-33.

Zielinski, S., Pörtner, H.O. (1996) Energy metabolism of the intertidal worm *Sipunculus nudus* below a critical temperature. J. Comp. Physiol. B 166, 492-500.

TITLE: ASSESSING THE CONSEQUENCES OF GLOBAL CHANGES FOR THE BARENTS SEA REGION: THE BARENTS SEA IMPACT STUDY (BASIS)

CONTRACT NO: ENV4-CT97-0637

COORDINATOR: Prof. Dr. Manfred A. Lange
Institute for geophysics, Westfälische Wilhelms-Universität Münster
Correnssstr. 24, D48149 Münster, Germany
Ph.: +49-251-833-3591; FAX: +49-251-833-6100;
Email: langema@uni-muenster.de

PARTNERS:

Prof. Terry V. Callaghan
Univ. of Sheffield, Sheffield Centre for Arctic Ecology
26 Taptonville Road
Sheffield S10 5 BR , UK
Ph.: +44-114-2826101, FAX: +44-114-2682521;
Email: T.V.Callaghan@shef.ac.uk

Prof. Dr. Eduard Koster
University of Utrecht
Dept. of Phys. Geograph.y, Faculty of Geogr. Scienc.
P.O. Box 80115, Utrecht 3508 TC, The Netherlands
Ph.: +31-30-2532749/2533786, FAX: +31-302540604;
Email: e.koster@frw.ruu.nl

Dr. Peter Kuhry
BASIS Information Office, Arctic Centre
P.O. Box 122, FIN-96101 Rovaniemi , Finland
Ph.: +358-16-324-755, FAX: +358-16-324-777;
Email: pkuhry@levi..urova.fi

Dr. Garreth Rees
Scott Polar Research Institute,
University of Cambridge
Lensfield Road, CB2 1ER Cambridge , UK
Ph.: +44-1223 336554, FAX: +44-1223-336 571;
Email: wgr2@cus.cam.ac.uk

Dr. Hein Rune Skjoldal
Inst. of Marine Res., Dept. of Marine Environment
1870 Nordnes, N-5024 Bergen , Norway
Ph.: +47-55-238497, FAX: ;
Email: hein.rune.skjoldal@imr.no

Prof. Dr. U. Streit
Geschf. Direktor; Institut für Geoinformatik,
Westfälische Wilhelms-Universität Münster
Robert-Koch-Straße 26-28, 48149 Münster, Germany
Ph.: 0251-83-33081, FAX: 0251-83-39763;
Email: streit@uni-muenster.de

Dr. Paul Wassmann
Norwegian College of Fishery Science,
University of Tromsø
N-9037 Tromsø , Norway
Ph.: +47-776-44459/86103, FAX: +47-776-46020;
Email: paulw@nfh.uit.no

Dr. R. J. Harding
Institute of Hydrology, Maclean Building
Crowmarsh Gifford,
Wallingford Oxfordshire OX10 8BB, UK
Ph.: +44-1491 838800, FAX: +44-1491-692424;
Email: r.harding@ua.nwl.ac.uk

Dr. Mikhail V. Kozlov
Laboratory of Ecological Zoology, Dept. of Biology
University of Turku, FIN-200014 Turku , Finland
Ph.: +358-2-3335492, FAX: +358-2-3336550;
Email: MIKOZ@sara.utu.fi

Mr. Åge Mariussen
Research Manager, Nordland Research Institute
N-8002 Bodø , Norway
Ph.: +47-75 51 76 00, FAX: +47-75-517234;
Email: aage.mariussen@hibo.no

Dr. Vladimir Romanovsky
GeoPh.ysical Institute, University of Alaska, Fairbanks
903 Kayukuk Drive, P.O. Box 757320 Fairbanks AK
99775-7320, USA
Ph.: +1-907-474 7459, FAX: +1-907-474 7290;
Email: ftver@aurora.alaska.edu

Dr. Dag Slagstad
SINTEF, Electronics and Cybernetics
N-7034 Trondheim , NORWAY
Ph.: +47-73594375, FAX: +47-7359439;
Email: dag.slagstad@regtek.sintef.no

Dr. Piers Vitebsky
Scott Polar Research Institute,
University of Cambridge
Lensfield Road, CB2 1ER Cambridge , UK
Ph.: +44-1223 336554, FAX: +44-1223-336 571 ;
Email: PV100@cam.ac.uk

Prof. Ulf Wiberg
Department of Social and Economic GeograPh.y,
Umeå University
S-90187 Umeå , Sweden
Ph.: +46-90-165537, FAX: +46-90-149145;
Email: ulf.wiberg@geograPh.y.umu.se

ASSESSING THE CONSEQUENCES OF GLOBAL CHANGES FOR THE BARENTS SEA REGION: THE BARENTS SEA IMPACT STUDY (BASIS)

MANFRED A. LANGE
Institute for Geophysics, Westfälische Wilhelms-Universität Münster, Germany

1. INTRODUCTION / BACKGROUND

Anthropogenically driven global changes rank high on the current political agenda of world leaders. While the success of international initiatives addressing these issues might be arguable, conferences such as the *Earth Summit* in Rio de Janeiro, Brazil in 1992 or the recent conference on the *United Nations Framework Convention on Climate Change* (UNFCCC) in Kyoto, Japan attest to the importance of global changes in international politics. While the main emphasis of possible strategies dealing with global changes has been on mitigation measures such as the UNFCCC, which calls for major reductions in greenhouse gas emissions by the industrialised countries, the issue of (possibly pro-active) adaptation to the impacts of global changes has not been dealt with appropriately. However, the UNFCCC is only gradually gaining acceptance and momentum. A possible explanation for the slow progress made so far lies in a lack of broad public understanding of the concrete consequences of global changes for a particular country or region. The specific non-uniform manifestations of global changes which are, for instance, obvious when comparing climate predictions for the Arctic with those for the mid-latitudes imply that the impacts of these changes will similarly have a distinctly regional character. This underlines the need for regionally focused impact studies. In order to understand not only the environmental- but also the societal consequences of global changes, impact studies will have to take into account both aspects in an interdisciplinary manner. *Integrated regional impact studies* (IRIS) attempt to address both requirements.

The Arctic is seen as a region which will experience severe warming within the next 50 to 100 years. Global climate models unanimously indicate that the Arctic will be the region of the Earth that will show the most pronounced increase in temperatures due to anthropogenically driven global warming. Thus, the latest assessment of the *Intergovernmental Panel on Climate Change (IPCC)* states that "... maximum warming in high northern latitudes in late autumns and winter associated with reduced sea ice and snow cover" and „...little warming over the Arctic in summer" can be derived as one of the major findings from the modelling studies". This result is not surprising, given the complex but highly efficient feedback mechanisms that dominate the response of the Arctic to global climate processes.

However, the Arctic is not only subject to prospective climate changes, it is also a region, which has been and continues to be affected by significant environmental changes/threats (in this paper meant to include processes other than climate changes such as pollution, the over-exploitation of natural resources and a reduction in species variability). These pressures add to stresses imposed by climate variations in a manner not yet understood. However, it is obvious that the consequences of various stresses on a particular ecosystem or region will be more severe than for a single stressor. Similarly, compound effects of changes will have a significant bearing on the socio-economic system related to or dependent on that particular ecosystem or the natural resources of a given region. Thus, when carrying out an integrated assessment of global change impacts, possible cumulative effects of environmental and climatic changes on the environmental and the socio-economic level have to be taken into account.

Environmental degradation and changes, similarly to climate variations are known to occur on a regional scale. Thus, certain regions will be more vulnerable to global change impacts than others and should therefore be considered first. The Barents Sea region is one such region deserving particular attention. This is due to a number of factors.

On the one hand, the Barents Sea is strongly influenced by the input of relatively warm Atlantic water (the North Cape Current, a branch of the Golf Stream). Changes in the timing and volume of this inflow, as experienced in the past and as may be caused by global warming will have major consequences for the physical and biological regime of the Barents Sea and will impact fish stocks and the fisheries in the region. Terrestrial ecosystems in the Barents Sea region are similarly vulnerable to changes in climatic conditions. This is due to a number of unique factors including the particular vulnerability of polar plant species to rapid climate changes, the slow growth and conservative growth strategies which render the vegetative stage of the live cycle relatively vulnerable to changing environmental conditions and the fact that since some of the species occur close to the lower temperature limits of survival, a given increase in temperature will result in a greater response than those likely to occur if a similar temperature change is experienced in the middle of their tolerable temperature range.

On the other hand, the Barents Sea region is rich in renewable and non-renewable resources (timber, fish, minerals, ore, oil and natural gas). This has resulted in extensive exploitation of these resources and has been associated by significant environmental stress. Smelters and refineries on the Kola Peninsula are known to have emitted vast amounts of contaminants with devastating effects on the local to regional flora and fauna. Similarly, the already occurring exploitation of oil and natural gas in the Barents Sea and the Pechora Basin has lead to significant environmental threats. However, these activities are also the reason for population densities that are highest throughout the circumpolar North. A relatively large population in urban and rural communities in the Barents Sea region is thus endangered by possible global change impacts. Such impacts on natural conditions, which will have a bearing on the availability of natural resources will lead to major changes in economic conditions with repercussions on the societal and cultural level.

The factors explained above, though far from providing a complete picture of the current situation, underline the need to address global change impacts in the Barents Sea region. This has been the major incentive to initiate, define and implement the *Barents Sea Impact Study* (BASIS), which will be briefly described below.

2. OBJECTIVES

The long-term, overarching goal of the *Barents Sea Impact Study* (BASIS) as an integrated regional impact study is to:

assess the impacts of global changes on cultural and socio-economic systems which are dependent on renewable and non-renewable resources in the Barents Sea region.

While such an assessment requires the integration of investigations on both the environmental and the socio-economic level, during its initial period, the BASIS project will concentrate on assessing the impacts of global changes on marine, terrestrial and freshwater ecosystems. These assessments will then be utilised to evaluate the consequences which derive from impacts on the environmental level for a few key economic sectors in the Barents Sea region. In addition, the project will design and implement a dedicated information and GIS system for the Barents Sea region and will initiate stakeholder consultations in the region.

BASIS in its present form is built around the following objectives:

Objective (1)

BASIS will assess the likely magnitude of global changes on regional to sub-regional scales in the Barents Sea region; this will include an assessment of past changes as deduced from historical records.

Objective (2)

BASIS is going to provide insight into the consequences of global changes for terrestrial, freshwater and marine ecosystems.

Objective (3)

BASIS, by using the results of investigations carried out for issues related to the environmental level is going to develop an integrated assessment of global change impacts for a number of major economic sectors in the Barents Sea region.

Objective (4)

BASIS will determine major changes in the socio-economic system of the Barents Sea region and will determine the conditions for a sustainable development in the Barents Sea region undergoing global changes.

WORKPLAN

BASIS has been funded for a two-year initial phase, which started on January 1st 1998. The project will be a combination of

- **field work**, both in terms of natural sciences oriented observations as well as through more social-sciences oriented interviews and surveys
- **statistical analysis and modelling** both with regard to physical, biological and chemical simulations as well as to socio-economic models
- and the **synthesis and integration** of already existing and/or results and data that are being derived by BASIS itself.

It is the latter point that will be of particular importance. There are various options for achieving this goal. One approach will be the creation and maintenance of a dedicated data and information system, including a collaborative Internet-based GIS (=Geographic Information System) database environment for the project (BASIS- Data and Information System or BASIS-DIS). Another means of integration will be a comprehensive socio-economic model aimed to derive answers to specific questions on overall economic development in the Barents Sea region and its consequences for the labour market, migratory activities and social institutions and conditions.

A further main task will address the **information, consultation and/or involvement of local or sub-regional stakeholders** through a number of activities carried out by the BASIS Information Office in Rovaniemi, Finland. This will include widely advertised public hearings and lectures, the publication of brochures and other material including a dedicated home page on the Internet. In addition, it is planned to create a network of stakeholders, which will be involved in a review of project results and the specification of guidelines for ongoing and future activities in BASIS.

Figure 1 shows the study area of BASIS which embraces the northern part of Fennoscandia including parts of Norway, Sweden, Finland and the Republic of Karelia, the Murmansk Oblast, parts of the Arkhangelsk Oblast, Novaya Zemlya, Svalbard and Franz Josefs Land. It furthermore includes parts of the North Atlantic, the Barents Sea and a fraction of the Kara Sea. Mainly motivated by focusing the investigations, the BASIS project will initially concentrate on a sub-region of the overall study area in northern Fennoscandia and the Kola Peninsula (indicated by the dashed circle in Figure 1). However, wherever necessary or meaningful, other parts of the overall study region will be included in order to enable comparisons between various sub-regions and/or derive a more complete picture.

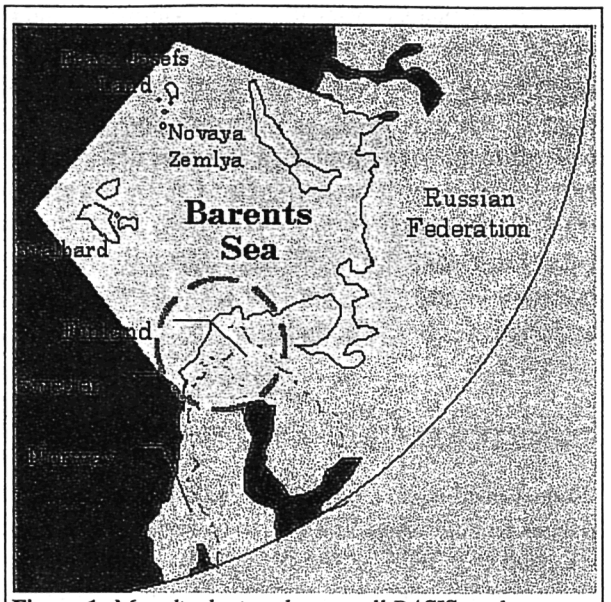


Figure 1: *Map displaying the overall BASIS study area (shaded) as well as the more specific study region in this project (circle).*

In order to focus on a feasible number of economic sectors to be addressed, the project will initially concentrate on forestry, reindeer herding and fisheries. Thus, neither the exploitation of hydrocarbons and minerals nor other potentially important sectors and issues such as tourism

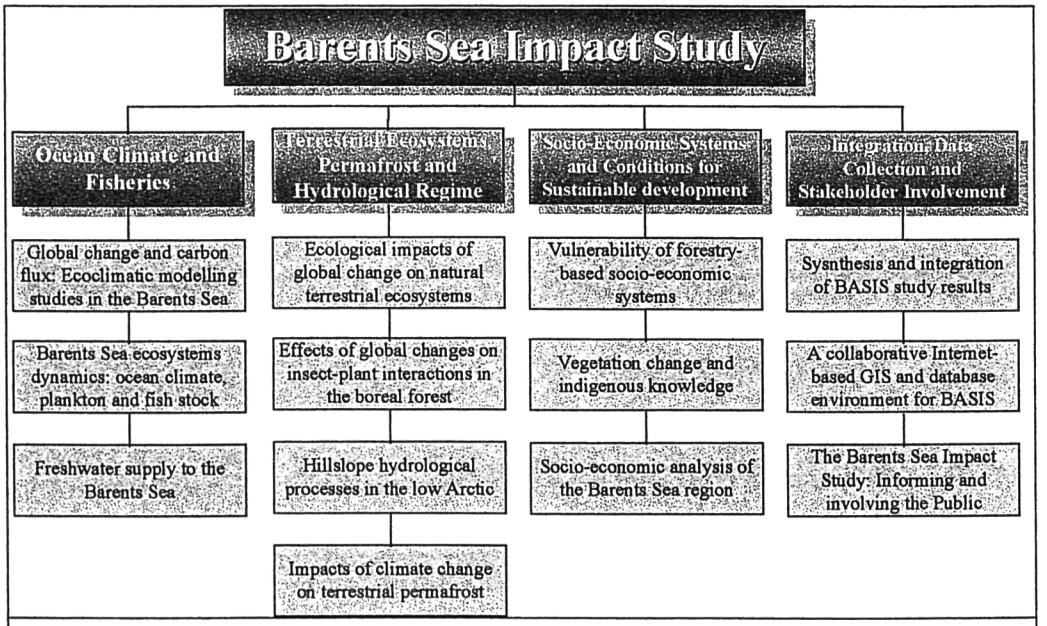


Figure 2: *The tasks and sub-tasks of the Barents Sea Impact Study*

or the large military installations near Murmansk and the associated dumps of nuclear material will be considered during the initial phase of the BASIS project.

BASIS is set out to look at a twenty to fifty year time frame from the present. In addition, hundred year long scenarios will be considered to evaluate long-term impacts in accordance with other studies such as the assessment of the *Intergovernmental Panel on Climate Change*. However, it is expected that regional global change scenarios can be provided with reasonable reliability only for the next twenty to fifty years.

BASIS will be carried out through four major tasks, each involving a total of three sub-tasks (except for Task 2; Figure2). Of particular importance will be the co-ordinated and timely exchange of information and data. The aforementioned BASIS-DIS will play a major role to achieve this.

EXPECTED RESULTS AND DELIVERABLES

While it is difficult to predict the outcome of a project that has just started, we expect that BASIS will during its first two years result in a refinement of the approach that needs to be followed in an IRIS for the Barents Sea region. We do expect to come up with initial results as outlined in the objectives, particularly with regard to Tasks 1 and 2 and less extensive results for Tasks 3 and 4. However, we will put special emphasis on the BASIS-DIS and the stakeholder involvement as part of Task 4.

We also expect that aside from reports and data compilations, a number of scientific publications will be written throughout the first phase of BASIS. The *First International BASIS Research Conference* (funded by a grant of the ENRICH Programme of the *European Commission*, MAS3-CT97-0127), which will take place in St. Petersburg from February 22 to 25, 1998, will result in a first *expert's assessment* on global change impacts in the Barents Sea region. It will also lay the foundation for the following stages of the *Barents Sea Impact Study*.

TITLE: CHANGES IN BACTERIAL DIVERSITY AND WATERS AS AFFECTED BY EUTROPHICATION (CHABADA)

CONTRACT NO: MAS3-CT96-0047

COORDINATOR:

Erko Stackebrandt
DSMZ-Deutsche Sammlung von Mikroorganismen
und Zellkulturen GmbH
Mascheroder Weg 1b
D-38124 BRAUNSCHWEIG
GERMANY
Tel: +49 531 2616-352 Fax: +49 531 2616-418
E-Mail erko@gbf.de

PARTNERS:

Philippe Lebaron
Aquatic Microbial Ecology
Université Pierre et Marie Curie
Paris 6 BP44
66651 BANYULS-SUR-MER, FRANCE
Tel: +33 6888 7353
Fax: +33 6888 7395
E-Mail: lebaron@arago.obs-banyuls.fr

Gerard Muyzer
Molecular Ecology Group
Max-Planck-Institute for Marine
Microbiology
Celsiusstr.1
D-28359 BREMEN
GERMANY
Tel: +49 421 2028 934
Fax: +49 421 2028 690
E-Mail: gmuyzer@mpi-bremen.de

Pierre Servais
ULB-Groupe de Microbiologie
des Millieux Aquatiques
Université libre de Bruxelles
Campus de la Plaine CP 221
B-BRUXELLES, BELGIUM
Tel: +32 2650 5995
Fax: +32 2650 5953
E-Mail: pservais@ulb.ac.be

Marc Troussellier
Laboratoire d'Hydrobiologie UMR
Université de Montpellier II
F-34095 MONTPELLIER CEDEX 05
FRANCE
Tel: +33 46714 4761
Fax: +33 46714 3719
E-Mail: troussel@hydrobio.univ-montp2.fr

Josep Vives-Rego
Department of Microbiology
University of Barcelona
Av. Diagonal 645
E-08028 BARCELONA
SPAIN
Tel: +343 4021 485
Fax: +343 4110 592
E-Mail: jvives@porthos.bio.ub.es

ASSESSMENT OF CHANGES OF DIVERSITY AMONG MEDITERRANEAN PROKARYOTS SUBJECTED TO EUTROPHYING CONDITIONS

Erko Stackebrandt, Phillipe Lebaron, Marc Troussellier, Claude Courties, Pierre Servais, Josep Vives-Rego, Gerard Muyzer, Rüdiger Pukall, Barbara Lehnberg, Daniela Buntefuß, Orsola Päuker, Gabriele UlrichsLaetitia Bernard, Teresa Guindulain, Hendrick Schäfer

Assembled from individual contributions of partners and harmonized by B. Lehnberg and E. Stackebrandt, DSMZ-Deutsche Sammlung von Mikroorganismen und Zellkulturen GmbH, Mascheroder Weg 1b, D-38 124 Braunschweig Germany

The impact of eutrophication on biological community structures in coastal areas is a major preoccupation but refers mainly to macrofauna. Today, its effect on bacterial communities has rarely been addressed, due to the lack of suitable methods for species isolation and/or identification which are classical ways to assess taxonomic diversity. Thus, regarding the impact of eutrophication on bacterial communities, basic questions remain unanswered and especially in modeling exercises, prokaryotes that lack photosynthetic pigments are lumped together into a black box called "heterotrophic bacteria". With he introduction of molecular tools and cytometric techniques in the field of microbial ecology the influence of community-changing parameters can be addressed more objectively.

It was the aim of the first phase of the CHABADA project to apply these modern methods to a known problem by analysing changes in demographic parameters and genomic diversity in a bacterial community from oligotrophic Mediterranean waters which were subjected to different simulated eutrophication conditions. Changes were determined for phytoplankton, bacterioplankton and protozoa, and for bacterial production. The molecular analyses confirmed the high degree of hitherto undescribed bacterial taxa and guided a revised strategy for the more detailed analysis of a defined mesocosm in phase 2 of the project.

Introduction

In aquatic ecosystems bacterial communities play a fundamental role in the organic matter decomposition. They also transform dissolved organic carbon into bacterial biomass which may be transferred through the foodweb via ingestion by bacteriovores. In almost all waters the content of inorganic nutrients, ammonia, nitrate and phosphate determines phytoplankton growth and productivity. In nutrient-poor (oligotrophic) waters productivity amounts to 7-25 mg C m^{-2} yr^{-1}, and in nutrient-rich (eutrophic) areas to 75-400 g C m^{-2} yr^{-1}. Eutrophication is produced by the addition of relatively large amounts of nutrients and results from man's activity.

The recent introduction of molecular biology has enable investigations on changes in community structures. However, the understanding of the effect of eutrophication on the diversity of bacterial communities should be considered not only at the taxonomic level but also at physiological and genetic levels. The effect of eutrophication may depends on the source of nutrients, and may be much more important on oligotrophic waters. Thus, Mediteranean coastal waters of the Gulf of Lyon off Banyuls-sur-Mer, France, were choosen in the framework of the CHABADA program due to their oligotrophic characterisitics. Here we report on the first phase of the program in which mesocosms were used to simulate the effect of the discharge of different nutrients on natural heterotrophic bacterial communities. Nutrients were choosen as representative of three main sources of organic and inorganic nutrients in coastal areas: (i) nitrate, ammonium and phosphate ions which are essential for bacterioplankton and phytoplankton autotrophic communities. (ii) phytoplankton lysates corresponding to the indirect effect of eutrophication on heterotrophic communities and, (iii) wastewaters which play a key role in stimulation of both autotrophic and heterotrophic communities. The aim of these experiments was to record temporal changes in bacterial communities structure by analysing the genetic diversity as well as changes in demographic parameters of both phyto- and bacterio-plankton communities, bacterial production, activity of individual cells and predation.

Material and Methods

Preparation of mesocosms and sampling

The mesocosms consisted of four rectangular tanks of 400 l capacity, 60 cm in height, 60 cm width and 110 cm length disposed in larger tanks (30 cm height, 80 cm width, 140 cm lengh). Each mesocosm was filled with 300 l of natural seawater collected from 1 m depth at a station (42°31' N, 03°11' E) located about 2400 m off Banyuls-sur-Mer, France (Mediteranean sea) and filtered through a 200 μm nylon mesh. Each mesocosm was temperature-controlled (17.7-19.6°C) to fit the temperature of Mediteranean coastal waters at the time of experiments. The two non-illuminated mesocosms A abd B were capped with an opaque cover. The two illuminated mesocosms C and D were covered with a fluorescent ramp consisting in five fluorescent tubes (36 W, 120 cm) providing illumination on a 12 : 12 h light : dark period.

Treatment of mesocosms

The initial seawater contained 0.32 μM nitrate, 0.175 μM ammonia, 0.05 μM phosphate. At the start of the experiment, after enclosing this water in the mesocosms, three different enrichments were performed. In the nutrient treatment (mesocosm B), nitrogen and phosphorus additions resulted in global N:P ratio of 16.5. In the bloom-simulated treatment (mesocosm C), a phytoplankton culture was added following cell lysis. Filtered wastewater was sterilized and autoclaved before addition to the D mesocosm.

Sampling

Five liters of each mesocosm were taken daily to analyse nutrients, demographic parameters (phyto- and bacterioplankton counts), bacterial production and chlorophyll *a*. The temporal evolution of total bacterial counts was used to determine the sampling times for all other parameters, including molecular biology. Sampling times were choosen corresponding to the starting time of each mesocosm, to the first significant increase in bacterial counts, to the peak, and then, after a significant decrease of total counts, and at the end of experiments which was determined by the stabilisation of total counts.

Isolation of bacterial strains from mesocosms

Isolation was done by spreading 100 microliters of sea water plates onto Marine Agar Difco 2216 (ZoBell's medium). Depending upon on the population density as determined by flow cytometry, samples were diluted (10^{-1},10^{-2}, and 10^{-3}). with sterile seawater prior to spreading Every dilution was inoculated in triplicates. The viable count was determined after 5-7 days of incubation at 20°C in the dark. The sampling times selected were: Mesocosm A : 000, 065, 113, 161, 281 hours; mesocosm B : 065, 113, 161, 281 hours; mesocosm C : 113, 137, 185, 281 hours, and mesocosm D : 113, 137, 185, 281 hours.

Molecular identification

Preparation of genomic DNA from pure cultures and PCR amplification of 16S rDNA sequence were done as described by Rainey et al. (1996). Sequence analysis was performed with the Taq DyeDeoxy terminator Cycle sequencing Kit (Applied Biosystems), using the primer 530r (5'GWATTACCGCGGCKGCTG3'). Purified sequence reactions were electrophoresed using an Applied Biosystems model 373A automated DNA sequencer.

For phylogenetic analyses, sequences were manually aligned with sequences stored in the DSMZ-internal database consisting of more than 5000 16S rDNAsequences. Similarity values were transformed into phylogenetic distance values that compensate for multiple substitutions at any given site in the sequence (Jukes and Cantor, 1969). The neighbor joining method contained in the PHYLIP package (Felsenstein, 1993) was used in the construction of phylogenetic dendrograms.

Molecular probes for hybridization

PCR products were purified with the Prep-A-Gene™ DNA Purification Kit and eluted in 50 μl of water. 3 μl of each of the 16S rDNA or 23S rDNA PCR products were denatured and applied to a nylon membrane (Hybond N, Amersham), using a dot blot apparatus (Bio-Rad) and fixed by UV (260 nm) for 100 s. Hybridization and detection were performed according to the manufacturer's instructions using the DIG Luminescent Detection Kit (Boehringer). Hybridization was carried out at room temperature for four hours. The temperature of the stringency wash in 6 SSC, 0.1% SDS buffer was 37 °C. Exposure to an X-ray film (Fuji 51209) was for 2 h. Oligonucleotide probes used were taxon-specific for members of the alpha subclass of *Proteobacteria* (16S rDNA), beta subclass of *Proteobacteria* (16S rDNA), gamma subclass of *Proteobacteria* (23S rDNA), Gram-positive bacteria (16S rDNA), *Cytophaga- Flavobacterium-Bacteroides* phylum (16S rDNA), *Sulfitobacter pontiacus* and *Roseobacter denitrificans* (16S rDNA)

Genetic diversity as measured by DGGE

Bacterial cells (approximately 2.5 x 10^8) were collected from water samples by filtration on Durapore filters (Millipore GVWP 02500). DNA and rRNA were extracted using the protocol of Teske et al. (1996). The extracted genomic DNA was used as target DNA in the polymerase chain reaction (PCR; Saiki et al., 1988) to amplify the 16S rRNA genes. The rRNA was amplified using RT-PCR (Teske et al., 1996). Two different primer sets were used, i.e., one primer pair (GM3F/DS1542) which amplifies the nearly complete 16S rRNA gene and a second primer set (GM5F+GC-clamp/907) which amplifies a 550 bp long 16S rDNA fragment (Muyzer et al., 1995). The nearly complete 16S rDNA fragments were used for the generation of clone libraries; the smaller fragments were used for denaturing gradient gel electrophoresis (DGGE; Muyzer et al., 1993). Denaturing gradient gel electrophoresis (DGGE) followed the method of Muyzer et al. (1996).

Genetic diversity as measured by the composition of 16S rDNA clone libraries

The nearly complete 16S rRNA gene fragments were purified using the Qiaquick PCR Purification Kit (Qiagen Inc., USA). The PCR products were cloned using the pGEM-T (easy) Vector System II (Promega, Inc.). Inserts of recombinant plasmids were amplified using Taq Polymerase (Boehringer) and M13 (-20) and M13rev primers in a reaction volume of 50 μl, and with the PCR cycles as indicated above. Individual clones were picked for subsequent 16S rDNA analysis using the 537r primer as indicated above. Also, determination of similarities and generation of dendrograms of relatedness followed the procedures given above. Plasmids from clones were isolated using the Wizard Plus Minipreps DNA purification system (Promega Inc.). Cloned PCR products were purified as described above. 5'- and 3'-end partial sequences were obtained from clones generated from DNA isolated from biomass of mesocosm A, while those of mesococm B were partially sequenced at the 5'terminus only. The sequence reactions were electrophoresed on an Applied Biosystems 373S DNA sequencer.

Bacterial production

Bacterial production was determined by ^{3}H-thymidine incorporation into DNA (Servais, 1988) and by incorporation of ^{3}H-leucine into bacterial proteins (Servais, 1990). 10-ml water samples were incubated in parallel in the presence of different concentrations of tritiated thymidine (6.5, 13, 26 and 39 nM) and ^{3}H-leucine (2 to 77 nM) for two hours in the dark at the temperature of the mesocosms. Cold trichloroacetic acid was added (final concentration 5 %) and the samples were filtered through 0.2 μm pore size cellulose acetate membrane. Incorporation rates expressed in pmol l^{-1} h^{-1} were calculated and plotted against the thymidine concentrations. The maximum incorporation rates were estimated by best fitting a hyperbolic function to the experimental data using a software based on the least squares criterion (Servais, 1995).

Grazing

Measurement of bacterial mortality and contribution of protozoa grazing in the overall mortality process was measured by following the disappearance of radioactive tracer from the genetic material of ^{3}H-thymidine of bacterial assemblages (Servais et al., 1989). 200 ml were

sampled five times in each mesocosm and the bacteria were labelled with triated thymidine (final concentration 4 nM) for 10 to 12 hours in the dark. After all the thymidine has been exhausted or eliminated by dialysis, a subsample was filtered through a 2 μm pore size Nucleopore membrane for retaining most of the eukaryotic micro-organisms. A mixture of cycloheximide-colchicine at respective concentrations of 200 and 100 mg l^{-1} was added in order to inhibit protozoan grazing (Sherr et al., 1986). A linear decrease of the disappearance of radioactivity is usually observed in semilog plot for each subsample. The slope for the unmodified subsample gives the first order rate of overall mortality while the slope in the other subsample corresponds to the first order rate of mortality non attributable to grazing. The difference between the two rates was considered to be the consequence of grazing by protozoa.

Activity of individual cells

Flow cytometry was used to enumerate substrate responsive cells by the DVC method (Kogure et al., 1979). Substrate responsive cells (DVC^+) were characterized by an elongation during incubation with nutrients and nalidixic acid, a specific inhibitor of DNA gyrase that prevent cell division but not metabolic activity. Samples of 9 ml were added to 1 ml of MB containing 200 μg (20 μg ml^{-1}, final concentration) of nalidixic acid. DVC tubes were incubated in the dark at 20°C and fixed after a 4, 10 and 24 h period with formaldehyde to a final concentration of 2% (vol/vol) and stored at 4°C. The control was treated with formaldehyde (2%, vol/vol) before incubation with nutrients and nalidixic acid. Cells were stained with DAPI (2.5 μg ml^{-1}, 30 min) and analyzed by FCM.

Active respiring cells were identified by the method of Rodriguez et al. (1992). CTC-labelled cells were then counterstained with DAPI (2.5 μg ml^{-1}, 30 min) and filtered through black polycarbonate membrane filters (0.2-μm-pore-size, 25-mm, Nuclepore). Epifluorescence counts were performed with an Olympus BH-2. Respiring cells (CTC^+) were first enumerated using filter set B (BP490, DM500, and AFC+O515) and then total cells were counted by switching to filter set U (UG-1, DM400, and L420). A minimum of 400 cells were counted for each sample. Control was treated with fomaldehyde (2%, vol/vol) before incubation with CTC. Proportion of CTC^+ cells was calculated as the ratio of CTC^+ cell on total cell ($DAPi^+$ cells) counts.

Analysis of carbon, nitrogen and phosphorous

A Shimadzu TOC 5000 instrument was used for HTCO analysis of DOC. The combustion tube, made of quartz, is filled with a catalyst and its temperature is fixed at 680°C. Analysis was done as described (Cauwet, 1994). Nitrates and phosphates were analyzed with a Skalar autoanalyzer according to Treguer and Le Corre (1975). Subsamples for ammonium (NH4) analysis were analyzed following the Koroleff's manual.

Bacterial counts and sizes

Bacteria were fixed with formalin (2% final concentration), stained with DAPI and counted with an epifluorescence microscope (Lebaron et al, 1994). Bacteria were also enumerated by flow cytometry by labeling the cells with SYTO 13 (2.5μM, final concentration) (Molecular Probes Europe, Amsterdam, Netherlands).

FCM analyses were performed using a FacsCalibur flow cytometer (Becton Dickinson, San Jose, CA) equipped with an air-cooled argon laser (488 nm, 15 mW). Phytoplanktonic cells were detected from living samples according to their right angle light scatter (SSC, related to cell size) and their orange and red fluorescence emissions related to phycoerythrin (orange) and chlorophyll (red) pigments, respectively. Orange fluorescence was collected throught a 585/42 nm band-pass and red fluorescence through a 650 nm long-pass optical filters. One micron beads (Polysciences, Warrington, PA) which are used as internal standard, were systematically added to analysed samples in order to normalize cell fluorescence emissions and scatters and to allow a comparison day after day of the different cellular populations. To detect bacterial populations, living samples were stained with 5 μM of SYTO 13 (Molecular probes, Eugene, OR). Stained cells, excited at 488 nm, emitted a green fluorescence collected at 530/30 nm allowing a good FCM discrimination and accurate enumerations of the smallest picoplanktonic cells (bacteria). Bacterial enumerations were found closely related to EM counts by DAPI staining.

Phytoplankton counts, sizes and pigments

Global phytoplanktonic biomass was estimated in the different mesocosms by measuring chlorophyll a by spectophotometric technique. One litre samples were filtered through GF/F Whatman filter and chlorophyll a was extracted in 5 ml of acetone 90 %. For phytoplankton counts, one-micron beads were also added to analysed samples in order to normalize cellular properties (scatter and nucleic acids contents).

Protozoan counts

The abundance and biomass of protozoa was determined by epifluorescence microscopy (Leitz, Laborlux D) DAPI staining. 20 ml of glutaraldehyde-preserved (0.5% final concentration) water samples were stained with DAPI (0.1 $\mu g\ l^{-1}$, final concentration) for 15 min. Stained protists were collected by filtration on a 0.8 μm Nuclepore black filter. Pico-sized (0.2 -2 μm in diameter) and nano-sized (2-20 μm in diameter) micro-organisms were identified, counted and measured at a magnification of x1250 and x625 while micro-sized (20-200μm in diameter) microorganisms were analysed at a magnification of x125. Autotrophic species were distinguished from heterotrophs by the red autofluorescence of chlorophyll a observed under blue light excitation. Dinoflagellates, flagellates and ciliates were enumerated distinctly among the autotrophic and heterotrophic microorganisms. Cell sizes were estimated visually by comparison with an ocular micrometer. Biovolumes were calculated from cell dimensions and shapes. Data presented in this report concerns only the heterotrophic protozoa.

Results and Discussion

Molecular analyses

Of the 675 isolates the 5'terminal 500 nucleotides of 16S rDNA of 40 strains were determined and the phylogenetic neighbor determined by assessment of their similarity values. The majority of the analysed organisms belong to the alpha and gamma subclass of *Proteobacteria* (38% and 44%, respectively) while the number of Gram-positive bacteria was much smaller (15%). The majority of strains clustered close to described species e.g.

Sulfitobacter pontiacus, Roseobacter algicola in the alpha subclass of *Proteobacteria,* and *Pseudoalteromonas haloplanctis, Alteromonas macloedii, Marinobacter hydrocarbonoclasticus and Vibrio splendidus* in the gamma subclass of *Proteobacteria.* However, absolute identity of the sequences were found in a few cases only.

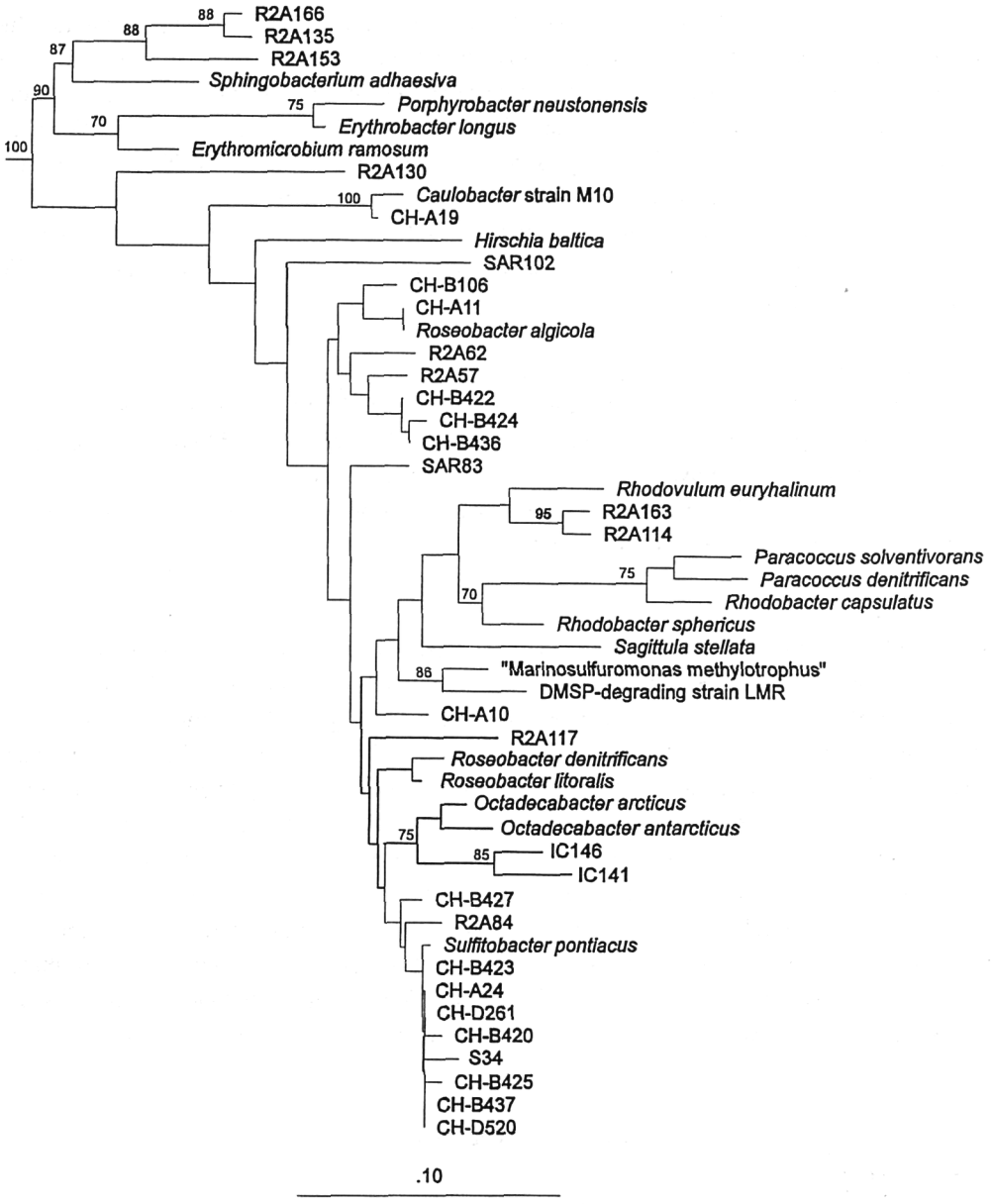


Figure 1. Phylogenetic position of cultured strains from mesococms A-D which belong to the alpha subclass of Proteobacteria. Also included are isolates from the North Adriatic sea (PAL, [Lebaron, unpublished]) and the Sargasso Sea (R2A).

Organisms analysed from the non-eutrophied mesocosm A are more or less related to members of the genera *Caulobacter, Marinosulfonas, Roseobacter, Sulfitobacter, Aeromonas, Klebsiella, Moritella, Pseudoalteromonas,* and some Gram-positive genera. Other organisms were phylogenetically well separated from any cultured and described species and these isolates most like represent the nuclei of novel species and genera. Some of these organisms are found also in the eutrophied mesocosms but these contain organisms that have not been detected in mesocosm A, e.g, *Pseudomonas* (mesocosm B), *Vibrio* (B), *Alteromonas* sp. (D), *Rhodobacter* sp. (B), *Marinobacter*, and *Micrococcus* (B).
The phylogenetic position of members of the alpha subclass of *Proteobacteria* is indicated in Figure 1.

Molecular probes for hybridization
Of the 675 dots of 16S rDNA PBCR products 542 reacted with the probes used. 48% of the dots originated from the alpha subclass of *Proteobacteria* and 39% originated from the gamma subclass of *Proteobacteria.* It should be noted that the distribution only give some indication about the affiliation of strains to higher taxonomic levels but it cannot be used for strain quantification as colonies with similar morphologies and pigmentation were deliberately excluded from the isolation procedure.

Global genetic diversity of natural bacterial communities
PCR fragments of 16S rDNA were analysed by denaturing gradient gel electrophoresis (DGGE). All mesocosms, including the negative control, i.e., mesocosm A, shows successional population changes. In some mesocosms the DGGE profiles of later time points show more bands indicating an increase in genetic diversity (but not necessarily in taxonomic diversity).
PCR products of individual bacterial isolates and of environmental samples were compared by DGGE to investigate the representation of isolates in the natural assemblages. PCR products from different isolates were first screened by DGGE analysis to reduce redundancy. Subsequently, 'unique' isolates were compared with DGGE patterns of corresponding mesocosms and time points from which the isolates were obtained. PCR products from some isolates had a corresponding counterpart band in the pattern of the environmental sample, indicating a predominant representation of these cultured strains within the bacterial population.

16S rDNA sequence analysis of environmental DNA
Nearly complete PCR 16S rRNA gene fragments were obtained from genomic DNA extracted from water samples of mesocosms A and B. The clone library of mesocosm A was screened for redundant clones by DGGE. Phylogenetic analysis of mesocosm A clones (data not shown) indicate that at time point 0 sequences were found to belong to the alpha subclass of the *Proteobacteria*, especially to sequences of members of the genus *Roseobacter*. Four sequences had as nearest neighbors the sequences of the sulfur-oxidizing bacteria *Thiomicrospira* which belong to the gamma subclass. At time point A-161 hrs the community has changed. One sequence is affiliated to the cyanobacteria and chloroplasts. Two sequences are still affiliated with the *Thiomicrospira*-like bacteria. However, 12 sequences out of a total

of 15 sequences are affiliated to members of the genus *Alteromonas*. At time point A-281 hrs the composition has not changed, in that bacteria affiliated with *Alteromonas* are dominating (11 sequences out of 14). Three sequences are related to other members of the gamma subclass of *Proteobacteria*. Analysis of mesocosm B indicates that the vast majority of clone sequences are related to the sequence of *Alteromonas macloedii*. This clone cluster (data not shown), containing several subclusters, also includes the sequences of two cultured organisms from mesocosm D, as well as of one strains each of the North Adriatic Sea and the North Pacific Ocean. These sequences were intermixed with sequences from mesocosm A from similar sampling points. A few additional sequences were found to be remotely related to those of *Teridinibacter* sp., *Bathymodiolus* and Cyanobacteria, none of which were among the cultured strains.

Bacterial production

Bacterial production was very low in the control. In mesocosm B, the addition of inorganic nutrient resulted in a rapid and concomitant increase of DNA and protein syntheses which were maintained up to 144 hours and then fell close to the detection limit. In mesocosm C, the addition of nutrients was characterized by a strong and short increase by 144 hours. A similar trend was observed in the D mesocosm but was much more limited.

Figure 2 presents the fluctuations of the maximum incorporation rates of thymidine and leucine in the four mesocosms during the period of the study. In a general way, the same trends were observed with both methods even if slight differences can be observed in some situations.

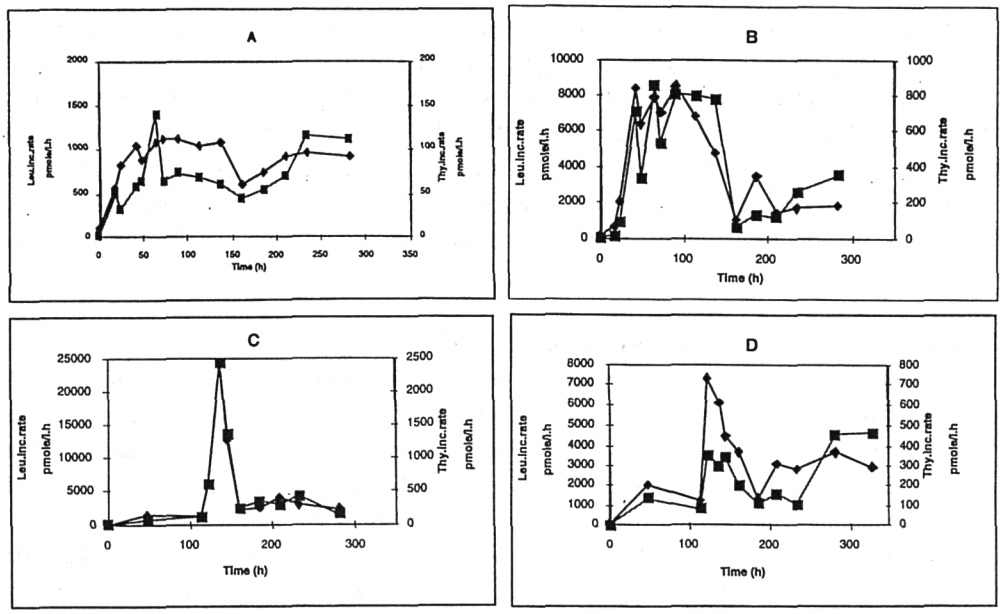


Figure 2. Fluctuation of incorporation of tritiated leucine (◆) and thymidine (■)

In mesocosm B, the increase in bacterial activity was more rapid and more intense than in mesocosm A. The maximum values observed (860 pmoles of thymidine l^{-1} h^{-1} and 8530 pmoles of leucine l^{-1} h^{-1}) were roughly 8 times higher than those measured in mesocosm A.
After a period of high bacteria activity between 40 and 120 hours, incorporation rates decreased. In mesocosms C and D, a rapid increase in bacterial activity was observed after the addition of organic carbon (filtered and sterilised phytoplankton lysate in mesocosm C and filtered and sterilised wastewater in mesocosm D) at time 113 hours. The maximum values of bacterial activity reached in mesocosm C (2440 pmoles of thymidine incorporated /l.h and 24300 pmoles of leucine incorporated/l.h) were higher than those maesured in mesocosm D (350 pmoles of thymidine incorporated /l.h and 7350 pmoles of leucine incorporated/l.h). In mesocosm C, the maximum of activity was followed by a rapid decrease while in mesocosm D the decrease was less rapid and a second increase in activity was observed after 250 hours of incubation.

Control of bacterial dynamics by grazing

In all the measurements performed in the four mesocosms, grazing by protozoa was the dominant process in the overall bacterial mortality. The rates of mortality not due to grazing (bacteriphage-induced lysis, autolysis) were in the range 0.5 to 3 x 10^{-3} h^{-1} while the rates of mortality due to grazing were between 2.5 and 13 x 10^{-3} h^{-1}. In all mesocosms, mortality rates due to grazing were highest in the period between 160 and 210 hours when the abundance and biomass of protozoa were at their maximum.

Evolution of NO_3, NH_4, PO_4 and DOC

In mesocosm A the nitrate, ammonium and phosphate concentrations were low, corresponding to those generally encountered in oligotrophic environments. The nitrogen forms, mainly ammonium, slightly increased during the experiment. Phosphate was totally consumed and fell close to the detection limit after 42 hours.
The inorganic additions in mesocosms B resulted in high amounts of the three inorganic nutrients corresponding to a 10 fold increase of each form when compared to *in situ* values. Ammonium was rapidly consumed and reached the detection limit after 89 hours. Then, the concentration increased, suggesting a recycling of this nutrient or ammonification from nitrate since this phenomena was concomitant to the decrease of nitrate. The first decrease of ammonium was concomitant to an important increase in chlorophyll *a* and total bacterial concentrations as well as bacterial production. The increase in chlorophyll values was bimodal, reached zero by 113 hours and then increase, corresponding to the increase in ammonium values. After the first increase, bacterial production was constant and decrease after 161 hours. The phosphate concentrations decrease up to 120 hours and then stabilized up to the end of the experiments.
The addition of phytoplankton lysates to mesocosm C resulted in a large increase in nitrate and a low increase in ammonium. Phosphate was rapidly consumed and then increase and stabilized at the initial level. On the other hand, addition of wastewater in mesocosm D resulted in a large increase in ammonium and low amounts of nitrate and phosphorous.

Bacterial production rapidly increased in the same time. Phosphate and ammonium were rapidly utilized. Moreover, phosphate was rapidly exhausted and remained close to the detection limit during the experiment. This decrease was concomitant to the decrease of bacterial production.

Bacterial and phytoplankton counts and pigments

Total bacterial counts slightly increased in the control concomitantly to phytoplankton degradation and decreased after 144 hours. In mesocosm B, total counts increased up to 72 hours and then decreased sharply by 120 hours, corresponding to phosphate and ammonium exhaustion. In the C and D mesocosms, bacterial counts increased rapidly and were then submitted to fluctuations. The fraction of culturable cells rapidly increased in both cases and reach 100 % of total counts by 160 hours in mesocosms D and 50% by 140 hours in C.

Concerning the phytoplankton counts, some common trends were observed in all mesocosms. Concentrations were low at the starting point and decreased mainly after 72 hours of the experiment. A large decrease was observed by 120 hours in all mesocosms. Figure 3 presents the fluctuations of the chlorophyll a concentration in the four mesocosms during the course of the study. In mesocosm A, a small increase (from 0.5 μg chlor. a/l to 0.8 μg chlor. a/l) was observed during the first twenty hours of incubation followed by a decrease. In mesocosm B, the addition of inorganic nitrogen and phosphorous did not result in a large increase in phytoplanktonic biomass; the increase was quite limited (from 0.5 μg chlor. a/l to 2 μg chlor. a/l after 42 hours of incubation in the mesocosm) and followed by a decrease. However, at the opposite of what was observed in the other mesocosms, the chlorophyll a concentrations always stayed below 1 μg chlor. a/l. or higher during the whole experiment.

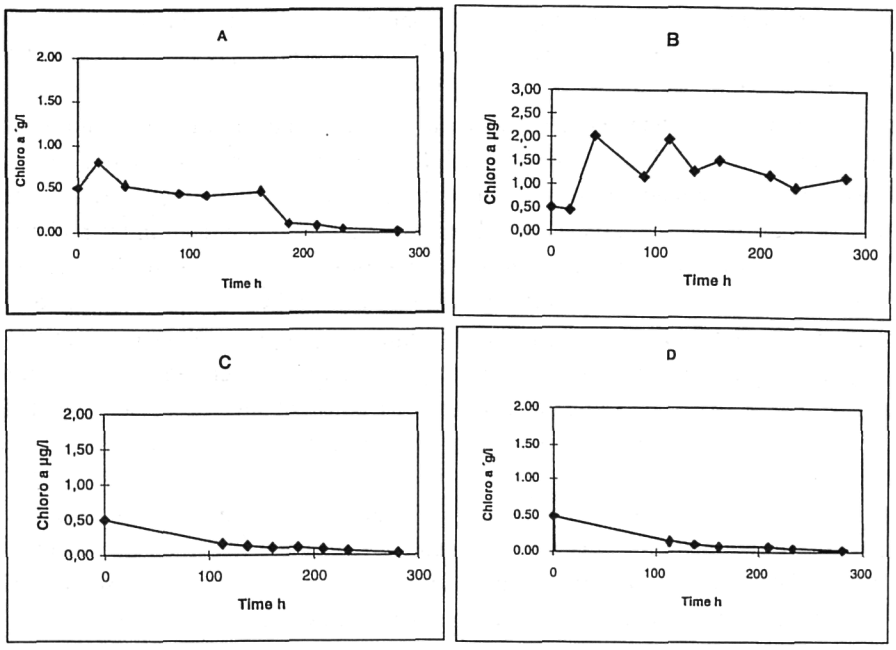


Figure 3. Fluctuation of the chlorophyll a concentration in the four mesocosms.

Bacterial and protozoan counts

In the four mesocosms, an increase of the biomass of protozoa with time was observed. The maximum of the protozoan biomass followed the maximum of bacterial abundance as it is often the case; predators development follows preys development.

Conclusions

In mesocosm A, the non-addition of nutrients resulted in very low variations of demographic parameters suggesting low production. However, a low but significant increase in bacterial production was observed just after the start of the experiments resulting in a slight increase of total and culturable counts. This first period may correspond to the growth of some populations which may have been induced due to the setup of the mesocosms. At the same time, the increase in cell size and nucleic acid content may suggest that production result in protein, DNA and RNA synthesis. The incorporation rate of radiotracers into proteins, DNA and RNA should correspond to the growth of some cells but also the resuscitation of some cells as suggested by the increase in culturable counts. The percentage of culturable cells was maintained at a low level corresponding to less than 5% but increased by 170 hours. In fact, the resuscitation process may be more important in the second phase, and if this is true, it may correspond to less changes in genetic diversity but by a more significant contribution of a small number of dominating species. Indeed this observation was made after the analysis of DNA that was directly extracted from the environment. Here, according to analysis of clone libraries generated from DNA taken from several time points from f mesocosms A and B the majority of organisms belonged to the gamma proteobacteria that were phylogenetically related to members of *Pseudoalteromonas* and *Alteromonas*. Representatives of cyanobacteria and alpha proteobacteria, originally present among the cultured organisms, were hardly represented in the DNA clone library of PCR-amplified 16S rDNA genes.

In mesocosm B, the addition of nutrients resulted in a large increase of demographic and production parameters from 48 hours to 150 hours. Production was very close to the increase in total and culturable counts. The diversity of culturable cells may be modified by the growth of some populations which may have an increasing contribution to total genetic diversity. This increase was concomitant to that of size and nucleic acid content of individual cells. The added phosphorus and ammonium were rapidly consumed and reach zero by day 150 and 65, respectively. The resulting concentrations may be the limiting factor for production and most activity parameters. The decrease in total counts after 120 hours may be due to grazing whose effect on diversity should be observed in regard to culturable cells. However, analysis of directly extracted DNA revealed, that at sampling times 113h, 161h and 281 h hours the same groups of organisms were dominating that had already been found in mesocosm A, i.e. members of *Alteromonas* and *Pseudoalteromonas*. Surprisingly, the genomic variation within the individual clusters was enormous which may indicate that under certain environmental conditions the otherwise hidden variation is able to bloom. Analysis of sampling time points 65 h is still under investigation. These data are necessary in order to decide whether the huge genomic variation is an effect of grazing which will eliminate a certain portion of the

population with the effect that a different portion may become dominant. We think that the dominance of *Alteromonas*-like bacteria is the result of a specific trait of these bacteria. Whether the reason for their increase is a special metabolic adaptation is uncertain, since only little is known about the physiology of *Alteromonas* in situ. The concurrence of a shift to a comunity dominated by *Alteromonas*-like bacteria with a peak in the numbers of heterotrophic flagellates might indicate a relative advantage of these bacteria to grazing pressure. This might either be brought about by preferential grazing of protozoa on the *Roseobacter*-like bacteria or by phenotypic adaptions of the *Alteromonas*-like bacteria that results in grazing resistance (see Jargens and Gade, 1994, for a review on grazing resistance).

In contrast, mesocosm C and D were submitted to an important and instantaneous increase in demographic and activity parameters. The concomitant evolution of all parameters suggest the rapid growth of a limited number of bacterial cells. This may be observed by diversity measurements. In mesocosm D, the culturable fraction reached 100% of total cells by 161 hours, suggesting similar diversity in both communities. However, this evolution may correspond to important changes in the community structure since the growth may correspond to a specific population which is culturable and may cover the primary diversity. As judged from the analysis of the cultured cells the main difference in population structure is the moderate occurrence of members of the *Cytophaga-Flavobacterium* group, organisms with known ability to hydrolyze a wide spectrum of organisc compounds, such as those which may have been introduced to the mesocosm through sterilized phytoplankton.

In mesocosms C and D the production was not limited by ammonium but was P-limited in the D mesocosm. However, it does not result in different behavior of demographic and activity parameters suggesting that most phosphate from phytoplankton source may be not readilly utilizable by bacteria.

References

Cauwet, G. 1994. HTCO method for dissolved organic carbon analysis in seawater: influence of catalyst on blank estimation. Mar. Chem. **17**:55-64

Felsenstein, J., 1993. PHYLIP phylogenetic inference package version 3.5.1.. Department of Genetics, University of Washington, Seattle.

Jargens, K. and H. Gade. 1994. The potential importance of grazing resistant bacteria in planktonic systems. Mar. Ecol. Prog. Ser. 112: 169-188.

Jukes, T. H. and Cantor, C.R., 1969. Evolution of protein molecules, p. 21-132. *In* H. N. Munro (ed.), Mammalian protein metabolism. Academic Press, New York.

Kogure, K.. U. Simidu, and N. Taga 1979. A tentative direct mikroscopic method for counting living bacteria. Can. Microbiol. **25**:415-420

Lebaron, P., M. Troussellier, and P. Got. 1994 Accuracy and precision of epiflourescence microscopy count for direct estimates of bacterial numbers. J. Microbiol.Methods **19**:89.94.

Muyzer, G., E. C. de Waal, and A. G. Uitterlinden. 1993. Profiling of complex microbial populations by denaturing gradient gel electrophoresis analysis of polymerase chain reaction-amplified genes coding for 16S rRNA. Appl. Environ. Microbiol. 59: 695-700.

Muyzer, G., A. Teske, C.O. Wirsen, H.W. Jannasch. 1995. Phylogenetic relationships of *Thiomicrospira* species and their identification in deep-sea hydrothermal vent samples by denaturing gradient gel electrophoresis of 16S rDNA fragments. Arch. Microbiol. 164: 165-172.

Muyzer, G., S. Hottenträger, A. Teske, and C. Wawer. 1996. Denaturing gradient gel electrophoresis of PCR-amplified 16S rDNA - A new molecular approach to analyse the genetic diversity of mixed microbial communities. In: A. D. L. Akkermans, J. D. van Elsas, and F. J. de Bruijn (eds.). Molecular microbial ecology manual. 2. edition. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 3.4.4.1-3.4.4.22.

Rainey, F. A., Ward-Rainey, N.,Kroppenstedt, R.M. and Stackebrandt, E., 1996. The genus *Nocardiopsis* represents a phylogenetically coherent taxon and a distinct actinomycete lineage: proposal of *Nocardiopsaceae* fam. nov. Int. J. Syst. Bacteriol. 46:1088-1092.

Rodriguez, G.G., D. Phipps, K. Ishiguru, and H.F. Ridgway. 1992. Use of flourescent redox probe for direct visualization of actively respiring bacteria. Appl. Environ. Microbiol. 58:1801-1808

Saiki, R.K., D.H. Gelfand, S. Stoffel, S.J. Scharf, R. Higuchi, G.T. Horn, K.B. Mullis, and H.A. Erlich. 1988. Primer-directed enzymatic amplification of DNA with a thermostable DNA polymerase. Science 239: 487-491.

Servais, P., 1988. Mesure de la production bactérienne par incorporation de thymidine tritiée. *Revue des Sciences de l'Eau*, 1 : 217-237.

Servais, P., Billen, G., Martinez and Vives-Rego, J., 1989. Estimating bacterial mortality by the disappearance of ^{3}H-labelled intracellular DNA.Technical validation and field measurements. *FEMS Microbiol. Ecology*, 62 : 119-126.

Servais P., 1995.- "Measurement of the incorporation rates of four amino-acids into proteins for estimating bacterial production".- *Microbial Ecology*, n° 29 p. 115-128.

Servais, P., 1990 Estimation de la production bactérienne en milieux marin par mesure du taux de synthése protéique. Oceanologica Acta. 13:229-235.

Sherr, B.F., Sherr, E.B., Andrew, T.L., Fallon, R.D. and S.Y. Newell. 1986. Trophic interactions between heterotrophic protozoa and bacterioplankton in estuarine water analysed with selective metabolic. *Mar. Ecol. Prog. Ser.* 32: 169-179

Teske, A., C. Wawer, G. Muyzer, and N. B. Ramsing. 1996. Distribution of sulfate-reducing bacteria in a stratified Fjord (Mariager Fjord, Denmark) as evaluated by most-probable-number counts and denaturing gradient gel electrophoresis of PCR-amplified ribosomal DNA fragments. Appl. Environ. Microbiol. 62: 1405-1415.

Treguer, P., and Le Corre, P. 1975 manuel d'analyes des sels nutrifs dans l'eau de mer. Utilisation de l'auto.analyser II - Technicon, 2è Eds UBO , Brest 110p.

TITLE: Nitrogen Cycling in Estuaries (project NICE)

CONTRACT NO.: MAS3-CT96-0048

COORDINATOR:

Dr. Tage Dalsgaard
National Environmental Research Institute
Department of Freshwater and Estuarine Ecology
Vejlsøvej 25, DK-8600 Silkeborg, Denmark
Tel. No.: +45 8920 1400 Fax: +45 8920 1414
E-mail: tda@dmu.dk

PARTNERS:

Dr. Vanda Brotas
Departmento de Biologia Vegetal
Faculdade de Ciencias da Univ. de Lisboa
Campo Grande, Edificio C2, Piso 4
1700 Lisboa, Portugal
Tel. No. +351 1 757 3141 (ext. 2907)
Fax: +351 1 750 0009
E-mail: vbrotas@fc.ul.pt

Dr. Graham J. C. Underwood
Department of Biological and Chemical Sciences
John Tabor Laboratories
University of Essex
Colchester, Essex. CO4 3 SQ, UK
Tel. No.: +44 1206 873337
Fax: +44 1206 873416
E-mail: gjcu@essex.ac.uk

Dr. Pierluigi Viaroli
Institute of Ecology
University of Parma
Viale delle Scienze
I-43100 Parma, Italy
Tel. No.: +39 521 905617
Fax: +39 521 905402
E-mail: pier@eagle.bio.unipr.it

Dr. Lars Peter Nielsen
Department of Microbial Ecology
University of Aarhus
Ny Munkegade, bygn. 540
DK-8000 Aarhus C, Denmark
Tel. No. +45 89 42 32 47
Fax: +45 86 12 71 91
E-mail: lpn@bio.aau.dk

Dr. Kristina Sundbäck
Dept. of Marine Botany
University of Göteborg
Box 461, S-405 30 Göteborg, Sweden
Tel. No.: +46 3177 32703
Fax: +46 3177 32727
E-mail: kristina.sundback@marbot.gu.se

Project homepage:
http://www.dmu.dk/LakeandEstuarineEcology/NICE

NITROGEN CYCLING IN ESTUARIES
NICE

TAGE DALSGAARD

National Environmental Research Institute
Vejlsøvej 25, P. O. Box 314
DK-8600 Silkeborg, Denmark

ABSTRACT

The overall aim of NICE is to obtain an overview of nitrogen removal in European estuaries and to understand how this is affected by climate, tidal amplitude, and benthic primary producers. We focus on the fate of anthropogenic nitrogen in coastal waters and estuaries and evaluate to what extent these waters intercept the transport of nitrogen from land to the open sea. The work is divided into 4 major parts: development and standardisation of methods, quantification of the major N-transforming processes over a full annual cycle at selected sites in Europe, investigation of the interactions of benthic primary producers and high tidal amplitude with the nitrogen cycle and finally development of a classification system for nitrogen removal. The classification system will allow estimation of nitrogen removal in a given coastal area based on simple monitoring parameters.

BACKGROUND

The anthropogenic nitrogen input to the aquatic environment is to a large extent politically regulated. Decisions regarding the allowable nitrogen discharge require knowledge not only about the impact on the waters immediately around the site of discharge, but also about the effects on the open seas and hence a possible removal of nitrogen from the water on its way to the open sea. Changes in nutrient levels in the open seas will affect their primary productivity and induce changes in the balance of carbon dioxide on a global scale. The possible change in release of the greenhouse gas nitrous oxide from coastal waters, due to changes in nitrogen turnover, has obvious implications for global change.

Estuaries are the interfaces between land and sea, and some 11.4 - 35 Tg N y^{-1} have been estimated to be exported globally through estuaries (e.g. Walsh et al, 1981). A significant part of this nitrogen is assumed to be removed as the water passes through estuaries and coastal areas (e.g. Seitzinger, 1988). This assumption is based on very few studies on few localities. Factors like tidal range, climate, and the vegetation dominating the coastal zone have not been taken into account, although it is presently known that activity of photosynthetic organisms dramatically affects the nitrogen dynamics (e.g. Sundbäck et al., 1991; Risgaard-Petersen et al., 1994). The studies published so far have been carried out using different methods rendering direct comparison difficult. The actual removal rates of anthropogenic nitrogen are, therefore, presently known only for very few European estuaries. However, without a clearer understanding of all the processes and variables that influence the fate of nitrogen in estuaries, it is difficult to predict the final loading of the sea, or the extent to which estuaries could recover from the effects of severe nitrogen loading once this is stopped. Furthermore, detailed knowledge about how the nitrogen removal is controlled will allow us

to predict in what way this will be affected by changes in nutrient loading, biological structure etc.

Removal of nitrogen from the estuaries occurs mainly in the sediment either via anaerobic bacterial respiration of nitrate to gaseous nitrogen, which then will be lost to the atmosphere, or via burial of refractory organic nitrogen compounds in the sediment. The activity of benthic micro- and macrophytes can markedly affect these removal processes. In the relatively shallow coastal waters primary production can occur both in the water column and on the sediment surface. In estuaries with large tidal amplitude concentrations of suspended solids tend to be high and light is rapidly attenuated. In estuaries with small tidal amplitude the water tends to be clearer stimulating both pelagic and benthic primary production. Seagrasses, macroalgae and benthic microalgae can be significant primary producers in such areas. They are furthermore capable of regulating the flux of regenerated nutrients from the sediment to the water column due to the position between these two compartments and will markedly affect nitrogen removal in the coastal waters.

The east/west and north/south differences in Europe are large. The west coast of Europe and the British isles are subject to large tidal amplitudes whereas they are very small in the Mediterranean and Baltic regions. Within Europe also large climate differences between north and south exist. The differences in temperature, length of growing season, and solar irradiance can be expected to influence primary production and in turn the whole nitrogen cycle.

In this project we quantify the most important processes in the nitrogen cycle on an annual basis in different types of European coastal waters and identify the regulating factors of these processes in the different environments. We focus on sediment related processes as the balance between these determines whether remineralized nitrogen will be available for primary producers or will be removed. Another major theme is the role of benthic primary producers and their role in nitrogen cycling as these characterise shallow coastal areas. Techniques have been standardised in order to make results comparable.

WORK CONTENT

The overview of nitrogen removal in European coastal waters is currently being obtained by quantifying the involved processes on an annual basis in four different areas within Europe. The study sites have been selected in order to represent ecosystems along gradients of key environmental parameters: climatic differences between northern and southern Europe and differences in tidal range between the Mediterranean/Baltic estuaries and the west coast of Europe. Differences in climate between northern and southern Europe are mainly related to solar radiation, temperature, and duration of the growing season. The tidal ranges found at the study sites on the European west coast are as high as 5 - 7 m (Colne estuary, England and Tagus estuary, Portugal) and as low as 0.2 - 0.3 m in the Kattegat and Mediterranean.

It is necessary to understand the regulation of processes leading to nitrogen removal in order to apply results obtained in one ecosystem to other ecosystems. The role of tidal range is currently addressed mainly by comparing areas with small and large tidal range but also by a more experimental approach in which especially the role of tidal flushing is studied. Climatic effects on nitrogen removal is investigated by comparing the study areas in northern and Southern Europe. Influence of benthic primary producers on nitrogen removal is addressed

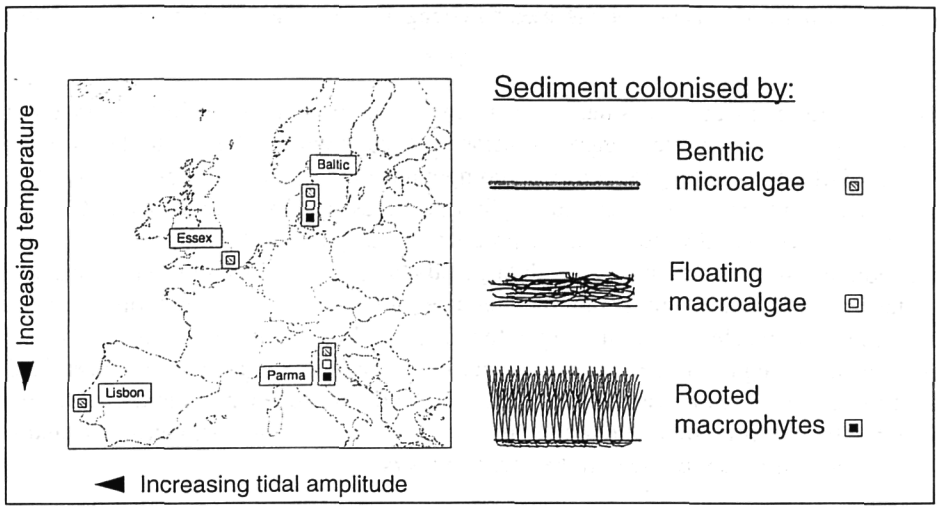


Figure 1: Location of sampling sites and the dominant type of primary producer at each location.

both by comparing areas dominated by different types of organisms and by more detailed experiments.

The project is carried out at four main field sites (Figure 1); a micro and macro tidal site in northern and southern Europe respectively. In the micro tidal sites three functional groups of primary producers are selected: rooted macrophytes, floating macroalgae, and benthic microalgae. Areas dominated by each of these functional groups are studied at both the northern and southern sites, and comparison of results are made for all three groups. The macrotidal sites are dominated by benthic microalgae whereas the other two groups are of very low importance. The study here is hence limited to benthic microalgal communities on the intertidal flats and comparison of results will be made with micro tidal sites dominated by benthic microalgae.

The results will be generalised to describe nitrogen removal in estuaries and coastal waters as a function of tidal range, climate, and type of dominant primary producer. On this basis a classification of coastal waters and estuaries will be established to facilitate the evaluation of the ability of these waters to regulate nitrogen transport from land to open sea.

TASK STRUCTURE OF THE PROJECT

The practical work of the project is divided into five main tasks. In Task 1 the techniques necessary for the other tasks were developed and standardised. After the first 6 months of the project a protocol handbook was produced. This manual contains a detailed description of all methods and calculations to be used in task 4. It furthermore contains a checklist of all the variables to be sampled in task 4 and at what frequency each variable must be sampled.

In Task 2 and Task 3 the effects of benthic primary producers will be investigated in detail. The workform will be a combination of common workshops and each group working experimentally on its own. A workshop focusing on the effects of floating macroalgae will be held in Parma, Italy, in April/May 1998 and a workshop dealing with the effects of benthic microalgae on nitrogen cycling will be held in September 1998 at Tjärnö, Sweden.

Task 4 deals with quantification of nitrogen removal, fluxes, and turnover on an annual scale. A standard program was developed in Task 1 and has since February 1997 been carried out at all four locations (22 sampling stations) throughout an annual cycle. Furthermore, the effects of high tidal amplitude on nitrogen cycling in general and denitrification in particular will be detailed investigated during a workshop in Lisbon, Portugal, in June 1998.

Synthesis of the results from the other workpackages will be made in Task 5. All partners will contribute to this task during workshops, meetings and e-mail and telephone discussions.

Task	Title	Partner responsible
1	Development of techniques	Tage Dalsgaard
2	Influence of benthic microphytes on nitrogen turnover	Kristina Sundbäck
3	Influence of benthic macrophytes on nitrogen turnover	Pierluigi Viaroli
4	Annual cycle of nitrogen turnover and fluxes in European coastal waters: Effects of climate and tidal range	Graham Underwood/ Dave Nedwell
5	Synthesis: Nitrogen cycling in estuaries	Lars Peter Nielsen/ Nils Risgaard-Petersen
6	Coordination	Tage Dalsgaard

Table 1: Task structure of NICE and list of partner responsible for each task.

STATUS

The project started in June 1996. The required technical developments (task 1) have been made and the protocol handbook describing all the methods for task 4 has also been prepared. The sampling for quantification of the annual cycle of nitrogen turnover and fluxes (task 4) will be completed in March 1998, whereas the analysis of samples and data will continue several months after that. The more detailed experiments dealing with the mechanisms by which microphytes (task 2), macrophytes (task 3) and high tidal amplitude (task 4) interact with nitrogen cycling will be initiated very soon.

The results presented in the following are only from task 1 because data from the study of the annual cycle of nitrogen turnover are not ready for presentation yet.

METHODS FOR FLUX AND DENITRIFICATION MEASUREMENTS

Fluxes of O_2, dissolved inorganic nitrogen and N_2O are determined from changes in solute concentration with time in the water overlying the sediment in the incubation system. Denitrification is determined with the isotope pairing technique (Nielsen 1992) and this technique is validated by comparison experiments (Risgaard-Petersen et al. 1997; see below). Flux rates and denitrification are determined both in light and darkness to include any effects of the activity of benthic primary producers on these processes. To improve the comparability of rates measured in light and darkness these measurements are performed sequentially on the same cores. Such paired measurements are, however, only executed when possible. For denitrification measurements in microphytobenthos vegetated sediments a destructive sampling technique is applied and light and dark rates are obtained with parallel cores.

Microphythobenthos colonised sediments
For these types of sediments the standard flux/denitrification incubation system, widely described in literature (e.g. Rizzo 1990; Rysgaard et al. 1995), is used. Sediment cores are incubated in transparent Plexiglas tubes (ID. 8 cm), equipped with transparent floating lids or transparent fixed lids that allow sampling of the overlying water during incubation. Mixing the water column is provided by a Teflon coated magnet mounted inside the cores. The magnet is driven by an external rotating magnet.

Rooted macrophytes
For sediments with rooted macrophytes it has been necessary to develop alternative incubation systems to measure denitrification and fluxes on intact plant-sediment systems.

Large transparent Plexiglas tubes (ID. 20 cm, height 40 cm) are used to obtain a representative sampling of the macrophyte biomass, and to minimise damages of the incubated root-leaf system. The cores are equipped with transparent floating lids, that can be removed when sampling the water overlying the sediment. Mixing of the water column is provided by a water circulation system with an external pump. This setup is chosen instead of the standard magnet stirring system, to avoid that the macrophyte leaves become entangled in the magnet preventing mixing of the water column.

The pumping rate was adjusted to yield a homogenous mixing of the water column and not cause resuspension of sediment. No leaking of gases into or out of the system could be detected.
Fluxes of solutes between the sediment-plant compartment are calculated by linear regression, and linear changes in solute concentrations with time are therefore tested for every incubation performed during task 4.

Examples from typical light - dark incubations are shown in Figure 2. Oxygen concentration increased linearly (r^2 =0.99) during light incubation due to photosynthesis by the plants and decreased linearly (r^2 =0.99) in darkness due to respiration by the sediment-plant community

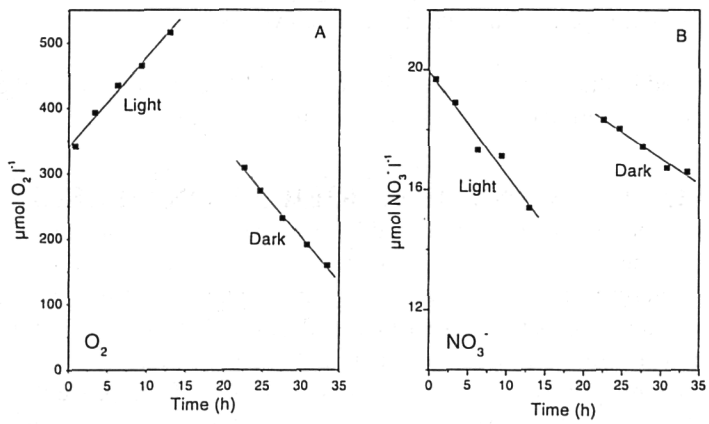


Figure 2. Time series of O_2 (A) and NO_3^- concentrations (B) in the water column of the rooted macrophyte incubation system during a typical paired light-dark incubation

(Figure 2A). Nutrient concentrations also exhibited linear changes during light and dark incubations, as shown in Figure 2B for NO_3^- (Light: $r^2 = 0.96$, dark $r^2 = 0.98$).

Denitrification associated to the sediment surface is estimated with the isotope pairing technique from the production of ^{15}N labelled N_2 species $^{14}N^{15}N$ and $^{15}N^{15}N$. Production of these species are calculated by linear regression, and linear changes in $^{15}N_2$ concentration with time is therefore also for the denitrification measurements tested for every incubation performed during the field study. Examples from typical light - dark incubations (Figure 3) shows that both $^{14}N^{15}N$ and $^{15}N^{15}N$ increase linearly with time (Dark: $r^2 = 0.96$, Light $r^2 = 0.93$, for both $^{15}N_2$ species).

Coupled nitrification-denitrification associated with the rhizosphere of the plants is estimated by a modified version of the isotope pairing technique. It is assumed that the roots release O_2 which can be used for NO_3^- production by nitrifying bacteria. This NO_3^- can undergo denitrification in the anoxic sediment surrounding the roots. To monitor this coupled process $^{15}NH_4^+$ is added to the rhizosphere of intact plant vegetated sediment cores by means of a perfusion technique. The porewater of the cores is drained with a vacuum pump, and ^{15}N enriched NH_4^+ is added. Hereafter the pore water is drawn back into the intact sediment core.

This perfusion process takes <5 min per core and does not cause compaction of the core or channelling of the perfused pore water. For verification, the technique has been tested on three different macrophyte -sediment systems: *Zostera marina, Lobelia dortmanna* and *Litorella uniflora* vegetated sediments (Ottosen et al., 1997). The freshwater amphiphytes *L. dortmanna* and *L. uniflora* both release most of the photosynthetically produced O_2 to the sediment via the roots (Sand-Jensen et al. 1982; Christensen et al. 1994) and both plants stimulate coupled nitrification-denitrification (Risgaard-Petersen et al. 1997; Christensen and Sørensen 1986). *Z. marina* releases most of the O_2 to the water column via the leaves (Sand-Jensen et al. 1982), and therefore poor ability of the plant to stimulate coupled nitrification-denitrification can be expected.

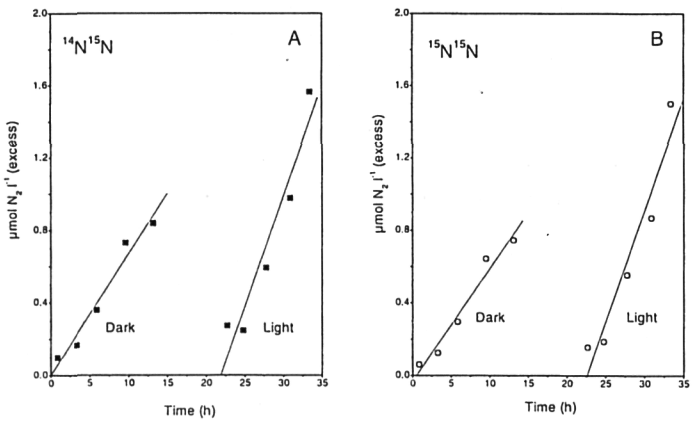


Figure 3. Time series of $^{14}N^{15}N$ (A) and $^{15}N^{15}N$ concentrations (B) in the water column and the sediment of the rooted macrophyte incubation system during a typical paired light-dark incubation

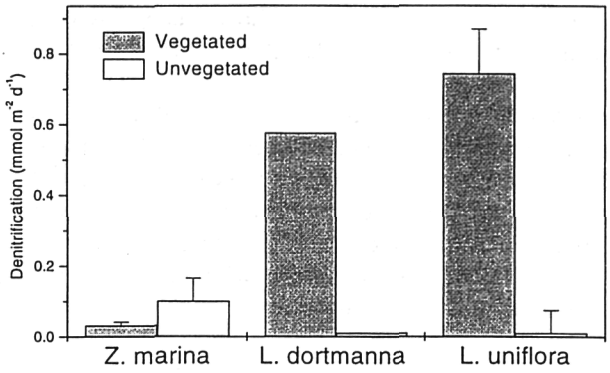


Figure 4. Depth integrated rates of coupled nitrification-denitrification obtained with the $^{15}NH_4^+$ perfusion technique for three different sediment-plant systems:, *Zostera marina*, *Lobelia dortmanna*, and *Litorella uniflora*. Rates are compared with rates obtained on unvegetated sediment sampled in close proximity to the macrophyte beds. Error bars represent SE (n=3). For the *L. dortmanna* vegetated sediment and control n=1.

With the perfusion technique it was possible to detect that presence of *L. dortmanna* or *L. uniflora* stimulates coupled nitrification-denitrification, whereas presence of *Z. marina* had no significant stimulating effect on the process (Figure 4). These findings are in general agreement with current knowledge of plant sediment interactions, and suggest that the technique can be used to estimate the potential for a given rooted macrophyte to stimulate coupled nitrification-denitrification.

Floating macroalgae

The effects of floating macroalgae can not realistically be estimated using standard sediment cores as for the microphytobenthos. Consequently a new incubation system has been developed which allows analysis of the effects of floating macroalgae on fluxes of oxygen and nitrogen species as well as denitrification.

The overall idea for this system is to eliminate the relatively large rim effect that would be in 8 cm ID cores and, furthermore, to change the stirring mechanism of the overlying water to prevent uncontrolled flushing within the mat of macroalgae. The usual stirring mode of sediment cores and flux chambers is circular. In general a central rotating rod creates a circular motion of the water which keeps the water column well stirred. However, the centrifugal force will create a pressure gradient within the chamber with highest pressure along the periphery and the lowest pressure at the centre of the core. A water flow will hence be created from the periphery to the centre of the core. For a core with fine grained sediment this will create a good stirring of the overlying water and there will not be a water flow through the sediment. For a macroalgal mat the situation is different. In for example a *Chaetomorpha* mat around 2 % of the mat is algal mass and the rest is water. The resistance towards convective water movement through the macroalgal mat is hence very low. Consequently water flow through the mat will occur at even very small pressure gradients and uncontrolled and irreproducible convective transport would be the result.

The new system developed for use in NICE is based on a square flux chamber with a stirring system that creates a horizontal flow of water along the surface of the macroalgal mat. This is

obtained by drawing water out through a horizontal slit at one side of the chamber and pumping it back in through an identical slit at the other side. The slits are positioned 1 - 2 cm above the mat. The pumping is set at a rate high enough to keep the water column above the algal mat homogeneously mixed and so low that significant water current through the mat is not induced. This has been verified by addition of dye to the overlying water and following the dispersion of the dye

An example of the data obtained by this system is shown in Figure 5. Here the oxygen flux in light and dark is measured in flux chambers containing sediment covered by 9 cm thick mats of *Chaetomorpha linum* by analysing the change in oxygen concentration with time. The oxygen concentration changes in a sigmoid manner in light (Figure 5A). When light is switched on the amount of oxygen within the mat will begin to increase and the flux out of the mat will not reflect the production within the mat. This will first be the case when the amount of oxygen in the mat has reached a constant level. Therefore an increasing flux out of the mat is seen in the beginning of the incubation. After a while (4 - 5 hours in this case) the formation of oxygen bubbles starts. Since the Winkler technique only detects dissolved oxygen not all the oxygen produced after bubble formation starts will be measured. Consequently the flux rate of dissolved oxygen out of the mat decreases. The best estimate of oxygen production is hence the slope of the fitted third order polynomium at the point where it is steepest. When switched to darkness the mat will start to consume oxygen (Figure 5B). The amount of oxygen within the mat will start to decline and first when the amount of oxygen within the mat is constant the flux from the water into the mat will reflect the oxygen consumption within the mat. In Figure 5B a second order polynomium has been fitted to the data and the slope of this curve after 20 hours is the best estimate of the oxygen consumption within the mat. This experiment was done in October in Limfjorden, Denmark at only 9 °C, which is an unusual situation for this thick macroalgal mats. During most of task 4 the incubation times will be considerably shorter.

Quite often bubble formation in the macroalgal mats in light will begin before the amount of oxygen within the mat has become constant. Even the slope of the steepest part of the curve

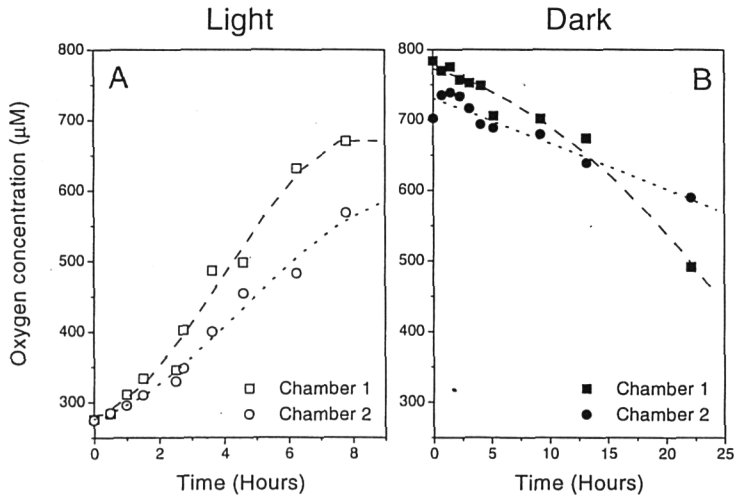


Figure 5. Changes in oxygen concentration with time in flux chambers with sediment covered by 9 cm thick mats of *Chaetomorpha linum*. Dashed and dotted lines represent second (B) third (A) order polynomia fitted to the data

will then be an underestimate of the actual oxygen production. A system to delay bubble formation has been developed. The principle is to remove nitrogen gas from the incubation water, leaving oxygen at air saturation and total CO_2 unchanged. Thereby the total pressure of gases in treated water is ca. 0.2 atm whereas it is ca. 1 atm in untreated water. Bubble formation starts when the total pressure of gases in the water gets significantly above 1 atm. This will obviously take longer time in treated than untreated water and bubble formation is consequently delayed.

METHODS FOR MEASURING PRIMARY PRODUCTION ON MICROPHYTOBENTHOS COLONISED SEDIMENT

The objective was to select a suitable method for primary productivity measurements in undisturbed sediment to be used in the annual study (Task 4). Three methods were available: Percolation of ^{14}C into intact sediment cores (Jönsson 1991), measurement of net photosynthesis as light/dark oxygen flux, and the oxygen microsensor-technique (Revsbech 1989). Two techniques were chosen for the annual study in task 4, i.e. the oxygen flux method and the microsensor technique. Both methods were demonstrated during the workshop for standardisation of methods. The ^{14}C percolation technique was abandoned because it was found not to be applicable to all kinds of sediments, particularly not to cohesive fine sediments. The oxygen flux method, where change in oxygen concentration with time is measured by traditional Winkler titration, has several advantages: (1) Light/dark measurements of both oxygen and nutrient fluxes can be measured in the same cores, thus providing paired data for each core. (2) The method integrates productivity/respiration over the entire sediment surface of the core, while values obtained from oxygen microprofiles are subjected to a larger spatial variation due to micropatchiness. (3) The technique is rapid, reliable and fairly inexpensive. The oxygen microsensors are used to measure profiles of oxygen, from which primary productivity can be calculated according to Fick's first law of diffusion. The intercalibration of the two applicable methods was omitted, as they are not intended to produce comparable results but rather to supplement each other.

Comparison of techniques

The choice of methods for primary production measurements was preceded by two sets of comparisons in 1996. Work carried out at Essex, UK, investigated the comparability of microsensors and ^{14}C incorporation techniques for measuring *in situ* microphytobenthic primary production. Both techniques were found to be comparable at low light levels (< 800 µmol photons m^{-2} s^{-1}), but at higher light levels ^{14}C incorporation underestimated *in situ* benthic primary production (Figure 6). This underestimation was probably due to (a) inability to accurately measure specific isotope activity within the thin photosynthetically active layer of the sediments, (b) difficulties with diffusion of label into the very cohesive sediments (percolation techniques not being suitable for these sediment types), and (c) possible pH-induced shifts in the $CO_2/HCO_3^-/CO_3^{2-}$ equilibrium during high light levels resulting in carbon limitation.

Oxygen flux measurements and $^{14}CO_2$ incorporation was compared by incubating intact sandy sediment cores collected in the vicinity of Tjärnö Marine Biological Station on the Swedish Skagerrak coast in September 1996 (Göransson, 1997). The cores were incubated in the laboratory at *in situ* temperature at a light level of ca 300 µmol photons m^{-2} s^{-1}. On the

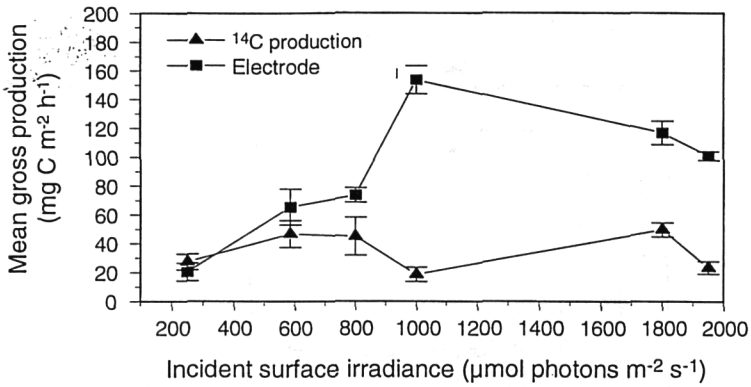


Figure 6. Comparison of ^{14}C and O_2 microelectrodes in cohesive sediments. Mean ± Se, n = 5. (Miles, Underwood & Patterson, unpublished obs.)

whole, the oxygen method gave slightly higher values (mean ± SD = 3.54 ± 1.31 mmol O_2 m^{-2} h^{-1}, n=6), as compared with the ^{14}C -method (3.03 ± 1.13 mmol C m^{-2} h^{-1}, n=5), resulting in a mean photosynthetic quotient (PQ) value of 1.2, which in good agreement with literature values (e.g. Colijn et al. 1983). No statistically significant difference between the two methods was found (ANOVA, p=0.47). However, it must be pointed out that the number of replicate cores was rather low, and the spatial heterogeneity of the sediment high. It is concluded that the $^{14}CO_2$ percolation technique works well in sandy but not in muddy sediments and that it can not be used in task 4.

METHODS FOR MEASURING DENITRIFICATION

The principal method for measuring denitrification in the NICE project is the ^{15}N isotope pairing technique (Nielsen 1992). To evaluate this method we tested it against the two hitherto most commonly used techniques for measuring denitrification , the N_2 flux method (Seitzinger et al. 1980) and the acetylene blockage technique (Sørensen 1978).

The most direct way to measure denitrification is to measure the end-product of the process directly. However, the N_2-flux method is troubled with a number of practical problems. One major problem is the long preincubation time (> 10 days) and the denitrification measured after preincubation does not reflect the *in situ* denitrification. The isotope pairing technique does not have this problem and can be applied in a routine program as task 4. The acetylene technique is only suitable when NO_3^- in the water column is the major source of NO_3^- for denitrification.

Isotope pairing versus N_2 flux

The two methods were compared in the same experimental setup (Risgaard-Petersen et al. 1997). Intact sediment from a freshwater lake was used as test material. We used a continuos flow-through (Figure 7) system that allowed us to maintain constant O_2, NH_4^+ and NO_3^- concentrations in the water above the sediments (n=3). By adding $^{15}NO_3^-$, (200 µM) and eliminating the background N_2 concentrations (< 1.5 µM N_2) in water supplied to the sediments, we could measure the fluxes of $^{28}N_2$, $^{29}N_2$ and $^{30}N_2$ across the sediment water interface with high precision using mass spectrometry. From these fluxes we estimated rates of denitrification with both the N_2 flux method and the ^{15}N isotope pairing technique. This approach ensured that the two methods could be compared directly because the different

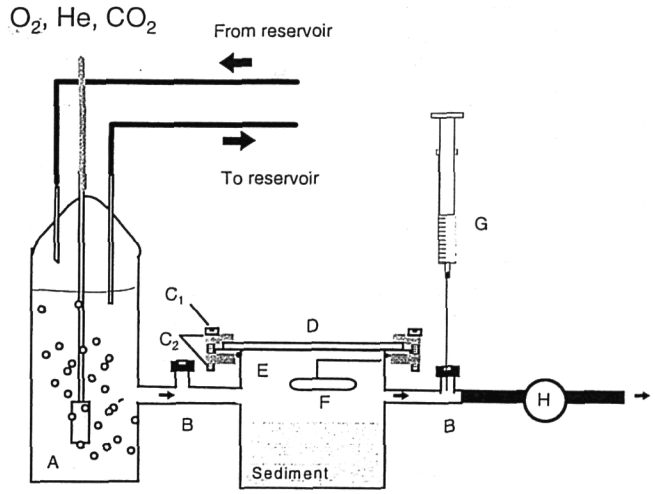


Figure 7: The continuos flow through system. A gas equilibrium chamber (A) holding the inlet water of the chambers is flushed with a well-defined mixture of O_2, He, and CO_2. The gas equilibrium chamber is supplied with water from a reservoir by means of a peristaltic pump. Surplus water and gas is returned to the reservoir. The gas equilibrium chamber is directly connected to the glass incubation-chamber (E) by glass tubes. The incubation chamber is sealed with a glass lid (D) kept in position by a set of flanges (C) where C_1 represents a bolt, and C_2 represent PVC flanges. Water is drawn from the gas-equilibrium chamber through the incubation-chamber by means of a peristaltic pump (H), that is placed after the glass out flow tube of the incubation--chamber. This construction minimised gas exchange with the environment. The overlying water in the incubation chambers is stirred by small Teflon-coated magnets positioned about 3 cm above the sediment surface (F). The small magnets receives momentum from an external rotating magnet (100 r.p.m.). Inflow and outflow sampling ports (B) are placed < 2 cm from the incubation-chambers, thus minimising the disturbing effect of biofilms forming on the tube walls. The sampling ports are sealed with butyl rubber membranes. Water samples can be withdrawn with a glass syringe (G).

methodologies only were reflected in difference in calculation procedure. Raw data were identical and artefacts introduced by differences in experimental setups were thus eliminated.

Fluxes of the three different N_2 species $^{28}N_2$ $^{29}N_2$ and $^{30}N_2$ reached steady state after ~ 26 days of incubation. From these stable fluxes (Table 2) denitrification activity could be calculated. Overall there was a good agreement between the estimates of total denitrification activity obtained by the N_2 flux method and the isotope pairing technique (Figure 8). With the N_2 flux method denitrification was 151 ± 4 μmol N m^{-2} h^{-1} and with the isotope pairing technique denitrification was 149 ± 4 μmol N m^{-2} h^{-1}. Approximately 70% of the denitrification was based on the $^{15}NO_3^-$ added to the water above the sediments. This is calculated directly from the formation of ^{15}N labelled N_2. Denitrification of $^{14}NO_3^-$ is calculated from the formation of $^{29}N_2$ and $^{30}N_2$ using the calculation procedure of the isotope pairing technique (Nielsen 1992). Since the 2 calculation methods match that closely it suggests that the assumptions underlying the isotope pairing technique are valid.

The N_2 flux method as presented in this study presumes that the flux of N_2 across the sediment-water interface is exclusively the result of the denitrification process. This presumption implies that the initial pore water pool of N_2 must be exhausted, or reduced to a level where its diffusive contribution to the N_2 flux from the sediment is insignificant.

Core #	$^{28}N_2$ (μmol m^{-2} h^{-1})	$^{29}N_2$ (μmol m^{-2} h^{-1})	$^{30}N_2$ (μmol m^{-2} h^{-1})
1	6.41	30.69	40.54
2	7.69	30.12	39.47
3	7.67	29.91	34.55

Table 2. Steady state fluxes of $^{28}N_2$, $^{29}N_2$, $^{30}N_2$ across the sediment water interface of the three cores. Data from the last 3 days of sampling, equivalent to 26-31 days of incubation.

We estimated the N_2 flux from the initial N_2 pool, using a numerical solution of Fick's second law of diffusion. When the steady-state was detected after 26 days of incubation the flux of N_2 originating from the initial N_2 pool was < 1 μmol m^{-2} h^{-1}, which is < 2% of the measured total N_2 flux. Thus, the diffusive contribution of N_2 from initial N_2 pool did not seriously affect the denitrification estimates obtained by the N_2 flux method, and we therefore conclude that the method obtained good estimates of the actual denitrification activity in the sediment cores investigated.

The isotope pairing technique, as presented in this study estimates denitrification as the sum of denitrification of $^{14}NO_3^-$ (D_{14}) and denitrification of $^{15}NO_3^-$ (D_{15}) Denitrification of both NO_3^- species is estimated from fluxes of $^{29}N_2$ and $^{30}N_2$ but only D_{15} is estimated directly. The estimate of D_{14} is based on the assumption that $^{28}N_2$, $^{29}N_2$ and $^{30}N_2$ fluxes are ideally binomial distributed. The recovery of D_{14} can be estimated comparing rates of denitrification of $^{14}NO_3^-$ estimated by the isotope paring technique with the actual activity. Assuming that the fluxes of all three N_2 species were the result of denitrification, the actual rate of denitrification of $^{14}NO_3^-$ can be calculated from the fluxes of $^{28}N_2$ and $^{29}N_2$:

$$D_{14} = F^{29} + 2 \times F^{28} \quad (1)$$

Given that rates estimated by Eq. 1 represents the actual D_{14} activity in the sediment cores, a conservative interpretation of our data shows that the isotope pairing technique recovered 92-97% of the actual rate of denitrification of $^{14}NO_3^-$ (Table 3). We therefore conclude that the technique obtained realistic estimates of the actual denitrification activity in the sediment core

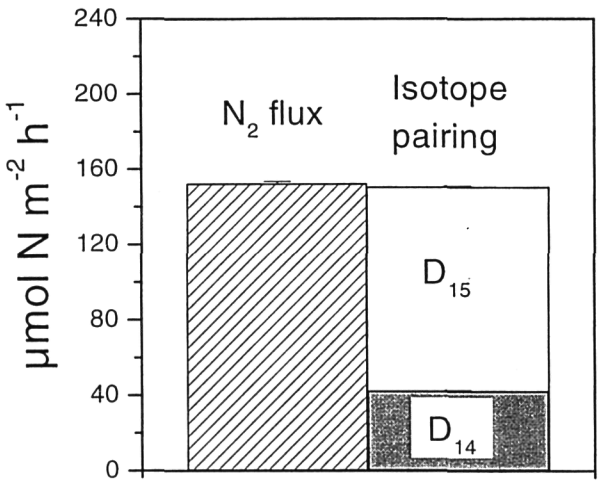


Figure 8. Denitrification of $^{14}NO_3^-$ and total denitrification as measured by the ^{15}N isotope pairing and the N_2 flux method. Error bars represent SE (n=3). D_{14} denotes denitrification of $^{14}NO_3^-$ and D_{15} denotes denitrification of $^{15}NO_3^-$.

Core #	F_{28} µmol N_2 m^{-2} h^{-1}	F_{28} estim µmol N_2 m^{-2} h^{-1}	D_{14} real µmol N m^{-2} h^{-1}	D_{14} µmol N
1	6.41	5.81	43.51	42.30
2	7.69	5.75	45.50	41.61
3	7.67	6.48	45.26	42.82

Table 3: Measured $^{28}N_2$ fluxes (F_{28}) and fluxes of $^{28}N_2$ estimated from the $^{29}N_2$ and $^{30}N_2$ fluxes (F_{28} estim). Denitrification rates of $^{14}NO_3^-$, measured from $^{28}N_2$ and $^{29}N_2$ fluxes (Eq. 1) (D_{14} real), and the rate of denitrification of the same NO_3^- species estimated with the isotope pairing technique (D_{14}).

investigated.

^{15}N isotope pairing versus acetylene inhibition

The two methods were compared in parallel cores incubated in triplicate (Bartoli et al. unpublished.) Sediments from 3 different types of benthic community were used as test material. These types were microphytobenthos colonised sediment, sediments with macroalgae, and sediments with rooted macrophytes. Standard procedures for the isotope pairing technique (Nielsen 1992), and the acetylene inhibition (Sørensen 1978) technique were used.

The isotope pairing technique obtained highest estimates of denitrification for all sediment types investigated (Figure 9). The largest difference between denitrification estimates obtained with the isotope pairing technique and the acetylene inhibition technique were observed for the microphytobenthos colonised sediment.

On all stations investigated the acetylene inhibition technique obtained lower estimates of denitrification than the ^{15}N isotope pairing technique. Lohse et al. (1996) obtained similar results on sediment sampled in the North sea. The acetylene inhibition technique may underestimate denitrification due to incomplete inhibition of N_2O reductase (Kaspar 1982). Furthermore C_2H_2 inhibits nitrification (Walter et al. 1979), and NO_3^- diffusing into the sediment from the overlying water is the only source feeding the process. If NO_3^- from

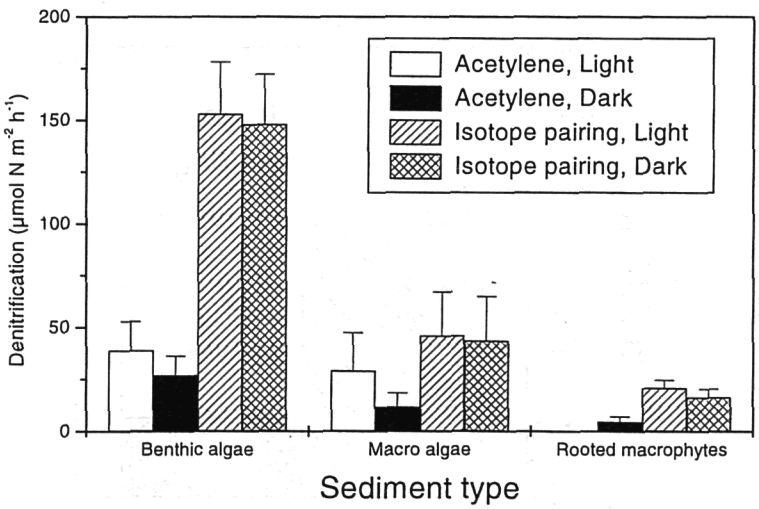


Figure 9. Denitrification estimates obtained with the acetylene inhibition method and the isotope pairing technique at three different localities. Error bars represent SE (n=3).

sedimentary nitrification is a significant source for denitrification *in situ*, the method will therefore underestimate the activity.

The high similarity between rates obtained with the isotope pairing method and the N_2 flux method validates the isotope pairing technique, and justify the use of this method within the NICE project. The acetylene inhibition technique underestimates denitrification activity and the method is therefore not acceptable within the project.

CONCLUSION

In a study like this it is crucial that measurements done by all involved laboratories are directly comparable. We have therefore devoted much work to developing, testing and standardising the techniques. All this has been described in detail in a Protocol Handbook which is the basis of all sampling and analysis in all the involved laboratories. The chemical analysis following each sampling round are quite extensive and will first be finished a few months after the final sampling in task 4. Data analysis will last another few months and the database containing all data from the annual study will be ready at the end of 1998.

REFERENCES

Colijn, F., Gieskes, W. W. C. and W. Zevenboom (1983). The measurement of primary production: Problems and recommendations. Hydrobiological Bulletin, 17, 29-51.

Christensen, P. B., N. P. Revsbech, and K. Sand-Jensen (1994). Microsensor analysis of oxygen in the rhizosphere of the aquatic macrophyte *Litorella uniflora* (L.) Ascherson. Plant Physiol 105: 847-852.

Christensen. P. B. and J. Sørensen (1986). Temporal variation of denitrification activity in plant covered littoral sediment (Lake Hampen, Denmark). Appl. Environ. Microbiol. 51:1174-1178.

Göransson, E. (1997). Nontidal microphytobenthos: Aspects of movement behaviour and primary productivity measurements. MSc. thesis, Göteborg University, 13 p., 10 appendices.

Jönsson, B. (1991). A ^{14}C-incubation technique for microphytobenthic primary production in intact sediment cores. Limnology and Oceanography, 36, 1485-1492.

Kaspar H.F. (1982). Denitrification in marine sediments: measurements of capacity and estimate of in situ rates. Appl. Environ. Microbiol 43: 522-527.

Lohse, L., H. Kloosterhuis, W. van Raaphost and W. W. Helder (1996). Denitrification rates as measured by the isotope pairing method and by the acetylene inhibition technique in continental shelf sediments of the North Sea. Mar. Ecol. Prog. Ser. 132: 169-179.

Nielsen, L. P. (1992). Denitrification in sediments determined from nitrogen isotope pairing. FEMS Microbiol. Ecol. 86: 357-362.

Ottosen L. M., N. Risgaard-Petersen, L. P. Nielsen (1997). Rhizosphere denitrification in *Zostera marina* vegetated sediments. Manuscript.

Revsbech, N. P. (1989). An oxygen microelectrode with a guard cathode. Limnology and. Oceanography 34, 474-478.

Risgaard-Petersen, N. and K. Jensen (1997). Nitrification and denitrification in the rhizosphere of the aquatic macrophyte Lobelia dortmanna (L). Limnol. Oceanogr. 42:529-537.

Risgaard-Petersen N., S. Rysgaard, L. P. Nielsen & N. P. Revsbech (1994). Diurnal variation of denitrification and nitrification in sediments colonized by benthic microphytes. Limnol. Oceanogr. 39:573-579.

Rizzo, W. M. (1990). Nutrient exchanges between the water column and a subtidal benthic microalgal community. Estuaries 13: 219-226.

Rysgaard, S., P.B. Christensen and L. P. Nielsen (1995). Seasonal variation in nitrification and denitrification in estuarine sediment colonised by benthic microalgae and bioturbating infauna. Mar. Ecol. Prog. Ser. 126: 111-121.

Sand-Jensen, K., C. Prahl, and H. Stokholm (1982). Oxygen release from roots of submerged aquatic macrophytes. Oikos 38: 349-354

Seitzinger, S. P. (1988). Denitrification in freshwater and coastal marine ecosystems: ecological and geochemical significance. Limnol. Oceanogr. 33:702-724.

Seitzinger, S., S. Nixon, M.E.Q. Pilson and S. Burke (1980). Denitrification and N_2O production in near-shore marine sediments. Geochim. Cosmochimica Acta 44: 1853-1860.

Sundbäck, K., V. Enoksson, W. Granéli & K. Petterson (1991). Influence of sublittoral microphytobenthos on the oxygen and nutrient flux between sediment and water: A laboratory continuos-flow study. Mar. Ecol. Prog. Ser. 74:263-279

Sørensen, J. (1978). Denitrification rates in a marine sediment as measured by the acetylene inhibition technique. Appl. Environ. Microbiol 36: 1979

Walsh, J. J., G. T. Row, R. L. Iverson & C. P. McRoy (1981). Biological export of shelf carbon is a sink for the global CO_2 cycle. Nature 291:196-203.

Walter, H. M., R. D. Keeney, and I.R. Fillery (1979). Inhibition of nitrification by acetylene. Soil Sci. Soc. Am. J. 43: 195-196.

TITLE: Dynamics of Matter Transfer and Biogeochemical Cycles: Their Modelling in coastal systems of the Mediterranean Sea (project: METRO-MED)

CONTRACT NO: MAS3-CT960049

COORDINATOR:
Dr. Chr. Anagnostou
National Centre for Marine Research (NCMR)
Institute of Oceanography
Agios Kosmas
GR-16604 ELLINIKO - ATHENS, GREECE
E-mail: chanag@erato.fl.ariadne-t.gr

PARTNERS:

Jean-Yves Bottero
Laboratoire des Géosciences
de l' Environnement
URA 132 CNRS,
C.E.R.E.G.E., Europole Méditerrannéen
de l' Arbois, BP 80
F-13545 AIX EN PROVENCE Cedex 4
Tel.no: +33 4 42 97 15 00
Fax.no: +33 4 42 97 15 40
E-mail: bottero @cerege.fr

Danielle Marty
Microbiologie Marine, CNRS UPR 223
Campus de Luminy, Case 907
163, Avenue de Luminy
F -13288 MARSEILLE Cedex 9
Tel.no.: +33 4 91 82 90 53
Fax.no.: +33 4 91 82 90 51
E-mail: marty@luminy.univ-mrs.fr

Xavier Durrieu de Madron
Laboratoire de Sedimentologie et
Géochimie, Marines,
URA CNRS 715,
Université de Perpignan
52, Avenue de Villeneuve
F -66860 PERPIGNAN Cedex
Tel.no.: +33 4 68 66 20 91, 68 66 20 19
Fax.no.: +33 4 68 66 20 96
E-mail: demadron@univ-perp.fr

Carl - Dieter Garbe-Schoenberg
Geologisch - Paläontologisches Institut
Christian - Albrechts - Universität zu Kiel
Olshausenstrasse 40
D - 24098 KIEL
Tel.no.: +49 4 31 88 02 688
Fax.no.: +49 4 31 88 04 376
E-mail: dgs@zaphod.gpi.uni-Kiel.de

Michael Collins
Department of Oceanography
University of Southampton,
European Way,
SOUTHAMPTON HAMPSHIRE,
SO14 3ZH, UK
Tel.no.: +44 17 03 59 27 86
Fax.no.: +44 17 03 59 30 59
E-mail: mbc@southampton.ac.uk

Claude Estournel
Laboratoire d' Aérologie,
U.M.R. CNRS/UPS 5560
Université Paul Sabatier
14, Avenue Edouard Belin
F- 31400 TOULOUSE
Tel.no.: +33 5 61 33 27 75
Fax.no.: +33 5 61 33 27 90
E-mail: estc@aero.obs-mip.fr

Josep-Maria Gili
Instituto de Ciencias del Mar / CSIC
Paseo Juan de Borbón s/n
E-08039 BARCELONA
Tel.no.: +343 221 64 16
Fax.no.: +343 221 73 40
E-mail: gili@cucafera.icm.csic.es

Helen Karamanos
Institute of Geology and
Mineral Exploration
I.G.M.E., Thessaloniki branch
Fragon1 - Moskof 10
GR-54626 THESSALONIKI
Tel.no.: +30 31 51 73 93, 54 37 38
Fax.no.: +30 31 51 70 71

Michel Albuisson
Centre d' Energétique, Armines
Ecole des Mines de Paris
BP 207
F-06904 SOPHIA ANTIPOLIS Cedex
Tel.no.: + 33 4 93 95 74 04
Fax.no.: +33 4 93 95 75 35
E-mail: albuisson@cenerg.cma.fr

Marie-Hélène Tusseau
Institut de Biogéochimie Marine,
CNRS DR1
1, rue Maurice Arnoux
F -92120 MONTROUGE
Tel.no.: +33 1 40 96 61 98
Fax.no.: +33 140 96 6199
E-mail: marieln@gironde.ens.fr

Jack Middelburg
Netherlands Institute of Ecology,
Centre for Estuarine and Coastal Ecology
P. O. Box 140
NL-4400 AC YERSEKE
Tel.no.: +31 113 577 476
Fax.no.: +31 113 573 616
E-mail:
Jack.Middelburg@cemo.nioo.knaw.nl

Olivier Raillard
CETIIS
Aix Metropole
BAT. D
30, av. Malacrida
13100 AIX-EN-PROVENCE
Tel.no.: +33 4 42 93 65 14
Fax.no.: ++33 4 42 93 65 15
E-mail: olivier@cetiis.fr

François Lusseyran
Laboratoire d' Energétique et de
Mécanique Théorique Appliquée
URA 875
2, Avenue de la Fôret de Haye
F-54516 VANDOEUVRE LES NANCY
Tel.no.: +33 83 59 56 28
Fax.no.: +33 83 59 55 31
E-mail: flussey@ensem.u-nancy.fr

Jean Claude Block
Laboratoire Santé et Environnement
Université Henri Poincaré Nancy I,
Faculté de Pharmacie
5, rue Albert Lebrun, B.P. 403
F-54001 NANCY Cedex
Tel.no.: +33 83 17 88 00
Fax.no.: +33 83 32 30 58
E-mail: block@pharma.u-nancy.fr

Patricia Bonin
Centre d' Océanologie de Marseille
Campus de Luminy. Case 901
F-13288 MARSEILLE Cedex 9
Tel.no.: +33 4 91 82 93 36
Fax.no.: +33 4 91 82 65 48
E-mail: P.bonin@com.univ-mrs.fr

François Nyffeler
Limnocéane, Institute of Geology,
University of Neuchâtel
11, rue Emile Argand
CH- 2007 NEUCHATEL
Tel.: ++41 327 30 46 65
Fax: ++41 327 30.31.50
E-mail: francois.nyffeler@geol.unine.ch

DYNAMICS OF MATTER TRANSFER AND BIOGEOCHMEMICAL CYCLES: THEIR MODELLING IN COASTAL SYSTEMS OF THE MEDITERRANEAN SEA METRO-MED

CH. ANAGNOSTOU

National Centre for Marine Research (NCMR)
Institute of Oceanography
Agios Kosmas
GR-16604 Elliniko - Athens, Greece

SUMMARY

The project ***METRO-MED (Dynamics of Matter Transfer and Biogeochemical Cycles: Their Modelling in Coastal Systems of the Mediterranean Sea)*** aims to ***study*** and ***model*** the key processes of matter transfer (exchange and storage) and the biogeochemical cycles in the coastal zone system. It started on the 1st of August 1996 and runs for 18 months. The tasks of the project are described in this contribution. while the first results of the project are presented.

1. INTRODUCTION - THE OBJECTIVES OF THE PROJECT

The coastal zone with its significant compartments and their intensive interactions forms a complicated environmental system. It is a need to understand processes which take place in this zone, processes in the boundary zone of the terrestrial fluxes and in the mixed zone, processes of the matter transfer in the water column, processes in the sediment / water interface (Fig. 1).

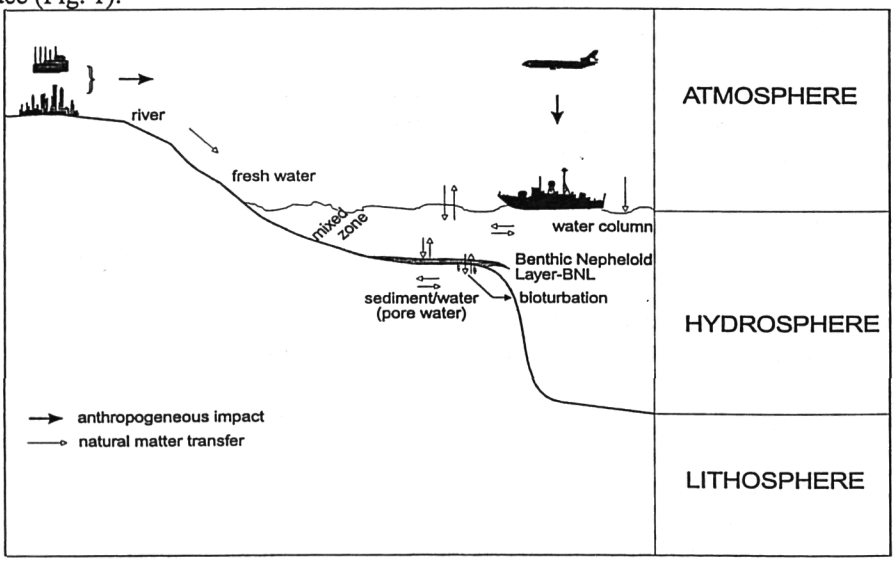


Fig. 1: The compartments of the coastal environment, the exchange of matter and the fluxes of natural and anthropogenic matter.

Particles can enter into the coastal systems through the following pathways (Fig. 2)
a) through the atmosphere as **eolian particles,**
b) through the rivers as **riverine particles,**
c) through the **hydrothermal** activity from the earth interior as **hydrothermal matter.**
Another important particle source for the marine ecosystem are the biological processes which lead to the production of **marine biogenic particles.** Additionally, the biological processes, especially the biological production, play an important role for the vertical particle flux in marine ecosystem, determines the **biogeochemical cycles.**

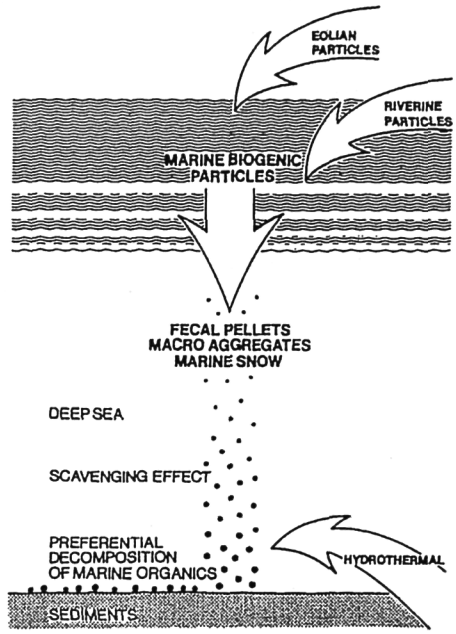


Fig. 2: Particles sources and transfer in the marine environment (from ITTEKKOT & HAAKE, 1990)

The particles during their sinking into the water column and the seafloor are underlied to decompositional processes, mainly through **bacterial activity.** This consists the main mechanisms controlling the **element cycling** and the **element balances.** The dynamic of the matter transfer in the coastal systems is one important mechanism for the carbon cycling especially regarding the **global changes.** The sediment particles in the different subbottom layers content information about the palaeoenvironment evolution and the climatic changes in the past.
In this context, it seems to be important to understand:

- the role of the adjacent land area, as a supplier of the marine system,
- the biological production and especially the dynamic of the C, N, P cycles,
- the physicochemical processes of flocculation and aggregation mechanisms in the different stages of the mixed zone fresh / salt water,
- the biogass production,
- the processes of the transfer of suspended matter,
- the sediment-water interaction and especially the resuspension processes and
- finally how to model all these processes.

These make up the objectives of the METRO-MED project. The investigations take place in two sites in the Mediterranean Sea, Gulf of Lions and Thermaikos Gulf (Fig. 3). Gulf of Lions and Thermaikos Gulf have, as ecosystems, similarities and differences. Comparative studies win a great importance since they give a more general understanding of the functioning of the coastal systems and they offer the opportunity for the development of scientific concepts in a wider dimension.
For the implementation of these scientific objectives, conventional methods and equipment advanced techniques for laboratory and field experiment, new observational and sample technology are used. In fixed stations, data are collected, ships are used for the collection of the environmental data and samples. Long-term systems (current meters and sediment traps) are used for the current measurements and the collection of samples of the suspended particulate matter. Advanced technology with in situ measurements, together with the use of bottom mounted tripods is used for the study of the benthic resuspension processes.

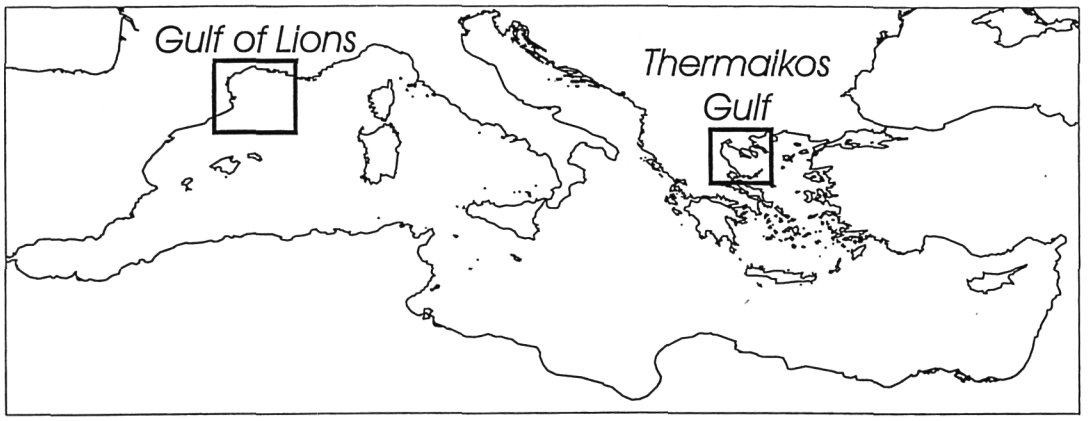


Fig. 3: Investigation areas in the framework of METRO-MED project

For the study of coagulation - flocculation - sedimentation rates under different bio-physico chemical conditions, referring to the mixed River Estuarine Coastal zone, batch reactor experimental approach is done. Biological experiments are carried out in order to approach the role of the suspension - feeders and deposit feeders. Biogass production processes are studied in order to contribute to the actualistic item of the global changes.

The knowledge produced through the project responds with a significant contribution:

- to the determination of the role of the coastal zone in the **land-ocean interaction**, in the perspectives of **global change** (carbon cycle),
- to the determination of the regional consequences of **human impact** in the coastal zone (nutrients and elemental cycles),
- to the formulation of a strategic plan for the **management of the coastal zone**, on the concept of the **Sustainable Development**,
- to the promotion of the development of a **European scientific infrastructure** for the coastal zone research and the data management, data base, modelling, GIS applications.

2. TASK STRUCTURE OF THE PROJECT

The project comprises of five main tasks, subdivided in subtasks, as following:

TASK 1: The processes of matter transfer in the fresh/salt water interface.

Subtask 1.1. The adjacent land area and its potentiality for the fresh water, sediment and pollutants supply.

Gulf of Lions: *Collection of existing data*

Thermaikos Gulf : *Collection of existing data, field work and sample analyses*

Subtask 1.2. The biological production in the fresh/salt water interface.

Gulf of Lions: *Collection of existing data, field work and laboratory analyses*

Thermaikos Gulf: *Collection of existing data, field work and laboratory analyses*

Subtask 1.3. Physico-chemical processes in the fresh/salt water interface.

Experimental work-Field Approach-Gulf of Lions and Thermaikos Gulf

Subtask 1.4. The production of biogases in the fresh/salt water interface.

Gulf of Lions and Thermaikos Gulf: *Field Measurements and Laboratory analyses*

Subtask 1.5. Modelling of the matter transfer in the fresh/salt water interface.

TASK 2: The transfer of suspended particulate matter and the resuspension processes in the shelf environment.

Subtask 2.1. The transfer of suspended particulate matter.

Gulf of Lions: *Evaluation of existing data and complementary field work*

Thermaikos Gulf: *Collection of existing data and field work*

Subtask 2.2. Biological production - biological activity in the shelf environment.

Thermaikos Gulf: *Collection of existing data and field work*

Experimental work: *Suspensivor organisms*

Subtask 2.3. The resuspension processes.

Gulf of Lions: *Field and laboratory work*

Thermaikos Gulf:*Collection of existing data and field work*

Subtask 2.4. Modelling of particulate transport on Mediterranean continental shelves

TASK 3: Biogeochemical Cycles

Subtask 3.1. High resolution circulation model of the Gulf of Lions.

Gulf of Lions: *Modelling based on existing data*

Subtask 3.2. Biogeochemical water column model of the Gulf of Lions.

Gulf of Lions: *Modelling based on existing data, complementary laboratory work*

Subtask 3.3. Sediment early diagenesis model.

Gulf of Lions: *Modelling based on existing data*

Subtask 3.4. Coupling of the hydrodynamical, biogeochemical water column and sediment models.

TASK 4: Data management , GIS, socio-economic approach.

Subtask 4.1. Data management and data quality

Subtask 4.2. Implementation of GIS techniques

Subtask 4.3. Trial of a socio-economic approach

TASK 5: Synthesis and integration of results of mechanistic modelling, prognostic modelling and field and laboratory measurements - Feasibility assessment of model transfer.

3. REVIEW OF THE PRELIMINARY RESULTS OF THE PROJECT

3.1 Introduction

This chapter includes the preliminary scientific results of a common trial to understand in wider dimensions the dynamics of matter transfer and the biogeochemical cycles in the coastal systems, which trial takes place in the frame of the MAST-III-ELOISE - European Union project "METRO-MED".
The present contribution is based on the **First Annual Scientific Report** of the project.
The presentation of the preliminary results is diverged, not substantially, from the structure of the Tasks and Sub-tasks of the project, in order to achieve a more coherent scientific work, and is structured as following:

- Matter transfer and biogeochemical fluxes in the Gulf of Lions (Study of processes, modelling of processes).
- Matter transfer in the Thermaikos Gulf (Study of processes, modelling of processes).
- Experimental part (physico-chemical processes in the fresh / salt water interfaces, production of biogasses, suspensivor organisms in energy transfer processes).
- Management of the results of the project.

3.2 Matter transfer and biogeochemical fluxes in the Gulf of Lions

Study of processes

Setting of the study area: The Gulf of Lions (Fig. 4) a region of 1.7 x $10^4 km^2$, located in the north-western Mediterranean represents a wide, progressive margin with a crescent-shaped continental shelf. The continental slope is heavily incised by numerous submarine canyons, descending to the flat Algero-Balearic basin.
The mechanism of the matter transfer and the biogeochemical cycles in the Gulf of Lions depositionnal system are controlled to a great extent by **topography, sediment supply, water circulation, biological production** and **biological activity** as well as by the **processes related to the bio-physico-chemical behaviour of the suspended particulate matter.**

The adjacent land area and its potentiality for the fresh water, sediment and pollutants supply (DURRIEU DE MADRON, 1997): The drainage area that influences the marine environment of the Gulf of Lions has an extension of 125,202 km^2 from which the drainage system of the Rhone river covers an area of 97,800 km^2 (78,1% of the whole drainage area). Geologically the drainage area consists of the alpidic formations and the climate of this part is continental. Approximately the 90% of the total fresh water discharge is supplied from the Rhone river (mean annual water discharge 1,700 m^3/s^{-1} for the Rhone, total discharge 2,013 m^3/s^{-1}). The rivers are the dominant source of terrestrial particles for the Gulf of Lions continental shelf. Approximately the 90% or $620x10^6$ Ty^{-1} of the total particles discharge ($6.24x10^6$ Ty^{-1}) are coming to the sea by the Rhone river (DURRIEU DE MADRON, 1997). The particles discharge underlies irregular seasonal variation. It is important to mention that the solid discharge decreased after 1960 by a factor two. Additionaly a very large spectrum of pollutants (heavy metals and organic pollutants) reach the marine environment through the river transport.

The Rhone delta is characterised by a strong and rapid trapping of particulate terrigenous material near the river mouth, so that only a small amount of riverborn particles finally escape to the open Mediterranean sea via a nepheloid layer.

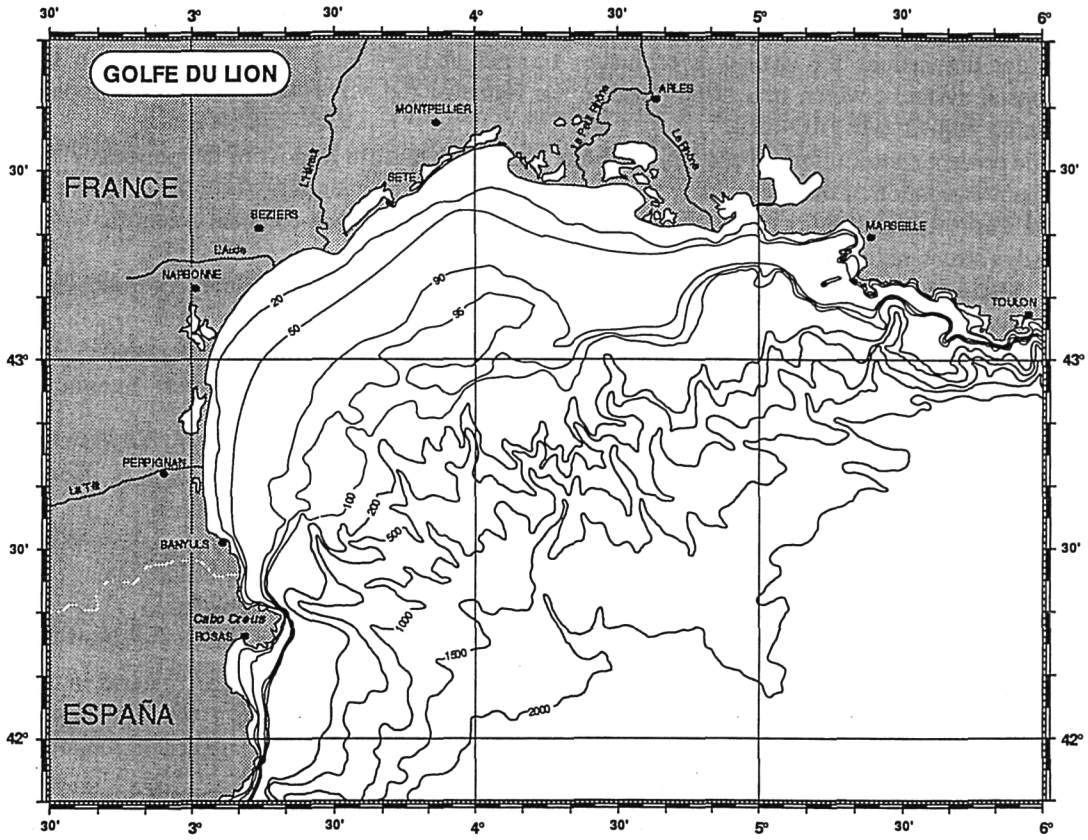


Fig. 4: Submarine morphological characteristics of the Gulf of Lions.

The biological production (RAIMBAULT & COSTE, 1997): The fresh / salt water zone of the Rhone river is an important zone for the biological production of the whole coastal system of the NW Mediterranean sea. Nitrate concentrations fluctuate between 50-160 µM and phosphate between 1-5 µM. The primary production of the system ranged from 295 to 513 $mgcm^{-2}d^{-1}$ and the new production is ranging form 10 to 80 nmoles l^{-1} d^{-1} (RAIMBAULT & COSTE, 1997).

The transfer of suspended particulate matter (NYFFELER, 1997; DURRIEU DE MADRON, 1997b). Water masses and hydrodynamic processes are the predominant factors controlling the particle transport. The water masses are stratified from spring to autumn. During wintertime, no stratification occurs. The most important feature is a cyclonic circulation (northern current) that follows the continental slope, from the coast of the Provence to the Catalonian Sea. Hydrodynamic phenomena are also induced by regional winds, on different space and time scales. The yearly deposition rate of matter and carbon was estimated for each sedimentary province as follows:

	Rhone prodelta	*Mid shelf mud belt*	*Outer shelf*
Mass	$> 2 \cdot 10^6$ Ty^{-1}	$8 \cdot 10^6$ Ty^{-1}	$4 \cdot 10^6$ Ty^{-1}
Organic Carbon	$4 \cdot 10^4$ Ty^{-1}	$6 \cdot 10^4$ Ty^{-1}	$2 \cdot 10^4$ Ty^{-1}
Inorganic Carbon	$0{,}8 \cdot 10^5$ Ty^{-1}	$3 \cdot 10^5$ Ty^{-1}	$1{,}6 \cdot 10^5$ Ty^{-1}

(Table constructed after the data of DURRIEU DE MADRON (1997b)).

Downflux of particulate matter, measured by sediment traps shows the following.

	Western slope	*Eastern slope*
Annual mass	$4{,}4 \cdot 10^6$ Ty^{-1}	$0{,}8 \cdot 10^6$ Ty^{-1}
Organic Carbon	$8 \cdot 10^4$ Ty^{-1}	$2 \cdot 10^4$ Ty^{-1}
Inorganic Carbon	$1{,}6 \cdot 10^5$ T y^{-1}	$0{,}3 \cdot 10^5$Ty^{-1}

(Table constructed after the data of DURRIEU DE MADRON (1997b)).

The surficial sediments over the shelf are distributed irregularly and display the following distribution : littoral sand mainly due to river input, large mud depocenters in front of river mouths and mid-shelf mud deposits between 50 and 70 m. From 80m to the shelf break the outer shelf is covered with relict sands deposited during the latest transgression.

The rususpension processes in the Gulf of Lions: The processes that lead to the establishment of near-layer in the sediment water interface with a high concentration in suspended matter, formed the so-called Benthic Nepheloid Layer (BNL), are studied with a specially designed mixing-box based on the properties of turbulence generated by an oscillating grid (DURRIEU DE MADRON, 1997c). The turbulence depends on various parameters. There are indications that the relation between the root mean square (rms) turbulence and the sediment deposition velocity can control the load in suspension.

Modelling

Modelling of matter transfer in the fresh / salt water interface (ESTOURNEL & MARSALEIX, 1997): In order to model a river plume region, it is necessary to develop a 3D model. This model takes into account processes specific to the particles transport and sedimentation in the water column and on the bed and resuspension of the sediment. To achieve this goal, comparison (validation) is made with data, coupling of the 3D model with a parameterization of the combined wave / current interaction as well as simulations in terms of bottom shear stress.

Modelling of particulate transport on continental shelves (Gulf of Lions) (NYFFELER, 1997b): The questions concerning this approach cover extended space and time scales, from the local resuspension processes up to the seasonal, annual or even secular period.

Modelling marine circulation of the Gulf of Lions (RAILLARD, 1997): On a hydrodynamic point of view, the Gulf of Lions can be considered as a very complex region, where several intense and highly variable phenomena interact:

I. the strong powerful Northern Current, which generally flows along the continental margin but can also penetrate into the continental shelf,
II. the dense water formation located both on the shelf and offshore,
III. the high energy movement associated to the frequent strong wind events.

Numerical models are quite powerful tools to understand the functioning of such a complex system. Embedding the Gulf of Lions model in the low resolution General Circulation Model allows a better resolution of the mesoscale activity inside the Gulf. The speed and the variavility of the Northern Current are described in a more realistic way. In particular results obtained by this approach show quite good agreements with the *in situ* observations. The model simulates strong temperature gradients as well as the formation of a anticyclonic eddy, which is a well-known feature of the Gulf of Lions.

Biogeochemical model of the Gulf of Lions (GUIEU & TUSSEAU, 1997): The aim of this trial is to describe the main interactions between phytoplankton and trace metals in the water column of the Gulf of Lions and to include these results into a biological model. The work is still in progress.

Sediment early diagenesis model (SOETAERT, MIDDELBURG, HERMAN & HEIP, 1997): In the benthic compartments the important exchange processes include sedimentation of matter, in particular organic matter, and the consumption of oxygen and regeneration of nutrients by the sediments. It is aimed to model these processes with the use of the Yerseke diagenetic model.

Coupling of the hydrodynamical, biogeochemical and sediment models in the Gulf of Lions (MORTIER & TUSSEAU, 1997): The biogeochemical transformations occuring on the coastal zones involve complex biogeochemical and physical interactions, for which coupled models provide a useful studying tool. This approach is needed in order to quantify, at the seasonal and annual scale, not only the internal biogeochemical functioning of the coastal zone, but also its exchanges with the open sea.
Concerning the spatial distribution of nitrate and phytoplankton, the model predicts that the spring bloom starts in early March in surface waters and lasts about one month, progressively settling down. Very low surface biomass levels are predicted during summer, as nutrients have been exhausted. The autumnal thermocline erosion allows nutrients to rise into the upper layer and in some cases induce a secondary bloom, often less extended than the spring one.
Concerning the annual budgets it is rather difficult to estimate an annual mean primary production for a complex area like the Gulf of Lions. However, the annual primary production estimated by the model (76 C m^{-2} y^{-1}) fits quite well with most of the observations.

3.3 The Matter transfer in the Thermaikos Gulf

Study of processes

Setting of the study area: *Thermaikos Gulf* (Fig. 5) forms the **NW Aegean continental shelf** and because of morphologically even and low sea bed gradient is referred as Thermaikos plateau too. A relatively steep continental slope leads to the *Sporadhes basin.*
Important factors controlling the mechanism of the matter transfer and the biogeochemical cycles in this area are the rivers as water and sediment suppliers, the water circulation, the biological production.

The role of the adjacent land area as fresh water, sediment and pollutants supplier (SKOULIKIDIS & KARAMANOS, 1997): The drainage area that influences the marine

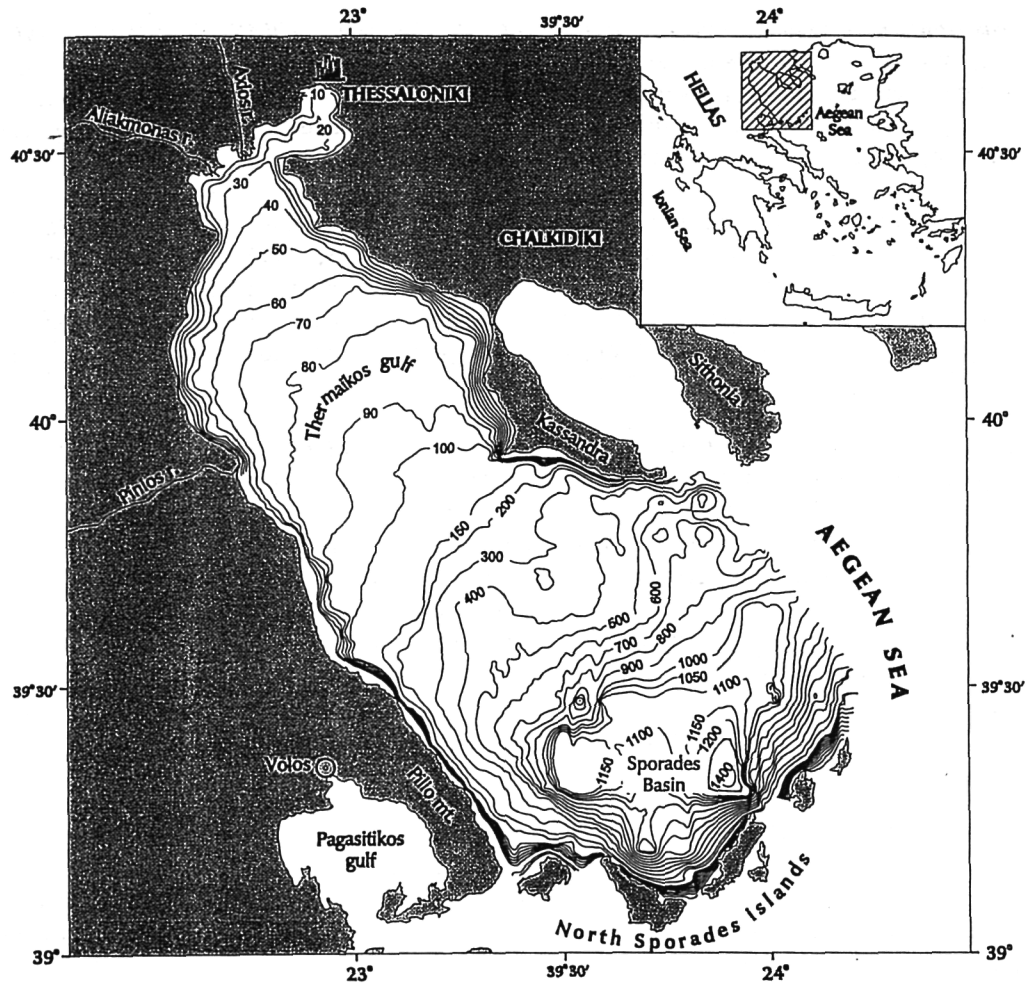


Fig. 5: Digital bathymetric map of the NW Aegean Sea, produced during METRO-MED project cruises (unpublished data)

environment of Thermaikos Gulf is very extensive. Geologically the drainage area consists of alpidic formations and the climate of this area is more continental.
Three very important rivers ***Aliakmon, Axios, Pinios*** and two smaller, ***Loudias and Gallikos,*** discharge to the Thermaikos plateau with a significant suspended sediment supply. The total annual sediment supply of the area is 3-4 10^6 ton/year.

Water-Mass characteristics and circulation patterns (KONTOGIANNIS & PAPADOPOULOS, 1997): In the Thermaikos Gulf there is a well-defined and slowly-moving anticlockwise water circulation over the entire area. Water masses consisting of both saline and relatively dense waters enter from southeast; they flow to the northwest, along the east coast and towards the inner gulf. Fresh (less saline) waters emanating from the *Axios, Aliakmon* and *Pinios* rivers move south-southeast along the western part of the gulf. In this way, under the influence of the winds from the north, which are dominant over the region, domestic, agricultural and industrial effluents reach the entrance of Thermaikos Gulf to the south. The structure of the water column is seasonally stratified.

Distribution of dissolved oxygen and nutrients (PAVLIDOU & KRASAKOPOULOU, 1997): The water masses of the study area have significant chemical signatures, the fresh water from the rivers and the saline waters from the open sea (Aegean sea). The fresh water is characterized by high values of nutrients and dissolved oxygen. The chemical data also reaveals the presence of the cyclonic gyre in the eastern part of the study area.

The pytoplanktonic primary production in Thermaikos Gulf (PAGOU & ASSIMAKOPOULOU, 1997; ANSELME & ALBUISSON, 1997): The total integrated chlorophyll concentrations show clearly the gardient of the existing trophic conditions, from the extremely eutrophic shallow northern part (chlorophyll - α 207,05 mg/m^2) to the oligotrophic Aegean waters in the south (18,08 mg/m^2). Total primary production rates (measured during May 1997) ranged from 0,001 to 180,82 $mgc/m^3/h$.

The structure of the nepheloid layers (ANAGNOSTOU et al 1997; KARAGEORGIS et al, 1997): The nepheloid structure in the Thermaikos Gulf and the Sporadhes basin shows usually a layered system with the main characteristics the Surface Nepheloid Layer and the Bottom Nepheloid Layer. The north, western and central part of the shelf environment shows significant values of the turbidity, the eastern part and the Sporadhes basin consist of clear water.
The same results are obtained through the measurement of the Suspended Particulate Matter. The Surface Nepheloid Layer in the northern and western part shows high values of Suspended Particulate Matter (higher than 5mgr/lt). In the eastern part of the Thermaikos plateau and in the Sporadhes basin the values are very low (between 0 and 1 mgr/lt). The distribution of Bottom Nepheloid Layer shows high values near the river mouths (2-2,5 mgr/lt).

The sedimentation mechanisms and the role of the resuspension in these mechanisms (ANAGNOSTOU et al, 1997b): The modern sedimentation in the Thermaikos Gulf is contolled by water circulation and by the carrier capacity of the sediment sources. Based on the surficial sediment distribution the following sedimentary provinces can be distinguished: shelf mud, shelf muddy sands, shelf break sediments, slope and basin mud. The shelf is a **typical deltaic platform** developed by delta progradation. In the inner shelf prodelta the deposits have been developed in prismatic deposition form, receiving the main amount of the discharged sediments. The mean annual sediment accumulation is estimated at $2,17x10^6$ ton/year on the Thermaikos plateau and $0,3x10^6$ ton/year on the continental slope and on the Sporadhes basin.
The annual accumulation of organic carbon and inorganic carbon is also estimated on the Thermaikos plateau and on the Sporadhes basin, 10,000 ton/year organic carbon is accumulated on the plateau and only 1,500 ton/year on the basin, 60,000 ton/near inorganic carbon is accumulated on the plateau and 12,000 ton/year on the basin.

Modelling

The Axios River plume (KOURAFALOU, 1997): A three-dimensional, primitive equation hydrodynamic model has been applied on the Thermaikos Gulf. For the modelling of the Axios River plume, a typically high value of discharge was prescribed at first: 200 m^3/s. The temperature of the river is the same as that of the basin, at it is assumed that the density charges are controlled by salinity. No forcing other than buoyancy due to freshwater discharge has been prescribed. A small amount of low-salinity water has entered the inner Thermaikos Gulf.
The core of the plume occupies the upper part of the outer Gulf and from the west to the east coast. Interestingly, strong anticyclonic circulation is found between the two coasts, within the "bulge" of the river plume; values of current speed reach as much as 30 cm/s.

Modelling the 3-D baroclinic circulation, (KRESTENITIS, 1997): The purpose of the simulations is to understand the physics of the Thermaikos Baroclinic circulation and explore some of its features. For the computational experiments following parameters were used: daily dicharges for the rivers Axios, Loudias and Aliakmon, hourly meteorological data (air T, pressure and humidity, cloud cover, precipitation, wind speed and direction). The pattern of the daily-overaged circulation in the bay is primarily baroclinic. The rivers enhance the circulation of the inner bay.

3.4 Experimental part

3.4.1 Physico-chemical processes in the fresh/salt water interfaces

Hydrodynamic mechanisms controlling the flocculation (AUDEMAR et al, 1997): Results acquired on the fieldwork have shown that the mixing between the sea water and the fresh water occurs very far upstream and the interface between the fresh and the salt water is well defined. There exists a well defined point for the ascension of the "salty patch", whose position depends strongly on the fluvial debit. This limit frontiers costitutes a zone of strong growth of the flocs.

Particles repartition in different hydrodynamic conditions (THILL et al, 1997): Suspended mater that goes through the mixing zone from the fresh water to the salt water is underlied some changes on its behaviour. The particle number of large aggregates seems to decrease along the mixing zone as the number of small aggregates increase. It seems that the large aggregates are breaking up into smaller species. The flood of the river can lead to an significant increase in suspended matter.

3.4.2 The production of biogasses in the fresh / salt water interface

Production of nitrous oxide by nitrification processes (BIANCHI & FOSSET, 1997): The distribution of nitrifying activities are higher near the mouth of the river and decreased outside of the plume area. In the benthic nepheloid layer the nitrification rates were higher than in the surface water, probably due to the proximity of the sediment. Depending on the samples, the nitrous oxide production corresponded to 0,5-3% of the measured nitrification.

Nitrous oxide production from denitrification process (BONIN & MICHOTEY, 1997): It will be focused on the nitrous oxide production from denitrification processes. Preliminary results have shown that the Rhone River plume is a source of nitrous oxide due to microbial processes. The experiments will be continued in order to gain a better estimation of nitrous oxide fluxes and to evaluate the contribution of each microbial processes in these fluxes.

Production of methane by methanogenesis process (MARTY, 1997): The production of methane by methanogenesis process was studied on surface nepheloid layer, bottom nepheloid layer and sediment along the Rhone River Plume (Gulf of Lions). Methane production activity, which is present in surface and bottom nepheloid layers as well as in underlying sediments, exhibits decreasing rates from the mouth of the river to the sea and in seawater is essentially linked to particulate material, present in nepheloid layers. The fluxes of the biogas from the sea to the atmosphere could be important in the desalted area, and decrease from the mouth to the sea.

3.4.3 Suspensivor organisms and energy transfer

The role of suspensivor organisms in the energy transfer processes in littoral marine ecosystems: The aim of this trial is to achieve a realistic quantification of energy transfer processes between the various ecosystem components of the marine system. This work is at this time in progress.

4. MANAGEMENT OF THE RESULTS OF THE PROJECT

Collection of existing data as well as of new produced data were undertaken and they are stored in a MEDATLAS compatible format (KARAGEORGIS et al, 1998). The collection of data runs parallel to the development of Geographical Information System applications. Additionally, a trial of a socio-economic approach is undertaken (ZANOU, 1998). The establishment of an economic value in the environment is an essential task in the effort to manage natural resources on a sustainable basis.

5. OUTLOOK

The investigations take place in the framework of the METRO-MED project have the objectives to study and model the key processes of matter transfer and the biogeochemical cycles in the coastal zone system. Two sites in the Mediterranean Sea, Gulf of lions and Thermaikos Gulf, are chosen as research areas. These areas have as ecosystems similarities and differences. It is the target of the project to compare the two ecosystems since comparative studies give a more general understanding of the functioning of the coastal systems and they offer the opportunity for the development of scientific concepts in a wider dimension. Furthermore, it is the target to review the different models used in the coastal marine ecosystem and to assess the communication between modelling and observational studies.

REFERENCES

ANAGNOSTOU, CHR., LYKOYSIS, V., KARAGEORGIS, A., KAPSIMALIS, V. & CHRONIS, G. (1997b): The sedimetnation mechanisms in the Thermaikos area and Sporadhes basin, and the role of the resuspension in these mechanisms. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 120-123, Novemb. 1997.

ANAGNOSTOU, CHR., KONTOGIANNIS, H., KARAGEORGIS, A. & PAPADOPOULOS, V. (1997a): The structures of the nepheloid layers in Thermaikos Gulf and Sporades basin - during the cruise of May 1997 - based on light transmission measurements. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 113-116, Novemb. 1997.

ANSELME, B. & ALBUISSON, M. (1997): Space and time chlorophyll-like pigments distribution in the Gulf of Thermaikos. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 105-110, Novemb. 1997.

AUDEMAR, C., IZRAR, B., SKALI, S. & LUSSEYRAN, F., (1997): Physico-chemical processes in the fresh/salt water interface: Hydrodynamic mechanisms controlling the flocculation - Modelling of these processes. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 129-136, Novemb. 1997.

BIANCHI, M. & FOSSET,Ch. (1997): Production of nitrous oxide by nitrification processes. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 151-156, Novemb. 1997.

BONNIN, P. & MICHOTEY, V., (1997): Nitrous oxide production from denitrification process. *In: First Annual Scientific Report of the EU-MAST-III METRO-MED Project, p. 157-161, Novemb. 1997.*

DURRIEU DE MADRON, X. (1997a): The adjacent land area and its potentiality for the fresh water, sediment and pollutants supply. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 6-11, Novemb. 1997.

DURRIEU DE MADRON, X. (1997b): The transfer of suspended particulate matter: Input, dispersion and sedimentation on the Gulf of Lions continental shelf. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 22-25, Novemb. 1997.

DURRIEU DE MADRON, X. (1997c): The resuspension processes in the Gulf of Lions. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 26-27, Novemb. 1997.

ESTOURNEL, CL. & MARSALEIX, P.(1997): Modelling of the matter transfer in the fresh / salt water interface. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 28-31.

GUIEU, C. & TUSSEAU, M.H. (1997): Biogeochemical model of the Gulf of Lions. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 44-46, Novemb. 1997.

ITTEKKOT, V. & HAAKE, B. (1990): The terrestrial link in the removal of organic carbon in the sea. In *ITTEKKOT, V. KEMPE, S., MICHAELIS, W. & SPITZY, A. (eds): Facets of Modern Biogeochemistry, Springer* - Verlag, Heideberg, p. 318-325.

KARAGEORGIS, A., ANAGNOSTOU, CHR., KAPSIMALIS, V., STAVRAKAKIS, SP. & ROUSSAKIS, G. (1997): The distribution and quality of the suspended particulate matter in Thermaikos Gulf and Sporades basin during Spring 1997. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 117-119, Novemb. 1997.

KARAGEORGIS, A., ANAGNOSTOU, CH. & LYKIARDOPOULOS, A., (1997): The implementation of Data Management in the framework of the EU MAST-III ELOISE project Metro-med. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 178-180, Novemb. 1997.

KONTOGIANNIS, H. & PAPADOPOULOS, V. (1997): Water-Mass characteristics and circulation patterns during the METRO-MED Cruise of May 97 in the Thermaikos Gulf and the Sporades Basin. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 76-82, Novemb. 1997.

KOURAFALOU, V., (1997): The Axios River plume - Thermaikos Gulf / Greece. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 124-126, Novemb. 1997.

KRESTENITIS, Y., (1997): Modelling the 3-D baroclinic circulation in Thermaikos Gulf. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 127-128, Novemb. 1997.

MARTY , D., (1997): Production of methane by methanogenesis process. In: First Annual Scientific Report of the EU-MAST-III METRO-MED Project, p. 162-166, Novemb. 1997.

MORTIER, L. & TUSSEAU, M.H. (1997): Coupling of the hydrodynamical, biogeochemical and sediment models in the Gulf of Lions. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 55-63, Novemb. 1997.

NYFFELER, F. (1997a): The transfer of suspended particulate matter: Assemble and review of existing data, based on hydro-optical profiles, related to the transport of particles on the shelf of the Gulf of Lions. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 19-21, Novemb. 1997.

NYFFELER, F. (1997b): Modelling of particulate transport on continental shelves (Gulf of Lions). In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 32-33, Novemb. 1997.

PAGOU, K. & ASSIMAKOPOULOU, G. (1997): The phytoplaktonic primary production in the Thermaikos Gulf. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 94-104, Novemb. 1997.

PAVLIDOU, A. & KRASAKOPOULOU, E. (1997): Distribution of dissolved oxygen and nutrients in Thermaikos Gulf and Sporades Basin, based on measurements of the METRO-MED Cruise of May 1997. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 83-93, Novemb. 1997.

RAILLARD, O. (1997): Modelling summer marine circulation of the Gulf of Lions: Use of an embedded model. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 34-43, Novemb. 1997.

RAIMBAULT, P.G. & COSTE, B. (1997): The biological production. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 12-18, Novemb. 1997.

SKOULIKIDIS, N. & KARAMANOU, E. (1997): The role of the adjacent land area as fresh water, sediment and pollutants supplier. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 64-75, Novemb. 1997.

SOETAERT, K., MIDDELBURG, J., HERMAN, P. & HEIP, C., (1997): Sediment early diagenesis model. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 47-54, Novemb. 1997.

THILL, A., LECOANET, H. & BOTTERO, J.Y., (1997): Physico-chemical processes in the fresh/salt water interface: Particles repartition in different hydrodynamic conditions. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 137-143, Novemb. 1997.

ZANOU, B., (1997): The economic valuation of environmental resources in the Gulf of Thermaikos. In: *First Annual Scientific Report of the EU-MAST-III METRO-MED Project*, p. 182-187, Novemb. 1997.

TITLE: Entangled Sulfur and Carbon cycles in *Phaeocystis* dominated Ecosystems (ESCAPE)

CONTRACT NO.: MAS3-CT96-0050

COORDINATORS:

Dr Winfried W.C. GIESKES
University of Groningen
Dept. of Marine Biology
PO Box 14, 9750 AA Haren, NL
tel (fax): 31-50-3632241 (2261)
e-mail: w.w.c.gieskes@biol.rug.nl

Dr Jacqueline STEFELS
University of Groningen
Dept. of Marine Biology
PO Box 14, 9750 AA Haren, NL
tel (fax): 31-50-3632253 (2261)
e-mail: j.stefels@biol.rug.nl

PARTNERS:

Dr Sauveur BELVISO
Centre des Faibles Radioactivites
Laboratoire des Science du Climat et de l'Environnement
CEN/Saclay, Bat 709 Orme des Merisiers
91191 Gif-sur-Yvette, FR
tel (fax): 33 1 69 08 81 51 (85 46 or 94 79)
e-mail: belviso@lsce.saclay.cea.fr

Dr Peter BURKILL
Plymouth Marine Laboratory
Prospect Place, West Hoe
Plymouth PL1 3DH, UK
fax: 44 (0)1752 633101
e-mail: p.burkill@pml.ac.uk

Dr Gill MALIN
School of Environmental Sciences
University of East Anglia
Norwich, NR4 7TJ, UK
tel (fax): 44 1603 592531(507714)
e-mail: g.malin@uea.ac.uk

Dr Paul WASSMANN
Norwegian College of Fishery Science
University of Tromsø
N-9037 Tromsø, NO
tel (fax): 47-776-44459/86103 (46020)
e-mail: paulw@nfh.uit.no

ENTANGLED SULFUR AND CARBON CYCLES IN *PHAEOCYSTIS* DOMINATED ECOSYSTEMS (ESCAPE)

J. STEFELS, S. BELVISO, G. MALIN, P. WASSMANN

SUMMARY

The principal aim of the project is to establish a link between the marine carbon and sulfur cycles. Both cycles are relevant to climate change studies, carbon being the main contributor to the greenhouse effect, and sulfur as an important source of cloud condensation nuclei, thereby regulating cloud albedo. Greenhouse effect and cloud albedo are two opposing mechanisms. The former results in global warming, the latter in cooling of the earth's climate. Both cycles meet intimately in the ubiquitous marine phytoplankton taxon *Phaeocystis* sp.. This colony-forming alga is an important source of the volatile organic sulfur compound dimethyl sulfide (DMS), and its dense blooms can act as a carbon sink.

A thorough inventory of the carbon and sulfur cycles will be made during two blooms of *Phaeocystis* in two different geographical areas: in northern Norwegian coastal waters and in the Southern Bight of the North Sea. These field campaigns will be preceded and followed by well defined laboratory experiments in order to study isolated processes relevant for the field situation.

In April 1997, the first field campaign in Northern Norway took place; in April 1998 the second campaign is planned. Here we will give an overview of preliminary data from the Norway campaign.

INTRODUCTION

Greenhouse warming and aerosol cooling are two opposing mechanisms that affect global climat. The two most important gases that contribute to these mechanisms are carbon dioxide (CO_2) and sulphur dioxide (SO_2) respectively. Since the industrial revolution, emissions of both gases have increased considerably. Anthropogenic CO_2 emission has given rise to an increase in the atmospheric CO_2 concentration from 280 to 365 ppm over the past 200 years. Anthropogenic sulphur emission has increased from 10% to 75% of the global sulphur flux. Because the oceans cover approximately 70% of the earth's surface, air-sea exchange of these gases will influence their global budgets.

Model studies indicate the importance of the oceans as a carbon sink, taking up about one third of the total anthropogenic CO_2 emission. The calculation of this figure is based on the build-up of new chemical equilibria between sea and atmosphere. About 20% of the anthropogenic CO_2 input can not yet be traced back, but may be found in a CO_2-stimulated plant growth. The contribution of the marine biota in this so-called 'missing sink' is not well understood. It can act as a carbon pump by producing particulate and dissolved organic matter that is transported to deeper waters during the wane of an algal bloom or via the faecal pellets of zooplankton. The question is, however, whether or not these processes change when atmospheric CO_2 concentrations increase. It has long been thought that this would not happen, because of the buffering capacity of the bicarbonate system in oceans. Recent insights, however, indicate that several algal species are unable to use bicarbonate, and will

become CO_2 limited under bloom situations where relatively high pH values can be reached. This implies that increased CO_2 concentrations can result in increased growth rates of these species (Riebesell et al 1993). Although this doesn't necessarily lead to an increase in total biomass, higher growth rates may enhance sedimentation of particulate material, thereby increasing the carbon pump.
Another process that may influence the carbon cycle is changes in species composition, which affects the ecosystem structure and thereby sedimentation characteristics, and thus the carbon cycle. There are also still open questions with respect to the amount of carbon that is removed from the water through sedimentation, relative to the amount of nitrate and phosphate removed. There are indications that more carbon is removed than can be expected on the basis of the Redfield-ratio (Sambrotto et al. 1993). This must imply the existence of a large pool of dissolved or particulate organic material with a high C:N ratio. This additional sink of carbon should than be added to the sink used in model calculations.
The role of the ocean with respect to the global SO_2 budget is related to its contribution to atmospheric SO_2 through the emission of the volatile organic sulphur compound, dimethyl sulphide (DMS), that is photo-oxidised to SO_2. DMS makes up 50 to 60 % of the total natural sulphur flux to the atmosphere. On a global scale, the antropogenic SO_2 production exceeds the natural SO_2 production by a factor of 3 (Bates et al. 1992). Its impact on the aerosol production is, however, largely confined to the industrialised areas in the northern hemisphere.
DMS is produced through enzymatic cleavage of dimethylsulfoniopropionate (DMSP), a sulfur compound found in several phytoplankton species. Consumption processes of DMS are: bacterial DMS oxidation, photo-oxidation into dimethylsulfoxide (DMSO) and sea to air exchange. The importance of DMS as global atmospheric sulfur source led Charlson et al. (1987) to speculate on a possible biological regulation of the climate, whereby an increased atmospheric CO_2 concentration ultimately would result in an increased DMS flux from the oceans. Consequently, the cooling effect of sulfate would counterbalance the greenhouse effect. Although many of the assumptions made by Charlson and co-workers are still under debate (see e.g. Malin et al. 1992), it has stimulated much research.

Within the ESCAPE project, we have choosen to study a model organism *Phaeocystis* sp. for several reasons. 1. Due to its ubiquitous distribution and its observed dominance during spring blooms *Phaeocystis* may play an important role in elemental cycles. 2. *Phaeocystis* blooms may increase the escape of carbon from the euphotic zone due to increased sedimentation of carbon enriched material (Riebesell et al. 1995). 3. The high intracellular DMSP levels of *Phaeocystis* plus its ability to convert DMSP into DMS enzymatically, may give rise to a short period of enhanced DMS flux to the atmosphere.
The observed variability in ecosystem structure during *Phaeocystis* blooms exhibits a potential for shifts in DMS emissions to the atmosphere and for variability in the biological carbon pump. Mechanisms determining the escape of carbon and sulphur compounds from the euphotic zone, are still unclear. Despite the global significance of *Phaeocystis* sp. for primary production, algal blooms, climate regulation and its structural influence on the plankton ecology of large ecosystems like the North Sea, the Barents Sea and the Greenland Sea, our understanding of its ecology is surprisingly limited (Lancelot & Wassmann 1994). Within ESCAPE we will examine the different ecosystem pathways in detail (Fig. 1), using an integrated approach of laboratory experiments and field expeditions. Lab results will be verified in the field, by exploring and comparing two different *Phaeocystis* dominated ecosystems: the unpolluted Northern Norwegian Shelf area and the highly eutrophied Southern Bight of the North Sea.

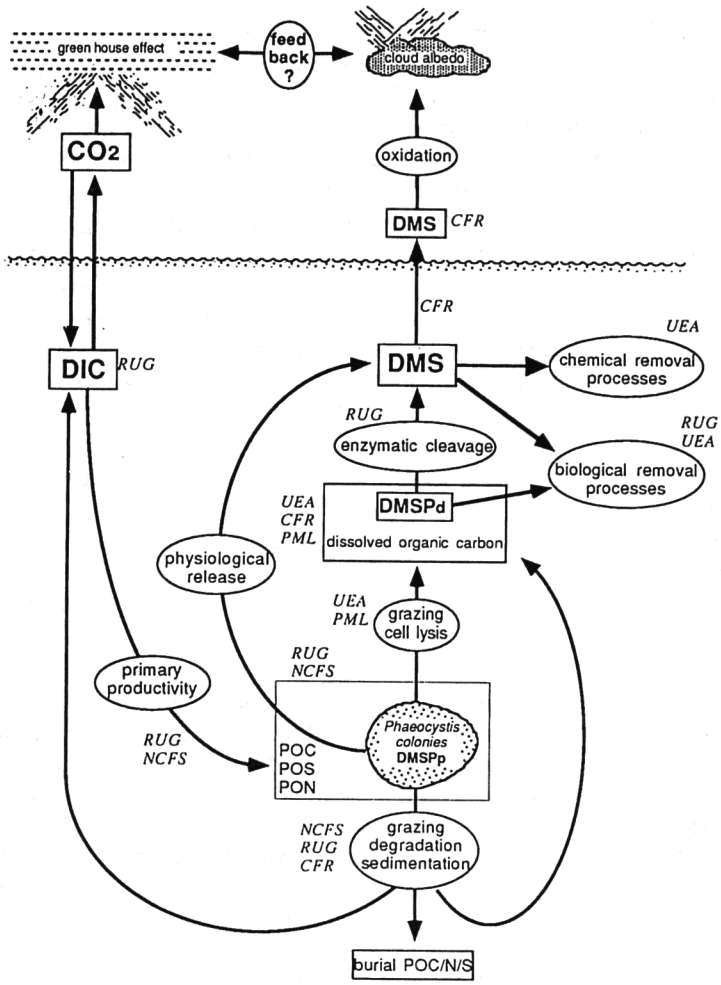


Fig. 1 Flow diagram of the processes studied in ESCAPE; involvement of the partners is indicated: CFR = Centre des Faibles Radioactivités - CNRS, FR; NCFS = Norwegian College of Fishery Science, NO; PML = Plymouth Marine Laboratory; RUG = University of Groningen, NL; UEA = University of East Anglia, UK;

METHODOLOGY

During the spring bloom of 1997, a field campaign of three weeks in the fjords around Tromsø was pursued. In order to sample different stages of the bloom within the three weeks, 3 different fjords were sampled alternatively; each day one fjord. The fjords were choosen for their difference in exposure to incoming ocean water, with, consequently, an expected difference in bloom development. In order of increasing oceanic influence, the fjords sampled were: Balsfjord (B), Malangen (M) and Ullsfjord (U). One fixed station in each fjord was choosen (Fig. 2). At each station, an 18 hour program was completed. In this way, Balsfjord and Ullsfjord were sampled 5 times, Malangen 4 times. During the transfer from one station to the other, surface samples were taken for DMS analyses.

The parameters and processes under study within ESCAPE are depicted in Fig.1. At each station, water samples were taken for the analyses of plankton parameters (cell counts, pigment analyses, activity measurements), dissolved and particulate sulphur, carbon and

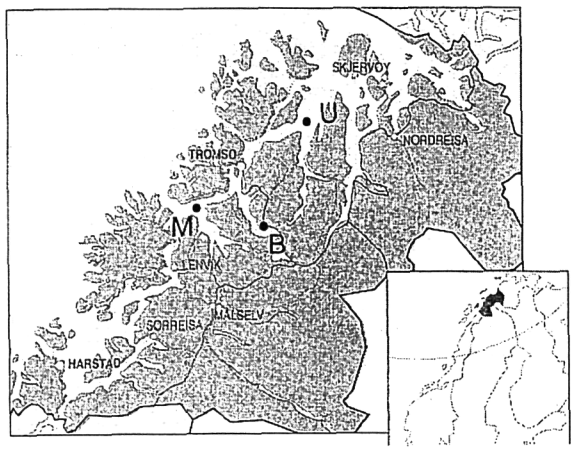


Fig. 2 Map of the sampling area. Balsfjord (B): 69:21N 19:06E, Malangen (M): 69:30N 18:22E and Ullsfjord (U): 69:49N 19:50E

nitrogen compounds and nutrients. Sediment traps were used to measure fluxes of carbon, nitrogen and sulphur compounds. A multi-corer took samples of bottom sediments. Atmospheric samples were taken for the analyses of particle density and size fractions, and for the analyses of the DMS oxidation products dimethyl sulphoxide (DMSO) and methane sulphonic acid (MSA). Mapping of the horizontal and vertical distribution of the different compounds was combined with process studies in incubation experiments. These incubation experiments were carried out using sea water collected from the surface layers of the three stations. They aimed at quantifying the key pathways in the turnover of DMS, DMSP and DMSO, including the impact on these pathways by virusses, bacteria, algae and zooplankton. Inhibitors such as chloroform and dimethyldisulphide (DMDS) and substrates such as dimethylsulphoniopropionate (DMSP) and glycine betaine (GBT) were added during several experiments. Bottles were incubated at near *in situ* temperature in a constant temperature room in the light (150 $\mu Em^{-2}s^{-1}$) or the dark.
Most of the samples collected during this field campaign has only recently been analysed, and in many instances interpretation still needs to be done. Therefore, the following section can only present part of the results.

RESULTS

The three fjords investigated in April 1997, Ullsfjord, Balsfjord and Malangen, characterising different hydrodynamic settings in the north Norwegian coastal zone. Bloom formation was different in these fjords: in Balsfjord diatoms (mainly *Chaetoceros socialis*) were dominant, whereas in Ullsfjord the colony-forming haptophyte *Phaeocystis pouchetii* was more abundant, with maximum cell numbers of $8 \cdot 10^6$ cells$\cdot L^{-1}$. Malangen had an intermediate position, with maximum *Phaeocystis* numbers of $1.8 \cdot 10^6$ cells$\cdot L^{-1}$. Net primary production measurements ranged from 0.7 to 3.2 gC m^{-2} d^{-1} (Fig. 3). This is somewhat lower than the

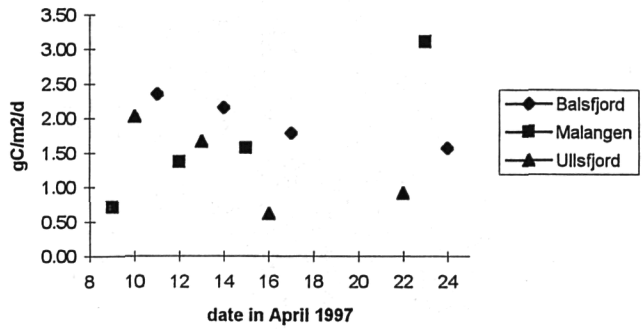


Fig. 3 Net primary production measured in north Norwegian fjords, in April 1997.

only data available from Balsfjord (1976 to 1978), which ranged from 2.4 to 5.4 gC m^{-2} d^{-1} (Wassmann et al. 1996). Bacterial activities integrated over the water column in all fjords increased little in time, and compared to 10 to 50% of the net primary productivity.
DOC and TDN concentrations in the upper waters consistently ranged from 70-100µM C, 10-18.5µM N; generally changing to around 65-90µM C, 15-20µM N at depth. Concentration gradients through surface waters were observed at most stations, and profiles showed significant vertical variability on a 'days' time scale. DOC concentrations revealed the greatest degree of micro-structure over the upper 20m. For each station the vertical distribution is quite different. This is typically indicative of a highly dynamic system; although it is currently unclear whether hydrographic or biogeochemical factors are the dominant forces.
Particulate DMSP accounted for more than 95% of total DMSP in surface waters of the three fjords. The standing stock of particulate DMSP, as obtained from the integrated profiles from the surface down to 60m depth, did not change markedly at Balsfjord and slightly increased at Malangen. On the contrary, it strongly increased at Ullsfjord, the standing stocks being about an order of magnitude higher on day 25 than on day 10. The pDMSP trend paralleled the abundance of *Phaeocystis* cells, and was opposite to that of DMS (Fig. 4). Thus, the DMSP results demonstrate that the DMS spatio-temporal variability at Ullsfjord was controlled by removal processes (i.e. ventilation and possibly bacterial degradation and DMS water photochemistry; see below). It is most probable that the high DMS levels observed at the beginning of the survey resulted from the decay of an earlier algal bloom.

DMS SEA-AIR EXCHANGE

The horizontal and temporal variability of the DMS sea surface concentration was measured during the transfers from Tromsø to the stations located at Balsfjord, Malangen and Ullsfjord. There was a clear decreasing trend in Tromsø's waters from April 13th (10.9 nM) to April 21st (1.4 nM) followed by a slight recovery (Fig. 4; 2.5 nM on the 23rd). Comparable trends were observed at Ullsfjord and Balsfjord. A net DMS removal rate in the range 2-3 nM·d^{-1} was estimated from the Ullsfjord data set.

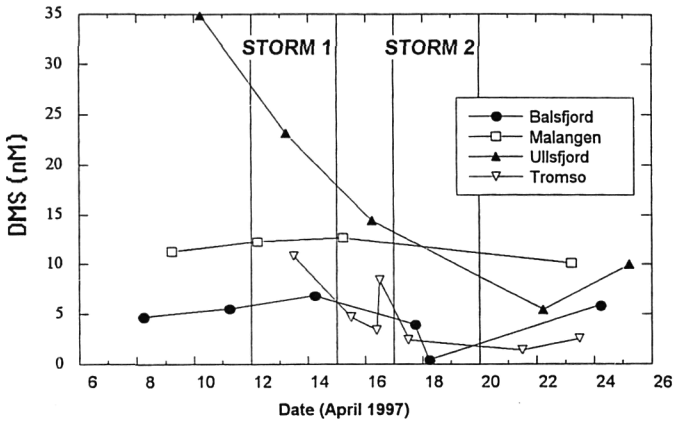


Fig. 4. Temporal variability of the sea surface DMS concentration at 4 sites in the north Norwegian coastal zone, in April 1997

Wind data from Tromsø in April 1997 (daily wind speeds were in the range 4-13 m/s) showed two major storm events centred around April 13th and 17th, each lasting for about 3 days (Fig. 4). The lowest DMS levels were observed during and just after the second storm. The decline of the DMS levels started during the first storm event at Ullsfjord. It is suggested that ventilation of DMS to the atmosphere due to increasing wind stress promoted the decline of sea surface DMS levels.

The Aitken nuclei with geometric mean diameter in the range 20-60 nm presented an important temporal and spatial variability. In terms of absolute numbers, 4 events with particle densities exceeding 4000 particles/cc were observed, two at Ullsfjord, one at Malangen, during days 12-15, and the last one at Balsfjord on the 23rd (Fig. 5). Such high densities by far exceeded both the oceanic background (200-500 particles/cc) and the typical continental levels (200-2000 particles/cc). It clearly characterises a strong nucleation process. The very low diameters associated with these gusts of particles indicated that they were produced nearby rather than transported over long distances. The maximum density of particles occurred between 4 and 7 pm. This is consistent with a photochemical gas to particle conversion of atmospheric DMS. Moreover, MSA and DMSO concentrations in aerosols, both specific oxidation products of DMS, and the particle densities covaried (Fig. 5).

VERTICAL EXPORT

Vertical export of biogenic matter was high, ranging between about 200-800 mg C m^{-2} d^{-1}. There were some differences in the timing and the composition between the fjords. The vertical export of biogenic matter in Balsfjord after mid April was characterised by the highest particulate organic carbon (POC) and chlorophyll *a* so far recorded in this area, 850 and 22 mg m-2 d-1, respectively. This could also be traced back in increased chlorophyll content of bottom sediment (Fig. 6). Phytoplankton carbon (PPC) contributed between 30-99

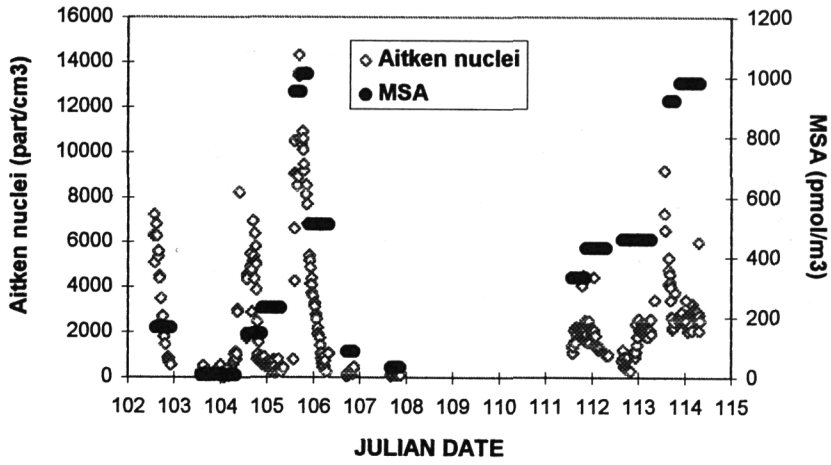


Fig. 5. Spatio-temporal variability of aerosols at the 3 fjords: Aitken nuclei and the DMS oxidation product MSA

% to the vertical export of POC with an average of 52±17 %. The diatoms *Thalassiosira angulata, T. nordenskjöldii, Chaetoceros socialis* and *C. furcellatus* were jointly by far the most important taxa contributing to PPC export, on average 82 %. *Phaeocystis poucheti*, did not contribute more than 56 mg C m^{-2} d^{-1} to the vertical export while *P. pouchetii* almost was absent in Balsfjord.

Downward fluxes of DMSP and subsequent deposition on the sediment surface revealed a slightly different picture than the carbon and chlorophyll data did, which may at least partly be explained by the difference in phytoplankton species composition; *Phaeocystis* being a major producer of DMSP. At the sediment surface in Balsfjord, DMS(P) levels were found to be in the range 0.6-3 µgS/g. There was no clear temporal trend, whereas downward fluxes increased markedly. DMS(P) levels were highest in the top cm of the sediment. At Malangen, DMS(P) levels were in the range 0.3-2 µgS/g. DMS(P) levels at the sediment surface increased 3-4 folds between April 8 and 22. This trend was highly consistent with the trend in downward fluxes. At Ullsfjord, DMS(P) levels were in the range 0.1-2 µgS/g. There was no clear temporal trend at the sediment surface.

Although downward fluxes of DMSP were up to 15-folds higher at the Ullsfjord than at the Balsfjord, DMS(P) levels in the sediment were similar. Moreover, no enhancement of DMS(P) was observed at the sediment surface of Ullsfjord (this was also observed for chlorophyll-a). This suggests that the flux of DMS(P) at Ullsfjord did not reach the sediment surface. We hypothesised that this was due to strong lateral advection of the sedimenting material. At Malangen, on the contrary, DMS(P) levels at the sediment surface and the DMSP downward fluxes increased more or less proportionally. This suggests strong coupling between the surface waters and the sediment. Sedimentation of DMSP at Balsfjord markedly increased during April but it remained much lower than at the other fjords, which can be explained by the low *Phaeocystis* numbers in this area. Nevertheless, DMS(P) levels in the surface sediment also increased but to a lesser extent than at Malangen.

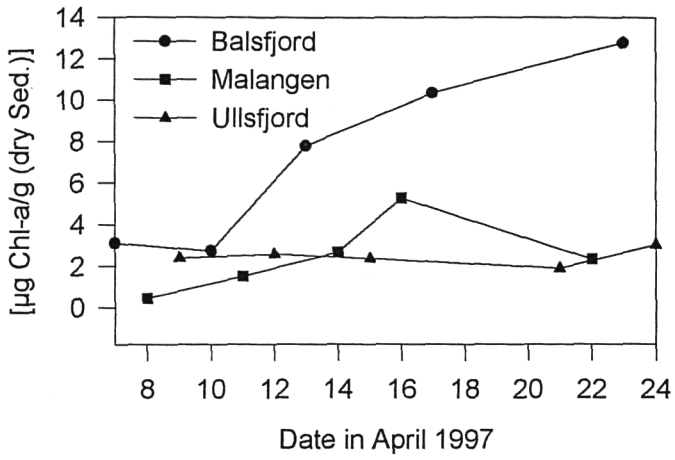


Fig. 6. Chlorophyll-a concentrations in surface sediments of the three fjords.

In contradiction to previous investigations in the area, vertical POC export was not dominated by faecal pellet carbon (FPC), which ranged in the between 20-380, with an average of 125±99 mg C m^{-2} d^{-1}. While previous investigations of vertical export in 1982, 1992 and 1996 revealed that the vertical export of POC in spring was strongly influenced through meso- and macrozooplankton grazing, giving rise to a large scale export of FPC, the results from the present investigation suggests that zooplankton in 1997 was unable to catch up with phytoplankton growth. That resulted in a mis-match scenario, resulting in the large-scale export of diatoms. It is hypothesised that interannual differences in over-wintering, but in particular advection of meso- and macrozooplankton from the shelf adjacent to the fjords, are the cause for the distinct changes in pelagic-benthic coupling in north Norwegian fjords in spring.

INCUBATION EXPERIMENTS

The addition of DMDS as a competitive inhibitor of DMS consumption in water from Malangen Fjord on 9th April (Expt B) had little effect on DMS concentrations (Figure 7a). Water from Ullsfjord which had a much higher initial DMSPp concentration (16th April Expt I) was also treated with DMDS (Figure 7b) and in this case it appeared to have slightly more inhibitory activity. Chloroform generally caused apparent inhibition of DMS consumption (Figure 7b), but this seemed to derive from turnover of DMSPd which increased due to leakage of DMSP from particulates. It has been suggested previously that the use of chloroform as an inhibitor may be problematic due to the release of DMSPp, possibly because of adverse effects on cell membranes (Wolfe and Kiene 1993). In most of our experiments

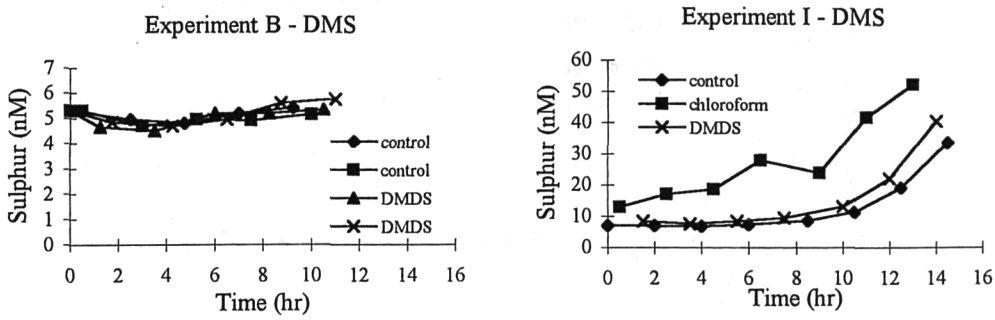


Fig. 7. DMS concentrations versus time for a) Malangen seawater (9th April Expt B) incubated with and without the addition of DMDS, and b) Ullsfjord seawater (16th April Expt I) incubated with DMDS or chloroform.

little change in DMSO concentration was observed. Our observations may relate to the low levels of bacterial activity observed.

Results from dark and light incubations of water from Ullsfjord showed a dramatic approximately 3-fold increase in DMS concentration after ~8 hours incubation in the dark (Figure 8). This increase was coincident with the start of the natural dark period and concomitant with decreasing DMSPp and increasing DMSPd concentrations. Additional experiments showed that this also occured when a bottle incubated in the light for the initial 8 hour period was switched into the dark, hence the result did not relate to prolonged dark incubation *per se*. If such an increase in DMS concentration occurs in the environment it could result in enhanced emissions of DMS to the atmosphere. The reasons for such an increase in DMS concentration are not clear at the present time and will require further investigation during our 1998 field campaign and via experiments with cultures of *Phaeocystis* in the laboratory.

Plate incubations of the bacterial fraction was carried out with three substrate types: a rich

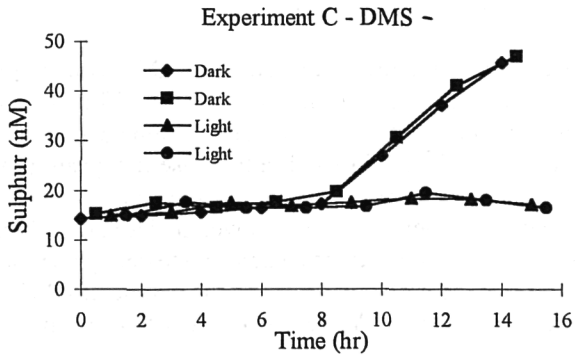


Fig. 8. DMS concentrations versus time for Ullsfjord seawater collected 10th April 1997 and incubated in continuous light or continuous dark conditions. Time zero is approximately 1100h local time.

coctail, DMSP and acrylate. This resulted in only 42 colonies, of which 7 were grown on DMSP and 4 on acrylate. Of the 7 grown on DMSP, only 2 actually used DMSP. They did not produce DMS.

CONCLUSION

Still a lot of work needs to be done, before any firm conclusion can be drawn on the ecosystem structure and functioning in these north Norwegian fjords. First impressions are that the physics of the area had a relatively larger impact on the fluxes of carbon and sulphur compounds than the ecosystem structure. There appeared to be a mis-match between the spring phytoplankton bloom and grazers, resulting in large-scale export of organic matter. Bacterial activity was low, and the contribution of bacteria to the turnover of DMS, DMSP and DMSO seems limited.

REFERENCES

Bates, T. S., Lamb, B. K., Guenther, A., Dignon, J., Stoiber, R. E. (1992). Sulfur emissions to the atmosphere from natural sources. J. Atmos. Chem. 14: 315-337

Charlson, R. J., Lovelock, J. E., Andreae, M. O., Warren, S. G. (1987). Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate. Nature 326: 655-661

Hatton, A. D., G. Malin, A. G. McEwan, A.G. and P. S. Liss, P.S. 1994. Determination of dimethyl sulphoxide in aqueous solution by an enzyme-linked method. Analytical Chemistry 66: 4093-4096.

Kiene, R. P. and S. K. Service. 1991. Decomposition of dissolved DMSP and DMS in estuarine waters: dependence on temperature and substrate concentration. Mar. Ecol. Prog. Ser. 76: 1-11.

Lancelot, C, Wassman, P. (1994). Dynamics of *Phaeocystis*-dominated ecosystems. J. Mar. Systems 5: 1-100

Malin, G., Turner, S. M., Liss, P. S. (1992). Sulfur: the plankton/climate connection. J. Phycol. 28: 590-597

Riebesell, U., Wolf-Gladrow, D. A., Smetacek, V. (1993). Carbon dioxide limitation of marine phytoplankton growth rates. Nature 361: 249-251

Riebesell, U., Reigstad, M., Wassman, P., Passow, U., Noji, T. (1995). On the trophic phate of *Phaeocystis pouchetii*. VII. Bloom and sedimentation of *P. pouchetii* in Balsfjord, northern Norway. Neth. J. Sea Res.

Sambrotto, R. N., Savidge, G., Robinson, C., Boyd, P., Takahashi, T., Karl, D. M., Langdon, C., Chipman, D., Marra, J., Codispoti, L. (1993). Elevated consumption of carbon relative to nitrogen in the surface ocean. Nature 363: 248-250

Wassmann, P., H. Svendsen, A. Keck and M. Reigstad. 1996. Selected aspects of the physiological oceanography and particle fluxes in fjords of northern Norway. J. Mar. Syst. 8: 53-71.

Wolfe, G. V. and R. P. Kiene. 1993. Radioisotope and chemical inhibitor measurements of dimethyl sulfide consumption rates and kinetics in estuarine waters. Mar. Ecol. Prog. Ser. 99: 261-269.

TITLE: Comparative analysis of food webs based on flow networks: Effects of nutrient supply on structure and function of coastal plankton communities.

CONTRACT NO: MAST III Contract: MAS3-CT96-0052

COORDINATOR: Professor Yngvar Olsen
The Norwegian University for Science and Technology,
Trondhjem Biological Station,
N-7034 Trondheim, Norway (UNIT)
Tel: + 47 7359 1592
Fax: + 47 7359 1597yngvar.olsen@vm.ntnu.no
E-mail:

PARTNERS:

Dr. Tom Andersen
University of Oslo,
Department of Biology,
P.O. Box 1066, Blindern
N-0316 Oslo, Norway (UIO)
Tel.: + 47 2285 4523
Fax.: + 47 2285 4438
E-mail: tanderse@bio.uio.no

Dr. Timo Tamminen
Finnish Environment Agency,
Impacts Research Division,
P.O. Box 140, FIN-00251
Kesäkatu 6, FIN-00260 (FEA)
FI-Helsinki, Finland
Tel.: + 358 9 4030 032
Fax.: + 358 9 4030 0390
E-mail: timo.tamminen@vyh.fi

Dr. Carlos M. Duarte
CEAB, Consejo Superior de
Investugaciones Cientificas, Centro de
Estudios Avansados de Blanes,
Camt de Santa Barbara S/N,
ES – 17300 Blanes, Espania
Tel.: + 34 7233 6101
Fax.: + 34 7233 7806
E-mail: duarte@ceab.csic.es

Dr. Christiane Lancelot
Universite Libre de Bruxelles,
Groupe de Microbiologie
Des Milieaux Aquatiques,
Campus de la Plaine
Boulevard du Triomphe, CP 221,
BE-1050 Brussels, Belgium (ULB)
Tel.: + 32 2650 5988
Fax.: + 32 2650 5993
E-mail: lancelot@ulb.ac.be

Professor Ulrich Sommer
Institut für Meereskunde an der Universität Kiel,
Abteilung Meeresbotanik,
Düsternbrooker Weg 20
DE – 24105 Kiel, Deutschland (IFM)
Tel.: + 49 431 597 3840
Fax.: +49 431 565 876
E-mail: usommer@ifm.uni-kiel.de

Msc. Espen Hoell
Hydro Research Centre Herøya,
P.O. Box 2560,
N-3901 Porsgrunn, Norway (HRE)
Tel.: + 47 3556 4505
Fax.: + 47 3556 3284
E-mail: Espen.Edward.Hoell@hre.hydro.com

COMPARATIVE ANALYSIS OF FOOD WEBS BASED ON FLOW NETWORKS: EFFECTS OF NUTRIENT SUPPLY ON STRUCTURE AND FUNCTION OF COASTAL PLANKTON COMMUNITIES (COMWEB)

Y. Olsen
The Norwegian University for Science and Technology
Trondhjem Biological Station,
N-7034 Trondheim, Norway

T. Andersen
University of Oslo
Department of Biology,
P.O. Box 1066, Blindern
N-0316 Oslo, Norway

SUMMARY

The main objective is to develop efficient analytical, numerical and experimental methods for assessing and predicting the effects of nutrient (N, P, Si) supply on the stability and persistence of pelagic food web structure and function in coastal areas.

COMWEB examines the effects of variable nutrient supply to coastal pelagic waters by analysis of the flows and components of the major biogenic elements C, N, P, and Si in the lower pelagic food web. The project is establishing mass-balanced flow networks for the major types of European coastal waters by use of mathematical inverse methods. Flow networks represent unified information which allow comparison of coastal waters across bio-geographical regions and trophic state gradients, and the project will contribute to further develop and improve these methods.

Five cases of European coastal waters are studied: 1) The Baltic Sea, 2) The Mediterranean Sea, 3) NE-Atlantic waters; unaffected by humans, 4) NE-Atlantic waters; artificially eutrophicated, and 5) NE-Atlantic waters; eutrophicated. These cases involve both a geographic gradient (1-3) and a trophic state gradient for NE Atlantic waters (3-5). Regionally representative flow networks of C, N, P and Si are established for all cases of coastal waters. The data needed are obtained in combined laboratory, mesocosm, and field experiments described briefly below. The regional flow networks will form the conceptual basis for diagnostic assessment tools for state and quality analysis of coastal waters.

A preliminary comparison shows that the Baltic food web is less stable and persistent during nutrient additions, whereas the Mediterranean food web is far more stable and persistent. This is a preliminary conclusion which will be further elaborated based on a broader set of data on all groups of organisms.

INTRODUCTION

(A) BACKGROUND

The coastal zone is the recipient for large amounts of nutrients and other wastes from human activities, including industrial effluents, agricultural runoff, and municipal sewage. Counter measures to reduce urban loads to coastal areas are being implemented within Europe, with the community costs of such measures already being very high. Manifested effects of eutrophication usually appear as qualitative changes to the biotic community (e. g. blooms of undesirable phytoplankton species, extinction of key species on higher trophic levels, reduced yields of harvestable fish or invertebrate populations), accompanied by major changes in the flows of energy and materials within the system.

Because the biological structure of the system may strongly affect the fate of the nutrients and hence the eutrophication process, the extent to which a certain nutrient load results in undesirable effects will not only be determined by chemical and hydraulic conditions. Natural systems have an ability to handle inputs of nutrients below a certain limit, or critical load, without manifestation of undesirable effects. The implicated role of biotic processes means that the critical nutrient load may change with food web structure, and that different community structures thus may show different susceptibilities to destabilization when subjected to increased nutrient supply. Such differences can be expected to appear on a regional scale between the different biogeographical constituents of European coastal waters.

Classical ecological theory predicts that idealized linear food chains close to equilibrium should show alternations between resource limitation and predator control at adjacent trophic levels (Hairston et al. 1960). Thus it can be inferred that since the top trophic level will always be resource limited, the bottom trophic level will be resource or predator controlled depending on whether there are an odd or even number of trophic levels in the food chain. Because only resource limited trophic levels will show biomass increases in response to increased resource supply, the trophic structure of an ecosystem will determine the biomass response to resource enrichment.

In an aquatic context, a nutrient limited primary producer level will correspond to what is typically associated with undesirable eutrophication effects in the form of an algal bloom situation, while a predator limited primary producer level should correspond to a situation in which any additional nutrient supplies should be channeled into increased harvestable biomass at higher trophic levels. Altogether this implies that for a given food web structure there should be a certain critical level of nutrient supply at which the likelihood of uncontrolled blooms should increase abruptly and non-linearly, and that for a given locality, this critical level can be changed by manipulations with the higher trophic levels. While the simplifying assumptions of linear food chain theory has a proven record as a management tool in freshwater systems (Carpenter 1988, Carpenter and Kitchell 1993), it is not readily obvious whether the same applies to marine systems.

There seems to be a strong consensus in food web theory that the resource supply rate acts as an important bifurcation variable that can control both the dynamical stability properties and the static trophic structure at the system's stationary state. However, the present incompleteness of theories, and perhaps also the general lack of appropriate experimental data, currently precludes the prediction of both the location and nature of such critical levels of enrichment. Much of the existing work on nutrient loading responses in coastal waters have been based on passive

collection of empirical data, which entails major difficulties in the assessment of supply-effect relationships. For the quantification of community responses to nutrient enrichment it would appear more feasible to take an experimental approach using mesocosms or other enclosed localities. In such experiments natural plankton communities can be subjected to experimental gradients of nutrient supply in order to quantify their domain of persistence.

Studies involving responses at the community level to external perturbations necessitate a holistic approach, where equal attention is given to different trophic levels and biogeochemical pathways. The kind of inherently multi-dimensional information implied by such an approach obviates a need for efficient ways of representing the dynamical state of a food web. A particularly strong candidate for this task is the network structure representing the flows of energy and major elements between main food web components. The current paradigm of plankton ecology regards pelagic communities as being organized in two parallel chains that may be interconnected at certain levels. Figure 1 indicates a minimal set of compartments and flows that are considered necessary for the generic representation of such a food web structure.

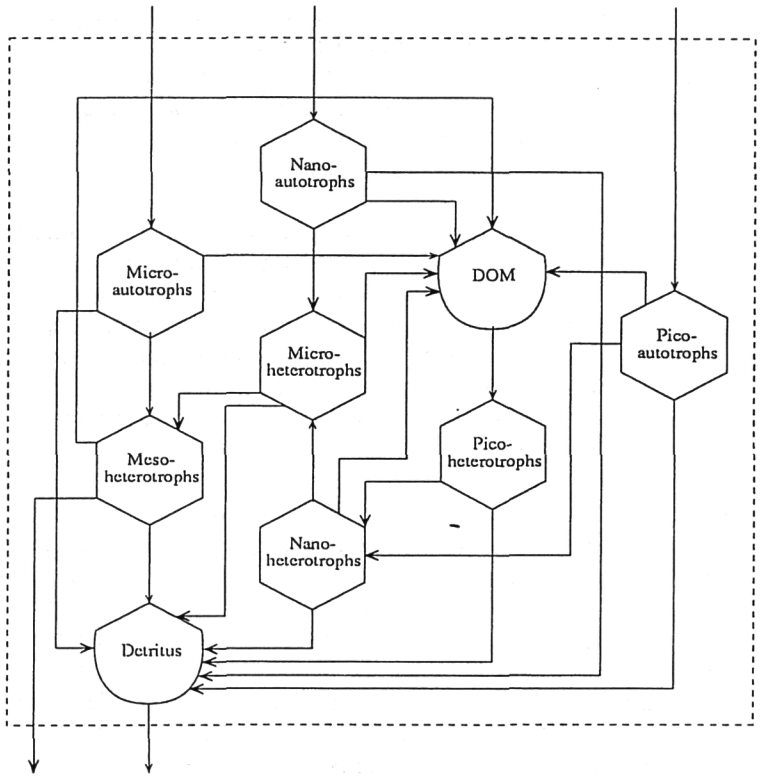


Figure 1. Schematic example of a flow network for a pelagic food web. The figure indicates a minimal set of compartments and flows that are considered necessary for the generic representation of such a food web structure.

Because food web components may have different stoichiometric properties (e. g. Sterner and Hessen 1994), a given component can show quite different relative contributions to the flows of different elements. For example, Vadstein et al. (1989, 1993) have shown that although carbon

flows through bacteria and bacterivorous protists may often seem to be minor, these microbial processes can actually represent a major contribution to the phosphorus flow in the pelagic food web. To avoid the biases inherent in a carbon-centric view of food webs, it will obviously be necessary to divide attention more evenly between carbon and other major biomass constituents.

In practice, it is hardly possible to measure directly all intercompartmental flows in a pelagic foodweb. However, each system component must also satisfy a mass balance equation, because flows into and out from each component must sum up to the net rate of change in that particular component. Theoretically this allows the estimation of one unknown transfer rate per mass balance equation, but this must be qualified on the fact that all terms that enter the mass balance equation will be subject to measurement noise. It should also be noticed that even in the simplest possible food web (the linear chain) there will be more unknown transfer rates than equations, such that the mass balance equations by themselves will always constitute an underdetermined equation system.

In addition, it is usually possible to determine a priori constraints on the solution, so that the flow network reconstruction can be formulated as a constrained least-squares problem. The solution of such problems are today unified into a coherent and general theory, where common estimation problems like regression analysis and optimal filtering turn out to be special cases. Inverse methods are well-established tools in the analysis of physical systems (e. g. Tarantola 1987; Menke 1989), but have only recently been applied to food webs (Vézina and Platt 1988; Jackson and Eldridge 1992; Stone et al. 1993; Vézina and Pace 1995, Lyche et al. 1996 a,b).

(B) MAIN OBJECTIVE

The main **objective** of COMWEB is *to develop efficient analytical, numerical and experimental methods for assessing and predicting the effects of nutrient (N, P, Si) supply on the stability and persistence of pelagic food web structure and function in coastal areas.*

COMWEB is an integrated holistic approach to understand mechanisms behind coastal eutrophication and to assess the impact of human and natural nutrient supply in marine coastal systems. The project addresses effects of nutrient (N, P, Si) supply on the stability and persistence of pelagic food web structure and function in coastal areas, and important issues are establishment of unified analytical, numerical and experimental methods for assessing and predicting state and quality of marine coastal systems. The use of mathematical inverse methods allow establishment of elemental flow networks within reasonable efforts, and flow networks represent unified information which allow comparison of coastal waters over wide bio-geographical and trophic state gradients.

(C) RESEARCH STRATEGY

COMWEB is examining and comparing the effects of variable nutrient supply on the structure and function of the planktonic food web. This is done through analysis of unified flow networks (patterns of food web compartment sizes and fluxes in between them, Fig. 1) of the major biogenic elements C, N, P, and Si. The strategic blocks of COMWEB are:

- Reconstruction of flow networks are carried out using mathematical inverse methods
- The data needed to establish 1) representative flow networks and 2) nutrient perturbed flow networks for three extremes types of European coastal waters; Baltic, NE-Atlantic, and Mediterranean, are obtained in combined laboratory and field experiments. Data from eutrophic coastal waters, the southern North Sea, are used as reference.

- A conceptual base for unified diagnostic tools for assessment of trophic state in coastal waters is being established through comparative analysis of the regional flow networks. The potential of experimental determination of critical nutrient loads for maintenance of food web integrity is evaluated and compared from flow networks of nutrient perturbed food webs.
- Thorough studies of the functional characteristics of regional key species or groups of algae and zooplankton are being undertaken to improve the general mechanistic understanding of harmful eutrophication and the changes observed in the regional flow networks.
- The knowledge on fluxes and biomasses derived during establishment and analysis of the flow networks will at the end of the project be implemented in a biogeochemical mechanistic model.

1. WORKING PLAN

(A) TASK STRUCTURE

The task structure of COMWEB is as follows:

Task 1.	Functional characteristics of key components and processes in food webs
Task 2.	Persistence and stability of planktonic food web structure and function following short-term nutrient perturbations
Task 3.	Persistence and stability of planktonic food web structure and function following sustained, enhanced nutrient supply to open systems
Task 4.	Manifest responses of food web structure and function caused by sustained natural and man-caused nutrient enrichment to coastal seas
Task 5.	Data reduction, comparative analysis and synthesis
Task 6.	Mechanistic biogeochemical model

The stability and persistence of the pelagic food webs in different regional water types are examined in Tasks 1-3, and in particular in Task 2. The results will contribute to explore the potential of experimental determination of critical nutrient loads for maintenance of food web integrity in regionally representative pelagic communities.

The integrated knowledge gained in Tasks 1-5 on components, flows, and mechanisms behind coastal eutrophication are being used for further development of the mechanistic food web model MIRO. The predictive capacity of the revised biogeochemical model will be examined through comparison of stock and flow measurements (Tasks 2 and 4) and model predictions made with the revised model (Sub-goal 4).

Task 5 treats the mathematical tools of COMWEB, and the experience gained in the project will contribute to develop computational methods for unified comparative analysis of structure and function of pelagic food webs across geographical and trophic state gradients (Sub-goal 1).

(C) PRELIMINARY RESULTS

The experimental activity has been comprehensive through the first 18 months, and has included the main components:

- Species characteristics and model food webs in microcosm systems.
- Three major mesocosm experiments examining the short-term ecological response of nutrient perturbations in the pelagic food web (Baltic, Mediterranean, and NE-Atlantic waters).
- Time series in the Southern North Sea and in a lagoon system in Central Norway (The Norwegian Coastal Current), the latter being fertilised in 1998 (experimental eutrophication).
- Establishment of data management procedures and the theoretical framework for analysing data and constructing flow networks.

We will here report some preliminary results derived in mesocosms and some results from the testing of the method used for flow network construction.

Figure 2. Overview of experimental sites for mesocosm studies.

i) Mesocosm experiments

Mesocosm systems are primarily used to study and compare the short-term effects of quantitatively and qualitatively different nutrient supply on the stability and persistence of

structure and function of pelagic food webs in regional coastal areas. The search for quantitative dose-response relationships and critical nutrient loading rates are key questions.

Three major experiments has been run in Finland, Spain, and Norway (Fig. 2) within the first 18 months of the project. The experimental design was identical, although locally adapted, in all experiments (Table 1). The experiments were run as single-factor experiments of 2-3 weeks duration. The nutrients were added in daily portions throughout the experiments, in contrast to most previous work in mesocosms. Enclosed communities (7 or 8 mesocosms, volumes of 40-50 m^3, depth of 12-14m) were added an increasing amount of nutrients (NO_3/NH_4, PO_4, SiO_3) in fixed Redfield-composition (N:P:Si = 16:1:16, by atoms.

A main challenge in selecting the range of doses used was that the 2-3 mesocosms receiving lowest dose should not react very much, whereas at least the two highest doses should cause significant blooms. The highest concentrations chosen in Mesobal96 were approximately half that of Mesonor97, and less than one tenth of the highest concentration used in Mesomed97. This difference in treatment, which were based on local experiences, were the first signs of a variability in dose-response and critical load in the different regions.

Table 1. Review of experimental conditions of the mesocosm experiments treating dose response carried out in 1996 and 1997. Phosphate and silica was added along with nitrogen in Redfield proportions.

Experiment	Conditions	Range of nutrient additions mmol $N/m^{-3}day^{-1}$
Mesobal97- Finland July-August 1996	8 mesocosms linear increase in dose	0 –1.03
Mesomed98 – Spain June-July 1997	7 mesocosms geometric increase in dose (factor 2)	0 – 12.7
Mesonor97 – Norway August-September 1997	7 mesocosms geometric increase in dose (factor 1.7)	0 – 2.16

The chlorophyll development in the Mesonor97 mesocosms are shown in Fig. 3. The response in chlorophyll was almost immediate, and a substantial bloom, constituting mainly diatoms, developed after a week in the mesocosms which received most nutrients. There was generally a close positive relationship between nutrient dose and chlorophyll concentration. Mesocosm 3 was added doses believed to be equal to the average summer situation in the lagoon, which indeed showed similar chlorophyll values at least in the first period.

The response in chlorophyll as a function of nutrient dosage is shown in Fig. 4. The chlorophyll response is represented by the average chlorophyll value from day 9 when the mesocosms had reached an apparent equilibrium. The response is slightly accelerating at low doses, and it reaches an apparent maximum at doses >1-1.5 mmol $N/m^{-3}day^{-1}$. The figure suggests that there is a critical dose for these mesocosm communities at about 1 mmol $N/m^{-3}day^{-1}$ or 0.063 mmol $P/m^{-3}day^{-1}$.

A preliminary comparison shows that the Baltic food web is less stable and persistent during nutrient additions, whereas the Mediterranean food web is far more stable and persistent. This is

a preliminary conclusion which will be further elaborated based on a broader set of data on all groups of organisms.

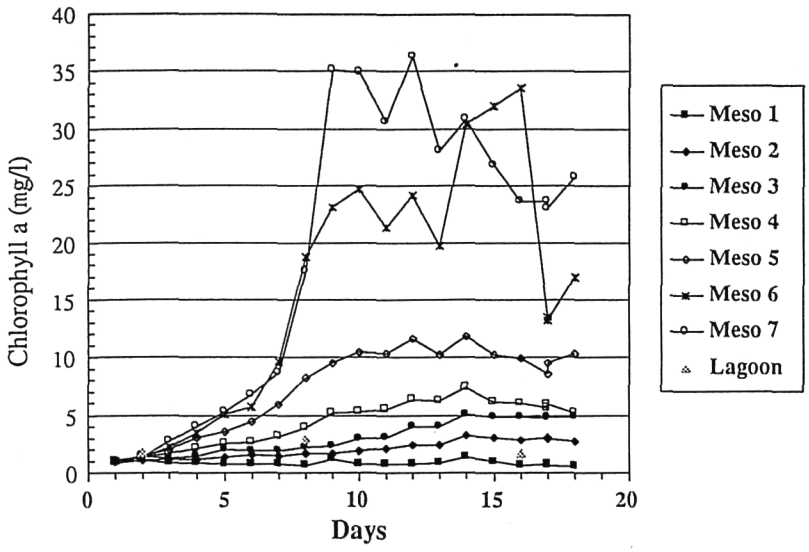


Figure 3. Development of chlorophyll with time in mesocosms added variable dose of nutrients, given in Redfield composition (from Mesonor97, doses are shown in Fig. 4).

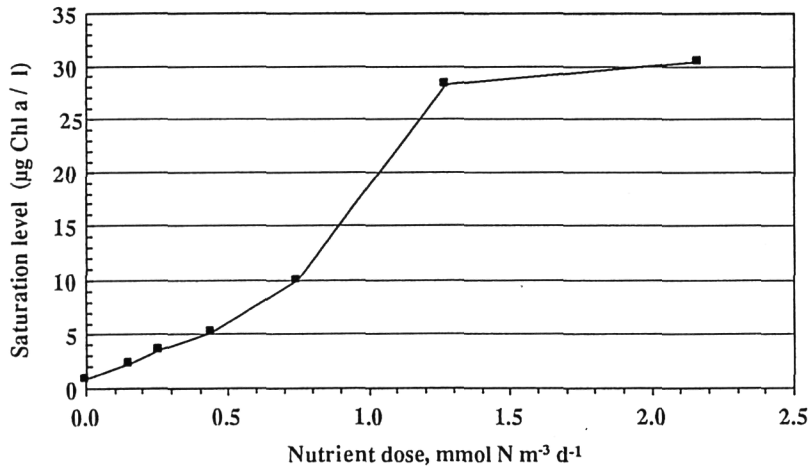


Figure 4. Response in chlorophyll as a function of the nutrient dose added. The chlorophyll value is the average chlorophyll concentration from day 9 onwards, the period when the mesocosms have reached an apparent equilibrium.

ii) Method for flow network construction

Flow network representations are useful for integrating measurements of biomass changes and process rates in biological systems. Since typical data sets are noisy and incomplete, such reconstructions are not trivial. The inverse method for flow network reconstruction proposed by Vézina and Platt (1988), has been successfully employed in several plankton food web studies (Jackson and Eldridge 1992, Stone et al. 1993, Vézina and Pace 1995, Lyche et al. 1996a,b). Still, the statistical properties of these methods have so far only been investigated to a limited extent. As part of our activities on evaluation and implementation of inverse methods within the context of COMWEB, we have initiated a series of Monte Carlo studies to assess the efficiency of different inversion procedures in reconstructing flow networks from synthetic input data generated by mechanistic food web models.

As a starting point, we have chosen to work with the nitrogen-based plankton dynamics model of Fasham et al. (1990). The particular choice of model is mainly based on the following factors: 1) it is reasonably widespread in the scientific community and also the ancestor of several more recent oceanic plankton models, 2) it is thoroughly documented and thus fairly easy to implement, 3) it has a sufficient level of flow complexity to make the network reconstruction non-trivial. At later stages in this process, more complex mechanistic models like MIRO (task 6) will be employed. In order to represent an experimental situation that corresponds to the core activities of COMWEB, we use the Fasham model to generate simulated mesocosm experiments. The enclosure of the water column is simulated by setting all mixing and entrainment variables to zero, and supplying nutrients (as nitrate) at a fixed rate for the duration of the experiment. All other model parameters are the same as in Fasham et al. (1990). Initial values for model state variables in the mesocosm simulations are taken from the stationary seasonal run of the full model.

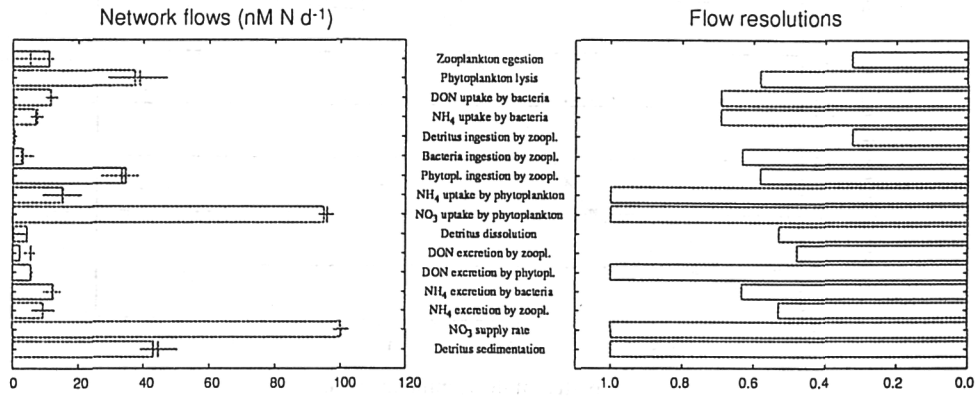


Figure 5. Monte Carlo simulation of flow network reconstruction from the Fasham et al. (1990) model. Left panel: Model generated N flows (bars) and N flows reconstructed from 1000 Monte Carlo samples by the inverse method (medians and 95% confidence limits). Right panel: *a priori* flow resolutions.

We use Monte Carlo methods to quantify bias and uncertainty in the flow networks generated by the inversion procedure. For a given simulated mesocosm experiment, we can easily generate a large number of synthetic observations, which can be run through the inversion procedure. The 95% confidence limits resulting from 1000 Monte Carlo data sets to the

inversion procedure are shown in the left panel of fig. 5. The general impression is encouraging: the inverse method is able to give unbiased estimates with reasonable precision for the majority of flows in the model food web. In other words, it seems indeed feasible to identify the flow structure of a generic plankton community, based on more or less standard methods of plankton ecology. In particular, it is surprising that the inverse method is able to resolve fluxes that are difficult to incorporate in routine sampling programs, such as the grazing fluxes from phytoplankton and bacteria to zooplankton – even without any direct measurements of grazing rates. The major exceptions are the flows between detritus, DON, and zooplankton, which are strongly biased. As can be seen from the right panel of fig. 5, these flows are also badly resolved according to the flow resolution index proposed by Vézina and Platt (1988). Since the flow resolution index is dependent only on the structural assumptions and experimental design, but not on the actual measurements, this index holds promise as a tool for *a priori* assessment of which flow estimates that can be improved adding additional measurements or by changing the structural.

iii) Comparative analysis of food webs

A long-standing goal of food web studies is to identify regular and repeatable patterns in the flows of energy and materials, and to compare these flow properties within and among systems. Flow networks can form the basis for constructing low-dimensional indices or aggregated measures for comparing different food web structures; such as cycling indices (Finn 1976), flow diversity and redundancy indices (Ulanowicz 1986), and ordination techniques (Vézina and Pace 1995). Even if flow network models are inherently linear, Vézina and Pace (1995) have shown that network-based analysis can nevertheless be used to make inferences about treatments resulting in highly non-linear changes to the food web. Indices based on flow properties (i.e. flow network properties) may turn out to have potentials as general indicators for the state of a food web, emphasizing functional aspects to a greater extent than possible with traditional biological indicators based on species inventories. While species inventories might be expected to change among biogeographical regions, one should still be able to identify more or less the same major food web components and intercompartmental flows. A flow-oriented food web description might therefore be more appropriate for comparing community responses over a regional dimension.

REFERENCES

Carpenter, S. R. 1988. *Complex interactions in lake communities*. Springer- Verlag.

Carpenter, S. R. and J. F. Kitchell. 1993. *The trophic cascade in lakes*. Cambridge Univ. Press. 385 pp.

Fasham, M. J. R., H. W. Ducklow and S. M. McKelvie. 1990. A nitrogen-based model of plankton dynamics in the oceanic mixed layer. J. Mar. Res. 48: 591-639

Finn, J. T. 1976. Measures of ecosystem structure and function derived from analysis of flows. J. Theor. Biol. 56: 363-380

Hairston, N. C., F. E. Smith, and L. B. Slobodkin. 1960. Community structure, population control, and competition. Am. Nat. 94: 421-425

Jackson, G. A. and P. E. Eldridge. 1992. Food web analysis of a planktonic system off Southern California. Prog. Oceanogr. 30: 223-251

Lyche, A., T. Andersen, K. Christoffersen, D. O. Hessen, P. H. B. Hansen & A. Klyssner. 1996a. Mesocosm tracer studies: 1. Zooplankton as sources and sinks in the pelagic phosphorus cycle of a mesotrophic lake. Limnol. Oceanogr. 41(3): 460-474

Lyche, A., T. Andersen, K. Christoffersen, D. O. Hessen, P. H. B. Hansen & A. Klyssner. 1996b. Mesocosm tracer studies: 2. The fate of primary production and the role of consumers in the pelagic carbon cycle in a mesotrophic lake. Limnol. Oceanogr. 41(3): 475-487

Menke, W. 1989. *Geophysical data analysis: Discrete inverse theory.* Academic Press. Int. Geophysics series, vol. 65. 289 pp.

Sterner, R. W. and D. O. Hessen. 1994. Algal nutrient limitation and the nutrition of aquatic herbivores. Annu Rev Ecol Syst 25: 1-29

Stone, L., T. Berman, R. Bonner, S. Barry & S. W. Weeks. 1993. Lake kinneret: A seasonal model for carbon flux through the planktonic biota. Limnol. Oceanogr. 38: 1680-1695

Tarantola, A. 1987. *Inverse problem theory.* Elsevier. 613 pp.

Ulanowicz, R. E. 1986. *Growth and development. Ecosystems phenomenology.* Springer-Verlag. 203 pp.

Vadstein, O., B. A. Harkjerr, A. Jensen, Y. Olsen and H. Reinertsen. 1988. Cycling of organic carbon in the photic zone of a eutrophic lake with special reference to the heterotrophic bacteria. Limnol. Oceanogr. 33: 489-503

Vadstein, O., Y. Olsen, H. Reinertsen and A. Jensen. 1993. The role of planktonic bacteria in phosphorus cycling in lakes – sink and link. Limnol Oceanogr 38: 1539-1544

Vézina, A. F. & T. Platt. 1988. Food web dynamics in the ocean. I. Best-estimates of flow networks using inverse methods. Mar. Ecol. Prog. Ser. 42: 269-287

Vézina, A. F. and M. L. Pace. 1995. An inverse analysis of plankton food webs in experimental lakes. Can. J. Fish. Aquat. Sci. 51: 2034-2044

TITLE: **Physical forcing and biogeochemical fluxes in shallow coastal ecosystems (project PhaSE, ELOISE)**

CONTRACT NO: (MAS3-CT-0053)

COORDINATOR: Dr. F. Møhlenberg
VKI – institute for the water environment
Agern Allé 11, 2970 Hørsholm, Denmark
Tel.no. (Fax): +45 45169523 (9292)
E-mail: flm@vki.dk

CO-COORDINATOR: Dr. J.K. Petersen
National Environmental Research Institute, NERI
Frederiksborgvej 399
PO Box 360, 4000 Roskilde, DK
Tel.no (Fax): +45 46301295 (1114)
E-mail: jkp@DMU.dk

PARTNERS:

Dr. Walter Eifler
European Commission, Joint Research Centre, Space Application Institute
I-21020 Ispra (Va), I
Tel.no (Fax): +39 332789415 (9034)
E-mail: walter.eifler@jrc.it

Dr. Peter Herman
Nederlands Instituut voor Oecologisch Onderzoek, NIOO
Centre for Estuarine and Coastal Ecology
Vierstraat 28, NL-4401 EA Yerseke, NL
Tel.no (Fax): +31 113571920 (3616)
E-mail: herman@cemo.nioo.knaw.nl

Dr. P. Jonsson
Tjärnö Marine Biological Laboratory, TMBL
SE-45296 Strömstad, SE
Tel. No (Fax): +46 52668627 (607)
E-Mail: Per.Jonsson@tmbl.gu.se

Dr. C. Duarte
Centre d'Estudis Avancats de Blanes
Camí de Santa Bárbara, CEAB
17300 Blanes (Girona), E
Tel. no (Fax): +34 72336101 (7806)
E-mail: duarte@ceab.es

Dr. T.C. Prins
National Institute for Coastal and Marine Management, RIKZ
POBox 80394330 EA Middelburg, NL
Tel. No (Fax) +31 118672285 (616500)
E-mail: t.prins@rikz.rws.minvenw.nl

Physical forcing and biogeochemical fluxes in shallow coastal ecosystems (project PhaSE, ELOISE)

F. Møhlenberg
VKI – institute for the water environment
Agern Allé 11, 2970 Hørsholm, Denmark

J.K. Petersen
National Environmental Research Institute
Frederiksborgvej 399, PO Box 360
4000 Roskilde, Denmark

SUMMARY

The shared cost action project PhaSE, an interdisciplinary study of the influence of physical forcing (tide, wind, solar radiation) on biogeochemical fluxes in European coastal waters, started on 1 June 1996 and runs for 3 years. A key element in PhaSE is campaign periods carried out in 3 European coastal waters of contrasting energy input, with contemporaneous measurements of physical mixing processes and biogeochemical fluxes.

1. INTRODUCTION

Coastal marine ecosystems are widely distributed throughout Europe. They receive large volumes of anthropogenic wastes, on one hand, while the biotic resources of these ecosystems are being heavily exploited, on the other hand. In recent decades there have been numerous reports of dramatic changes in the biological structure and processes in coastal ecosystems, many of which have been attributed to human activities. As many European societies are heavily dependent on the coastal environment it is of utmost importance to understand the basic physical, chemical and biological processes that structure coastal ecosystems. Otherwise, we will not be able to distinguish between ecosystem changes caused by natural events and human activities.

Estuaries and coastal seas are among the most productive ecosystems in the biosphere. Food chain efficiency is generally high, and secondary production, including fisheries yield, per unit nutrient load are generally higher than in lakes or oceans. The underlying mechanisms for the high production are poorly understood, but the interactions between the benthic and pelagic environment in these shallow systems are likely to be important. In contrast to deep, stratified ecosystems where exchange of matter and energy between the pelagic and benthic zone occurs on an annual scale, coupling between the mainly autotrophic pelagic zone and the mainly heterotrophic benthos varies on a continuum in time, from hours to months, depending on the intensity of vertical mixing and establishment of stratification. By that mechanism a relative small input of physical energy from the wind or tide can modify the effects of the much larger energy inputs of solar and chemical energy and thus direct the biological processes that structure coastal ecosystems.

Several gaps in our understanding of important biogeochemical processes have been filled in recent years (e.g. SAFE (MAST-0020-C), MEICE (MAST 2-CT92-0031), however the importance of physical forcing and high frequency variability on biogeochemical processes in shallow coastal waters hitherto have been almost completely ignored, primarily due to lack of

technology. Turbulent mixing and benthic boundary layer processes in shallow water are extremely complex and vary rapidly, and the techniques to measure and record time series of all the relevant parameters at high frequency has simply not been available. Recent improvements in instrumentation (i.e. MICSOS (EUREKA/EUROMAR)), however, now allow us to measure spatial and temporal variation in turbulent kinetic energy dissipation rate directly, even close to the water column boundaries: atmospheric-water, water-sediment interfaces. Given these opportunities we have put together a cohesive, interdisciplinary project PhaSE, addressing the effect of physical forcing functions on biological processes in coastal ecosystems.

The central objectives of the research are a) to determine how biogeochemical fluxes and trophic structure in coastal ecosystems are related to the nature and strength of physical forcing functions and b) to evaluate the importance of biological macro-structures in modifying the physical mixing processes in the benthic boundary layer. These objectives are fulfilled by:

• determining how turbulent dissipation rates and vertical mixing intensity respond to the physical forcing functions: tide, wind and heat flux;

• determining the relationship between vertical mixing intensity and the role of macrobenthic suspension feeders in structuring and controlling planktonic populations;

• determining the relationship between near-bed current velocity, particle flux and food uptake in macrobenthic suspension feeders. In this context, we are interested in to what extent the presence of macrobenthic organisms (e.g. mussels and macrophytes) modify near-bed turbulence and hence, vertical food flux;

• integrating the obtained knowledge into a mechanistic dynamic model for shallow coastal environments by linking a set of biogeochemical process models directly to a physical transport/turbulence model allowing a high spatial and temporal resolution.

To address these objectives, an interdisciplinary team of European scientists from 5 countries representing expertise within boundary-layer physics, nutrient cycling, autotrophic and heterotrophic processes and ecological modelling has been assembled. A key element in PhaSE is campaign periods carried out in 3 European coastal waters of contrasting energy input, with contemporaneous measurements of physical mixing processes and biogeochemical fluxes. Focussed studies by individual partners will supplement the campaign studies and thereby provide the necessary data for building the integrated model. In the PhaSE the main focus is on physical and biogeochemical interactions on the vertical scale in the coastal zone. Therefore, PhaSE is complementary to recent and ongoing international research programmes including several MAST projects focussing on the interaction between physics and biogeochemical fluxes on larger horizontal scales (e.g. Integrated modelling (MAST-0050-C), EROS 2000 (MAST-0063-C)).

2. WORK

The work of PhaSE is organised into 5 major tasks, each forming a natural entity. The main responsibility for each task is allocated to one of the partners.

Task 1: Physical mixing functions, the vertical mixing of the water column as a function of difference in intensity of driving forces are studied. Equipment and methodologies to study turbulence and physical microstructure are developed and used during campaign periods.

Task 2: *Bentho-pelagic coupling*, effects of turbulence and vertical mixing on biological structure and coupling between benthic suspension feeders and pelagic communities are the main theme. Different approaches including laboratory experiments, mesocosms and field studies are employed.

Task 3: *Benthic boundary layer* studies the particle flux in the benthic boundary layer as a function of near-bed hydrodynamics, the benthic boundary layer being the border between the benthic and planktonic communities. A part of the studies focus on suspension feeding in the benthic boundary layer.

Task 4: *Benthic canopies* studies the modifying effect of plant canopies on hydrodynamical conditions, light penetration and particle flux to and from the benthic community.

Task 5: *Integrate* the results of the other activities by building a coupled physical-biogeochemical model. Results from the campaign periods together with process models developed within the different tasks are joined into a common coastal zone model.

Highlights from the first campaign period in Oosterschelde, NL are presented below together with selected results from focussed studies by individual partners.

2.1 Measurement Campaign Oosterschelde

Time: 20.06.96 - 28.06.96
Place: Oosterschelde Zandkreek site, 51° 33,4' N 3° 54,5' E
Depth: -1.5 m - 28 m
Ships: R/V Luctor from NIOO, various smaller boats.

Principal measurements and instruments
Subtidal:

- meteorological forcing (meteorology mast installed on R/V Luctor)
- water column forcing (mooring with Anderaa current meters and CTD, tripod with magnetic current meters)
- falling EDP profiler, one cast every 20 min.
- rising EDP profiler, one cast every 20 min.
- nutrients (every 24 h)
- suspended solids, vertical profiles every 3 h
- chlorophyll, vertical profiles every 3 h
- phytoplankton composition and growth rate
- mussel grazing rate

Intertidal:

- water column forcing (tripod with electromagnetic current meters)
- nutrients (every 24 h)
- vertical profiles of current velocity and direction in- and outside mussel beds
- vertical profiles of suspended solids in- and outside mussel beds
- vertical profiles of chlorophyll in- and outside mussel beds
- phytoplankton composition and growth rate
- degradation of organic matter in sediments inside mussel beds

The measurement location and the applied deployments at the subtidal site are indicated in Fig. 1.

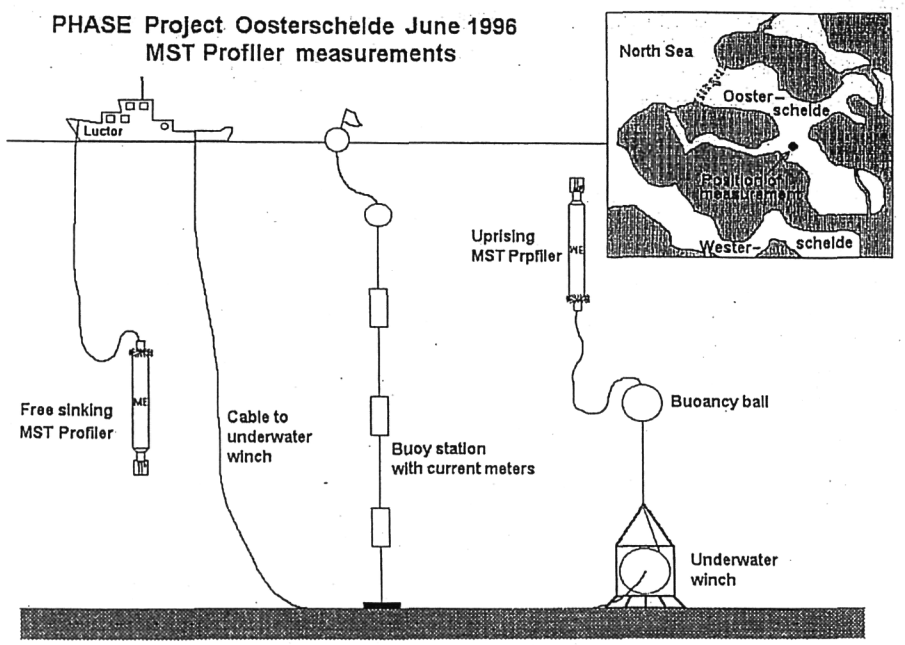


Figure 1: Location of Oosterschelde measurements and applied experimental set-up, comprising buoy station and a sinking and rising MST profiler.

General conditions:
The measurement location was characterised by a strong slope from the inter-tidal flat to the ship channel of about 30 m depth over a distance of about 400 m (slope 0.07). The tidal range is about 3 m, the tidal period about 12.4 hours. The water column was nearly well mixed with a maximum vertical variations of about 0.5 K and 0.4 PSU. Temporal variations were of comparable magnitude. Tidal currents of up to about 1 m s^{-1} are typical for the Oosterschelde, the measurement location is further characterised by a residual current of about 0.1 m s^{-1}.
Prevailing North-westerly winds about 6-10 m s^{-1} appeared the first five days, thereafter the wind was only weak (2 ms^{-1}) blowing from changing directions. Because of strong winds the vessel had to relocate several times. The changing position of Luctor imposed problems on the microstructure measurements, because the anchor chain made a mess with the underwater winch.

This lead to additional gaps in the time series of the uprising profiler. Altogether 595 profiles were collected from the falling probe, from which 575 were used for the data elaboration. The rising probe collected 370 profiles.

Data were compressed to 0.2 m intervals. Salinity and density were then calculated and data were low-pass filtered with a Gaussian filter.

Table 2. Overview of sensor data used in Enhanced Dissipation Profilers in Oosterschelde.

Sensor used	Falling EDP	Rising EDP
Precision temperature	✔	✔
Precision conductivity	✔	✔
Precision pressure	✔	✔
Shear sensor	✔	✔
Reference shear sensor		✔
Fast temperature	✔	✔

Dissipation rate was calculated according to Prandke and Stips (1996), applying a band-pass filter for eliminating unwanted shear variance in an iterative manner. Every 0.2 m interval one dissipation estimate was calculated (non-overlapping). From the reference shear data a reference dissipation rate is calculated. A threshold criterion for reference dissipation is then applied for eliminating vibration contaminated dissipation estimates.

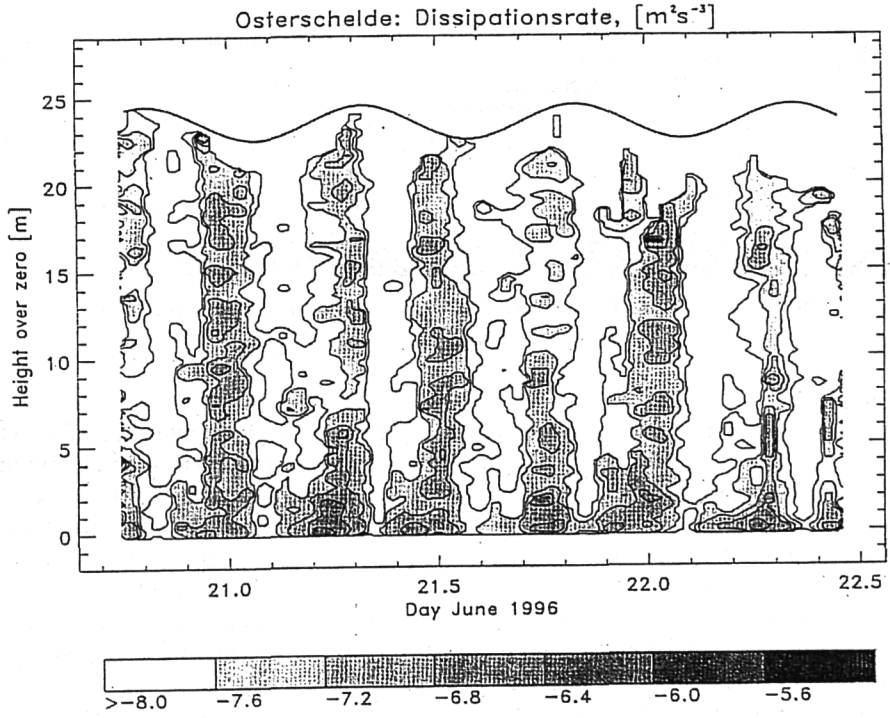


Figure 2: Temporal and vertical variation of the dissipation rate during 42 hours.

The dissipation was related to the M4 component of the tidal cycle (period about 6 hours). This is seen in Fig. 2, where the increase in dissipation starts at the bottom (less then 1 h after the break down) and is propagating upward until the maximum appears. Thereafter a rapid break down (< 1 h) of dissipation throughout the whole water column appears. Despite high currents and dissipation rates the water column was not completely mixed, although the vertical stratification was weak (not shown).
The measured dissipation rate compared favourably to dissipation rate calculated from the current speed using the k-ε turbulence closure (Burchard & Baumert, 1995, Burchard & Petersen, 1998).

Fig. 3 shows a contour plot of sediment concentration in the water, as determined at three depths over a time interval from the R/V Luctor. For reference, the wind speed as measured on the Luctor is plotted above this contour plot.

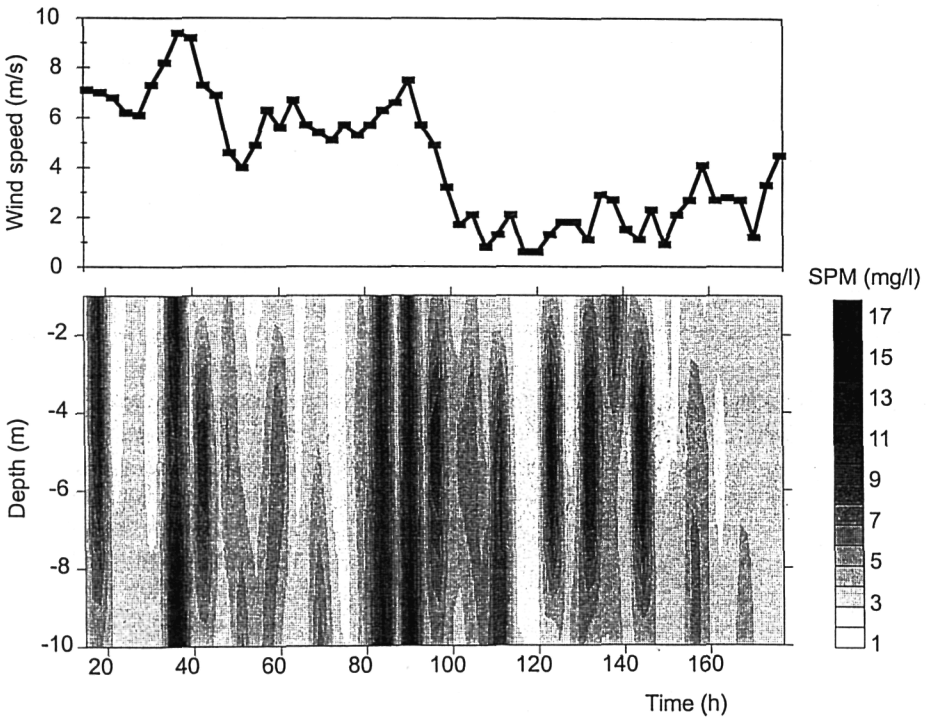


Figure 3. Contour plot of sediment concentration in the water at the subtidal site. For reference, the wind speed is plotted above the contour plot.

Although the vertical resolution in the sampling was not sufficient to resolve possible suspended matter gradients very near to the bottom, the general picture in Fig. 3 is the lack of vertical structure in the SPM content. At almost all times the water column appears to be well mixed, which is partly consistent with the salinity and temperature data obtained. Throughout the period of sampling, three periods with elevated suspended matter concentrations were observed: right at the beginning of the measurements, around hour 40 and around hour 90. These peaks coincide with peaks in wind speed, and are most probably the result of resuspension at more shallow sites in the Oosterschelde. Some elevated mid-water values were observed around hour 130. It is unclear what caused these patterns.

The concentration of inorganic nutrients varied profoundly at the subtidal site. The increase during the period of low solar insolation (22-26 June) was mirrored in the decreasing concentration of chlorophyll (Fig. 4), and probably reflects dominance of heterotrophic over autotrophic processes in the water column during this period. The stochiometry of mineralisation (i.e. μg Chla/μM NH_4^+; -/μM PO_4^{3-}; -/μM SiO_2) suggest that ca 30% of the nutrients stem from the algae.

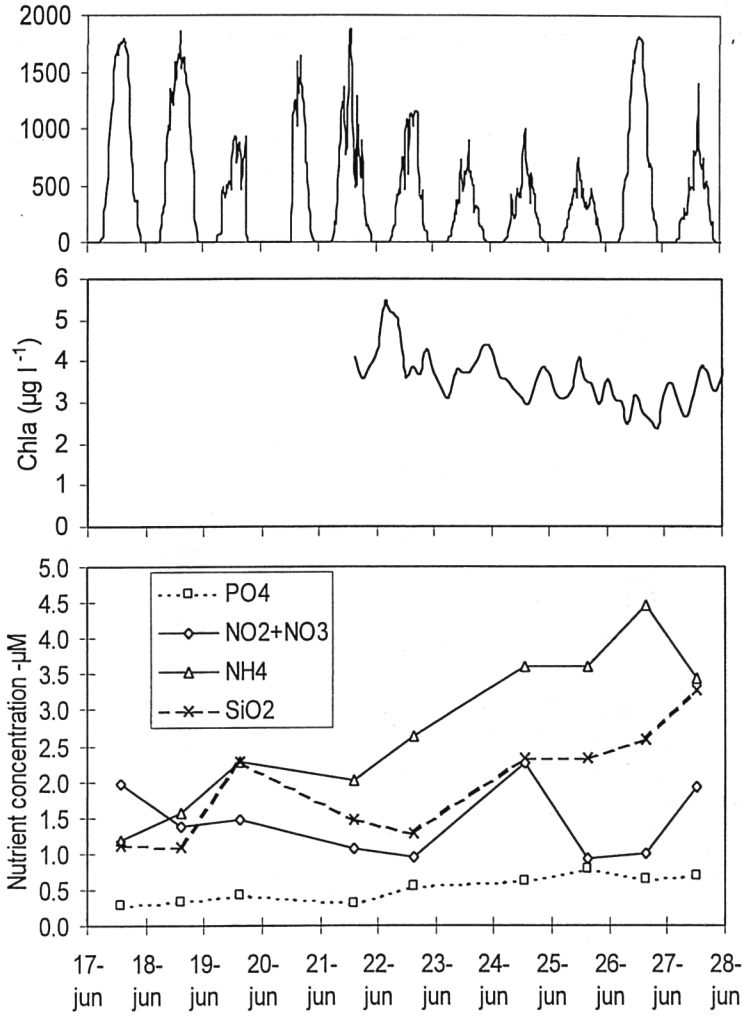
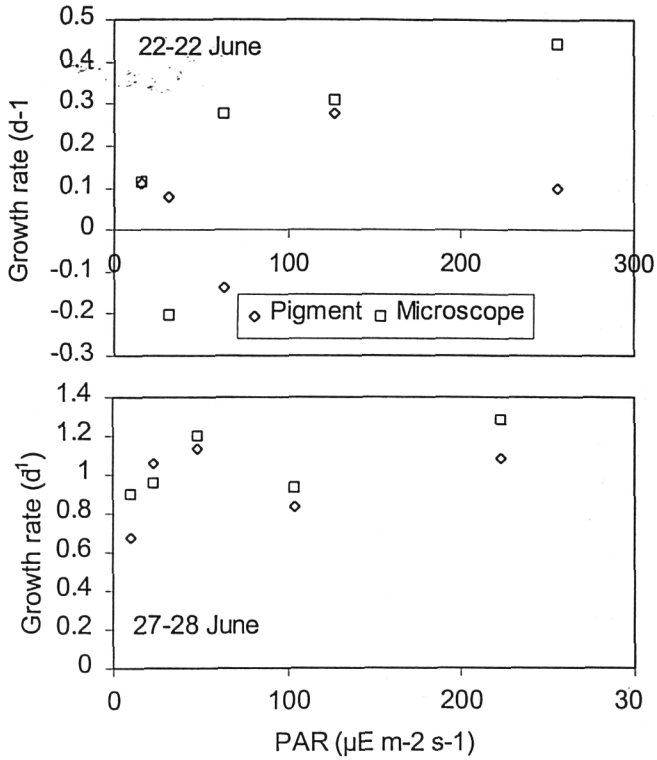


Figure 4. Photosynthetic active radiation at surface (top, μE m^{-2} s^{-1}), concentration of chlorophyll a (middle, 9 h moving average) and concentration of inorganic nutrients (bottom) at the subtidal site (Luctor). Mean of 3 depths.

Net growth of phytoplankton was estimated from in situ incubations (Møhlenberg 1995). Briefly, concentration and composition were quantified by 1) HPLC analysis for diagnostic pigments (Schlüter & Havskum 1997) and 2) microscopic counting at start of incubation and after 24 hours. Eight sets (subtidal and intertidal station) of incubations were carried out. Net growth rate varied between – 0.4 and 1.8 d^{-1} depending on algal species and availability of nutrients and light (see Fig. 5). Averaged over the water column net autotrophic growth varied between 0.2 and 1.1 d^{-1} on the subtidal flats. These rates do not include loss due to grazing from the benthic mussels present at high densities at inter- and subtidal culture plots.

Filter-feeding mussels occur in high densities at depths less than 10 m. Their filtration activity constitutes a important loss for planktonic algae transported by tidal advection from the deep gully. However, being associated with the bottom mussels rely on vertical mixing and transport processes to bring algae near to their feeding region in the bottom boundary layer. Furthermore, the food resource of these bivalves needs to be better defined which



involves analysis of the near-bed flux of particles. In particular, there is a lack of knowledge considering the role of larger particles including aggregates which, based on sedimentology theory, are expected to show considerable accumulation in the near-bed region under certain hydrodynamic regimes. To this end we have developed a non-intrusive optical method to measure particle concentration, particle size and flow velocity in the benthic boundary layer. For comparison we have estimated the near bed flux of small particles using current meters and siphon mimics to collect suspended matter in various heights above the bottom.

Figure 5. Growth rate of diatoms at subtidal station. Diatoms constituted >90 % of algal biomass during the campaign in Oosterschelde. The growth of algae was estimated by incubating 5 L samples in transparent bags at 5 depths throughout the water column for 24 hours. Concentration at start and end of incubation was estimated by pigment analysis using HPLC and microscopic counts. Net growth rate was low during the period of low nutrient concentration. At high nutrient concentrations the net growth rate was larger than 1 d^{-1} at photosynthetic available radiation (PAR) above 30 $\mu E\ m^{-2}\ s^{-1}$.

Video-recording of near-bed particles

Particle flux in the near-bed region was recorded with a newly developed *in situ* video system based on a rod-lens borescope. The viewing angle is 90° allowing a side view of horizontal particle transport when the borescope is lowered perpendicular to the sediment surface (Fig. 6). The borescope is fitted to a light-sensitive black and white CCD video camera and built into an under-water casing. The scanning frequency is about 100 Hz which produces two images of each particle if translating in the plane of the sheet. The field of view at the distance of the laser-illuminated sheet is 1.85 x 1.3 cm (width x height) giving a total sample volume of 1.44 ml. Allowing for noise and the limited thickness of the laser-sheet, particles in the size range 0.1 to 3 mm could be analysed.

The recorded sequences were digitised using sequential frame-grabbing software. Between 300 and 500 independent frames were sampled from each 3-min sequence. The batch of digitised frames from each sequence was then analysed for the number of particles, x- and z-coordinates, length of major and minor axes and area of each particle image. The video-recorded particles in the near-bed flow were used as flow markers for estimates of flow velo-

city. Due to the over-scanning (100 Hz) of the laser beam many particles were represented by two images on each frame. From measurements of the laser scanning velocity it was possible to calculate the time difference between doublet particle images which allowed the instantaneous flow velocity to be estimated.

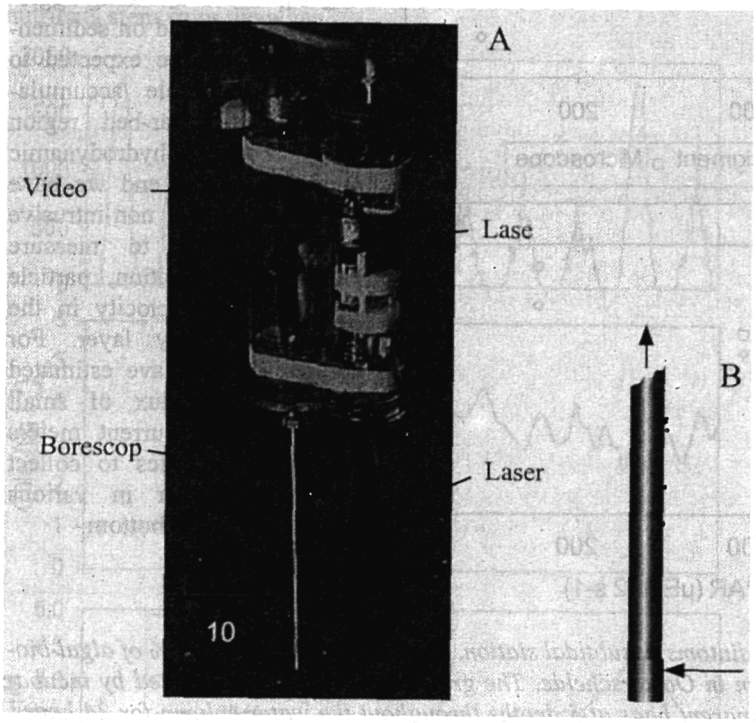


Figure 6. A. Unit with borescope, video camera and laser used for optical recording of near-bed particles. A known volume of illuminated particles in front of the borescope lens is generated with a laserscanning system. The collimated beam of an infra-red laser is deflected with an oscillating mirror generating a laser-illuminated sheet of 6 mm thickness. B. The tip of the borescope with arrow indicating the side-view optics.

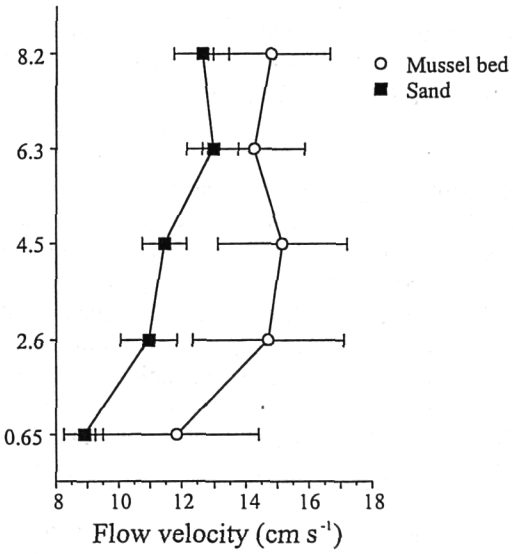


Figure 7. Flow velocity as a function of the height above the bottom (mean± 95% CI).

As expected from the tide-driven Oosterschelde with its coarse sand and mussel beds the flow was rough turbulent ($Re_* = 10\text{-}100$) and in the near-bed region (0-9 cm) flow velocities from 3.7 to 26 cm s^{-1} were recorded (Fig. 7). Root-mean-square of the flow was on average ca 20% of the velocity. In accordance with Rouse's theory of vertical particle gradients in shear flow more particles accumulated close to the bed (not shown). However, this effect was rather weak which is expected considering the high shear velocities found which will promote mixing of most particles except for those with fast fall velocities (> 1 mm s^{-1}). The distribution of particle sizes was also consistent with Rouse's theory where significantly larger particles occurred close to the bed.

Particle volume for each vertical layer was then multiplied with the estimated flow velocity to obtain flux of larger particles. No difference between the two bed types could be detected, again with low statistical power due to large differences among dates. At some dates there was a tendency that flux increased towards the bed.

Vertical algal gradients - siphon mimics

As a supplement and an extension to the video recording of larger particles we used siphon mimics to collect samples for quantifying smaller sized particles in the benthic boundary layer. As only the siphons were extending above the sediment surface physical disturbance were kept at a minimum (see Fig. 8). Samples were collected through 20 m plastic tubes and subsequently analysed for chlorophyll and particle size distribution (Elzone particle counter).

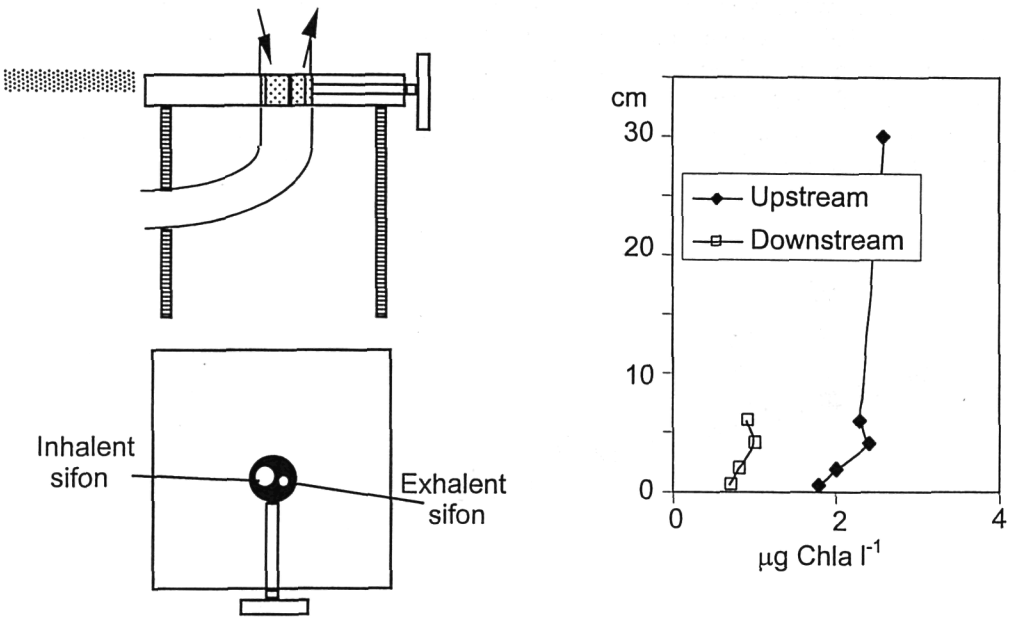


Figure 8. Left: schematic drawing of siphon mimic. Water can be sampled from various heights above the bottom through the inhalent aperture using a multi-channel peristaltic pump. Up to 9 sets were used to carry out synoptic samplings to characterise vertical and horizontal distribution of particles in the benthic boundary layer. Right: example of concentration of Chla sampled with mimic siphons at different distance from bottom (26 June 1996, 10:00). Values from positions upstream and downstream a large bed with mussels and oysters (ca 20 x 20 m). Currents at 2 cm and 65 cm above bottom were 1.5 and 8.2 cm s^{-1}, respectively. Assuming a logarithmic current profile in the benthic boundary layer the instantaneous loss of chlorophyll in the bed was calculated to ca 80 µg Chla m^{-2} min^{-1}.

Within mussel beds concentration of chlorophyll decreased in the benthic boundary layer due to bivalve filtration. The concentration profile showed the strongest gradient at low current speeds. Outside mussel beds, on the other hand, concentration was uniform throughout the water column. The decrease in concentration across the bivalve bed allowed us to calculate the actual filtration of the mixed bivalve population at a horizontal scale of meters (see Fig. 8). During a tidal cycle (during immersion) the loss due to filtration varied between 50 and 90

µg Chla m^{-2} min^{-1}. With an average concentration of 1.2 µg Chla l^{-1} in the benthic boundary layer the loss was equivalent to a population clearance rate of 40-75 l m^{-2} min^{-1}. Based on the abundance and size distribution of mussels and oysters in the bed the theoretical clearance rate was calculated to 65 l m^{-2} min^{-1}. Hence, the filtration capacity of the benthic bivalves was fully exploited. However, as reflected by the low food concentration in the benthic boundary layer and in the strong vertical chlorophyll gradient, the removal of algae (i.e. ingestion rate) was not satiated because of limited vertical mixing.

Horizontal algal gradients – large scale grazing impact

Filter-feeding mussels occur in high densities on the tidal and subtidal lease plots in the Oosterschelde. Juvenile mussels are dredged in the Wadden Sea and deployed on subtidal plots. During growth stocks are relocated several times. Therefore, density and mean size show great variation between plots, while the within-plot variation usually is small. By release of drifting buoys from the anchor station at rising tide we determined a characteristic advective track from the gully to the intertidal flat. Along this track we took quantitative samples for estimating the clearance capacity (calculated from abundance and size distribution) of mussels (Fig. 9).

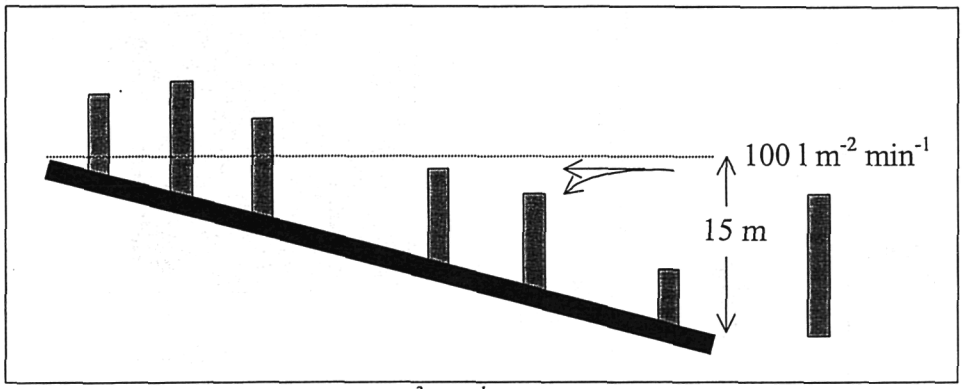


Figure 9. Estimated clearance rate (l m^{-2} min^{-1}) of mussels in the subtidal and intertidal zone in Oosterschelde (see Fig.1). Horizontal distance 800 m. For reference a value-bar is shown.

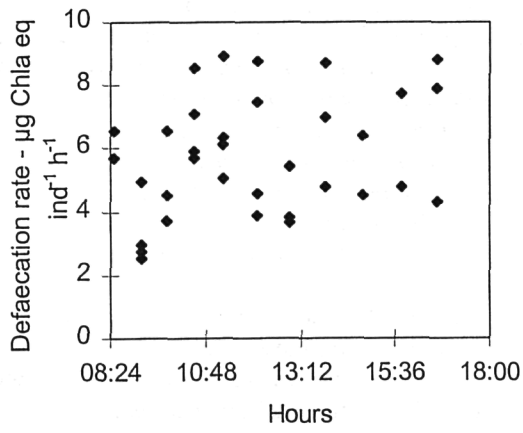


Figure 10. Rate of defaecation in mussels (50 mm) through a tidal cycle at subtidal site.

The individual grazing rate was estimated from the rate of defaecation of chlorophyll equivalents (Chla + phaeopigments) in mussels. Mussels were sampled through a tidal cycle, transferred to small beakers with filtered water and faeces collected every 20 min through 2 h (Fig. 10). At steady-state ingestion rate will equal defaecation + loss due to absorption and breakdown of pigment in the gut. The loss was estimated in aquaria experiments to ca 30 % of ingestion h^{-1}. The rate of defaecation (and ingestion) in the subtidal population showed substantial individual variation but the rate was unrelated to tidal period.

Following the drifting buoys water was sampled regularly for chlorophyll analysis. The reduction along the track (from anchor station to intertidal flat) varied between 6 and 35 % on different days. Based on this reduction and the current speed the mean ingestion rate of chlorophyll along the 800 m track was estimated to 70-140 µg Chla m^{-2} min^{-1} (see Fig. 11). These rates compared favourably to the population defaecation rate (corrected for loss) that was estimated by an independent method (defaecation, see above) but also to the rate calculated from the small scale variation using siphon mimics (see Fig. 8).

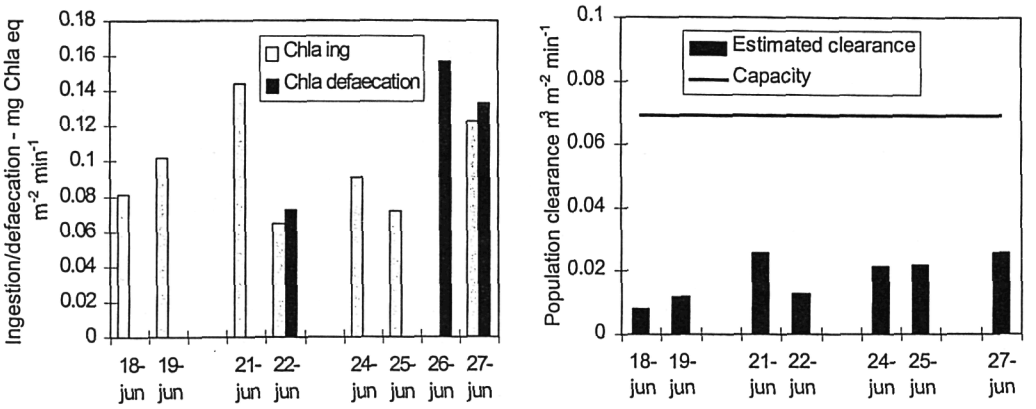


Figure 11. Left: ingestion rate calculated from horizontal decrease in chlorophyll concentration and defaecation rate; right: estimated and maximal clearance rate of the mussel population.

The realised mean clearance rate of the mussel population was less than 30 % of the capacity calculated from the abundance and size distribution (Fig. 11). The low efficiency was probably related to (too) high stocking of mussels and limited vertical mixing in the benthic boundary layer.

2.2 Hydrodynamics and particle distributions in and around the sea-grass beds

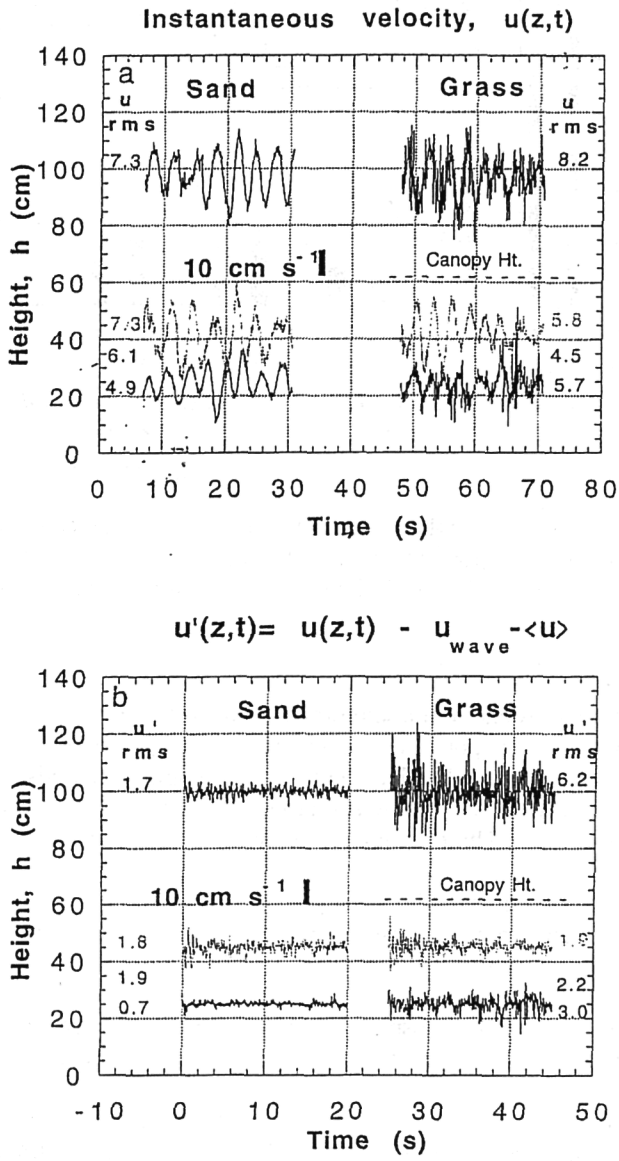
The effect of sea-grass beds on particle transport and associated benthic processes were studied in *Posidonia* spp beds in Spain. The studies have entailed developing methods for measurements of velocity and particle distributions above, and around plant canopies on both fine and coarse spatial and temporal scales. Three scales are relevant to transport in these canopies:

1) Large scale (10 m-1 km and times of hours-days);
2) Small scale (0.25-50 m and times of minutes-hours);
3) Fine scale (mm's-cm's and seconds).

A number of methodologies to study momentum transport in canopies on these three scales have been employed. In this context only the fine scale methodology will be described.

The velocity profiles are measured using an *in situ*, Acoustic Doppler Velocimeter equipped with a compass/tilt sensor (SonTEK, Inc. San Diego, CA, USA) attached to a vertical frame to stabilise it on the sea bottom. The ADV measures velocity at a small volume of approximately 3 cm^3 centred at a distance of 18 cm in front of the transmitting acoustic transducer. The sensor can be positioned so that measurements are made on a small, undisturbed volume of water, away from upstream perturbations of the flow field.

The measurements provide time series of the 3 velocity components (u, v, w), at fixed depths, with each depth corresponding to the distance from the bottom to the centre of the sampling volume. At each depth, velocity is sampled at 25 Hz (25 times per second) for duration of between 2-5 minutes. ADV data are preconditioned by a series of signal processing boards and put in engineering units by the acquisition software. Estimates of the mean velocity profile are calculated as root mean square of the time series at fixed depths. In this way, shear velocity (the vertical gradient of the dominant horizontal components, dU/dz) can be estimated as a function of canopy characteristics, such as plant density, leaf area, void volume, and canopy height.



For the fine scales, turbulent velocities, Reynolds stresses, and vertical diffusivity are calculated from ADV time series. Vertical turbulent diffusion is estimated using the model, $K_z = -\langle u'w' \rangle / (dU/dz)$, where $\langle u'w' \rangle$ is the average Reynolds stress and dU/dz is the vertical shear. Additional details of measurements of Reynolds stresses using ADV's can be found in Lohrmann et al. (1994). Fluctuating velocities (i.e. u' and w') are calculated by subtracting wave and mean velocity components from the instantaneous velocities, i.e. $u'(z,t) = u(z,t) - u_{wave} - \langle u \rangle$. To remove influence from waves, curve smoothing is performed, either using a 4 point moving average or a sine fit. The velocity that results by removing the mean velocity ($\langle u \rangle$), the unsteady flow (f[u(t)]), and the wave velocity (u_{wave}) is the turbulent velocity or the fluctuating velocity, u' (Fig. 12b). This processes is repeated on the v and w components to give v' and w' velocities.

Figure 12. a: 60 s time series of instantaneous vertical velocity (w component) at 25, 45 and 100 cm above the bottom above sand (left) and a Posidonia canopy (right). Velocities have been scaled to 10 cm s^{-1} bar. Canopy height (60 cm) indicated by dashed line. Root mean square values for each time series also shown; b: same as a, but for turbulent velocities (w'). Data was sampled at Aguamarga, Spain, 16 Sept 1996.

Conclusion

The field campaign in Oosterschelde was highly successful in integrating measurements of physical transport/mixing with measurement of important biogeochemical fluxes. Based on laboratory and field experiments we have *established*: a) protocols for measurements of turbulent transport and particle distributions in and around sea-grass meadows, b) pigment algorithms for the purpose of determining phytoplankton group composition on the basis of the concentration of diagnostic phytoplankton pigments, c) series of sub-models describing the growth kinetics of different phytoplankton groups under various nutrient conditions. Besides, during the field campaigns and in mesocosm studies we have generated large data series to calibrate the integrated physical mixing/biogeochemical process models.

To describe the physical environment a new type of numerical one-dimensional turbulence model has been developed which allows for the exact reproduction of standard current point measurements without using data assimilation.

For a tidal area such as Oosterschelde a three-dimensional numerical model for well-mixed tidal flow has been developed. The model is equipped with a k-ε model and movable lateral boundaries in order to account for flooding and drying of mudflats. The model design and validation is documented in an internal JRC report. This model will constitute the "back-bone" for the integrated model development for Oosterschelde.

References

Burchard, H. & H. Baumert, 1995. On the performance of a mixed-layer model based on the k-ε turbulence closure. J. Geophys. Res. 100: 8523-8540.

Burchard, H. & O. Petersen. 1998. Comparing the performance of the k-ε and the Mellor-Yamada level 2.5 two-equation turbulence models. J. Phys. Oceanogr. (in print)

Lohrmann, A., R. Cabrera, G. Gelfenbaum and J. Haines. 1994. Acoustic-Doppler velocimeter (ADV) for laboratory use. Fundamentals and Advancements in Hydraulic Measurements and Experimentation, Proceeding, sponsored by the Hydraulic Division/ASCE, August 1-5, 1994, Buffalo, NY, 351-365.

Møhlenberg, F.1995. Regulating mechanisms of phytoplankton growth and biomass in a shallow estuary. Ophelia 42: 239-256

Schlüter, L. & H. Havskum. 1997. Phytoplankton pigments in relation to carbon content of phytoplankton communities. Mar. Ecol. Prog. Ser. 155: 55-65.

TITLE: **MARINE MONITORING SYSTEM 2000+ (MMS2000+)**

CONTRACT NO: MAS3 CT96 0057

COORDINATOR :

Ir. R.J. Akkerman
Rijkswaterstaat, North Sea Directorate
Koopmansstraat 1
P.O. Box 5807
2280 HV Rijswijk
The Netherlands
Tel: +31 (70) 3366671, Fax: +31 (70) 390 0691
E-mail: r.j.akkerman@dnz.rws.minvenw.nl

PARTNERS:

Secretariat

Rijkswaterstaat
North Sea Directorate
Steven Groenewold
P.O. Box 5807
2280 HV Rijswijk
THE NETHERLANDS
Tel.: +31703366677
Fax: +31703900691
Email: s.groenewold@dnz.rws.minvenw.nl
Internet: Http://www.minvenw.nl

Denmark

Royal Danish Administration of Navigation and Hydrography
Erik Buch
Overgaden o. Vandet 62B
P.O. Box 1919
Dk. 1023 Copenhagen K
DENMARK
Tel.: +4532689500
Fax: +4531541012
Email: ebu@fonfrv.dk

Belgium

Coastal Waterways Division
Guido Dumon
Vrijhavenstraat 3
8400 Oostende
BELGIUM
Tel.: +3259554248
Fax: +3259507037
Email: guido.dumon@lin.vlaanderen.be

Great Britain

CEFAS
David Mills
Pakefield Road
Lowestoft
Suffolk NR33 OHT
GREAT BRITAIN
Tel.: +44 1502 562244
Fax: +44 1502 513865
Email: d.k.mills@cefas.co.uk
Internet: Http://www.meteo.gov.uk

France

Ifremer Nantes
Direction Environnement et
Aménagement du Littoral
Jean Paul Berthomé
rue de l'Ile d'Yeu
P.O. Box 21105
44311 Nantes Cedex 03
FRANCE
Tel.: +33240374106
Fax: +33240374073
Email: jberthom@ifremer.fr
Internet: Http://www.ifremer.fr

Germany

Bundesamt für Seeschiffahrt und
Hydrographie
Dieter Kohnke
Postfach 301220
D-20305 Hamburg
GERMANY
Tel.: +494031903400
Fax: +494031905000
Internet: Http://www.bsh.de

Netherlands

Rijkswaterstaat
North Sea Directorate
Ronald Akkerman
P.O. Box 5807
2280 HV Rijswijk
THE NETHERLANDS
Tel.: +31703366790
Fax: +31703900691
Email: r.j.akkerman@dnz.rws.minvenw.nl
Internet: Http://www.minvenw.nl

Norway

Institute of Marine Research
Trygve Gytre
P.O. Box 1870 Nordnes
N-5024 Bergen
NORWAY
Tel.: +47 55 238500
Fax: +47 55 238531
Email: trygve.gytre@imr.no
Internet: Http://www.imr.no

Sweden

Swedish Meteorological and
Hydrographical Institute
Dr. Hans Dahlin
Fack S 60101
Norrköping
SWEDEN
Tel.: +4611158000
Fax: +4611158350
Email: hdahlin@smhi.se
Internet: Http://www.smhi.se

Ireland

The Irish Marine Data Centre
Bronwyn Cahill
80 Harcourt Street
Dublin 2
IRELAND
Tel.: +353 1 4757100
Fax.: +353 1 4757104
Email: bronwyn.cahill@marine.ie
Internet: Htpp://www.marine.ie

MARINE MONITORING SYSTEM 2000+ (MMS2000+)

Steven Groenewold, Secretariat SeaNet
Rijkswaterstaat, North Sea Directorate
Koopmansstraat 1, 2280 HV Rijswijk
The Netherlands

SUMMARY

At present all countries around the North Sea operate monitoring systems for proper management and scientific research of the marine environment. These systems feature differences with respect to technical concept and application. However they deliver valuable data to study the dynamics of the marine system in the North Sea basin for application in the management of the marine environment.

Optimum use of the existing facilities is prevented by two major stumbling blocks, they are:

- Most systems are meant for use on a local or national scale. With the exception of meteorological parameters, there is still little exchange of data for use on a regional scale.
- In most systems the integrated approach of real time in-situ measurements using fixed platforms, buoy stations, satellites and operational data-assimilation modelling to produce complete and detailed information and forecasts has not yet been implemented

Recognition is growing among agencies operating national marine monitoring networks that integrated use (data exchange) and integrated system concept (integration of measurements and modelling) are necessary from an economic and operational point of view. In view of this an initiative has been taken to form a international workshop called SeaNet. The workshop is held once a year and participating countries are Belgium, Denmark, France, Germany, Great Britain, Ireland, the Netherlands, Norway and Sweden. SeaNet has focused its attention on fixed monitoring networks in the North Sea region and has taken the initiative to start a concerted action called MMS2000+ (Marine Monitoring System 2000+) which is funded by the EU.

Long term objective of SeaNet:

The long term objective within MMS2000+ is to realise a North Sea monitoring system based on fixed monitoring networks as a contribution to an integrated European marine monitoring and forecasting system.

INTRODUCTION

Nearly every country around the North Sea has its own monitoring activities at sea and at the coast-line. The collected monitoring data fulfils operational needs as well as temporary demands like for example, scientific research and calamity prevention. Because of the scale of the phenomena it is obvious that these activities and demands cannot be restricted to one part of the continental shelf. Therefore more co-operation between the North Sea countries in their fixed monitoring activities will achieve benefits for all.

In several frameworks the North Sea countries already collaborate in monitoring programs and development of new measuring techniques and information systems. Examples are the Committees 'PRAM' (Programmes and Measures Committee), 'ASMO' (Environmental Assessment and Monitoring Committee) under the 'OSPARCOM' (Oslo and Paris Commission) and the MAST-programs of the 'EU' (European Union). These programs are nearly completely limited to environmental monitoring and data collection from ships and off-line data exchange. In the field of on-line collection at fixed stations, the co-operation is mainly restricted to bilateral data exchange.

Therefore the 'Bundesamt für Seeschiffahrt und Hydrographie' in Hamburg, Germany and 'Rijkswaterstaat' in the Netherlands took the initiative for an 'International Workshop on fixed Monitoring Networks on the North Sea' called SeaNet. All the countries around the North Sea, except for England and Sweden, participated in the first workshop, held in Rijswijk (the Netherlands) in April 1993. At the second session in Hamburg (Germany) in December 1993, every North Sea country was represented. SeaNet has taken the initiative to start a concerted action 'MMS2000+' which is funded by the EU.

OBJECTIVES

More specific objectives of SeaNet are:

- A homogenous distribution of fixed monitoring sites.
- Promotion of online data exchange between fixed monitoring networks.
- Standardisation of data collection, processing methods and validation techniques.
- Co-operation in the development of new measuring techniques and sensors, and testing of existing sensors.
- Exchange of experience in data communication and data collection, particularly on fixed structures.

Objectives of MMS2000+ are:

- Survey the needs of the end users of information and opportunities of the fixed monitoring network agencies around the North Sea.
- Define a system based on the integrated use of national networks and integration of monitoring and modelling techniques.
- Facilitate the technological developments needed to establish such an integrated system.
- Organise the implementation of a marine monitoring and forecasting system for the North Sea region.

WHAT HAS BEEN ACHIEVED

Knowledge of what is measured where

Overviews have been generated containing every location (position, owner, type of construction,..) existing in each monitoring network. Furthermore for each location information is available on which hydrological, meteorological, chemical and biological parameters are being measured. This information is available in geographical overviews. In order to make it accessible for everyone the information is available on the Internet (http://www.minvenw.nl/projects/seanet).

SeaNet Survey

The first phase was called the SeaNet Survey, and its purpose was to meet the first goal. This part has been successfully finished in June 1996. Between February and April 1996 a selected group of 56 so called "Key persons" was interviewed. This group represented 42 organisations from the eight different North Sea countries. This interview consisted of four parts:

- The needs / parameters
- Benefits / applications
- Opportunities / technologies
- Costs / incentive

Some result of the survey

One of the questions asked was the importance of in-situ measurements, remote sensing and operational modelling now and in 2005. It is interesting to see that the in-situ measurements will become of less importance towards 2000, but will stay the most important one, compared to the remote sensing and operational modelling. The results are put into histograms in figure 1, 2 and 3.

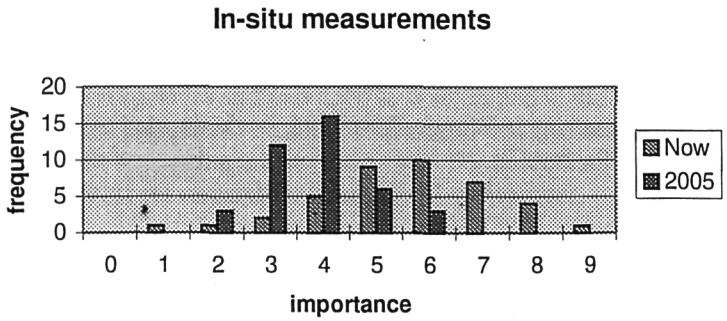


Figure 1- The importance of in-situ measurements now and in 2005

The expectation for the in-situ measurements is that the importance will decrease towards the year 2005. But it will not become less important than the operational modelling (figure 2).

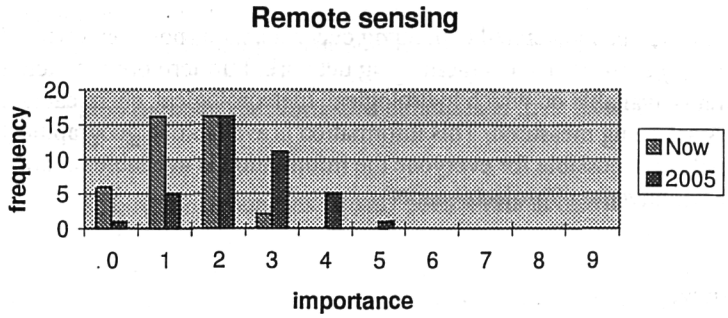


Figure 2 - Importance of remote sensing now and in 2005

After the high expectations of remote sensing in the early 90's remote sensing is found not to be very important at this moment. In future the importance will rise, but not become greater than in-situ measurements or operational modelling.

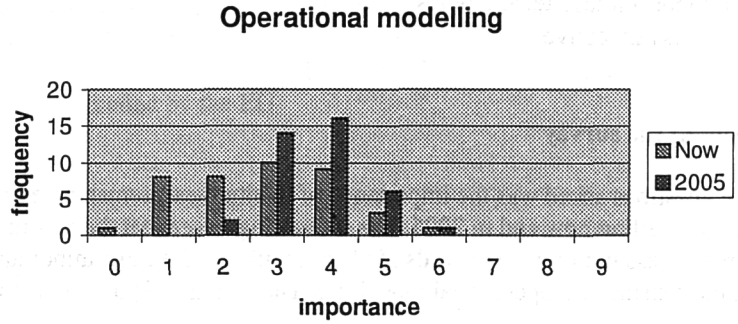


Figure 3 - Importance of operational modelling now and in 2005

Work groups

During the SeaNet meeting in Brugge, June 1996, it was decided to create three project groups: the DIG, CTS & ACB

The data interface project group (DIG)

From the SeaNet Survey it appeared that the SeaNet data interface for data management and transfer is essential to accomplish the first phase of SeaNet. Realisation and installation of this dedicated interface between a national network and the SeaNet members, will make the basic version of SeaNet reality.

The goal of this project group is to work out a plan for such an interface. This project group is the most important one and also the one closest to implementation.

The current / temperature / salinity (CTS) project group.

Good instruments have been developed, for example current measurements (the ADCP's - Acoustic Doppler Current Profilers). But when implementing these instruments in fixed monitoring networks all kind of problems occurred. One of the most difficult problems is how to get the data on shore.

The project group has the task to set up recommendations for the application of CTS sensors in the monitoring networks and combining experiences in this field of interest and to work out way's to overcome the still existing difficulties. This project group is somewhat further from realisation compared to the data interface project group.

Automated measurement of chemical & biological parameters (ACB) project group.

This is the project group which is the furthest away from implementation. Attempts have been made to develop instruments for the different parameters (for example the MERMAID project) but these instruments are not very well-known to the end-users and the organisations who are running the monitoring networks.

The goal of this project group is to combine the knowledge and experiences that are available within the North Sea countries and to work out a way on how to measure the requested parameters (results from the SeaNet Survey) and how to realise this within the existing fixed monitoring networks.

DIG MASTIII EC PROPOSAL: SEANET DATA INTERFACE

During the SeaNet DIG-meeting in Hamburg on November 4, 1996, the decision was made to work out a project proposal for the definition, development and implementation of a SeaNet Data Interface and seek the support of the MAST programme for this proposal. The proposal, by a consortium of six SeaNet agencies and four SME's, is submitted to the European Commission. The consortium proposes to execute the SeaNet Data Interface Project as a MAST RTD action in area D: supporting initiative; Sub area D3: modelling, ocean-data management and quality control for research and operational applications.

The objective of the SeaNet Data Interface project is to define, develop and implement a Data Interface to facilitate the adequate data exchange between fixed monitoring networks in the North Sea region to make oceanographic data available for research, marine environmental management and operational applications.

SEANET - EUROGOOS

The SeaNet initiative was taken before the GOOS initiative. But when GOOS was started, and later the European component of GOOS - EuroGOOS, it became clear that the SeaNet goals and EuroGOOS goals were much alike, when looking at the area of interest of SeaNet. The aim of GOOS is to design and implement a scientifically based system of ocean observations and predictions to fulfil economic, social, environmental and scientific objectives. EuroGOOS identifies European priorities for operational oceanography, promotes the development of scientific, technological and computer systems, assesses the economic and social benefits and established a concerted European approach for GOOS and methods for routine collaboration between European agencies. EuroGOOS covers all aspects of operational oceanography. SeaNet covers the fixed monitoring networks module for the North Sea region. Maybe in future SeaNet will be one of the groups that can contribute to EuroGOOS.

TITLE: Feed-backs of Estuarine Circulation and Transport of Sediments on Phytobenthos (**F-ECTS**)

CONTRACT N°: MAS3-CT97-0145

COORDINATOR: Dr. Alessandro Bergamasco
Thetis S.p.A.
Castello, 2737/f I-30122 Venezia, Italy
Tel.: +39-41-2406307, Fax: +39-41-5210292
E-mail: bergamasco.a@thetis.it

PARTNERS:

Mogens Flindt
University of Copenhagen
Helsingørsgade 51
DK-3400 Hillerød, Denmark
Tel: +45-42267600; Fax: +45-48241476
E-mail: flabms@inet.uni-c.dk

Jurgen Suendermann
University of Hamburg
Troplowitzstraße 7
D-22529 Hamburg, Germany
Tel: +49-40-41235095; Fax: +49-40-5605724
E-mail: mayer@ifm.uni-hamburg.de

Klaus Pfeiffer
Hydromod Scientific Consulting
Banhofstrasse 52
D-22880 Wedel, Germany
Tel: +49-4103-13057; Fax: +49-4103-3317
E-mail: pfeiffer@hydromod.de

Richard Whitehouse
HR Wallingford Ltd
Howbery Park
Wallingford, Oxon
OX10 8BA UK, United Kingdom
Tel: +44-1491-835381; Fax: +44-1491-825539
E-mail: rjsw@hrwallingford.co.uk

Carl Amos
University of Wales
P.O. Box 914 Cardiff
CF1 3YE UK, United Kingdom
Tel: +44-1222-874830; Fax: +44-1222-874326
E-mail: amos@agc.bio.ns.ca

Georg Umgießer
Consiglio Nazionale delle Ricerche
ISDGM, S.Polo 1364
I-30125 Venezia, Italy
Tel: +39-41-5216875; Fax:
E-mail: georg@lagoon.isdgm.ve.cnr.it

Rui O.P. Santos
Unidade de Ciências e Tecnologias
de Recursos Aquáticos
University of Algarve
Campus de Gambelas
P-8000 Faro, Portugal
Tel/fax: +351-89-800900
E-mail: rosantos@mozart.si.ualg.pt

Adélio Silva
Hidromod Modelação em Engenharia
Tagus Park Nucleo Central 349
Estrada de Porto Salvo
P-2780 Oeiras, Portugal
Tel/fax: +351-1-8460530
E-mail: hidromod@individual.eunet.pt

Umberto Simeoni
University of Ferrara
Corso Ercole I d'Este 32
I-44100 Ferrara, Italy
Tel:+39-532-210341; Fax:+39-41-206468
E-mail: cvp@dns.unife.it

FEED-BACKS OF ESTUARINE CIRCULATION AND TRANSPORT OF SEDIMENTS ON PHYTOBENTHOS F-ECTS

ALESSANDRO BERGAMASCO[1], LUCA DE NAT[1], MOGENS FLINDT[2], OLE GERTZ- HANSEN[2], BERNHARD MAYER[3], KLAUS PFEIFFER[4], KEIRAN MILLARD[5], ADRIAN CRAMP[6], GEORG UMGIESSER[7], RUI O.P. SANTOS[8], ADELIO SILVA[9], PAOLO CIAVOLA [10]

[1]Thetis S.p.A., Venezia, Italy; [2]University of Copenhagen, Hillerød, Denmark; [3]University of Hamburg, IFM, Hamburg, Germany; [4]Hydromod Scientific Consulting, Wedel, Germany; [5]HR Wallingford Ltd, United Kingdom; [6]University of Wales, Cardiff, United Kingdom; [7]Consiglio Nazionale delle Ricerche, ISDGM, Venezia, Italy; [8]Unidade de Ciências e Tecnologias de Recursos Aquáticos, University of Algarve, Faro, Portugal; [9]Hidromod Modelação em Engenharia, Oeiras, Portugal; [10]University of Ferrara, Ferrara, Italy

1. INTRODUCTION

Coastal Zone Management (CZM) is widely recognised as a practice necessary for the sustainable use of coastal resources. Central to CZM is the recognition that in order to promote sustainability, coastal resources cannot be sectorially managed and the interactions that occur between adjacent sectors have to be fully considered. This is referred as an 'holistic' management approach.

Many complex interactions occur between and within the different biological species in coastal ecosystems and their respective habitats. The ability of phytobenthic communities to locally modify the environmental characteristics of the ecosystem in which they live is one of the more significant relationships related to the human interactions .

In fact, complicated feed-back and feed-forward loops exist, that couple the establishment of phytobenthic communities, water quality and physical oceanographic parameters. Accurate understanding of these interdependancies will represent a significant improving of the environmental management capabilities, particularly allowing a reliable foreseeing of the evolution of phytobenthic ecosystems and their reactions to man-generated disturbances.

F-ECTS main focus is the interdisciplinary investigation of the ecosystem loops in estuarine environments involving phytobentos communities, hydrodynamics, nutrient cycling and sediment transport, with the aim of integrating some of the aspects already investigated in other research projects.

The Lagoon of Venice (Italy) will be considered as a pilot case study. Two major seasonal field campaigns will be carried out and will allow the parameterization of the main physical and biological processes of the ecosystem, providing a specific background for the assessment of the exportability of the obtained results in other two different european estuarine ecosystems: Laguna della Ria Formosa (Portugal) and Roskilde Fjord (Denmark).
Based on the parameterized biophysical interactions, the modeling activities within F-ECTS will enable the set up of linked modules for the simulation of the feed-back loop between the physical processes and the phytobenthic habitat. This loop controlling the survival and evolution of an estuarine ecosystem will be considered from the biological perspective. To accomplish this, biological, hydrodynamic and sediment transport processes will be modelled together in F-ECTS. In particular a new SPM-phytobenthos-reaction model for cohesive sediment and estuarine ecosystems will be developed and used as a common module to which different hydrodynamic models tailored for each specific case study site can be coupled.
To demonstrate how the joint exploitation of the field measurements and the model outputs provide support to the production of new "environmental information" on the estuarine territories, GIS-based tools will be developed and implemented in the context of the pilot case study in a way that such new tools can be easily exported to other sites.
These tools are expected to support the decision makers in identifying and planning CZM actions such as the ones related to wetland conservation and restoration, fishing, dredging and port operations.

2. OBJECTIVES AND MAIN EXPECTED DELIVERABLES

F-ECTS (Feed-backs of Estuarine Circulation and Transport of Sediments on Phytobenthos) aims to research the complex interactions occuring between phytobenthos communities, hydrodynamics, nutrient cycling and sediment transport in estuarine ecosystems. Its main focus is therefore the interdisciplinary investigation of the complex ecosystem loops involving these components.

F-ECTS has the following five objectives:

- To investigate the role of estuarine and lagoonal phytobenthos (rooted macrophytes, non-attached macroalgae, microflora) in modifying and in being influenced by the local habitat conditions of the ecosystem in which they exist.

- To develop a direct monitoring scheme and to identify a set of bed and watercolumn bio-dependent parameters that will enable the description and evaluation of the feed-back mechanisms between phytobenthos and physical/chemical processes in coastal ecosystems.
- To use the above approach for accurate predictive numerical modelling that couples both the biogeochemical and physical components within the context of a pilot case study.
- To assess the effectiveness of exporting the results obtained in a micro-tidal environment (Venice Lagoon-Italy) to a different micro-tidal environment (Roskilde Fjord-Denmark) and to a meso-tidal lagoon (Ria Formosa-Portugal).
- To demonstrate how the joint exploitation of the field measurements and the model outputs in the frame of a GIS application leads to practical tools for decision makers to use in order to identify and plan CZM actions in estuarine areas.

The complex estuarine processes will be approached by linking together in situ and remotely sensed measurements, conceptual and numerical modeling and GIS tools according to the scheme shown in Fig. 1. The following main project deliverables are expected:

a) scientific guidelines in order to support management strategies taking account for the "quality" of an estuarine ecosystem in terms of habitat requirements (such as dissolved nutrients, SPM concentration, etc.), restoration needs and targets (such as wetland reconstruction, seagrass transplantation and so on) and utilization of environment by human activities (navigation, port operation and dredging impact, flood defence measures, fisheries);
b) detailed guidelines for the selective generation of new field data in sites where interaction and feed-backs among the ecosystem components are suspected. A monitoring protocol will be set up aiming at making available a minimum data set able to support the model analyses, responding to the main issues in estuarine management;
c) a demo CD-ROM of the structured data/model set of the pilot site illustrating the joint use of field data and model outputs for environmental issues (such as for example the map of the mean daily submersion time and the habitat classification). A comprehensive collection of data, results, and information will also be produced as final delivery and merged for further dissemination and utilisation on the CD-ROM.

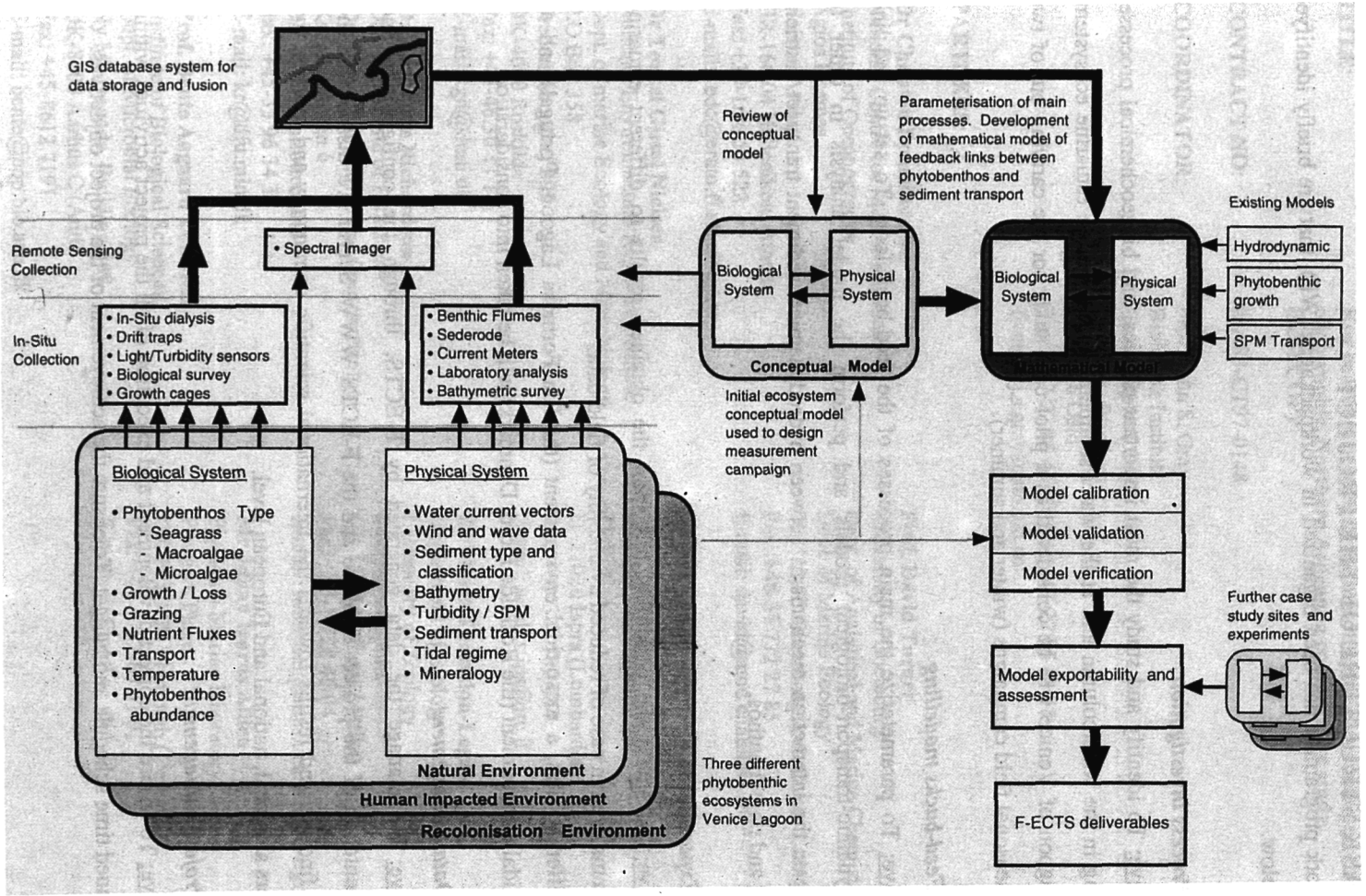


FIG. 1: INTERLINKING OF THE F-ECTS PROJECT ELEMENTS

3. TASK STRUCTURE OF THE PROJECT

The work programme has been organized in workpackages (WP), that are briefly identifyed here-below.

WP1 Process investigation

Objective: To identify and study the most important physical and biogeochemical processes occuring in the watercolumn and at the water/sediment interface in an estuarine ecosystem. The Lagoon of Venice will be considered as a pilot case study for the carrying out of two major seasonal field campaigns (winter and summer).

WP 2 Feed-backs modelling

Objective: To parameterize the main processes of the feed-back loop. To set up and link hydrodynamic-transport-biological models and perform the model analysis in order to investigate the interaction mechanisms between hydrodynamics, sediment transport, nutrient cycling and phytobenthos.

WP 3 Exportability

Objective: To assess the possibility to export the obtained results to different estuarine ecosystems even in case of reduced availability of field data.

Two different sites, a meso-tidal environment (the Ria Formosa Lagoon, Portugal) and a micro-tidal environment (the Roskilde Fjord, Denmark) will be taken into consideration.

WP 4 Data management

Objective: To manage the data generated by F-ECTS, through the configuration and implementation of the project database and the F-ECTS WWW Server. To disseminate the project findings and results towards the international scientific community and towards the end-users at a local, national and European level.

WP 5 Project management

Objective: To ensure the correct development and execution of all the project activities within the planned time schedule and budget. To ensure the achievement of the project objectives.

TITLE: **Key coasta processes in the mesotrophic Slagerrak and the oligotrophic, Northern Aegean: a comparative study. (KEYCOP)**

CONTRACT NO: MAS3-CT97-0148

COORDINATOR:

Prof. John S. Gray
Biologisk Institutt
Universitetet I Oslo
Pb. 1064, Blindern
NO-0316 Oslo
Tel.: +47-22 85 45 10, fax: +47-22 85 44 38
E-mail: j.s.gray@bio.uio.no

PARTNERS:

Dr Christou Epaminondas
National Centre for Marine Research
Institute of Oceanography
Agios Kosmas
Nomos Attikis
GR-166 04 Hellenikon, Athens
Fax: +30-1.96 53 522
E-mail: edc@erato.fl.ariadne-t.gr

Dr Torkel Gissel Nielsen
National Environmental Research Institute
Dept. of marine Ecology and Microbiology
P.O.Box 358
Frederiksborgvej 399
DK-4000 Roskilde
Fax: +45-46.30 11 14
E-mail: tgn@dmu.dk

Dr Katherine Richardson
Danish Institute of Fisheries
Department of Marine and Coastal Ecology
Kavalergården 6
DK-2920 Charlottenlund
Fax: +45-33 96 34 34
E-mail: kr@dfu.min.dk

Prof. Bente Aagaard Lomstein
Institute of Biological Sciences
Dept. of Microbial Ecology
Ny Munkegade, Building 540
DK-8000 Aarhus C (Amt)
Fax: +45-8612 7191
E-mail: bente@pop.bio.aau.dk

Prof. David Turner
University of Goeteborg
Dept. of Analytical and Marine Chemistry
Dept. of Marine Ecology
SE-412 96 Goeteborgs och Bohus Laen
Fax: +46-31 772 27 85
E-mail: david@amc.chalmers.se

Dr Adolf Stips
Space Applications Institute
Marine Environment Unit
TP 272
IT-21020 Ispra (Lombardia)
Fax: +39-332 789 034
E-mail: adolf.stips@jrc.it

Dr Marta Thessalou-Legaki
Department of Biology
Laboratory of Zoology
Panepistimiopolis
GR 157 84 Athens (Attiki)
Fax: +30-1-728 46 04
E-mail: mthessal@atlas.uoa.ariadne-t.gr

Mr Julian Icarus Allien
Plymouth Marine laboratory
Prospect Place
UK-PLI 3DH Plymouth (Devon)
Fax: +44-1752-63 31 01
E-mail: jia@pml.ac.uk

(no manuscript submitted)

TITLE Importance of dissolved organic matter from terrestrial sources for the production, community structure and toxicity of phytoplankton of the European Atlantic and Baltic coastal waters; role of micropredators for transmissions of toxins to commercial shellfish and fish larvae (**DOMTOX**)

CONTRACT NUMBER: **MAS3-CT97-0149**

CO-ORDINATOR

Serge Y. Maestrini
Centre de Recherche en Ecologie Marine
et Aquaculture de L'Houmeau (CNRS-
IFREMER)
BP 5, F-17137 L'Houmeau, France
Voice: (33) 546-50-06-21 and -94-40
Fax: (33) 546-50-06-00.
E-mail: smaestri@ifremer.fr

PARTNERS

Maija Balode
Institute of Aquatic Ecology
University of Latvia,
3 Miera Iela, 2169 Salaspils, Latvia
Voice: (371) 2-94-54-05
Fax: (371) 9-34-54-12
E-mail: maija@hydro.edu.lv

Edna Granéli
Department of Natural Sciences
The Royal University of Stockholm
Box 905, S-39129 Kalmar, Sweden
Voice: (46) 480-44-62-24
Fax: (46) 480-44-62-62
E-mail: edna.graneli@ng.hik.se

Geoffrey Codd
Department of Biological Sciences
University of Dundee, Scotland
Dundee DD1 4HN, United Kingdom
Voice: (44)-1382-34-42-72
Fax: (44)-1382 -32-23-18
E-mail: g.a.codd@dundee.ac.uk

Tonis Pöder
Estonian Marine Institute
Paldiski Road 1, EE-0001 Tallinn, Estonia
Voice: (372) 245-35-74
Fax: (372) 631-10-69
E-mail: poder@udukogu.sea.ee

IMPORTANCE OF DISSOLVED ORGANIC MATTER FROM TERRESTRIAL SOURCES FOR THE PRODUCTION, COMMUNITY STRUCTURE AND TOXICITY OF PHYTOPLANKTON OF THE EUROPEAN ATLANTIC AND BALTIC COASTAL WATERS; ROLE OF MICROPREDATORS FOR TRANSMISSIONS OF TOXINS TO COMMERCIAL SHELLFISH AND FISH LARVAE

« DOMTOX »

Serge Y. MAESTRINI[1], Maija BALODE[2], Geoffrey CODD[3], Edna GRANÉLI[4], Tonis PÖDER[5]

[1]CNRS-IFREMER, L'Houmeau, France; [2]Institute of Aquatic Ecology, Salaspils, Latvia; [3]University of Dundee, Scotland, U.K.; [4]University of Stockholm at Kalmar, Sweden; [5]Estonian Institute of Oceanography, Tallinn, Estonia

Abstract: DOMTOX will investigate whether uptake of dissolved organic nutrients from terrestrial sources promote growth and toxin production of toxic microalgae and cyanobacteria and thus influence the community structure, and whether the predation of cyanobacteria by ciliates and toxic mixotrophic dinoflagellates is a pathway for the transfer of toxin to commercial shellfish and fish larvae. The workplan combines (i) field studies in the Baltic Sea and the French Atlantic with laboratory experiments, and (ii) natural phytoplankton communities with monospecies culture studies.

1. INTRODUCTION

In recent decades, toxic events have emerged as a major environmental problem in many coastal European waters. Most responsible species were dinoflagellates or cyanobacteria. Two major hypotheses have been invoked to explain such a trend: (1) Continuous relative depletion of silica in river would led in coastal waters to diatoms being replaced by non-siliceous forms such as cyanobacteria, dinoflagellates and green algae. (2) Organic compounds from land drainage, such as humic acids, have favoured

dinoflagellates growth versus that of harmless species. DOMTOX will focus on mechanisms related to hypothesis (2)*.

Many microalgae can take up dissolved organic nutrients. Moreover, some species, including the potentially highly toxic dinoflagellates, are mixotrophic and have been hypothesised to feed on cyanobacteria in addition to aquatic heterotrophic bacteria. On the other hand, bacteria associated with toxic algae have been shown to produce a significant fraction of the toxins.

On this basis, two new working hypotheses have been formulated: (a) The feeding of dinoflagellates on toxin producing cyanobacteria by phagotrophy is a source of toxins in toxic dinoflagellates. (b) Micropredators' phagotrophy is a route for the transfer and accumulation of toxins in commercial molluscs and fish larvae.

2. OBJECTIVES

The overall aim of DOMTOX is to obtain enough information on the importance of dissolved organic matter from terrestrial sources for the production, community structure and toxicity of phytoplancton and protists of the European Atlantic and Baltic coastal waters. The overall strategy is to combine field studies with land-based and laboratory experiments, and natural phytoplankton communities with monospecies culture studies, thus allowing for the determination of some of the regulatory mechanisms behind toxic planktonic blooms.

The specific objectives of DOMTOX are:

(i) To investigate whether uptake of dissolved organic nutrients from terrestrial sources promote the growth of toxin-producing microalgae and/or cyanobacteria, and thus influence the community structure.

(ii) To investigate whether dissolved organic nutrients from terrestrial sources can promote toxin production in toxin-forming microalgae and cyanobacteria.

(iii) To determine whether the predation of cynobacteria may be a source of toxins in toxic dinoflagellate blooms, and to investigate whether the predation of cyanobacteria by ciliates and toxic mixotrophic dinoflagellates is a pathway for the transfer of toxin to commercial filterfeeding shellfish and fish larvae.

* Hypothesis (1) is the basis of another MAST program, « NUTOX », to which two DOMTOX partners are also contributing.

3. WORKPLAN

The overall strategy of DOMTOX is to combine (i) field studies (cruises at sea) with land-based (mesocosms) and laboratory experiments, and (ii) natural phytoplankton communities with monospecies culture studies (cyanobacteria, dinoflagellates, ciliates), thus allowing for the determination of some of the regulatory mechanisms behind toxic planktonic blooms.

Work package 1: Concentration of dissolved organic matter (DOM), community structure and toxicity of potentially-toxic phytoplankton from the Daugava River mouth to the open Baltic Sea. Field and associated land-based research.

Work package 2: Concentration of dissolved organic matter (DOM), community structure and toxicity of potentially-toxic phytoplankton from the Charente River mouth to the open French Atlantic Ocean. Field and associated land-based research.

Work package 3: Effect of addition of DOM from land origin on growth and toxin levels in summer natural coastal assemblages. Land-based mesocosm experiments in Kalmar (Sweden, Western Baltic Sea)

Work package 4: Effect of DOM from land sources on growth and toxin levels in several potentially-toxic species of importance. Laboratory experiments with cultured strains.

Work package 5: Role of phagotrophy upon cyanobacteria for the accumulation of toxins in toxic dinoflagellates and ciliates and further transfer of toxins to commercial shellfish and/or fish larvae. Laboratory experiments with cultured strains.

TITLE: Effects of Eutrophicated Seawater on Rocky Shore Ecosystems Studied in Large Littoral Mesocosms **(EULIT)**

CONTRACT NO: MAS3-CT97-0153

COORDINATOR: **Tor L. Bokn**
Norwegian Institute for Water Research (NIVA)
P.O.Box 173 Kjelsaas
N-0411 Oslo, Norway
Tel +47 22 18 51 73
Fax +47 22 18 52 00
E-mail: tor.bokn@niva.no

PARTNERS:

Hartvig Christie
Norwegian Institute for Nature Research (NINA)
P.O.Box 736 Sentrum
N-0105 Oslo, Norway
Tel +47 22 94 03 73/22 94 03 00
Fax +47 22 94 03 01
E-mail: hartvig.christie@bio.uio.no

Carlos M. Duarte
Consejo Superior de Investigaciones Cientificas
Centre d'Estudis Avancats de Blanes
Cami de Santa Bàrbara s/n 17300 Blanes, España
Tel +34 72 - 33 61 01
Fax +34 72 - 33 78 06
E-mail: duarte@azathoth.ceab.es

Ole Geertz-Hansen
Freshwater Biological Laboratory
University of Copenhagen
Helsingørgade 51
DK-3400 Hillerød, Denmark
Tel +45 42 26 76 00
Fax +45 48 24 14 76
E-mail: ogh@post4.tele.dk

Espen E. Hoell
Norsk Hydro, Research Centre Porsgrunn (HRE)
P.O.Box 2560
N-3901 Porsgrunn, Norway
Tel +47 35 56 45 05
Fax +47 35 56 33 84
E-mail: espen.edward.hoell@hre.hydro.com

Kees Kersting
IBN-DLO
PO Box 167
1790 AD Den Burg
The Netherlands
Tel +31 222 36 97 16
Fax +31 222 319235
E-mail: k.kersting@ibn.dlo.nl

Patrik Kraufvelin
Department of biology, Aabo Akademi University
BIOCITY Artillerigatan 6
Fin-20520 Aabo, Finland
Tel +35 822 65 40 70
Fax +35 822 65 47 48
E-mail: pkraufve@abo.fi

Cecilia Lindblad
Department of Botany, Stockholm University
S-10691 Stockholm, Sweden
Tel +46 816 39 59
Fax +46 816 22 68
E-mail: lindblad@botan.su.se

Morten Foldager Pedersen
Institute of Biology and Chemistry, 17.2.
Roskilde University Center
PO Box 260
DK-4000 Roskilde, Denmark
Tel +45 46 75 20 88
Fax +45 46 74 30 11
E-mail: mfp@virgil.ruc.dk

Ulrich Sommer
Institut für Meereskunde an der Universität Kiel
Marine Botany Department
Düsternbrooker Weg 20, D-24105 Kiel, Germany
Tel +49 431 597-3840
Fax +49 431 56 58 76
E-mail: usommer@ifm.uni-kiel.d400.de

EFFECTS OF EUTROPHICATED SEAWATER ON ROCKY SHORE ECOSYSTEMS STUDIED IN LARGE LITTORAL MESOCOSMS EULIT

Tor L. Bokn[1], Hartvig Christie[2] Carlos M. Duarte[3], Ole Geertz-Hansen[4], Espen E. Hoell[5], Kees Kersting[6], Patrik Kraufvelin[7], Cecilia Lindblad[8], Morten F. Pedersen[9], Ulrich Sommer[10] and Frithjof Moy[1].

[1]Norwegian Institute for Water Research (NIVA); [2]Norwegian Institute for Nature Research (NINA); [3]Centre d'Estudis Avancats de Blanes (CEAB); [4]Freshwater Biological Laboratory, University of Copenhagen (FBLUC); [5]Norsk Hydro, Research Centre Porsgrunn (HRE); [6]DLO Institute for Forestry and Nature Research, AE (IBN-DLO); [7]Department of Biology, Aabo Akademi University (FINABO); [8]Department of Botany, Stockholm University (SU); [9]Institute of Biology and Chemistry, Roskilde University Center (RUC); [10]Marine Botany Department, Institut für Meereskunde an der Universität Kiel (IFM)

Abstract

The project addresses the following intentions: (1) To improve the health of the coastal ecosystem and environmental management. (2) To understand the coastal ecosystems necessary to advance the sustainable use of the living marine resources of the oceans. (3) To answer needs of European industry in the fields of marine exploitation. (4) To use a common shared facility and infrastructure as well as coordinated research to create synergy between research groups. (5) To take advantage of the partners network to environmental management, ensuring a good integration of environmental protection issues.

Current problems in biological oceanography that could be approached through experimental ecosystem research fit into three broad categories: (1) General biological oceanography, particularly the need to understand processes and to measure fluxes. (2) Aspects of exploitation and management of resources, and (3) Fates and effects of nutrients and pollutants. To meet these objectives and solve current problems EULIT shall perform different work packages. Eight basins (mesocosms) are constructed for littoral community experiments.

Changes in ecosystem structure and flow of energy and matter are measured by biomass and abundance of plant and animal communities, organismal size spectra, biodiversity, chemical analyses and metabolic measures. The link between subsystem measurements and the whole system behaviour in the mesocosms is regarded as an outstanding feature. Population responses as causes of ecosystem change are measured as growth and productivity of all important plant components and metabolism, growth and reproductive effort of the most important fauna groups. Plant-grazer interactions are studied in relation to nutrient richness in the system, as grazing rate by herbivores and food quality, and the faunal community change versus changes in the algal assemblage. Species interactions and succession patterns between functional groups as changes from a dominance by detrivores to a dominance by herbivores as a result of increased nutrient richness are described.

An effective data bank will support the statistical analyses and the modelling tool. The ten partners/associated partners origin from five universities, four research institutes and one industrial partner situated in seven different countries.

Keywords: nutrients, seawater, eutrophication, macroalgae, benthic animals, mesocosms, primary production, community structure, ecosystem modelling.

1. Objectives

1.1 Overall objectives

The overall objectives are to predict the response of rocky shore ecosystems to increased nutrient availability by
1) modelling the changes in ecosystem processes,
2) evaluating the increased production of herbivores,
3) assessing effects on growth responses of key organisms, and
4) predicting the resulting ecosystem structure and metabolism.

In doing so, EULIT would allow the formulation of tolerable nutrient inputs to coastal waters, and to evaluate the capacity for increased production of animal protein as a side benefit of the buffering effect exerted by herbivores.

1.2 Specific objectives:

Use of experimental ecosystems (mesocosms):

- To detect quantitative and qualitative changes in the plant- and associated animal-community with increased nutrient availability.
- To test whether increased nutrient loading may affect biodiversity characteristics in the rocky shore ecosystem either directly or indirectly through changes of key species.
- To study how nutrients may affect growth of kelp species (*Laminaria* spp.) in particular.
- To analyse the relationship between eutrophication induced changes at the level of individual species performance (biomass, cover, growth rates, production) with changes at the community level (species composition, species interactions, dominance-diversity patterns) and at the ecosystem level (overall production and respiration, flows of matter and energy).
- To detect if functional changes such as primary production and consumption occurs before structural changes are observed.
- To follow the changes in processes at different organizational scales and compare the turnover rates of the communities and the sub-communities.
- To explain changes in plant community composition and production from alterations in growth rates and grazing losses of the specific components (species or functional groups).
- To develop a model of rocky shore responses to increased nutrient load, based on the processes measured and make simulations of large scale events and predict effects of nutrient addition.

To support the European ELOISE initiative with increased knowledge on: nutrient cycles in the coastal environment, relation between excess nutrient load and eutrophication effects, pressure in the coastal shore line, and ecological management of coastal zone resources.

2. Methods

The littoral mesocosms have been prepared for the EULIT purpose by a national pilot project in 1996 and 1997. The system consist of eight outdoor concrete basins, each 26 m^3 (3.7 x 4.7 x 1.5 $m^{3)}$ and containing about 13 m^3 of sea water at mid-tide. A wave generator runs along the entire side of each basin, moving up and down pneumatically (18 strokes min^{-1}) creating regular waves running across the basin to the opposite side, where the main model community is established on a series of steps constructed to imitate a slanted shore. Figure 1 shows diagramme of one of the mesocosms, and Table 1 lists the technical data of the basins.

The basins are supplied with running sea water from 1 m depth, ensuring a stable flow rate of 5 m^3 h^{-1} per basin. Water exchange rate will normally be in the range of 2 to 4 hours. From each basin, a subsurface outlet is raised and lowered automatically to regulate the basin water level in a 12 hour sinusoidal cycle following the tidal rhythm and nominal amplitude (36 cm) on the shore (Figure 1). During extreme temperatures, the water is taken at 20 m depth, with well mixed sea water, to prevent overheating or ice formation.

To assure an appropriate experimental period a pilot project was started in spring 1996, and the communities were established in June 1996, by transplantation of rocks covered by algae and animals from the littoral zone. Rocks were positioned on four steps in all the basins covering all levels of the littoral and upper part of the sublittoral zones. During the succeeding months establishment has continued by self-propagation and from larvae, zygotes and spores entering the basins with the seawater. Four species of fucoids represent the key species, and one species dominates each of the steps.

Natural community development has been allowed for about 2 years before any nutrient additions. During 1997 the pilot project has employed the relevant techniques and statistical design for the EULIT experiments in the mesocosms to test the efficiency ahead of the nutrient manipulation. The pilot project has thus provided an appropriate length of the experimental period, with 2 1/2 years of nutrient elevation.

Nutrient addition will start in May 1998. In the pilot project, two years ahead of the experiments, all eight mesocosms have acted like controls.

Temperature, salinity and oxygen are continuously measured by automatic registration equipment, while the nutrients nitrogen and phosphorus are sampled from inflow water and each mesocosms weekly from May 1998.

Table 1. Technical data.

Volume each tank	≈ 26 m^3
Volume seawater - mid tide	≈ 13 m^3
Wave generator	18 strokes min^{-1}
Water intake, summer (winter)	1 m depth (20 m)
Flow rate	≈ 5 m^3 h^{-1}
Water exchange	2 - 4 h
Tide level mimic (sinusoidal cycle)	12 h 25 min
Nominal amplitude (similar to the fjord outside)	36 cm
Steps imitating the littoral levels	4 each tank
N & P treatment (N:P = 16:1) - 30 months	0, 0, 2, 4, 8, 16, 32, 64µmol N l^{-1} (Nitrate)

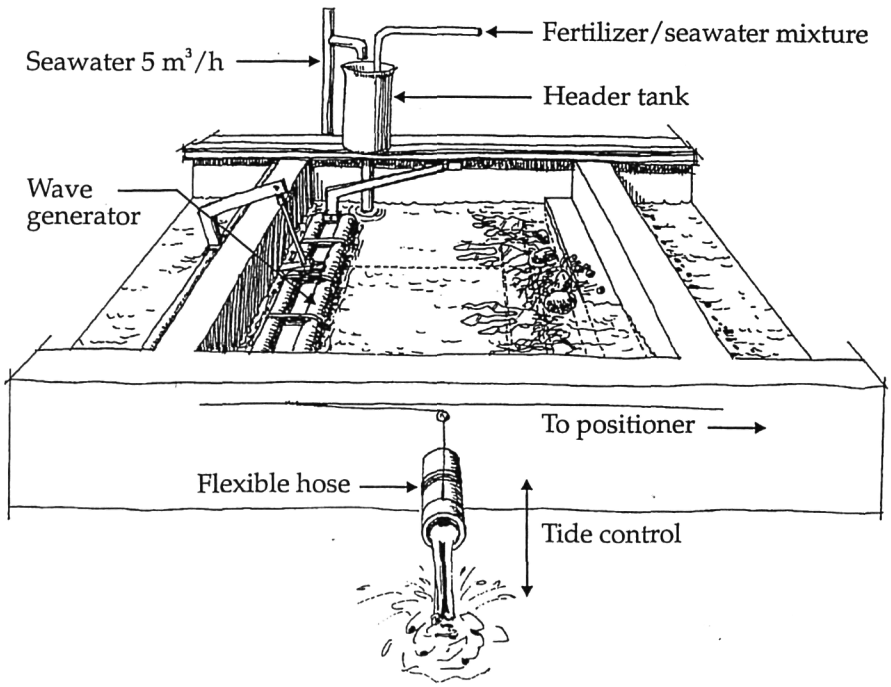
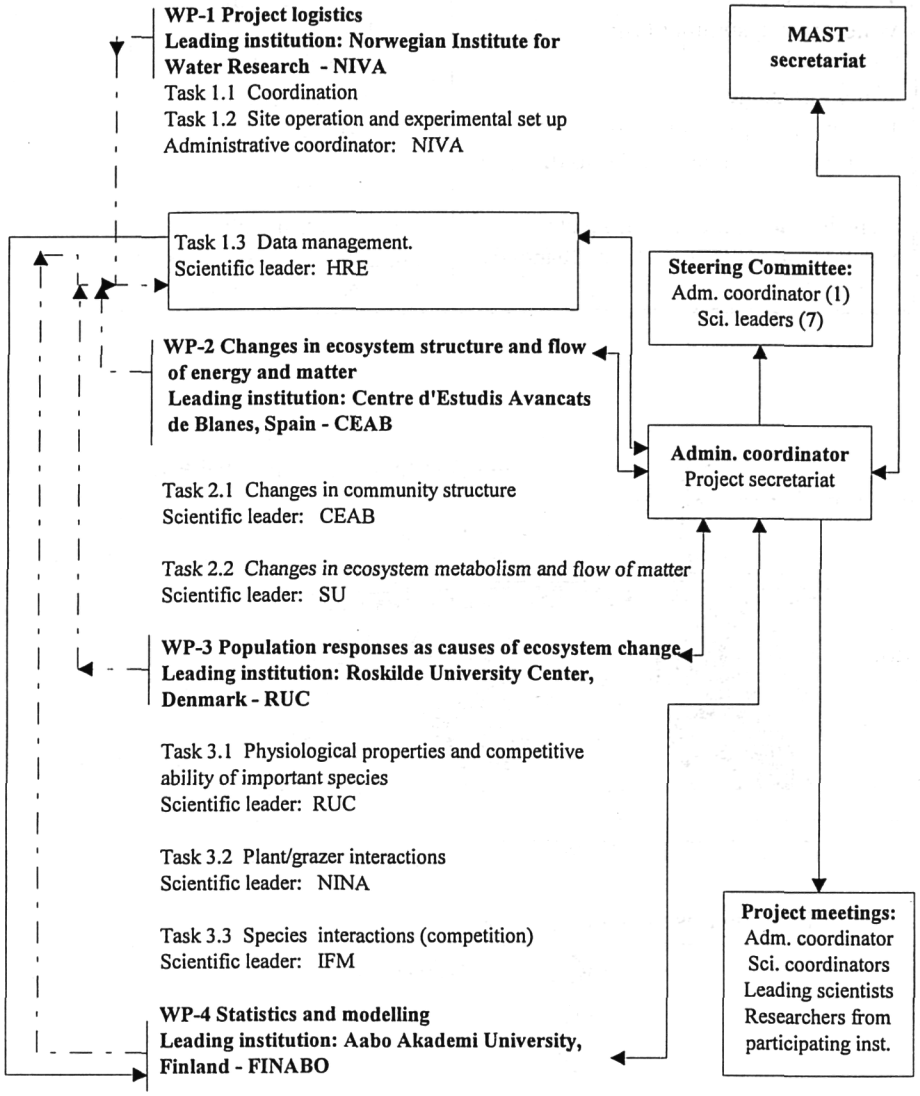


Figure 1. Diagramme of one of the rocky shore mesocosms.

Flow diagram of the EULIT-organisation.
Work packages (WP) and tasks to be performed.



TITLE: Long-term Changes in Baltic Algal Species and Ecosystems **(BIOBASE)**

CONTRACT NO: MAS3-CT98-0160

COORDINATOR:

Dr. Poul Møller Pedersen
University of Copenhagen (UC)
Botanical Institute
Department of Mycology and Phycology
Ø. Farimagsgade 2D
DK-1353 Copenhagen K, Denmark
Tel.: +45 35 32 23 05, fax: +45 35 32 23 21
E-mail: poulmp@bot.ku.dk

PARTNERS:

Dr. Jeanine Olsen & Dr. Wytze Stam
University of Groningen (UG)
Biological Centre
Department of Marine Biology
Kerklaan 30, Postbus 14
NL-0750 AA Haren
The Netherlands
Tel.: +31 50 363 22 52, fax: +31 50 363 22 61
E-mail: olsenjl@biol.rug.nl
or w.t.stam@biol.rug.nl

Dr. Akira Peters
University of Kiel (UK)
Institut für Meereskunde
Abteilung Meeresbotanik
Düsternbrooker Weg 20
D-24105 Kiel
Germany
Tel.: +49 431 597 38 34, fax: +49 431 565 876
E-mail: afpeters@ifm.uni-kiel.de

Prof. Jan Rueness
University of Oslo (UO)
Department of Biology
Section for Marine Botany
N-0316 Blindern, Oslo
Norway
Tel.: +47 22 85 45 24, fax: +47 22 85 44 38
E-mail: jan.rueness@bio.uio.no

Dr. Elina Leskinen
University of Uppsala (UU)
Department of Genetics
Box 7003
S-750 07 Uppsala
Sweden
Tel.: +46 18 67 26 61
Fax: + 46 18 67 27 05
E-mail: elina.leskinen@genetik.uu.se

Other persons responsible:
Dr. Aase Kristiansen
University of Copenhagen (UC)
Botanical Institute
Department of Mycology and Phycology
Ø. Farimagsgade 2D
DK-1353 Copenhagen K
Denmark
Tel.: +45 35 32 23 04
Fax: +45 35 32 23 21
E-mail: aasek@bot.ku.dk

Dr. Kaj Sand-Jensen
University of Copenhagen (UC)
Freshwater Biological Laboratory
Helsingørsgade 49-51
DK-3400 Hillerød
Denmark
Tel.: +45 48 24 24 70 (ext. 311)
Fax: +45 48 24 14 76

LONG-TERM CHANGES IN BALTIC ALGAL SPECIES AND ECOSYSTEMS BIOBASE

POUL MØLLER PEDERSEN[1], JEANINE OLSEN[2], WYTZE STAM[2], AKIRA PETERS[3], JAN RUENESS[4], ELINA LESKINEN[5], AASE KRISTIANSEN[1], KAJ SAND-JENSEN[6]

[1]Botanical Institute, Department of Phycology, Copenhagen, Denmark; [2]Biological Centre, Department of Marine Biology, Groningen, The Netherlands; [3]Institut für Meereskunde, Abteilung Meeresbotanik, Kiel, Germany; [4]Department of Biology, Section for Marine Botany, Oslo, Norway; [5]Department of Genetics, Uppsala, Sweden; [6]Freshwater Biological Laboratory, Hillerød, Denmark

1. INTRODUCTION

The extended Baltic ecosystem, to include the Skagerrak-Kattegat area and part of the North Sea, provides a unique salinity gradient ranging from marine to brackish. The area is geographically circumscribed and geologically young (ca. 7000 years old). These characteristics have led to strong selection pressures on marine algae. Photosynthetic performance, growth rate and salinity tolerance between Atlantic and Baltic Sea algae show that morphological and physiological variation is widespread. Genetic differentiation has been found along the salinity gradient, but no apparent hybridization in the contact zones. Because the Baltic seaweed flora is diverse but still relatively small (ca. 350 spp), with attenuation in species number with decreased salinity (ca. 100 spp), and because relatively comprehensive species lists and locations have been carefully documented over the past fifty years, the opportunity now exists to select a core set of taxa and explore ecotypic and genetic differentiation at the species and subspecies level. Selection of taxa is based on distribution, ecological importance/impact, and life-history pattern. The three integrated tasks of the study include: the establishment of a comprehensive culture collection of core species, which will include detailed biogeographic sampling and experimental studies of ecotypic responses to salinity and temperature. These affect growth, survival and dispersal, and determine relationships among morphological, physiological and genetic adaptation across the salinity

gradient. Analysis of genetic population structure including phylogeographic structure for at least five key species (complexes) in the Fucales, Laminariales, Ulvales and Ceramiales based on DNA sequencing and microsatellite loci. These data will collectively establish links to recent paleoclimatic events that have shaped the Baltic algal flora.

2. OBJECTIVES

The central and measurable objectives of BIOBASE are:

1) The culture collection will be unique in that it will strive for a range of biogeographic representatives for each important species and intensive population level sampling for key species as opposed to the more common exemplar approach. The culture collection will therefore be a baseline culture collection and will serve as model for other European efforts.

2) BIOBASE will assess ecotypic differentiation and the effect of other factors than salinity, for example the distribution of suitable hard substrata and variation over large-scales and long-term time series. This will make it possible for the first time to assess hypotheses about stability, resilience and natural variability associated with vegetational cover and composition.

3) BIOBASE will also explore the genetic diversity at both the species and population level in selected key species. Species level phylogenies will be generated from DNA sequence data, and the purpose of the phylogenies is two-fold. First, species and species complexes need to be sorted out and this may or may not have a geographic component in it. In the case of the Baltic, which is itself a giant gradient, it is of interest to know whether or not sibling species have developed which are morphological indistinguishable (= cryptic species). There is reason to suspect this in the *Ceramium tenuicorne* complex. Having recovered a phylogeny, it is then possible to overlay other types of data on the topology. In this case those data will include salinity adaptations and biogeographic information related to origins of particular species. The population level studies will include single-locus, microsatellite markers and to lesser extent RAPDs in key species with different life histories and markedly different distributions. All data will collectively link to recent paleoclimatic events.

3. WORK PLAN

The scientific programme of BIOBASE is divided into three tasks which include 5 work packages. The work packages are designed to fulfil the objectives mentioned above.

Work package 1 and 2 will provide an overview of the role of ecotypic differentiation in relation to biodiversity and will be compared with the result of the genetic work. Work package 3 and 4 will provide the first detailed analyses of large- and small-scale genetic differentiation of red, brown and green algae in the Baltic region along the salinity gradient. The results from all work packages will help to discriminate among hypotheses about recent and ancient adaptations in the context of recent glacial events.

Work package 0: Comprehensive culture collection of Baltic marine algae including extensive subcollections of key and important species.

Work package 1: The role and effects of salinity adaptations in selected species of red, brown and green algae as well as the key taxa.

Work package 2: Diversity and dispersal of benthic algae on regional and local scales.

Work package 3: Phylogenetic and phylogeographic studies at the species level for key taxa.

Work package 4: Population level questions related to life history, gene flow and spatial scale.

II.1.3. Methods for monitoring, forecasting and management of shelf seas and coastal zones

TITLE: Mesoscale Ocean Radar Signature Experiments (Project **MORSE**)

CONTRACT N°: MAS3-CT-95-0027

COORDINATOR:

L. Leviandier
Thomson Marconi Sonar / Thomson CSF Airsys
7-9, rue des Mathurins
92221 Bagneux cedex, France
Tel. 33 1 40 84 48 42
Fax 33 1 40 84 43 62
E-mail : luc.leviandier@airsys.thomson.fr

PARTNERS:

Pr. H. Griffiths
University College London
Department of Electronic & Electrical Engineering
Torrington Place
London WC1E 7 JE, UK
Tel. 44 171 380 7310
Fax 44 171 387 4350
E-mail : h.griffiths@eleceng.ucl.ac.uk

Pr. W. Alpers
Institut für Meereskunde, Fernerkundung
Troplowitzstr. 7 / III
D-22529 Hamburg, D
Tel. 49 40 4123 5432
Fax 49 40 4123 5713
E-mail : alpers@ifm.uni-hamburg.de

Dr. A. C. Edwards
Oxford Computer Services
52 Saint Giles'
Oxford OX1 3LU, UK
Tel. 44 1865 511433
Fax 44 1865 559141
E-mail : ocs@cix.compulink.co.uk

Pr. R. Garello
Ecole Nationale Supérieure des Télécommunications de Brest
Département Image et Traitement de l'information
Technopôle de Brest Iroise - B.P. 832
29285 Brest cedex, F
Tel. 33 2 98 00 13 71
Fax 33 2 98 00 10 98
E-mail : rené.garello@enst-bretagne.fr

Dr. E. Barthelemy
Université Joseph Fourier de Grenoble
Laboratoire des Ecoulements Géophysiques et Industriels - B.P. 53 X
38041 Grenoble cedex 9, F
Tel. 33 4 76 82 51 17
Fax 33 4 76 82 50 01
E-mail : eric.barthelemy@img.fr

MESOSCALE OCEAN RADAR SIGNATURE EXPERIMENTS MORSE

L. LEVIANDIER
Thomson Marconi Sonar / Thomson CSF Airsys
7-9, rue des Mathurins
92221 Bagneux cedex, France,

E. BARTHELEMY[1], P. BRANDT[2], P. BRENNAN[3], G. CONNAN[3], A.C. EDWARDS[4], R. GARELLO[5], J. RODENAS[5], H. GRIFFITHS[3], D. RENOUARD[1], R. ROMEISER[2], A. RUBINO[2], J.O. THOMAS[4], K. WOODBRIDGE[3]

SUMMARY

The CEC MAST III project MORSE is devoted to furthering the understanding of the physical processes involved in Synthetic Aperture Radar signatures of oceanic internal waves.
The overall project is described and significant results regarding image processing, numerical modelling and laboratory experiments are presented.

1. INTRODUCTION

General context and objectives

It is now well established that satellite-borne SAR (synthetic aperture radar) is a powerfull mean to image those ocean surface phenomena like swells or surface slicks that modify its roughness. Besides, internal dynamics of the ocean (internal waves and tides, mesoscale oceanographic features) interacts with its surface roughness through associated surface currents. Among these, long internal waves generated by tidal flow over the slope and propagating on the continental shelf are very energetic and have a considerable oceanographic and economic impact in the coastal zones. So local or global-wave information is needed by a wide range of users in various activities like off-shore drilling and mining, ship routing, fisheries and aquaculture, environmental monitoring, acoustic communication, acoustic detection or coastal engineering in addition to physical oceanography itself.

Nevertheless, at the present time, radar imagery is not widely used by the potential users community. This is due to the lack

- of sufficiently reliable models able to retrieve quantitative results on the 3D structure of the hydrodynamic processes,
- of user-friendly software tools able to automatically process the images, releasing the user from a complex "manual" interpretation task.

[1] LEGI: Laboratoire des Ecoulements géophysiques et industriels
[2] IfM: Institut für Meereskunde, Universität Hamburg
[3] UCL: University College London
[4] OCS: Oxford Computer Services ltd
[5] ENSTB: Ecole Nationale Supérieure des Télécommunications de Brest

The objective of the project is then to furthering the understanding of the physical processes involved in radar signatures of internal waves in the ocean. Tools are developped that will contribute to fill the gap between availability of images and routine use of them.

Methodology

MORSE is a multidisciplinary approach in the above mentionned direction. It combines:

- Laboratory experiments using a dedicated small W-band (3 mm wavelength) radar imaging surface wave fields produced in laboratory tank and flume in Grenoble.
- Theoretical research aimed at assessing and developping a three scale hydrodynamic model to improve radar backscattering predictions.
- Development of methods for the extraction of ocean surface characteristics at high spatial resolution and for the resolution of the inverse problem consisting of retrieving the internal wave fields from surface information.

The project is structured into four inter-linked technical and scientific parcels, namely:

- the development of image processing algorithms for automatic extraction of surface wave parameters from radar images (together with their implementation and testing on ERS[6]-1 and 2 imagery).
- Experimental and theoretical research on basic non-linear hydrodynamic interactions between internal waves and surface gravity waves/capillary waves.
- The laboratory W-band SAR design, construction and test for tank experiments.
- Research on radar backscatter modeling (including modelling, especially for C-band, and inversion).

The following sections of this paper outline characteristic results obtained in these areas.

With regards to software products, three of the above listed areas, the two first and the last one will result in precommercial software packages: WASP[7], SWARM[8], and RADSIG[9]. These are presented in the corresponding sections. They constitute the elements of a pre-competitive global tool for automatic extraction of information on ocean hydrological and dynamical conditions from radar images.

As part of the data management plan of the project a MORSE Web site[10] has been set up at OCS. This web site has been building up gradually and now contains general information regarding MORSE activities, some ERS-1 imagery of internal waves, and samples of data from the experiments carried out in the flume tank and Coriolis tank by LEGI scientists. Interested users may download and analyse some of this sample data from the web site before requesting complete data sets from LEGI (please visit the web site for further information).

The MORSE consortium comprises four university group (UCL, IfM, ENSTB, LEGI) and two commercial companies (OCS, TMS[11])

---

[6] ERS: European Remote-sensing Satellite
[7] WASP: WAves parameter extraction Software Package
[8] SWARM: Surface WAves and Radar signature Modelling software package
[9] RADSIG: RADar SIGnatures software package
[10] URL of the MORSE Web Site: http://www.compulink.co.uk/~ocs/morse
[11] TMS: Thomson Marconi Sonar

2. OCEAN SURFACE PARAMETERS EXTRACTION FROM IMAGES

The objective of this part of the project is to provide software tools for automatic extraction of wave parameters at high spatial resolution from radar images. Image processing algorithms have been provided by ENSTB: periodogram, auto-regressive (AR), Auto-regressive moving average (ARMA), and maximum entropy methods. These methods, presently included in the WASP package described below, as well as a Time-frequency one, the SPWVR (smoothed pseudo Wigner-Ville representation) have been presented elsewhere (see for exemple (MORSE, 1997)). The second part of this section is devoted to another approach for detection and location of internal waves using wavelets.

2.1 WASP

WASP is the practical wing of the overall software approach and is based on past OCS experience and ENSTB's state-of-the-art knowledge of wave parameter extraction. WASP incorporates an image handling segment (images readable from CD-Rom, tape or hard disk) which includes a bespoke (and simple) macro-language to enable users to define any new image data structures (within reason) so that such images may be read in for further processing. This should future-proof the system to some extent Sampling, clipping, selection, and sub-image export and storage operations are allowed. An image catalogue/index system is being included in order to supply a complete image/sub-image/process audit. In the next segment, various high-spatial-resolution parameter extraction algorithms (supplied by ENSTB) may be applied to sub-images to obtain a map of dominant and sub-dominant wavevectors over the image. Numerical data may be exported. The numerical data may be used to generate an image-overlay curvi-linear coordinate system. A third component of the system will enable 'transects' (grey level profiles along specified paths) to be obtained and stored.

2.2 Detection and Location of Internal Wave from SAR Images using wavelets

ENSTB is currently developing a prototype system for automatic detection, verification, assesment and characterisation of internal waves from satellite images. The long-range objective of this work is to develop image and signal processing algorithms that would allow a computer to produce analysis product as given by human analyst given satellite imagery. This is a difficult image analysis and understanding problem due to a lack of precise mathematical descriptions of the ocean features, coupled with the time-varying nature of these features and the compilation of frequent partial obscuration by cloud cover. The total automation of this task is not presently feasible, but efforts toward that end will result in many tools that the analyst can use to reduce labor requirements and improve the quality and consistency of the analysis. Results so far indicate that it should be possible to reach this goal (Ródenas et al., 1997).
Here, we present a case study for the detection and location of internal wave patterns from high-resolution SAR images collected either by the European satellites ERS-1/2 or the Canadian RADARSAT over the Strait of Gibraltar or the Andaman Sea.

Automatic Internal Wave Detection and Location

In Figure 1, the main modules of the internal wave detector and location system are shown. Our strategy is to detect all possible internal waves, and then locate each individual internal wave packet. Methods for mesoscale feature extraction from SAR images often apply some

kind of filtering as a first step. Therefore, the first step in our system involves averaging the original SAR image, 8000 x 8000 pixels in size, using a 8 x 8 pixel nonoverlapping window. This produces an image 1/8 the size of the original, thus reducing subsequent processing times. The image also exhibits substancially reduced speckle noise.
In this non-supervised internal wave detection approach, we begin by separating land from sea in order to avoid false alarms in the detection process. Extraction of the shoreline in SAR images is a difficult task to perform using simple image processing operations such as grey-value thresholding, due to the presence of speckle and because the signal returned from the sea surface may be similar to that from the land. Thus, an automatic method for detecting the shoreline accurately and efficiently from SAR images is also introduced in the system. It would be possible to replace the coastline detection step by a manual delineation of the coastline obtained by digitising a map. However, changes that have evolved since the map was produced, such as small sandbanks near the coastline, may then be missed. Then, the image is wavelet transformed with various scales, based on the Wavelet Transform Modulus Maxima (WTMM) method. The wavelet transform gives spectral decomposition via the scale concept. By decomposing signals into elementary building blocks that are well localised both in space and scale, the wavelet transform can characterise the local regularity of signals, such as internal waves, via the study of the wavelet local modulus maxima across decomposition scales. Internal waves features are detected at multiple scales and characterised by their positions and magnitude. Then, a method for internal wave feature enhancement, based on an edge linking algorithm, is required in order to link these features. At this stage, we also discard significant local maxima belonging to the land class by means of the sea-land mask obtained from the coastline detection method. The remaining features are significant features of the important structures in the SAR image, e.g. internal waves, oil slicks, eddies, natural films, etc. Once we have detected the significant features in the SAR image, some *a priori* oceanographic knowledge usually is required on the geometric shape and size of the internal wave signatures and look-alikes for the identification and extraction of internal wave features. For this purpose, we use the phase information given by the wavelet maxima for all the significant detected features from the SAR image. Finally, a clustering algorithm, based on the neighboring features, is applied for internal wave packet location in the SAR image.

Results and Discussion

In this sub-section, we present several results of applying the proposed method for internal wave detection and location to two SAR images containing inernal wave patterns. The first SAR image to be analysed is show in Figure 2(a). This is a 3-look ERS-1 SAR image from the Strait of Gibraltar (Spain), 8000 x 8000 pixels in size, with a pixel spacing of 12.5 m x 12.5 m, covering an area of approximately 100 km x 100 km and acquired on September 10, 1993, is used as first test image. The image has been displayed using histogram equalisation, to reduce loss of contrast in the reproduction process. This image shows roughness patterns associated with a short wavelength soliton-like internal wave train propagating eastwards into the Strait. It also shows other oceanic processes as for instance : possible oil slicks, ship and ship wakes, natural films, and dark spots due to wind conditions. In the image, these several possible internal wave look-alikes are also underlined. The proposed method for internal wave detection and location has then been tested on this SAR image. From Figure 2(b), it can be seen that internal wave features are well detected and located against background noise or other internal wave look-alike phenomena. Mainly six internal wave packets are detected, and located in the SAR image. From the observation of the wavelengths and crests of the detected internal wave packets, we can estimate that the largest packets are propagating westwards, since the spacing between waves increases away from the leading edge, as to be expected in dispersive waves. The image also shows the detected coastline from sea-land classification.

Figure 3(a) shows a RADARSAT SAR image from the Andaman Sea which was acquired on May 4, 1996, covering an area of 300 km x 900 km. This image shows the interactions between several internal soliton packets propagating westwards in the Andaman Sea. The attractive of this image remains in its difficulty to well detect internal wave features due to the high amount of oceanic information in the sea surface. In the image, we can observe several packets of large internal solitons together with radar signatures of possible tropical rain cells and dark spots due to wind conditions. The fact of having several islands close to the coastline introduces a problem in the detection system. Figure 3(b) show the results obtained from the application of the internal wave detection method. Most of the internal wave features have been detected although the difficulty due to noise, dark spots, and tropical rain cells in the image. It can be observed that the detected internal wave crests have their origin in the interaction with the shallow bottom topography of the shelf, which coincides with the estimations in the Andaman Sea given in (Alpers et al., 1997).

Perspectives

An automatic method for internal wave detection and location has been applied to two satellite SAR images, and the feasibility of this technique for feature extraction has been demonstrated. The presented coastline detection method is accurate enough for the application on the internal wave detection problem. The wavelet transform in its multiscale edge detection version has been seen to be an excellent method for internal wave feature extraction. Several SAR images from two of the main world´s places in generation of internal waves in the sea surface have been studied. Internal wave structures are well detected and located against background noise by means of local modulus maxima methods across scales. Internal wave packets are quite well distinguished against internal wave look-alikes using an a priori oceanographic knowledge of the internal wave geometry shape and size.
Our future research directions will be to introduce a next stage in the internal wave detection system for the internal wave characterisation problem based on the Hough and Radon transforms. The current work here serves as a motivation and explanation for the ongoing work on the understanding of internal waves from satellite data.

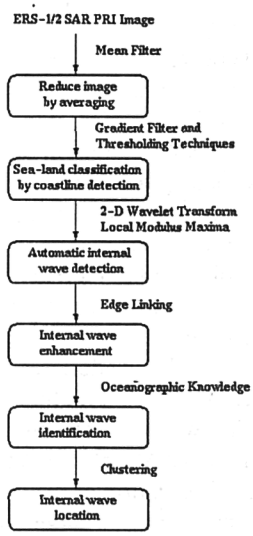


Figure 1: Stages of the internal wave detection and location system.

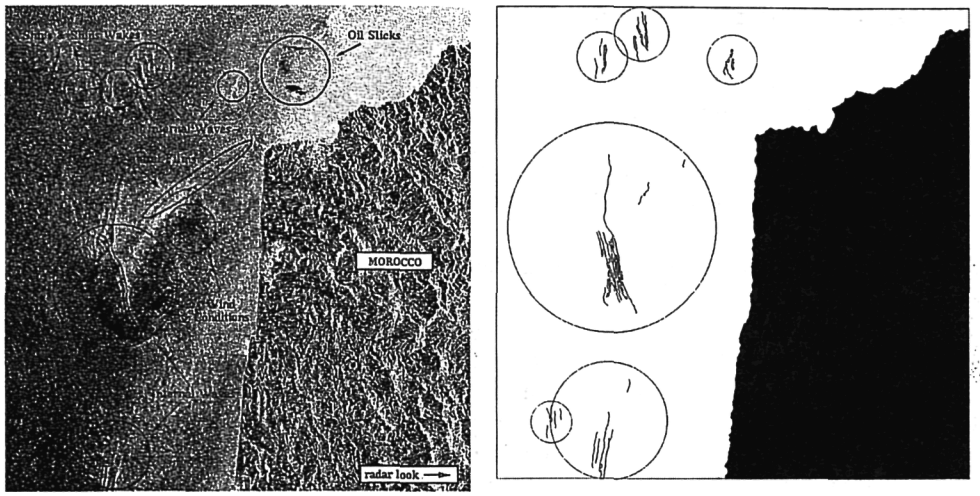


Figure 2: Internal wave feature detection. (a) ERS-1 SAR image from the Strait of Gibraltar which was acquired on September 10, 1993, covering an area of 100 km x 100 km. It shows several internal wave packets together with other oceanic features. (b) Detected internal waves features by the proposed method.

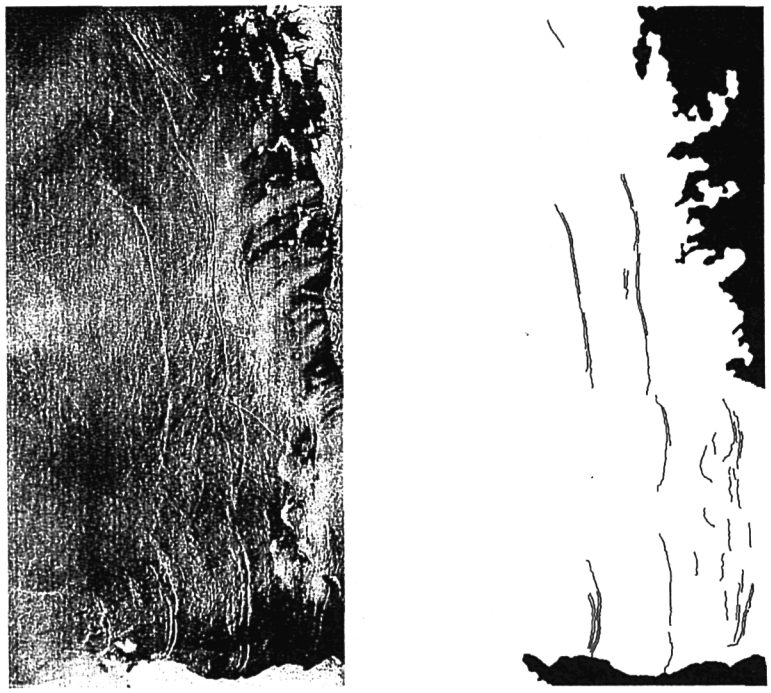


Figure 3: Internal wave feature detection. (a) RADARSAT SAR image from the Andaman Sea which was acquired on May 4, 1996, covering an area of 300 km x 900 km. (b) Detected internal waves features by the proposed method.

3. UNDERSTANDING OCEAN WAVE INTERACTIONS

This part of the project is devoted to better understanding of non linear interactions between long gravity waves and surface gravity/capillarity waves both on experimental and theoretical grounds.
For this purpose, tank experiments have been conducted and interpreted by LEGI, IfM has improved its numerical hydrodynamical model and OCS has developped a software package.

3.1 Internal solitary wave refraction by a step shelf:

Experiments are conducted in the 13 m diameter rotating tank equipped with a rectilinear shelf and an internal solitary wave generator. The shelf is 8 m long, 2 m wide and 0.7 m high ; a 0.5 m wide Cos^2-shaped profile links the shelf to the flat bottom of the tank. The internal solitary wave generator is 5 m long box, one side of which is a dam. Thus it is possible to have a thicker upper layer in the box. By lifting the dam, the light water behind the dam is released, generating a wave train which propagates downstream. We set the difference in the upper layer thickness across the dam so that, in non-rotating fluid, there is only one KdV solitary wave generated, followed by a train of dispersive waves. The internal wave generator can be moved so as to change the angle of the incident wave with respect to the shelf (30° and 60° in this set of experiments). The tank is filled with a two-layer system of fresh and salted water. The upper and lower layer thicknesses are fixed for all experiments and equal to 3 cm and 77 cm in the deeper part of the tank and the relative density difference between the upper and lower layer is O(1%). The interface height variations with time are recorded by ultrasonic interface followers. The accuracy of the probes is ± 1 mm. Two of the probes are fixed along the axis of the internal wave generator and close to the slope, in the deep water, whereas the other 19 probes are along a rod which is moved between each run. The measurement field is thus 3.5 m along shelf and 2.9 m across shelf (1.5 m over the shelf and 1.4 m over slope and deep water). We check that the waves recorded at the fixed probes are identical in amplitude and celerity for all runs. Thus, for given experimental conditions, we can normalize all records by the maximum amplitude recorded at the first probe. Experiments are done first without rotation, then at two different rotation rates, f= 0.0314 s^{-1} and 0.0628 s^{-1}.

Top views of the measurement field at successive times allow to compute the refraction angle between the incident and the transmitted wave over the shelf. A linear theory shows that the transmitted wave angle is linked to the incident wave angle by a relation similar to Snell's law for surface waves (Pinettes et al., 1995). When the amplitude of the incident solitary wave is small, so that their celerity is very close to the critical phase speed, then we verify that the measured incident and transmitted wave angles are in agreement with the angles computed from Snell's law, using the critical phase speeds in the deep and shallow parts of the tank. However, when the solitary wave amplitude is large and the celerity significantly different from the critical phase speed, then the transmitted angle is smaller than predicted by the linear theory. The discrepancy between the predicted and the measured transmitted angle increases with increasing wave amplitude. We check that Snell's law is still valid granted that the (linear) critical phase speeds are replaced by the actual (nonlinear) celerities measured over the deep and shallow waters respectively. Then it appears that nonlinearity accounts for most of the discrepancy between the linear approximation and the measurements (fig. 4). This result is new, to our knowledge. Rotation has an influence upon the amplitude of the incident wave, which decreases when rotation increases, and upon the waves' celerity which tends to increase when rotation increases. We check that, with or without rotation, there is a maximum

of wave amplitude, located over the slope. It correponds to the local perturbation which is necessary to link the incident and the transmitted waves.

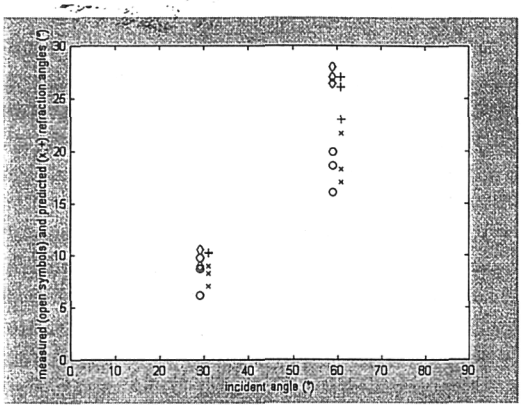


Fig.4- Refraction angle as function of the incident angle. Open symbols (o and ◊) correspond to the measured angles for two different initial conditions and the x and + to the angles computed from the actual nonlinear celerities.

3.2 Solitary free surface wave interaction with high frequency free surface waves.

The experiments are conducted in the 36 m long glass flume equiped with 2 different wave makers. At one end solitary wave are generated by a piston wave maker with highly efficient law of motions prescribed by computer program. The high frequency waves (frequencies between 1 Hz and 4 Hz, amplitudes approximately of 0.5 cm) are produced by a wedge wave maker driven sinusoidally by an electrical motor. The interactions are either strong (both wave trains travelling in the same direction) or weak (both wave trains travelling in the opposite direction). The main phenomenon is the phase shifting between the short wave train before interaction and the wave train after interaction.

The phase shift produced by the interaction between a surface solitary wave and a short surface wave can be analyzed using very simple arguments. We recall that a fluid particle affected by a solitary wave travelling at constant speed is dispaced horizontally by a given length l whcih therefore induces net mass flux associated to such waves. During the interaction with a short wave both motion combine. As a first approximation this combination may be regarded as linear. In consequence the short surface wave profile is shifted. The phase shift $\Delta\varphi$ is the measure of this displacement between the wave train before and the wave train after the passage of the solitary wave. An approximate expression is thus:

$$\Delta\varphi = \frac{4}{\sqrt{3}} kh_0 \sqrt{\frac{A}{h_0}}$$

where h_0 is the water depth, k the short surface wave number and A solitary wave amplitude. Note that $\Delta\varphi$ is independant of the short wave frequency. Nevertheless experiments suggest a slight increasing departure from this law with decreasing frequency (see MORSE, 1997).

3.3 Interfacial solitary wave interaction with high frequency free surface waves.

This type of interaction is physically very close to the ones encountered in Ocean. Oceanic long nonlinear internal waves of characteristic length L of about 1 km are advantageously

reproduced with solitary waves. On the other hand oceanic swells of wavelength Λ between 200 and 400 m are in our set-up produced as high frequency waves. The ratio of horizontal wave scales Λ/L is of order 0.5 in both the experiments and the ocean.

For this topic the experiments are also conducted in the glass flume of LEGI. However 15 m of the total length was isolated and filled with brine and fresh water on the top. This produces an interface of finite thickness (of order 2cm for a fractionnal jump in density of 1%). The experiments are instrumented with two kinds of probes. Ultrasonic probes measure the interface displacement and capacitive probes measure free surface displacement. The wave generators are on one hand the wedge wave maker described above and an internal wave generator of the type used by Michallet & Barthélemy (1997, Exp. in Fluids, **22**, pp380-386). The wave interaction is measured with an array of 6 probes of each type. Both strong interactions (both wave trains travelling in the same directions) and weak interactions (waves travelling in the opposite directions) are performed. Experimental records consist of free surface and interface displacements against time at 6 locations in the flume 20 cm apart. For this set of experiments phase shifts were also expected. The weak velocity field associated to internal solitary waves compared with surface ones produces phase shifts too small to be measured with sufficient accuracy. However surface wave modulations are easily noticed. Strong interactions show that the surface wave is modulated with a decrease in amplitude as it interacts with the internal wave during strong interactions while the contrary is measured for weak interactions. This seems to agree with wave refraction on slowly varying currents theory as reported by Mei (1992, The Applied Dynamics of Ocean Surface Waves, World Scinetfic, p107). This experimental study should be supplemented in a near future by analytical modelling based on refraction-like 2D theories.

3.4 Numerical hydrodynamical modelling

The simulation of radar signatures of oceanic internal waves requires the knowledge of several physical mechanisms affecting the radar signal modulation. Among these are physical processes related to the internal wave dynamics itself, to its interaction with the ocean surface, and to the interaction between the sea surface and the electromagnetic radar waves, which constitutes the radar imaging of the ocean surface. At IfM an attempt is being made to describe all these physical processes by a set of different numerical models (the third one will be consideredin the last section):

1) A state-of-the-art internal wave model has recently been developed at IfM. This model, which has been applied to the simulation of the tidally induced dynamics in the straits of Gibraltar and Messina in the Mediterranean Sea, is capable of describing the generation and propagation of internal bores and their disintegration into trains of internal solitary waves (Brandt et al., 1997). Moreover, it allows for the numerical computation of realistic surface current fields associated with the internal wave dynamics.

2) The variable surface current fields calculated by the internal wave model are used as input data for the wave current interaction model of IfM. The wave current interaction model consists of a fast algorithm for the integration of the action balance equation according to weak hydrodynamic interaction theory. The existing software allows the employment of different source functions and parameterizations of the equilibrium waveheight spectrum and the relaxation rate. It can handle fully two-dimensional surface current fields as well as time-dependent surface currents. Also events like blocking and trapping of wave packets at certain positions or propagation of waves through shear currents can be handled without numerical problems.

3.5 SWARM

SWARM is the theoretical/modelling wing of the overall precommercial software and is based on past OCS experience and IfM's state-of-the-art knowledge of radar signature formation. (its scope goes beyond the hydrodynamical processes dealt with in this part and includes radar response).

Its purpose is to generate numerical models representing ocean surface wave spectra at a number of surface spatial points throughout a straining current system. At the moment only 1-D steady-state current systems are allowed (satisfactory for the surface distribution of current in internal tides, internal wave trains, swell waves, flow over bathymetry etc). However, the user has control over the distribution of wavevectors in the basic wave spectrum, and the distribution of spatial points. The physics of wave refraction is used to determine wave paths, with the dispersion relation for deep water gravity/capillary waves being employed. The energy content of each wavevector is determined by the physics of wave action, with a variety of wind input and wave breaking terms to be made available (for example Romeiser et al., 1997). Because of the number of parameters involved, it is possible to generate many wave spectra models for a given current distribution, e.g., just consider the multiplicity of models that may be generated using different wind speeds and wind directions. The number of radar signatures that may be predicted (radar wavelength, incidence angle, polarisation, imaging mechanism) becomes prodigious. A database of computed signatures, called a 'features data base', is therefore set up using the same cataloguing system as WASP.

4. LABORATORY SAR DEVELOPMENT

Radar construction

The aim of this part of the MORSE project is to design, construct and test a high resolution W-band polarimetric imaging radar. The radar is designed for a resolution of approximately 6 cm in range, requiring a sweep bandwidth of 3 GHz, and 6 mm in azimuth. The maximum range is very small (7 m) and so the transmit power requirement is just 10 mW with antenna gains of 15 dBi. The VCO sweep bandwidth is 3 GHz, the pulse repetition frequency 625 Hz and the image is formed in 1 second, during which time it is assumed that there is little movement within the imaged area. Antennas of 15 dBi gain should be suitable for these laboratory tank measurements, giving a S/N ratio of 20 dB or better across the image. Because of the very short range requirement, the IF frequency range is very low (100s of kHz) and so may be sampled directly.

The FMCW technique is preferred to a pulsed radar for such high resolution at relatively short ranges. The design of the radar is simplified by using separate transmit and receive antennas, and this has the additional benefit of providing a polarimetric capability supporting HH, VV and HV modes though, of course, these are obtained with successive passes of the radar rather than simultaneously. To obtain azimuthal resolution of a similar order to the range resolution requires the use of aperture synthesis techniques with the radar moving along a rail. Usually the motion would be linear, but in this case a circular path is taken which somewhat complicates the azimuth processing. Aperture synthesis has been shown to be compatible with the FMCW technique (Griffiths, 1988) and a practical radar of this kind has in fact already been built and demonstrated by UCL at lower frequencies.

The beamwidth of the transmit and receive antennas should be sufficiently broad to provide full coverage of the swath in the vertical plane. In the horizontal plane the maximum achievable azimuth resolution is half the azimuth dimension of the antenna. For this application, horn-type antennas are used with apertures of approximately 6 mm × 4 mm and with beamwidths of approximately 35° and gains of approximately 15dBi. This gives a maximum achievable azimuth resolution of 3 mm, though the particular geometry used means that this resolution is not realised, however an azimuth resolution superior to the range resolution is easy to achieve.

The radar velocity is 1 m/s requiring a minimum theoretical PRF of 333 Hz though again because of the unusual geometry a somewhat higher value is required to suppress the aliased doppler beams. VCO linearity is important, and is managed by standard calibration techniques in which the VCO frequency-against-voltage characteristic is measured and the required voltage-against-time characteristic derived and stored in digital form in RAM. Motion errors, which become significant at 0.8 mm (a quarter of a wavelength), are likely to be a more challenging problem, especially in field trials where autofocus processing will certainly be required. It is planned to use corner reflectors in order to determine the exact path of the radar and correctly focus the aperture. A summary of the principal radar parameters is given in table 1.

radar centre frequency:	94 GHz	size of antennas	6 mm × 4 mm
sweep bandwidth	3 GHz	gain of antennas	15 dBi
PRF	625 Hz	range resolution	6 cm
imaging time	1 s	azimuth resolution	1.5 cm
transmit power	10mW	operating range	7 m
radar velocity	1 m/s	S/N ratio	>20 dB

Table 1. Principal radar parameters

First trials

During the first 12 months of the contract the radar design was established and the unit was successfully constructed at UCL. The basic design is shown in figure 5. The VCO linearity was measured and an EPROM was programmed with the necessary calibration at ENSTBr. Initial measurements at UCL confirmed that the radar was working as expected although there appeared to be excessive mixer noise. Subsequent trials during the next 6 months at LEGI revealed that sensitivity was indeed below expectations due to the low-frequency mixer noise which is a fundamental weakness of the homodyne radar achitecture employed in the design. Subsequently, efforts have been made to reduce the mixer noise and its impact by increasing the PRF (by a factor of 4) which increases the IF frequencies and means that the mixer operates in a region which suffers less from low-frequency noise. The increased PRF results in reduced S/N ratio from the azimuth processing, but this can be restored simply by coherently averaging 4 adjacent looks (or, indeed more than 4 if a further improvement is required at the expense of azimuth resolution). These improvements are currently being finalised, after which it is planned to undertake further trials in both the stationary flume tank and the Coriolis turntable at LEGI.

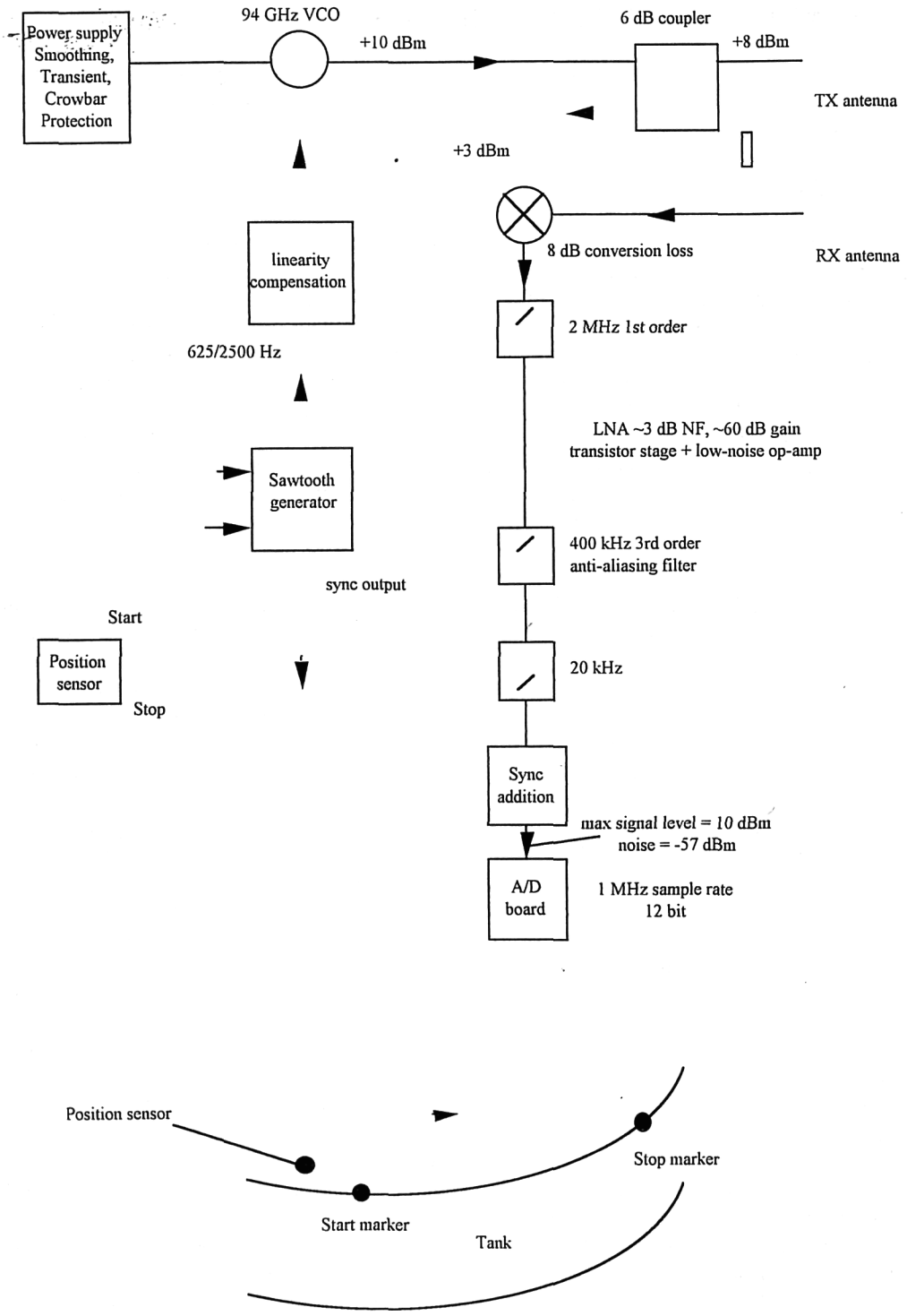


Figure 5. The MORSE radar architecture

5. RADAR BACKSCATTER MODELLING

The objective of this part is on one hand to further develop models for radar signatures generation, and on the other hand to address the inverse problem. This results in basic research as well as in software developpement.

5. 1 Imaging theory

The output of the model described in section 3.4, a two-dimensional modulated wave spectrum for each grid point, is fed into the advanced composite surface scattering model of IfM for the numerical computation of radar signatures. This model is based on the standard expression of Bragg scattering theory, but it includes a number of second-order terms of the normalized radar backscattering cross section (NRCS) of the sea surface, which are obtained from a Taylor expansion of the NRCS with respect to the surface slopes parallel and normal to the radar look direction. The second-order terms of the NRCS account for the contribution of waves which are long compared to the short Bragg waves (Romeiser and Alpers, 1997; Romeiser et al., 1997). For each radar image according to the composite surface scattering model, an additional image is generated for comparison, which represents the result of a simple Bragg model without higher-order terms.

For the comparison between simulated and measured radar signatures of internal waves we used ERS 1/2 SAR images acquired over the straits of Gibraltar and Messina. It turned out that only very few of the available SAR images of internal waves are suited for a complete quantitative comparison with model results. This results from the fact that the signatures of internal waves are often noisy and two-dimensional in a way which is not accounted for in the internal wave model, or they are camouflaged by superimposed signatures of fronts, atmospheric features, or surface films. While the locations of the internal solitary waves does not seem to be affected strongly by such phenomena, the modulation depth of the NRCS can be affected very much. The analysis of internal wave signatures on ERS SAR images acquired over the Strait of Messina shows that the location of the internal solitary waves can be used to infer characteristics of the interior ocean. In fact, Brandt et al. (1997) show by using the internal wave model of IfM that the distance between the first two internal solitary waves of a wave train can be related, at least qualitatively, to the depth of the thermocline. Here, we want to focus on the possibility to gain information about the interior ocean from an analysis of the measured modulation depth of the NRCS over internal waves.
For first simulation runs an ERS 2 SAR image was selected, which shows signatures of an internal wave train near the Strait of Gibraltar. The signatures are well visible and have a regular shape. A comparison of the simulated surface current field with the observed radar signatures shows reasonable agreement between the measured and simulated locations of internal solitary waves. The wind speed at the station on the shore at the time of acquisition of the image was specified to be 6.1 m/s with a direction towards -15° with respect to our x-axis (which denotes the direction of the current as well as the azimuthal radar look direction). Figure 6a shows the corresponding simulated NRCS profile (marked as '1'), together with the measured one as obtained from the ERS 2 SAR image (marked as 'ERS'). In order to demonstrate that the simulated radar signatures depend significantly on the choice of the wind speed and direction, the figure includes also results for a wind direction rotated by 90° (line '2') and for a reduced wind speed of 3.0 m/s (line '3'). In order to demonstrate the effect of the second-order terms of the NRCS in the composite surface scattering model, Figure 6b shows

model results which would be obtained from a simple Bragg model without higher-order terms.

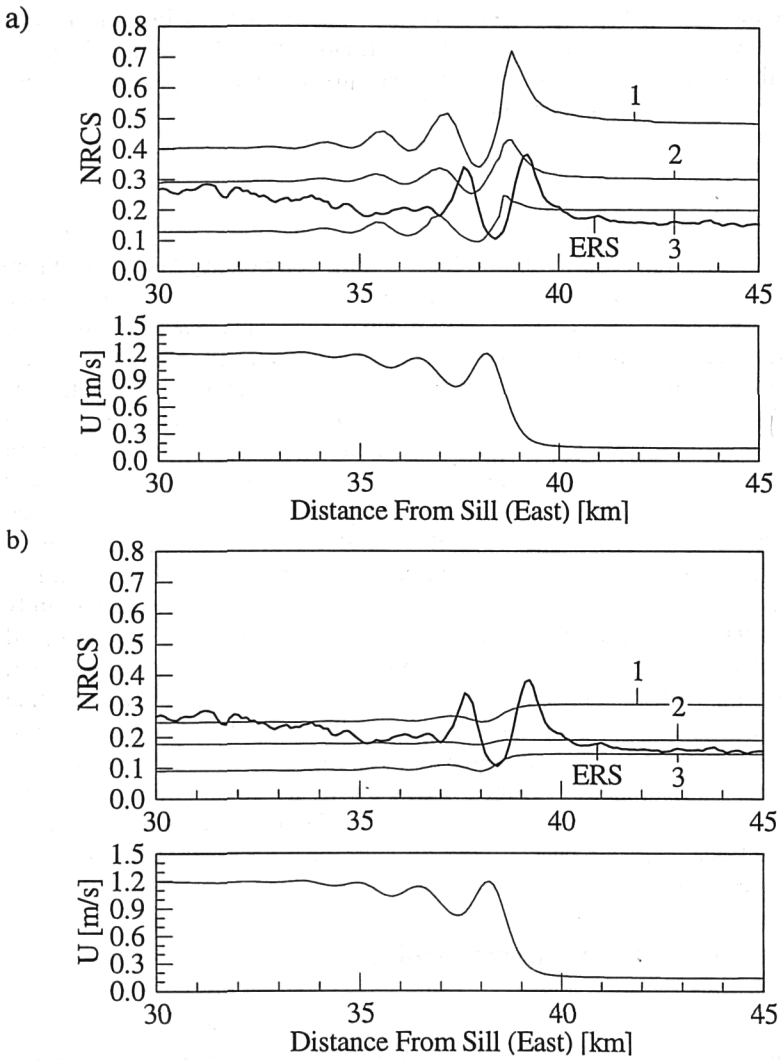


Figure 6: Simulated surface current (bottom) and radar signatures for a scenario corresponding to an existing ERS 2 SAR image of internal waves near the Strait of Gibraltar. 'ERS' - NRCS as obtained from the ERS 2 SAR image, '1' - NRCS as obtained from the model for the nominal wind speed (6.1 m/s) and direction (-15° with respect to the x-axis), '2' - NRCS as obtained from the model for a wind direction rotated by 90°, '3' - NRCS as obtained from the model for a reduced wind speed of 3.0 m/s; (a) full composite surface scattering model, (b) Bragg model without higher-order terms. The azimuthal radar look direction is equal to the x-direction.

Although the simulated and measured variations of the NRCS agree quite well without any dedicated tuning, the absolute (mean) level is clearly overestimated by the model in case '1'. This behavior is already known from other simulated ERS SAR images and may result from

the relatively steep incidence angle of 23°, which is close to the limits of models based on Bragg scattering theory. However, our results for various wind speed vectors show that the absolute NRCS as well as the modulation depth predicted by the model depends clearly on the wind speed and direction, which is often not well known. We conclude from this that, even if we had a perfect imaging model, not only the complex structures in typical radar images but also the uncertainties of the available wind information would make it difficult to derive information on the surface currents of internal waves just from a comparison between measured and simulated modulation depths of the NRCS.

5.2 RADSIG

RADSIG combines WASP and SWARM and introduces a third component, MATCH. From WASP the user obtains an 'observed' signature (transect) from a desired and processed image; from SWARM the user has a data base of computed signatures made according to his/her intelligent input specification. By specifying/limiting parameters, the user enables MATCH to search the data base for the 'best fit' model that most closely resembles the observed signature. The 'inversion' process is the statement that the parameters of the observed signature are then those of the best-matched computed model. This inversion procedure has been followed based on our past experience and our knowledge of the complexity of the physics involved, e.g., internal hydrodynamics coupled with surface hydrodynamics and environmental conditions, coupled with electrodynamical backscattering from a near-random rough surface, and SAR technology. In brief, there is NO simple inversion technique and one is forced to the model-matching route. The algorithm presently intended for use in MATCH is based on matching the Fourier content of the observed signatures with the Fourier content of the computed signatures. This has the advantage that the Fourier data for the computed signatures may be computed but once and stored along side that of the 'physical' data. Preliminary studies of this physically motivated approach suggest that the method is quick, captures most of the essential information, and also restricts the number of 'matching' data base signatures to either one or a few, where the few may then be interrogated by the user. Most usefully, a user may 'customize' the feature data base so that it is representative of conditions that may be met with on a regional and seasonal basis, e.g., Straits of Gibraltar in September say.

5.3 Internal wave field reconstruction methodology

This part of the project is directly devoted to addressing the inverse problem of retrieving information on the water column from the manifestation of internal waves on radar images and is handled at TMS. This is a difficult inverse problem since highly non-linear transfer function are involved. More precisely, the corresponding forward problem consists in predicting radar signatures from some parameters describing the volume of the ocean. This forward problem decomposes into three successsive ones:
The first one is the prediction of the surface current associated with the internal wave. The governing parameter is the density profile, especially the picnocline deph and density contrast. Assuming some external excitation, namely the tidal wave, the transfer function is given by a propagation model for the internal wave.
The second one consists in evaluating the perturbed wave spectra for a given (straining) surface current, using weak hydrodynamic interaction theory. The first stage of the SWARM software is dedicated to this task.

The third one is the calculation of radar backscattering cross sections for a given surface wave spectrum. This can be done with various models ranging from simple Bragg scattering to advanced composite surface model as developped by IfM (see section 5.1 and 3.5).

One can search to solve the global inverse problem "directly" using a global forward model. It seems more realistic to adress successively the above mentionned problems, or at least two distinct ones, namely the first one and the other two together . This is made possible since they are independent in the sense that the output of one problem is the input of the following one. There are some advantages to proceed in this way. It is likely to save computer time with regards to the global method and allows to keep physical insight on the different physical processes involved. On the other hand, the method presents the drawback of relaxing some constraints on the solutions. In fact this is not a drawback if the model constraining the solution is not so reliable.
This way to proceed has then been chosen for first investigation of the inverse problem.
The main characteristic/difficulty of the inverse problem associated to the first forward problem is the multiplicity of models describing internal waves propagation either linear (modes, rays) or non-linear (Korteweg-De Vries, Benjamin-Ono, Joseph), some of wich only qualitatively match the experimental data. This leads to a non standardly posed inverse problem. We have focussed on non-linear waves propagating far from their generation place.
The main feature of the second forward problem is the large amount of computer time required to perform the calculation of perturbed surface wave spectra, especially when two-dimensionnal spectrum are taken into account. This precludes the use of global optimization schemes suitable for hihly non-linear inversion. At least as a first step, we limit our investigations to one dimensionnal spectra. The third forward problem, taken alone, would lead to an inverse problem that needs, to be solved, some minimization constraint.
The development of works related to the inverse problem will be an important issue of the third year of the project.

6. CONCLUSIONS

Substancial progress have been achieved towards the MORSE objective to better understand the physical processes involved in radar signatures of oceanic internal waves:
On the experimental ground, nonlinear waves interaction experiments have been conducted and interpreted. For the refraction of internal solitary wave by a step shelf, a Snell's law is valid granted that nonlinear celerities are taken into account. In the case of long surface wave - short surface wave interaction, a phase shift of the short wave has been measured and shown to behave like predicted by an analytical model.
Regarding SAR image processing, besides classical algorithms for parameters extraction, an automatic method for internal wave detection and location using wavelet transform has been successfully applied to images from two important areas for internal waves generation.
The project dedicated high resolution W-band radar has been designed, constructed and tested. First measurements show that the radar is working as expected but with an excessive mixer noise. Improvements are being finalised.
On the numerical modelling ground, an improved model for computing two-dimensional perturbed wave spectra has been developped. Once associated to a composite surface model for backcatter, it leads to the computation of radar signatures. The influence on these signatures of wind speed and direction, often badly known parameters, has been emphasised.
Three user-friendly precommercial software packages are produced during the project, version 1 of the first two being completed: WASP for extraction of wave parameters from SAR images,

SWARM for radar signatures generation, and RADSIG for matching observed signatures with computed ones.

ACKNOWLEDGEMENTS

The ENSTB group would like to thank the Centre for Remote Sensing and Processing, CRISP, National University of Singapore, for providing a WWW Catalogue Browse whence to obtain the RASARSAT SAR images from the Andaman Sea.

REFERENCES

Alpers, W., H. Wang-Chen, and L. Hock, "Observation of internal waves in the Andaman Sea", IEEE Proceedings of IGARSS'97, 2-9 August, Singapore, 1518-1520, 1997.

Brandt, P.; A. Rubino, W. Alpers, and J. O. Backhaus, Internal waves in the Strait of Messina studied by a numerical model and synthetic aperture radar images from the ERS 1/2 satellites. *Journal of Physical Oceanography*, **27**, 648-663, 1997.

Griffiths, H.D., 'Synthetic aperture processing for full-deramp radar altimeters', *Electronics Letters* **24** (7), 371-373, 1988.

MORSE, CEC, Contract MAS3-CT95-0027. *First Year Annual Report*, 1997

Pinettes et al., *Fluid. Dyn. Res.* **16** ,217-235, 1995

Ródenas, J. A., and R. Garello, "Wavelet analysis in SAR ocean image profiles for internal wave detection and wavelength estimation", *IEEE Trans. On Geoscience and Remote Sensing* **35** (4), 933-945, 1997.

Romeiser, R., and W. Alpers, An improved composite surface model for the radar backscattering cross section of the ocean surface, 2. Model response to surface roughness variations and radar imaging of underwater bottom topography. *Journal of Geophysical Research*, **102**, 25 251-25 267, 1997.

Romeiser, R., W. Alpers, and V. Wismann, An improved composite surface model for the radar backscattering cross section of the ocean surface, 1. Theory of the model and optimization/validation by scatterometer data. *Journal of Geophysical Research*, **102**, 25 237-25 250, 1997.

TITLE: **Coastal region long-term measurements for colour remote sensing development and validation (COLORS)**

CONTRACT NO: **MAS3-CT97-0087**

COORDINATOR: **Giuseppe Zibordi**
Joint Research Centre (CEC-JRC)
Marine Environment Unit
21020 Ispra, Italy
Tel. +39 332 785902
Fax. +39 332 789034
E-mail giuseppe.zibordi@cen.jrc.it

PARTNERS:

Luigi Alberotanza
Institute for the Study of Large Masses (CNR-ISDGM)
San Polo 1364
30125 Venice, Italy
Tel. +39 41 5216842
Fax. +39 41 2602340
E-mail claudia@neuro.isdgm.ve.cnr.it

Jim Aiken
Plymouth Marine Laboratory (NERC-PML)
Prospect Place
Plymouth PL1 3DH
United Kingdom
Tel. +44 1752 633100
Fax. +44 1752 633101
E-mail j.aiken@pml.ac.uk

Simon Boxall
University of Southampton (USOU-DO)
Southampton Oceanography Centre
Southampton SO14 3ZH
United Kingdom
Tel. +44 1703 592744 / +44 802 227059
Fax. +44 1703 593161
E-mail simon.r.boxall@soc.soton.ac.uk

Orla Ni Cheileachair
Irish Marine Data Centre (ISMARE)
80 Harcourt Street
Dublin 2, Ireland
Tel. +353-1-4757100
Fax. +353-1-4757104
E-mail orla@marine.ie

Roland Doerffer
GKSS-Forschungszentrum (GKSS) Geesthacht GmbH
Max Plank Strasse
21494 Geesthacht, Germany
Tel. +49-4152-872480
Fax. +49-4152-871888
E-mail doerffer@gkss.de

Marcel Wernand
Netherlands Institute for Sea Research (NIOZ)
P.O. Box 59
1790 AB Den Burg, Texel
The Netherlands
Tel. +31 2223 69417
Fax. +31 2223 19674
E-mail wernand@nioz.nl

Richard Santer
Universite du Littoral (UL-PAMOC)
Station Marine
B.P. 80
28 avenue Foch
62930 Wimereux, France
Tel. +33-3-21992931
Fax. +33-3-21992901
E-mail santer@loalit.univ-littoral.fr

COASTAL REGION LONG-TERM MEASUREMENTS FOR COLOUR REMOTE SENSING DEVELOPMENT AND VALIDATION (COLORS)

G. Zibordi[1], L. Alberotanza[2], R. Doerffer[3], J. Aiken[4], M.Wernand[5], S. Boxall[6], R. Santer[7] and O. Ni Cheileachair[8]

[1]CEC-JRC, Ispra, Italy; [2]CNR-ISDGM, Venice, Italy;
[3]GKSS, Geesthacht, Germany; [4]NERC-PML, Plymouth, England;
[5]NIOZ, Texel, The Netherlands; [6]USOU-DO, Southampton, England;
[7]UL-PAMOC, Wimereux, France; [8]ISMARE, Dublin, Ireland.

ABSTRACT

COLORS is the first attempt to create a long-term European network program for the development and validation of water colour remote sensing in coastal zones and shelf seas.
Over a three year period COLORS will cover the following activities:
i. Extensive long-term measurements over three selected sites, located in different coastal/shelf areas (Adriatic Sea, English Channel, North Sea) representative of the main European water types. All test sites will be equipped with identical instrument packages and special attention will be paid to calibration and intercalibration of sensor to ensure high quality measurements and comparability of the data from the different sites.
ii. Analysis, interpretation and processing of the data acquired, aimed at deriving bio-geo-physical marine and atmospheric parameters. These will be used to develop robust marine and atmospheric algorithms accounting for site and season specific influences.
iii. Application of the ensuing algorithms and techniques on available satellite data. The resulting data products will be validated in order to assess the full potential of operational optical remote sensing in European coastal waters.

1. INTRODUCTION

Radiance measurements from space in the visible and near-infrared spectrum, enable estimates of the constituent of sea water including pthytoplancton-pigment concentration and suspended particulate matter (Bricaud and Morel, 1987; Barale and Zibordi, 1994; Leonard and McClain, 1996) which are needed in climate and environment related applications. Remote sensing techniques developed over the last decade have demonstrated their importance to marine research and management (i.e. in global productivity mapping).
Over the next five years a number of new advanced satellite ocean colour sensors (i.e. the already launched MOS and SeaWiFS and the forthcoming MODIS and MERIS) will be operational. International projects have been established to obtain in-situ measurements of relevant in-water optical, water quality and atmospheric parameters for the development and utilization of such remotely sensed data. Most of these studies (Hooker et al., 1992; Senga, 1994) are directed at open ocean water, characterised by phytoplankton pigments and relatively well known atmospheric aerosol type.
The European socio-economic marine zone is primarily coastal, and data collected by open ocean studies are of little direct relevance to the coastal/shelf sea environment. In European coastal waters there are three dominant, and generally only partially correlated constituents, that affect the water colour: suspended sediments, phytoplankton and dissolved

organic matter (*yellow substance*). Because of the different spatial variability and content of atmosphere and sea-water in coastal regions, compared to the open ocean, methods for remote sensing data analysis are more complex and at present do not produce operational products. This is primarily due to the lack of long term statistically representative data sets on optical characteristics of atmospheric and marine constituents which are necessary for the development and validation of inversion schemes. COLORS proposes the establishment of a major data collection and exploitation program for the assessment of algorithms and methods for the operational use of satellite colour data in European coastal/shelf water.

2. OBJECTIVES AND METHODOLOGY

The main objective of COLORS is to establish a European network of three differing sites, at which a systematic program of long-term measurements in water and in the atmosphere can be carried out. The sites, which provide a cross section of the European coastal waters, are: Adriatic Sea, English Channel, North Sea.
All three sites will be equipped with identical instrumental packages and special attention will be given to sensor intercalibrations to ensure comparability of the data collected at the different locations.
Over a three year period COLORS is expected to provide:

- series of optical and bio-geo-chemical measurements of the major types of European coastal atmospheres and waters;
- bio-optical and atmospheric models and algorithms for coastal and shelf sea areas, developed and assessed using the measurements collected;
- assessment of methods for the interpretation of satellite remotely sensed data of European seas, based upon the new bio-optical and atmospheric models and algorithms.

The flow schematic diagram of COLORS activities is given in figure 1.

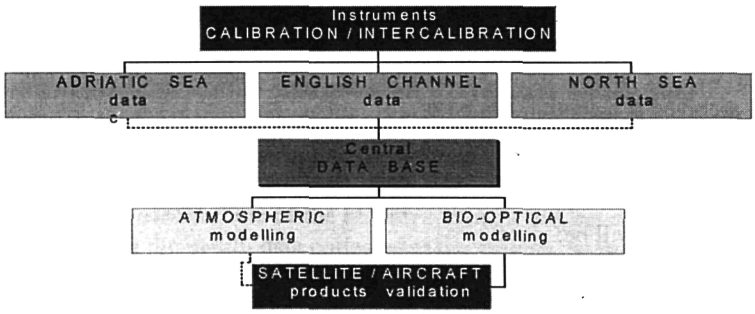


Figure 1. Flow of the COLORS activities

2.1 Optical and bio-geo-chemical measurements

The three measurement sites have been chosen to ensure that the main water types dominating European coastal/shelf waters, are considered.

- *A site off Venice in the Northern Adriatic Sea* (Lat. 45°18'50"N, Lon. 12°30'30"E). The site is representative of the marine features of the entire Adriatic Sea and is located in a transition region which is characterized by oceanic or coastal aerosols and Case-1 or Case-2 waters, depending on prevailing winds and currents. Both marine and atmospheric measurements will be taken from an oceanographic tower.
- *The area around the island of Helgoland* (Lat. 54°N, Lon. 09°E) in the North Sea. The site is characterized by maritime and coastal aerosol and Case-2 water with very high concentration of suspended matter and yellow substances from the Elbe river. The marine measurements will be performed from a research vessel. The atmospheric measurements will be taken from the island of Helgoland.
- *A long term mooring site off Plymouth* (Lat. 50°13'N, Lon. 04°05'W) *in the English Channel.* The site is mostly characterized by maritime aerosol and oceanic waters. However according to changes in direction of prevailing winds and currents, the site can be characterized by coastal aerosol and Case-2 water. A buoy and a ship will ensure the collection of marine measurements. The atmospheric measurements will be taken from the Eddystone Lighthouse located close to the site of the buoy.

An important objective of the project is the production of a large quantity of statistically representative, high quality oceanic and atmospheric data. To satisfy this requirement significant efforts will be applied to:

- *the calibration and intercalibration of instruments,* to ensure the highest possible accuracy in the conversion of measurements to geo-physical units and to make data sets from different sites fully comparable;
- *proper field operation of instruments reducing the intrinsic measurement errors,* which include for instance shadowing of platforms/ships (minimized by installing the underwater radiometers at suitable distance from structures) and bio-fouling (minimized by using suitable coating for underwater optics);
- *development of processing methods for data quality assurance* to avoid archival of measurements affected by errors.

Collected data will be stored at local archives at each measurement site and successively processed and archived at a central data base.

To satisfy the requirements of the COLORS objectives, the integrated program will comprise a combination of field and laboratory measurements to be made at frequencies ensuring seasonal characterization of sites.

The field measurements will be:

(d-i) *Subsurface upwelling radiance and downwelling irradiance*
(d-ii) *Above water downward irradiance*
(d-iii) *Direct sun irradiance*
(d-iv) *Sky radiance and polarization*
(d-v) *Water attenuation and absorption*
(d-vi) *Water temperature and salinity*
(d-vii) *Current speed and direction*
(d-viii) *Atmospheric pressure, humidity and temperature*
(d-ix) *Wind speed and direction*

The laboratory measurements, providing site specific data complementary to the field measurements, will include:

(i-i) *High Pressuree Liquid Chromatography (HPLC) for phytoplankton-pigments*

(i-ii) *In-vivo absorption spectra of pigments*
(i-iii) *Absorption spectra of filtered water for dissolved material*
(i-iv) *Particle size distribution*
(i-v) *Gravimetric filter analysis for total suspended matter and organic/inorganic fractions.*

All the measurement sites will use almost identical instruments. This will ensure the compatibility and mutual comparability of the data-sets from the different sites. All instruments will be based upon commercially available products and will be chosen to satisfy the requirement of extensive operation in the field with a minimum of maintenance.
The JGOFS (1994) and SeaWIFS (Mueller and Austins, 1995) protocols will be in principle accepted and applied at all sites. But, new or updated protocols will be adopted when made available in literature or from ongoing projects (i.e. CoASTS (Zibordi et al., 1995); PlyMBODy (Aiken, 1994)).

2.2 Bio-optical and atmospheric models and algorithms for coastal and shelf areas

The accuracy of water parameters obtained from the remote sensing of water colour is, to a great extent, determined by:
- the accuracy of the data used in the atmospheric correction process (i.e. the removal of atmospheric contribution from the remotely sensed radiance);
- the accuracy of relationships between water reflectance and, particulate and dissolved matter.

Although a basic parameterisation is available, simultaneous extended in-situ marine and atmospheric optical and bio-geo-chemical measurements have been available only rare in European coastal areas. Using the data collected at the three sites, the project will undertake the development and validation of atmospheric algorithms for parameterisation of atmospheric optical thickness and phase function, and the development and validation of bio-optical algorithms for water particulate and dissolved matter. The ultimate goal is to develop atmospheric and marine algorithms applicable in European waters. Nevertheless, it is probable that for some parameters the final algorithms will be functions of both site and time (season).

2.3 Assessment of methods for the interpretation of remotely sensed data

Inversion of remote sensing data (i.e. the retrieval of atmospheric and marine geophysical products) relies on modelling the radiative transfer processes in the atmosphere-surface-water system. The project will assess some of the radiative transfer models commonly used for marine colour applications using the in-situ data collected at the various measurement sites. Methods for deriving quantitative information from remote sensing data taken over coastal regions will be addressed. The mapping capabilities of colour sensors for pigments, total suspended matter and aerosol will be validated in each of the three coastal regions (i.e. characterised by different scattering absorption processes induced by maritime and land origin aerosol particles and by high concentrations of re-suspended sediments, terrigeneous particles and dissolved organic matter in sea water).

3. REMARKS

Observations of marine optical properties from satellites, offer a unique means to obtain synoptic information on the constituents in coastal waters. The data obtained thus forms an essential basis for coastal marine research and integrated operational management systems of the coastal zone. The results of COLORS will contribute to an improved quality of marine optical observations and consequently provide an essential element for integrated coastal management systems.
Further important aspects of the COLORS project are:

- a contribution to the development of operational use of European spaceborne marine observation systems like MOS, POLDER and the forthcoming MERIS;
- as a prototype project for future networks of in situ measurements systems for remote sensing calibration and validation (i.e. vicarious calibration of satellite data, atmospheric and sea water modeling, assessment of remote sensing products);
- as a model transnational and multidisciplinary project creating conditions for knowledge transfer among different teams and strengthening basis for collaboration on marine optics.

The COLORS data set and the developed models and algorithms will be made available on CD-ROM for future exploitation in oceanographic and atmospheric studies. General information on the project will be disseminated via the COLORS World Wide Web page at *http://www.marine.ie./datacentre/projects/colors/* .

REFERENCES

J.Aiken, G.Moore, M.Pinkerton, Radiometric and bio-optical calibration and validation of OCTS in the North East Atlantic and adjacent shelf sea. In Proceedings of the First ADEOS Symposium, Kyoto on December 6-9, 1994.

V.Barale and G.Zibordi, Trends in the surface colour field of the European marginal seas. In proceedings of the Second Thematic Conference on Remote Sensing for Marine and Coastal Environments, New Orleans, January 31-February 2, 1994.

A.Bricaud and A.Morel, Atmospheric corrections and interpretation of marine radiances in CZCS imagery: use of a reflectance model. Oceanologica Acta, 7: 33-50, 1987.

S.Hooker, W.E.Esaias, G.C.Feldman, W.W. Gregg, C.R.McClain, An overview of SeaWiFS and Ocean Colour. SeaWiFS Technical Report Series. NASA T.M. 103566, vol. 1, 1992.

JGOFS, 1991. Joint Global Ocean Flux Study Core Measurements Protocols. JGOFS Report N.6, Scientific Committee on Oceanic Research, 40 pp.

C.L.Leonard and C.R.McClain. Assessment of interannual variation (1979-1986) in pigment concentrations in the tropical Pacific using the CZCS. Int. J. of Rem. Sen., 17-721-732, 1996.

J.L.Muller & R.W.Austin, Ocean Optics Protocols for SeaWiFS Validation, Revision 1, NASA Technical Memorandum 104566, vol. 25,1995.

Senga, OCTS Sea-truth moored buoy on Yamato Rise. In Proceedings of the First ADEOS Symposium/Workshop, Kyoto on December 6-9, 1994.

G.Zibordi, V.Barale, G.M.Ferrari, H.Hoepffner, L.Alberotanza, P.Cova and C.Ramasco. Coastal Atmosphere and Sea Time-Series project (CoASTS): an ocean colour remote sensing calibration/validation project. Proceedings of the Third Thematic Conference on Remote Sensing for Marine and Coastal Environments, Seattle, September 18-20, 1995.

TITLE: Operational Modelling for Coastal Zone Management (OPCOM)

CONTRACT NO.: MAS3-CT97-0089

COORDINATOR:

Dr. K. Duwe
HYDROMOD Scientific Consulting (HYDROMOD)
Bahnhofstr. 52
D-22880 Wedel / Germany
Telephone: +49-4103 / 130 57
Telefax: +49-4103 / 33 17
E-mail: duwe@hydromod.de

Partners:

Dr. J.-L. Rahuel
Laboratoire d'Hydraulique de France (LHF)
6, rue de Lorraine
F-38130 Echirolles / France
Telephone: +33-4 / 76 33 42 08
Telefax: +33-4 / 76 33 42 39
E-mail: Jean.Luc.Rahuel@lhf.fr

Dr. M. Virtanen
Environmental Impact Assessment Centre of Finland Ltd. (EIA)
Tekniikantie 17 B
FIN-02150 Espoo / Finland
Telephone: +358-9 / 7001 8680
Telefax: +358-9 / 7001 8682
E-mail: Virtanen@EIA.fi

Dr. A. Silva
Hidromod Lda.
(Hidromod)
Taguspark, Núcleo Central, n° 349
P-2780 Oeiras / Portugal
Telephone: +351-1 / 421 13 73
Telefax: +351-1 / 421 12 72
E-mail: hidromod@taguspark.pt

Dr. M. Inkinen
Environmental Research Institute Väkipyörä Ltd. (ERIV)
Saaristokatu 2
FIN-65170 Vaasa / Finland
Telephone: +358-6 / 31 70 254
Telefax: +358-6 / 31 24 441
E-mail: matti.inkinen@vakipyora.fi

Dr. C. Bacher
CREMA l'Houmeau
Place du Séminaire
BP 5
F-17137 L'Houmeau / France
Telephone: +33-5 / 45 50 46 39
Telefax: +33-5 / 46 50 06 00
E-mail: cbacher@ifremer.fr

Prof. R. Neves
Instituto Superior Técnico (IST)
Av. Rovisco Pais
P-1096 Lisboa / Portugal
Telephone: +351-1 / 84 17 397
Telefax: +351-1 / 84 17 398
E-mail: rneves@hidrox.ist.utl.pt

Operational Modelling for Coastal Zone Management

K. Duwe, I. Nöhren
Hydromod Scientific Cons., Bahnhofstr. 52, D-22880 Wedel / Germany

1. Introduction

OPCOM is a EU-Research & Development Project which aims at improving methods and techniques for continuous monitoring and forecasting of coastal waters using already existing operational model and monitoring infrastructure. The OPCOM consortium consists of seven organisations from Germany, France, Portugal, and Finland.

2. Tasks

The individual technical and scientific tasks of the project may be outlined as:

A: Site-specific investigations on coastal management aspects to define user requirements:
Improvement of coastal management and monitoring practice by analysing operational data and model results and defining user requirements on model and monitoring systems for different hydrographic regimes and coastal management objectives.

B: Model investigations on operational aspects and forecast ability:
Improvement of operational and pre-operational coastal zone models regarding forecastability, field data assimilation, and long-term stability and reliability in continuous operation.

C: Integration of modelling, coastal monitoring, and user specifications:
Goal is a dedicated database structure as basic operational forecast segment of coastal zone management information systems also suitable for GOOS (Global Ocean Observation System) purposes.

The project pays special attention to two characteristic features:

a) coastal sites with strong tidal influence including estuarine phenomena to look at influences of strong advection, intensive vertical mixing, time-varying shorelines and tidal flats,
b) coastal sites with negligible tidal influence including estuarine phenomena to address wind driven advection, river plume meandering, and variable verical mixing.

3. Site-specific Investigations

Within OPCOM the following geographical areas and main coastal management problems will be investigated:

Bay of Marennes-Oleron (French Atlantic Coast)

The Bay of Marennes-Oleron is located on the Charentes Maritimes Atlantic coast of France, slightly north to the Gironde Estuary, within the so-called Pertuis Charentais. The intertidal flats within the bay are extensive and particularly sensitive to the nutrients which are brought by the inland rivers flowing into the bay. These areas are used for intensive oyster and mussel culture.

Special emphasis within OPCOM will be laid on questions concerning the impact of natural and anthropogeneous changes on the ecosystem of the bay, in particular management of the nutrient situation for a sustainable oyster farming activity.

Elbe estuary (German North Sea Coast)

The area of application is the tidally influenced Elbe river including the harbour area of Hamburg (the second biggest port in Europe). It comprises a large area of tidal flats at its mouth to the German Bight with strong dynamic and thermodynamic interaction. The river is intensively utilized for economic purposes. The port of Hamburg plays a key role as a transport link with central and eastern Europe. The navigational channel has been continuously adapted to meet the requirements of overseas shipping. In addition the outer Elbe estuary is the world's most frequented sea traffic area with routes linking the Central North Sea with Scandinavia and the Baltic States via the Kiel Canal. Intensive industrial utilization is present along the river (nuclear power plants, chemical plants, refineries).

The OPCOM activities will be concerned mainly with analysis of operational forecast data for vessel traffic information and data assimilation from operational models for fixed or moving (i.e. ship) monitoring platforms.

Tagus estuary (Portuguese Atlantic Coast)

The Tagus estuary, located near Lisbon, is a roughly pear-shaped estuary, approximately 30 km long and varying in width from approximately 15 km at the northern upstream section to 2 km at the downstream entrance, just south of Lisbon, covering an area of approximately 350 km^2. The circulation inside the estuary is mainly driven by the tidal flow, the tide has 2 to 4 m amplitude. In the entrance channel the velocity may reach 2 m/s in spring tide. The circulation in the mouth of the estuary is also influenced by the wave field.

The Tagus river is the main fresh water supplier of the estuary with average flow rates of the order of 200 m^3/s. Outside the estuary, in the zone where an important submarine outfall is located, the wind and density currents also play an important role in driving the flow along with the tide.

Primary objectives on this OPCOM site will be to address water quality monitoring in the vicinity of a subsurface effluent outfall.

Archipelago Sea and Kiryönjoki estuary (Bothnian Sea)

A very different hydrographic and ecological environment from the other three OPCOM sites is this area. The Archipelago Sea is situated at the connection between the Gulf of Bothnia and the central Baltic Sea. This regional sea may be characterized as a very large deep estuary with numerous coastal lagoons. Short-term variations in circulation and associated transport/mixing processes are pre-dominantly governed by meteorological phenomena, longer term processes are dominated by thermo-haline currents in the deeper Baltic Sea, fluctuations in the fresh water inflow from the coasts, and the very rare occasions of North Sea water penetration through the Danish straits which ventilate the deep water of the Baltic Sea. Even

more complicated are the interactions between the coastal lagoons (especially on the southern coastline) and the open sea, as most coastal bays are connected only by narrow channels. Tides are almost negligible in the Baltic Sea, this leads to a very high uncertainty in dynamical (and environmental) forecasting.

Very important from an ecological point of view are the large residence times of water in the Baltic once it has been transported from the rivers into the coastal waters. As most tributaries in the catchment area of the Baltic Sea are highly polluted this is especially of great concern for environmental protection. Only in some coastal areas there are already detailed measurement and monitoring activities which might enable a profound investigation as proposed for this study.

OPCOM partners will be especially looking at spill combatting and sea rescue activities and the impact of environmentally relevant discharges from rivers and other effluent sources.

4. Outlook

The project has started only recently and will last three years.

Within the next months existing model systems will be adapted to the areas of investigation. The already available knowledge from local monitoring and operational modelling systems will be collected and user requirements and expectations derived from interviews.

First model results from test calculations will be used to perform statistical analysis to establish statistically significant trends in the differences between forecasts and measurements of important boundary values for coastal models.

At the end of the project it is intended to have a "Definition of Important Criteria and Minimum Requirements on Operational Forecasts and Monitoring for Coastal Zone Management and Requirements on Operational Model Systems based on Existing Knowledge and Experiences".

TITLE: EUROWAVES - a user-friendly tool for the evaluation of wave conditions at any European coastal location

CONTRACT NO: MAS3-CT97-0109

COORDINATOR: **Dr. Stephen F. Barstow**
OCEANOR - Oceanographic Company of Norway ASA
Pir-Senteret
N-7005 Trondheim, Norway
Tel: +47 73 54 52 00, fax: +47 73 54 52 01
E-mail: sbarstow@oceanor.no

PARTNERS:

Prof. G.A. Athanassoulis
Dept. of Naval Architecture & Marine Eng.
National Technical University of Athens
P.O. Box 64070, Zografos 157 10
Athens, Greece
Tel: +30 1 772 1136
Fax: +30 1 772 1032
E-mail: mathan@central.ntua.gr

Dr. Luigi Cavaleri
ISDGM
S. Polo, 1364
I-20125 Venezia, Italy
Tel: +39 41 521 6811
Fax: +39 41 260 2340
E-mail: gigi@ocean.isdgm.ve.cnr.it

ASSOCIATED CONTRACTOR:
Prof. H.E. Krogstad
SINTEF Applied Mathematics
N-7034 Trondheim, Norway
Tel: +47 73 59 35 36
Fax: +47 73 59 35 24
E-mail: hek@math.ntnu.no

EUROWAVES - A USER FRIENDLY TOOL FOR THE EVALUATION OF WAVE CONDITIONS AT ANY EUROPEAN COASTAL LOCATION

STEVE BARSTOW[1], MAKIS ATHANASSOULIS[2], LUIGI CAVALERI[3] and HARALD KROGSTAD[4]

[1] - OCEANOR, Trondheim, Norway
[2] National Technical University of Athens, Athens, Greece
[3] Istituto Studio Dinamica Grandi Masse, Venice, Italy
[4] SINTEF Applied Mathematics, Trondheim, Norway

1. Introduction

A tremendous effort has been put into understanding and measurement of the characteristics of ocean waves during the last four decades. As far as the availability of wave statistics to ocean engineers and other users of such data are concerned, one can characterise each decade by a number of major developments as follows.

In the 1960s the major compilation "Ocean Wave Statistics" appeared providing for the first time at a glance information on wave statistics over the global oceans based on visual observations made by the voluntary observing fleet along the world shipping routes. This, and its successor "Global Wave Statistics", remained the most important sources of information on ocean waves for over 20 years.

Although instrumental wave measurements had been made earlier, the 1970s was the decade when measurements began to make an impact on the availability of wave data, mainly due to the reliable Waverider buoy and the Shipborne Wave recorder, although limited mainly to offshore oil exploration areas such as the North Sea at the start.

In the 1980s, wave modelling really took off, taking advantage of the fundamental advances in basic theory and computer capability. Large hindcast studies were performed and routine wave forecasts were introduced at most of the large meteorological centres around the world.

In the 1990s, satellite measurements have become the great novelty. Following the successful GEOSAT mission, a number of other satellites were launched, including ERS-1, Topex-Poseidon and ERS-2. The satellites offered, for the first time, the possibility of measuring waves worldwide. This triggered the production of related wave atlases, putting the results at the disposal of any user.

However, the above developments did not solve the problem of providing readily available information close to the coasts, where most of the economical interests and applications of wave data are to be found and are badly needed. Up until now this has been a question of resolution and cost. Global wave measurements from satellites do not provide good enough spatial resolution and repeatability in relation to the rather strong spatial gradients in the

ocean wave climate of the coastal zone and computer power has been the limiting factor when considering the resolution achievable in regional and global wave models.

2. Objectives and work scope

It is the aim of this project to develop a prototype tool (EUROWAVES) capable of quickly and reliably assessing the wave climate at a coastal or shallow water location, more or less anywhere in Europe, including the Mediterranean, the Canary Islands, the Azores and the Baltic, with acceptable accuracy and spatial resolution for most users, allowing, at the next stage, the development of commercial packages and/or atlases giving users easy and timely access to coastal wave statistics, initially for the European market, but with the option to relatively easily extend to any maritime nation worldwide.

To reach its objectives, the EUROWAVES project, which will run from 1998 to 2000, will be composed of several modules of work, each covering one of several building blocks, including an extensive, primarily deep water wave statistical data base, a detailed bathymetrical data base for European waters, one or more wave models to transfer the wave information to the desired location, and an advanced statistical package for the evaluation of the information to be provided to the user.

2.1 Wave Statistics

The information presently available on ocean waves in Europe is scattered among many different sources, e.g., raw data from different satellites are available from different space agencies, value added satellite data are available from different commercial organisations; different wave models are run with different grids and forcing wind fields in different countries, and wave data from the few long term wave measurement stations (buoys and offshore installations) in Europe are held by many different organisations. Some data are available at cost, but other data are only available at commercial rates.

This wealth of information needs to be collected and blended into a single data set, including a careful cross comparison between the different sources. The final result will be uniform wave statistics at a series of offshore points evenly distributed along the whole European coastline. The expected closest distance to the coast and between the sequential points will be at least of the order of 5 - 10 km.

2.2 Bathymetry

In order to reach the objective of a tool capable of providing wave data at a resolution of at least 5 km, detailed bathymetric data will be assembled for all European waters, from the coast up to a distance of typically about 100 km. Starting from an overall European map (Figure 1), a sequence of zooms will allow the automatic construction of a sub-grid specific for the area and the location of interest, such as the one in Figure 2.

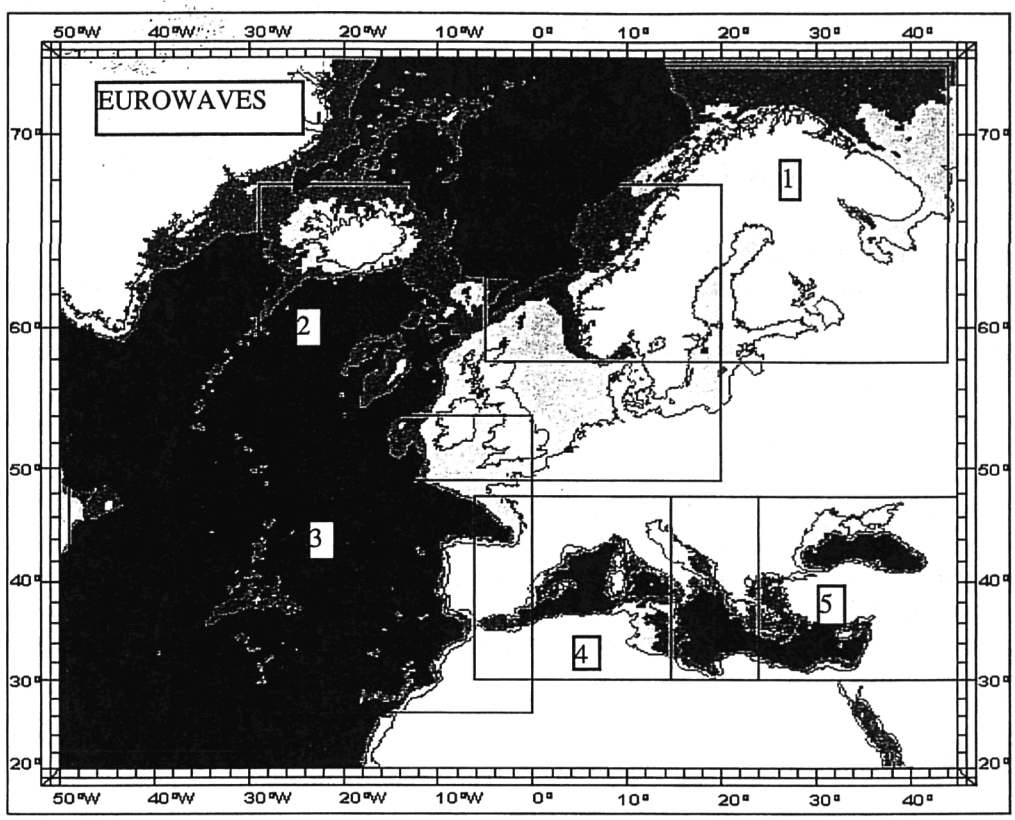


Figure 1. The concept of transferring from Level 0 to Level 1 Geographic Data

2.3 Wave modelling

Once the area of interest has been identified, EUROWAVES will extract from the archive the wave information at its borders, setting the conditions for its transfer to the specific location indicated by the user.

One or more wave models will be made available to the user, his choice being based on a trade-off between level of sophistication and computer time requirements. Full information to guide the user with the choice will be provided in a technical annex with explanations and examples.

Whatever the choice, the final result will be complete wave information, given as full statistics, at the location of interest.

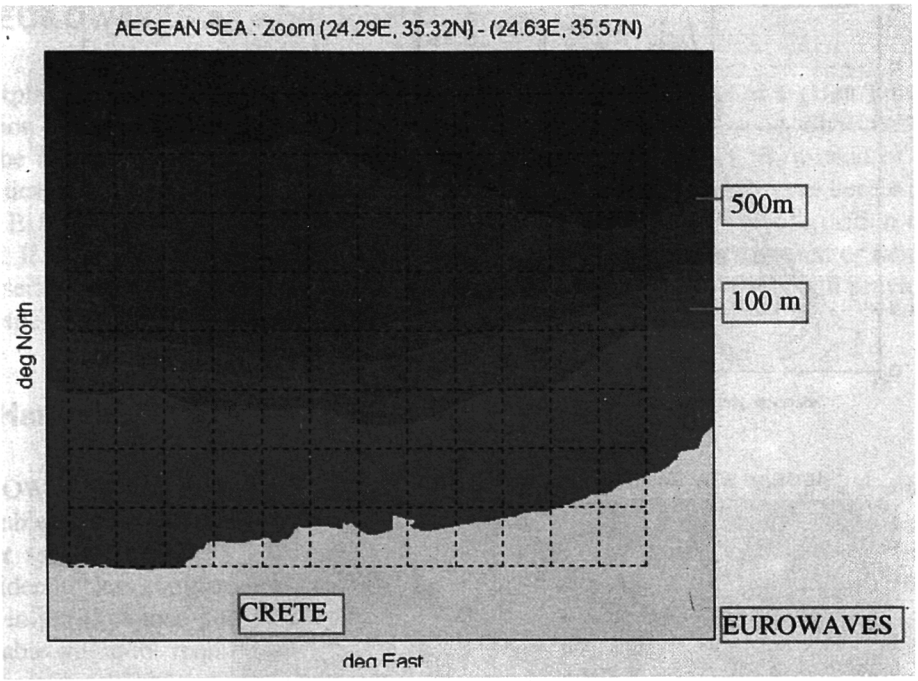


Figure 2. Final map for the wave transformation calculations.

2.4 Statistical package

This part of the project will provide all the necessary tools for the evaluation of all possible statistics required by a user from the wave information at the specified location. The results will be provided as graphical and tabular screen presentations, as in the example in Figure 3, as well as printed plots and data files.

3. Facilities

The whole process described in the previous section will be completely transparent to the user. His role will be simply to pinpoint the location of interest on the screen or as geographical coordinates, and EUROWAVES will provide the results at that location.

However, a more active role will also be allowed. A typical example will be the introduction of a more detailed or preferred bathymetry for the area of interest. A second interaction is the choice of the wave model (a default option will exist). It is expected that for a rough and ready estimate of wave conditions at the site, or as a first stage in the modelling procedure, the user will choose the simplest solution, moving on to more complicated models if time allows or as the final run.

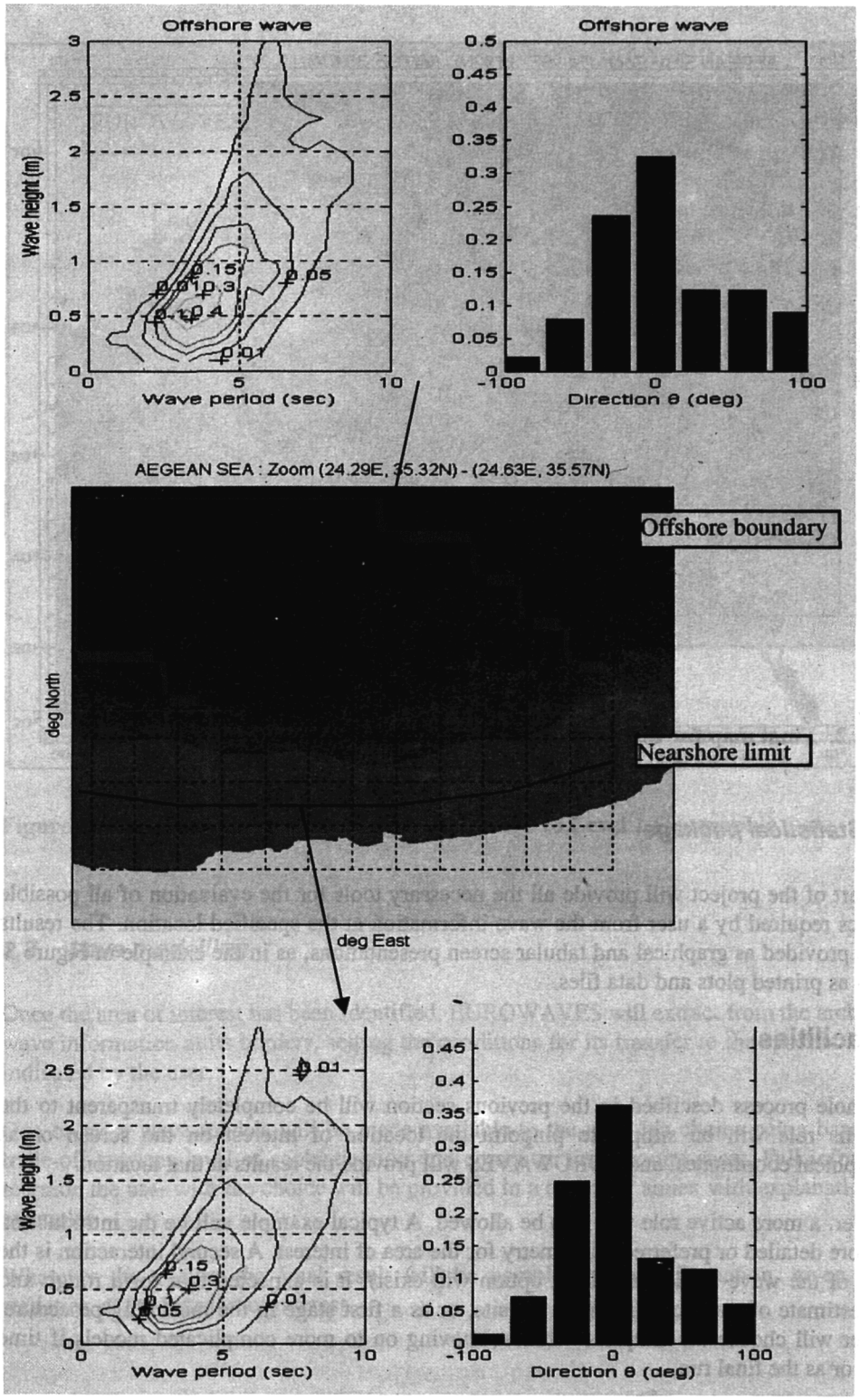


Figure 3. Example of EUROWAVES graphical screen presentation

4. EUROWAVES as a hindcast/forecast tool

As explained above, EUROWAVES will provide statistical wave data at a given European location in the coastal zone out to 100 km. or so from the coast. However, EUROWAVES will be designed to work, also, optionally, as a hindcast/forecast tool. If, instead of wave statistics, the full wave information at a specified time is available at the outer border of the grid, EUROWAVES will be able to be used as a model to transfer the information to the coast. If a full time series is available offshore (this could be either a measured or modelled time series in hindcast mode or a forecast model prediction), EUROWAVES will provide the corresponding predicted time series at the location of interest.

5. Hardware

EUROWAVES will be designed for use on the PC or workstations expected to be commonly available on the market in the new millenium. As such EUROWAVES will lead to a much larger spectrum of users getting access to coastal wave data, as the total cost will be considerably less compared to the case at present, which requires a large amount of resources both in terms of man power and direct expense, often also leading to the results not being available within the required time, or, through taking shortcuts, at an unacceptable accuracy.

TITLE: Testing Monitoring Systems for Risk Assessment of Harmful Introductions by Ships to European Waters

CONTRACT NO: MAS3-CT97-0111

COORDINATOR: Prof. Dr. Harald Rosenthal
Institut für Meereskunde
Düsternbrooker Weg 20
20146 Kiel
Germany
Tel.:++0431/597-3916, Fax.:++0431/565876

SUBCONTRACTOR: Dr. Stephan Gollasch
Institut für Meereskunde
Düsternbrooker Weg 20
20146 Kiel
Germany
Tel.:++0431/597-3780, Fax.:++0431/565876
E-mail: sgollasch@aol.com

PARTNERS:

Dr. Ian Laing
CEFAS Conwy Laboratory
Benarth Road,
Conwy, North Wales
LL32 8UB
United Kingdom, Wales
Tel.: ++0044-1492-593883
Fax.: ++0044-1492-592123
E-mail: i.laing@cefas.co.uk

Prof. Dr. Erkki Leppäkoski
ABO Akademi University, Dept. of
Biology, Bio City
FIN-20520 Turku / Abo
FINLAND
Tel.: ++358/2-215-4355
Fax.: ++358/2-215-4748
E-mail: eleppako@abo.fi

Dr. Elspeth Macdonald
Marine Laboratory Aberdeen
P.O.Box 101, Victoria Road
Aberdeen AB11 9DB
UNITED KINGDOM, Scotland
Fax.: ++44-1224-295511
E-mail: macdonaldem@marlab.ac.uk

Dr. Dan Minchin
Fisheries Research Centre, Department of
the Marine
Abbotstown, Dublin 15
IRELAND
Tel.: ++353-1-8210-111
Fax.: ++353-1-8205-078
E-mail: minchin@frc.ie

Manfred K. Nauke
Office of the London Convention 1972,
Marine Environment Division
International Maritime Organization
4 Albert Embankment
London, SE1 7SR
ENGLAND U.K.
Tel.: ++44-171-587-3124
Fax.: ++44-171-587-3210
E-mail: mnauke@imo.org

Dr. Sergej Olenin
Centre for System Analysis
Manto 84
5808 Klaipeda
LITHUANIA
Tel.: ++370/6-212936
Fax.: ++370/6-256526
E-mail: serg@hgf.ku.lt

Dr. Sue Utting
CEFAS Conwy Laboratory
Benarth Road,
Conwy, North Wales
LL32 8UB
United Kingdom, Wales
Tel.: ++44-1492-593-883
Fax.: ++44-1492-592-123
E-mail: s.d.utting@cefas.co.uk

Prof. Dr. Inger Wallentinus
Department of Marine Botany ,University of Göteborg
Carl Skottsberg gata 22 b
41319 Göteborg
SWEDEN
Tel.: ++46-31-7732702,
Fax.: ++46-31-7732727
E-mail: inger.wallentinus@marbot.gu.se

Dr. Matthias Voigt
Kampstr. 7
24601 Stolpe
Germany
Tel.:++04326/98737, Fax.:++04326/98738
E-mail: matthias.voigt@kiel.netsurf.de

TESTING MONITORING SYSTEMS FOR RISK ASSESSMENT OF HARMFUL INTRODUCTIONS BY SHIPS TO EUROPEAN WATERS

HARALD ROSENTHAL[1], STEPHAN GOLLASCH[1], IAN LAING[2], ERKKI LEPPÄKOSKI[3], ELSPETH MACDONALD[4], DAN MINCHIN[5], MANFRED NAUKE[6], SERGEJ OLENIN[7], SUE UTTING[2], MATTHIAS VOIGT[8], INGER WALLENTINUS[9]

[1]Institut für Meereskunde, Kiel, Germany, [2]CEFAS Conwy Laboratory, Conwy, North Wales, United Kingdom, [3]ABO Akademi University, Turku, Finland, [4]Marine Laboratory Aberdeen, Scotland, United Kingdom, [5]Fisheries Research Centre, Dublin, Ireland, [6]International Maritime Organization, London, United Kingdom, [7]Centre for System Analysis, Klaipeda, Lithuania, [8]Büro Dr. Matthias Voigt, Stolpe, Germany, [9]University of Göteborg, Sweden

1 ABSTRACT

During the last decades ballast water discharges have increased throughout the world in most of the major ports. Discharge volumes are considerable high in some cases and the probability of successful establishment of self-sustaining populations of exotic species is expected to increase with greater volumes of ballast water and reduced ship transit times. Ships have been recognized as a major vector for the introduction of non-indigenous and harmful organisms. The first reports appeared by Medcof (1975) followed by Carlton (1985, 1987), Hallegraeff & Bolch (1991) and Subba Rao et al. (1994). Rosenthal (1980) reviewed the state of knowledge and the risks associated with transplantation to fisheries and aquaculture, including ballast water, particularly indicating that modern aquaculture development in the coastal zone is at high risk of disease transfer from ballast water when the culture facilities and areas of fishing are located near shipping routes. The recent world-wide growth of aquaculture along such infrastructure elements amplifies this risk, possibly rendering tight disease regulations for this industry useless in many areas. A annotated bibliography on transplantation and transfer of aquatic organisms through various means (including ballast water) is presently under preparation, covering more than 10.000 literature entries (Rosenthal, 1996, final draft). The major problem in transmission of harmful aquatic organisms, therefore, resides with the continued transfer of ballast water in modern shipping. During this Concerted Action various sampling methods will be studied in order to qualitatively and quantitatively evaluate the fate of exotic species in ballast water.

2 INTRODUCTION

The intensity of shipping and the structure of vessels have undergone major changes over the past decade. In conjunction with this development, dredging of harbours and river estuaries has also changed the hydrodynamics and altered environmental conditions in coastal habitats, possibly leading to an increased opportunity for survival of exotic species. Risk assessment must consider criteria for quantifying survival probabilities in order to define appropriate management strategies to prevent introductions or to minimize risk of introductions. These may have to be adjusted regionally, depending on habitat, type of traffic, interrelationships with other coastal resource users as well as economic considerations. Risks from transfers of harmful species by aquaculture are now considerably reduced because deliberate introductions of useful species should follow the 1994 ICES Code of Practice, dealing with useful quarantine methods. This leaves shipping as the main vector for future introductions.

The efficient biocidal organotin anti-fouling paints used by shipping have also considerably reduced the number of fouling organisms on the hulls of present day trading ships. Should alternative anti-fouling paints and techniques be used then these will need to be equally as effective as organotin applications. The major problem in transmission of harmful aquatic organisms, therefore, resides with the continued transfer of ballast water in modern shipping by vessels of different design and dimension.

Carlton (1985) has given a review of ballast water as a mechanism for the dispersal of organisms which can be considered as comprehensive up to that time. Recent invasions and population explosion of non-indigenous species in various parts of the world are causing ecological and economical damages (Carlton & Geller 1993, Hedgpeth 1993, Gollasch & Mecke 1996). It is believed that more than 3,000 species are transported by ships each day (Carlton et al. 1995).

A joint research project between the Institut für Meereskunde, Kiel and the Universität Hamburg commissioned by the Umweltbundesamt, Berlin (German Environment Protection Agency) was launched in 1992 to investigate species introductions by international ships traffic. More than 400 species ranging from microalgae to 15 cm long fishes were collected from ballast tanks and ship hulls (Gollasch 1996).

Increasing toxic algal blooms of non-indigenous species in Australian waters have been associated with ballast water releases of Asiatic origin. Australian scientists have since intensified their ballast water studies (Hallegraeff & Bolch 1991, 1992). The USA and Canada tried to deal with the problem by developing voluntary guidelines for offshore ballast

water exchange in response to the tremendous impact of recently witnessed epidemic spread of introduced species in the Great Lakes area, such as Zebra mussels *(Dreissena polymorpha)*, Ruffe *(Gymnocephalus cernuus)*, and water flea *(Bythotrephes cederstroemi)*. In addition, IMO (International Maritime Organization) was sensitized in this matter and considered ballast water problems on its agenda as an official issue, trying to develop tentatively regulations for ballast water management in international ship traffic. Initial guidelines to exchange the ballast water in open ocean areas prevent the transfer of harmful species by ships' ballast water releases and sediment discharges. The voluntary guidelines were adopted by the IMO (1993).

Investigations from AQIS (1993) have shown, however, that often, because of the diverse shapes and sizes of ballast tanks, up to 5 % of the original ballast water volume remains in a tank after "complete" emptying, containing up to 25 % of the entire organismic ballast water load. Therefore, the proposed IMO offshore exchange method has to be taken as an initial attempt but not as a solution. Further studies on potential survival capacity of aliens and on the development of appropriate treatment methodologies are needed.

2. OBJECTIVES

There has been no EU project related to exotic introductions, except one dealing with the accidental introduction of the alga *Caulerpa taxifolia* into the Mediterranean Sea and its spread through regional shipping and boating. Close contacts exist to scientists and institutions working in this field. Most of the participants are involved in national or regional projects related to species introductions, some connected to ballast water transfer. The objectives of the Concerted Action include the following:

2.1 State of the art of ballast water studies

An evaluation of the various sampling methods presently used for ballast water studies in selected EU member countries will be carried out. The validation of the reliability of these sampling methods will be assessed through intercalibration workshops onboard ocean-going ships (see workplan). Sampling vessels en-route may result in an estimation of the in-transit survival of organisms in ballast water during voyages. The survival potential of organisms will depend on the type of ship, type of ballast tank, temperature changes while in transit, physical characteristics of donor and recipient habitats, the area of origin and the

duration in transit. It is therefore important to gain an understanding of the effects of these external factors on the survival potential of aquatic species operate.

2.2 Case histories

Studying and comparing case histories of species transmission through ballast water will be undertaken with the aim to identify potentially harmful invaders to EU waters. This should lead to the development of accounts of species likely to become established in European waters together with their consequences for the environment, aquaculture and fisheries, and human health.

2.3 Methods of study and standardization

A standard sampling methodology for collecting and analysing ballast water from ships for European workers, based on methods used elsewhere and our own peculiar needs will be developed. The sampling method may vary according to the behaviour and the taxa of species considered to be harmful to Europe. A simple and time effective technique is also necessary because manpower availability to carry out such studies will always be limited. It may be necessary to consider different techniques according to the local conditions of each port, country or region. Protocols need to be developed to address these issues.

2.4 Assessing potential control measures (treatment) to reduce the risks arising from ballast water releases

Assessing potential control measures will be undertaken in order to reduce the risks of unintentional introductions of non-native species arising from ballast water releases. Treatment measures for the control of exotics will be discussed. This assessment is an international and interdisciplinary problem. The Concerted Action is along the lines recommended by ICES and EIFAC and is extremely relevant to IMO and HELCOM. IMO has already recommended voluntary guidelines and so have the USA and Canada for the St Lawrence Seaway, Australia, New Zealand, Chile, Argentina and Israel. OSPARCOM has recently requested to prepare an inventory to assess the scope of the problem with regard to exotic species. The concerted action is meant to provide a forum to guide interested researchers, regulatory authorities and the shipping industry towards an interdisciplinary study which helps in the understanding of the management implications of this development. It is anticipated that the outcome of the Concerted Action will lead to a proposal for research, in conjunction with the industry, to develop management tools,

including ballast water treatment and regulatory measures associated with these technologies. This assessment includes the evaluation and development of guidelines for the methodological approaches for ballast water treatment.

2.5 Public awareness.

The importance of ballast water as a means of human intervention in aquatic ecosystem stability and biodiversity is not generally appreciated. Through press releases the Concerted Action intends to create a more realistic focus on the essential environmental concerns that relate to ships' ballast water and sediment and hull fouling while highlighting some potential preventive measures in order to minimize risks to changes or loss of biodiversity from transmitted species. Media broadcasts often overstate the effects of unwanted introductions.

2.6 European waters as a donor area

Within Europe, some port regions have a greater risk from ballast water introductions in account of the volume of ballast release, to topographic features or aquaculture activities, etc. Conversely, overseas port areas may be at greater risk from the introduction of some European species. The importance of European waters as donor areas will be addressed.

2.7 Documentation of European studies on introduced species in the past.

During the Concerted Action, all participants will provide as far as possible continuous input of references (in particular on grey literature: e.g. governmental reports, internal reports from harbour authorities, interim project reports, etc) into the database to be kept by the co-ordinator of the Concerted Action.

Additionally, the Concerted Action will consider the major pathways of the case histories (e.i. inventories of various types of transmissions) in order to assist in understanding the requirements for the development of adequate mitigation (treatment) techniques while at the same time creating awareness about the dimension and nature of the problem within the science community, the regulatory and inter-governmental bodies as well as in the shipping industry and the public.

3 WORKPLAN

This Concerted Action is planned for 2 years (starting point late 1997) and involves 9 partner institutions while a number of external experts will be invited for specific tasks and as a source of information and experience for the benefit of all partners. Additionally, the Concerted Action will be commenced in close co-operation with industry and international/regional and local organisations.

Invited experts from different institutions all over the world (e.g. USA, Canada, Israel, Australia and Japan) are expected to be involved in Concerted Action workshops. Further contacts to experts in relevant issues from France, Germany, Greece, Ireland, Norway, Poland and The Netherlands will result in additional participants in workshops.

The Concerted Action will include workshops with technical sessions, practical workshops for testing of methodologies including intercalibration exercises, methodological tests onboard ships to evaluate survival capabilities of in-transit species, and preparatory meetings to prepare documents (guidelines, manuscripts, statistical analysis, press releases, posters etc.).

Various methods will be studied in order to measure qualitatively and quantitatively the success of introduction of exotic species in ballast water. The sediment accumulating in ballast tanks and fouling biota on ship hulls will also be examined wherever possible during the two types of activities (land based workshops and sea-going workshops). Land based workshops will involve Concerted Action Partners and invited experts. Additionally, non-scientific authorities (e.g. shipping companies and ship owner associations) and institutions from near meeting sites will be also invited as guests and/ or observers.

Sea-going workshops will result in a total of 6 voyages quantifying the survival of organisms in ballast tanks. It is planned to accompany vessels from North America, South America, Middle East and Asia on their way to European ports. In addition ships will be boarded on their routes from the North Sea to the Baltic and vice versa.

These exercises will take place following the intercalibration workshops. It is hoped that the results of the cruise observations will lead to an overall comparative evaluation of the true risks associated with various types of shipping activity, in particular when considering a variety of ballast tank designs and operational procedures. Two teams using different methods should sample on board simultaneously. It is assumed that this part of the Concerted Action is extremely important as only a very few studies have ever followed the development

of exotic populations while in transit while at the same time being able to document the status of the biology of the water at the time of intake and at the point of release.

Experience has shown that the co-operation of major shipping companies with Concerted Action participants was smooth and easy. However, exact scheduling can only be carried out on relatively short notice as time tables and routings of ships of these companies have always to respond quickly to changing demands. Several partners already have established ongoing contacts with shipping companies which signalled very positive responses to our requests for participation and co-operation.

4 RESULTS

The results of the Concerted Action will be disseminated to the scientific community through a full scale final report and publications in peer-reviewed journals. Further, the results will also be made available to industry and intergovernmental organisations in form of manuals and recommended procedures (code of practice). A video on sampling methodology will be produced and distributed to all interested parties indicating the need for monitoring ballast waters. It is anticipated that this first EU-wide co-operation with partners involved in ballast water issues will lead to a clear definition of gaps in R&D so that a well-focused and practice-oriented research programme can be formulated.

CITED REFERENCES

AQIS (Australian Quarantine and Inspection Service) 1993. Ballast water. A serious marine environment problem. AQIS, 1-7. Australian Quarantine and Inspection Service, Australian Government Publishing Service, Canberra (Catalogue No. 92 2603 6).

Carlton, J.T. 1985. Transoceanic and interoceanic dispersal of coastal marine organisms: the biology of ballast water. Oceanogr. Mar. Biol. Ann. Rev. 23: 313-371.

Carlton, J.T. 1987. Patterns of transoceanic marine biological invasions in the Pacific Ocean. Bull. mar. Sci. 41(2): 452-465.

Carlton, J.T. & Geller , J.B.1993. Ecological roulette: The global transport of non-indigenous marine organisms. Science (Wash.) 261(5117): 78-82.

Carlton, J.T., Reid, D.M., van Leeuwen, H. 1995. Shipping study: The role of shipping in the introduction of non-indigenous aquatic organisms to the coastal waters of the United States (others than the Great Lakes) and an analysis of control options. National Sea Grant College Programme/ CT Sea Grant Project R/ES 6, 213 pp. (Appendices A - I (122 pp.)).

Gollasch, S. 1996. Untersuchungen des Arteintrages durch den internationalen Schiffsverkehr unter besonderer Berücksichtigung nichtheimischer Arten. Verlag Dr. Kovac, Hamburg, 314 pp. (Dissertation University Hamburg, Germany)
Gollasch, S. & Mecke, R. 1996. Eingeschleppte Organismen. pp. 146-150. In: Lozan, J.L. et al (eds.). Warnsignale aus der Ostsee. Parey Buch Verlag, Berlin.
Hallegraeff, G.M., Bolch, C.J. 1991.Transport of Toxic Dinoflagellate Cysts via ships' ballast water. Marine Pollution Bull. 22: 27-30.
Hallegraeff, G.M. & Bolch C.J. 1992. Transport of diatom and dinoflagellate resting spores in ships' ballast water: implications for plankton biogeography and aquaculture. J. Plankton Res. 14(8): 1067-1084.
Hedgpeth, J.W. 1993. Foreign invaders. Science 261: 34-35.
IMO, 1993. Guidelines for preventing the introduction of unwanted aquatic organisms and pathogens from ships' ballast water and sediment discharges. IMO Assembly, 18th Session, A18/RES. 14 pp.
Medcof, J.C. 1975. Living marine animals in a ships' ballast water. Proc. Natl. Shellfish Assoc. 65: 54-55.
Roberts, L. 1990. Zebra mussel invasion threatens U.S. waters. Science 249: 1370-1372.
Rosenthal , H. 1980. Implications of transplantations to aquaculture and ecosystems. Mar. Fish. Rev. 42 (5): 1-14.
Rosenthal, H. 1996 (final draft). Annotated bibliography on transplantations and transfers of aquatic organisms. (to be published as CD ROM, about 9,900 entries).
Subba Rao, D.V. , Sprules, W.G., Locke, A., Carlton, J.T. 1994. Exotic phytoplankton from ships' ballast water: Risk of potential spread to mariculture sites on Canada's east coast. Canadian Data Report, Fish. Aquat. Sci. 937: 1-51.

II.2. Coastal Engineering and Natural Defenses

II.2.1. Coastal structures

TITLE: Performance of soft Beach Systems and Nourishment Measures for European Coasts
(Project **SAFE**)

Contract N° : MAS3 -CT95-0004

COORDINATOR: **Dr. Luc Hamm**
SOGREAH Ingénierie
6 rue de Lorraine
F - 38130 ECHIROLLES, FRANCE
Tel.: +33 (0)4 76 33 40 00
Fax: +33 (0)4 76 33 42 96
E-mail : hamm-l@sogreah.fr

PARTNERS:

Dr. Hans H. Dette
Leichtweiss Institut fuer Wasserbau
Technischen Universitaet Braunschweig
PO Box 3329 -
D 38023 Braunschweig, Germany
Tel. : + 49 53 13 91 39 33
Fax: + 49 531 391 8217
e-mail : <H.Dette@tu-bs.de>

Dr. Antonio Lechuga
Centro de Estudios de Pueros y Coastas
CEDEX
c/Antonio López, 81
28026 Madris, Spain
Tel.: + 34 1 335 7650
Fax: + 34 1 335 76 22
e-mail : <Antonio.Lechuga@cedex.es>

Dr. Ruud Spanhoff
Rijkinstituut voor Kust en Zee
Gebouw "De Kortenaer"
Kortenearkade 1
P.O. Box 20907
2500 EX Den Haag, The Netherlands
Tel. + 31 70 3114 311
Fax: + 31 70 3114 321
e-mail <R.Spanhoff@rikz.rws.minvenw.nl>

Dr. Michele Capobianco
Tecnomare SpA
R & D Division Environment Area
San Marco No 3584
30124 Venezia, Italy
Tel.: + 39 41 796 717
Fax: + 39 41 796 800
e-mail : <Capobianco.m@tecnomare.it>

Dr. Hans Hanson
Dept. of Water Ressources Engng.
University of Lund
P.O. Box 118
1 John Erikssons vaeg
S-221 00 Lund, Sweden
Tel.: + 46 46 222 89 87
Fax: + 46 46 222 44 35
e-mail : <Hans.Hanson@tvrl.lth.se>

Prof. Yannis N. Krestenitis
Division of Hydraulics & Environmental Engineering
Aristotle University of Thessaloniki
54006 Thessaloniki, Greece
Tel. : + 30 31 995 654
Fax: + 30 31 995 654
e-mail : <ynkrest@civil.auth.gr>

Prof. Dr. Ir. Marcel J.F. Stive
WL | Delft Hydraulics
P.O. Box 177
Rotterdamseweg 185
2600 MH Delft, The Netherlands
Tel.: + 31 15 2 85 8887
Fax: + 31 15 2 85 85 82
e-mail : <Marcel. Stive@wldelft.nl>

Prof. Anthony Lewis
Hydraulics & Maritime Research Centre
Munster Institute
University College Cork
Cork, Ireland
Tel. : + 353 21 90 2165
Fax: + 353 21 343 580
e-mail : <HMRC@UCC.ie>

Dr. Rob J. de Meijer
Kernfysisch Versneller Instituut
Rijksuniversiteit Groningen
Zernikelaan 25
9747 AA Groningen - The Netherlands
Tel.: + 31 50 363 3600
Fax: + 31 50 363 40 03
e-mail : <Demeijer@kvi.nl>

Dr. Didier Moulis
Institut des Aménagements Régionaux et de l'Environnement
Parc Scientifique Agropolis 2
34397 Montpellier Cedex 5 - France
Tel. : + 33 (0)4 67 63 65 00
Fax: + 33 (0)4 67 63 03 66
e-mail :<didier.Moulis@iare.mnet.fr>

PERFORMANCE OF SOFT BEACH SYSTEMS AND NOURISHMENT MEASURES FOR EUROPEAN COASTS (PROJECT SAFE)

L. Hamm

SOGREAH Ingénierie
6 rue de Lorraine
F - 38130 ECHIROLLES, FRANCE

SUMMARY

The SAFE project is focussing on beach nourishments practices in Europe from the point of view of the morphodynamic behaviour of the coast. It includes an inventory of nourished sites and an intercomparison of past and present practices in the different participating countries, a monitoring of four selected sites, an assessment of the performance of past documented projects, the execution of large-scale laboratory tests, the development of innovative monitoring techniques and the improvement and validation of beach profile and shoreline evolution numerical models. These key elements will be briefly explained into the paper and illustrated by the first results obtained so far.

1. INTRODUCTION

The objective of this project is to improve design practice able to predict the medium (several months) and long (a few decades) term performance of artificial nourishment schemes by introducing reliable and validated numerical modelling tools. These tools will be solid and general enough to be able to deal with a wide variety of field situations from dune restoration to shoreface nourishment including or not supporting measures. To reach that goal, the project is divided into four topics with specific objectives.

TOPIC A: Overall integration
TOPIC B: Analysis of field data
TOPIC C: Large-scale flume tests experiments
TOPIC D: Development and validation of numerical models

The overall integration (topic A) continuously aims at integrating the results obtained in the different topics. Activities there will include the coordination of the work in the different topics, the reporting to EC and dissemination of the practical results with the preparation of a series of paper aiming at improving the design part of beach nourishment projects, providing recommendations on the use and monitoring of soft structures and supporting measures in coastal management schemes.

Analysis of high quality field data (topic B) shall lead to the improvement of our empirical knowledge which is a key element for the development of behaviour-oriented long-term numerical models. It shall also produce a scientific assessment of existing or on-going nourishment schemes in the European Union from the point of view of coastal morphodynamics.

Two large-scale laboratory experiments (topic C) have been performed focussing on a) the recovery of the beach profile under random waves attack and with a variable sea-level in a wave flume and b) on sediment transport with graded sediment in a wave tunnel.

The development and validation of beach profile and shoreline evolution numerical models (topic D) shall include a) improvements of existing medium-term process-based profile evolution models to fill the gap between their present capabilities and the field applications we are focussing on. Such improvements will deal with the link between the dune and aerial beach with the surfzone and the prediction/ taking account of grain sorting and b) development of long-term behaviour-oriented practical tools. Careful validation of these models will be also an integral part of this development.

2. ANALYSIS OF FIELD DATA

2.1 Importance of beach nourishment in the different countries

The work started with an inventory of nourishment projects completed in the countries participating to the project and large differences were found there concerning the strategies and legal frameworks as well as the importance of nourishment in the current engineering practices.

In Ireland and Greece, beach nourishment is not a well disseminated strategy against coastal erosion and small volumes of fills are reported here (one project in Ireland at Rosslare Strand for a total of 162,000 m^3 of placed sand and 9 projects in Greece with a total volume of about 50,000 m^3 of placed sand).

In Italy and France, beach nourishment is not a usual technique even if a few major projects have been completed. In Italy, Cavallino beach (near Venice) has recently received a total of 1.5 millions of m^3 of placed sand. In France, three sites have been regularly nourished at Anglet (8.2 millions of m^3) and Arcachon bay (0.5 millions of m^3) on the Atlantic Coast and les Bas-Champs (0.9 millions of m^3) on the Channel coast and two significant nourishments schemes have been completed at Chatelaillon and Malo-les-bains (0.35 and 0.36 millions of m^3 respectively). On the other hand, artificial beaches are more common.

In Germany, the technique is widely used along the sandy coasts of the North sea (East and Northfrisian islands) as well as along the Baltic coast with a total of 160 fills since 1951 totalising 48.4 millions of m^3 of sand. Special mention should be made of the coast of Sylt island (Northfrisian) where 25 millions of m^3 have been placed since 1972 representing more

than 50% of the total volume for Germany.

In the Netherlands, this technique is utilised extensively. 46 beach nourishments have been implemented before 1990 amounting to about 60 millions of m^3 of supplied sand. In 1990, the adoption of a new policy of dynamic preservation of the coast has increased the volume of supplied sand up to about 6 millions of m^3/ year annually. Special mention should be made here of the island of Texel totalising 14.8 millions of m^3 of sand since 1979.

Finally in Spain, a strong policy has been implemented since 1983 for recovering the coast by an extensive use of beach nourishment completed by supporting measures if necessary (Lechuga, 1997). 51.1 millions of m^3 of sand have been supplied to the beaches in the period 1983-1992 and about 10 millions of m^3/year of sand are presently supplied annually for a total over 1,000 beach fill projects.

2.2 An assessment of selected projects

A few nourishment projects have then been selected for a detailed assessment. It concerns the shoreface nourishment of Terschelling (The Netherlands) and beach nourishments at Sylt island (Germany) , Maresme (Spain) and Ocean City, Maryland (USA) where detailed field data were available.

Additional four sites have been selected where detailed monitoring are taking place as part of the project. It includes beach nourishments at Malagueta (Spain), San Sebastian (Spain) and Rosslare Strand (Ireland) and dune restoration at the Rhone delta (France). First results of this assessment have been published by Santas et al (1997) for the case of Zurriola beach at San Sebastian, Spanhoff et al (1997) for the case of Terschelling and Larson et al (1997) for the case of Ocean city.

2.3 A discussion on performance indicators and nourishment design methods

This first assessment of existing well documented beach nourishment cases raised among the project two discussions about a) A proper definition of performance indicators to be used and b) the monitoring program to carry out in order to define properly these indicators. Building on the experience acquired in the NOURTEC project (Nourtec, 1997) the following guidelines are presently being used in the project:

A careful analysis of the situation before nourishment shall lead to a precise definition of objectives regarding the design requirements and the performance assessment. The following list has been set up:

- Shoreline preservation is an annual long-term objective. It is related to the stability of the coastline and the protection of dune area which are often attacked as a result of recession of the coastline.

- Shore protection and prevention of flooding in case of extreme events. This objective aims at avoiding break-through of the dune row.

- Recreational beaches. In such a case, a widening of the beach area is looked for during the summer season. This may also be beneficial to shore protection and shoreline preservation.

- Protection of existing developments along the coast like roads or buildings against temporary erosion during the stormy season.

It is noted that a typical time-scale is associated to each of these objectives. Typical space-scales could also be defined according to the National legislative frameworks, the Institutions in charge of the intervention and the specific boundary conditions.

Then for each objective, appropriate indicators shall be defined in order to evaluate as objectively as possible the implemented scheme. A comprehensive list of 7 performance indicators has recently been used in the Netherlands in that respect. Five indicators refer to design parameters (design life times of dune foot, dune profile, coastline position[1], volumes of control) and two of them refer to the situation prior nourishment (annual mean erosion rate[2] and beach width). Three of them have been used in the NOURTEC project. Additional indicators have also been proposed by other participants and are under evaluation.

The key point to note here is that such a comprehensive list of performance indicators can only be applied if the corresponding data are available. Its means that a) the dune, beach and foreshore profiles shall be regularly monitored before and after the nourishment and b) that in the design process a prediction of these parameters is made.

2.4 Video-imaging as a new monitoring technique

Since 1992, hydrodynamics and beach morphodynamics are studied from ARGUS video observations, a technique developed at the Coastal Imaging Lab, Oregon State University. It is expected that this will contribute importantly to help resolving the morphology predictability issue, to help identify coastal erosion problems and to assess local nearshore wave and climate statistics (Aarninkhof and Stive, 1998). In this project, a video camera has been installed at Noordwijk, The Netherlands on a very dissipative beach system and images are studied to understand bar dynamics but also to develop a more sophisticated, quantitative interpretation of image intensities by relating them to the process of wave dissipation. With the help of numerical wave decay models, the surfzone hydrodynamics can be modelled inversely which enables the mapping of nearshore bathymetry, based on hourly taken video images. First results of this development have been published by Aarninkhof et al(1997).

---

1 In order to eliminate as much as possible seasonnal effects, an integrated definition of the shoreline based on the volume of sand in a control volume covering the beach up to the dune foot and the foreshore down to a waterdepth H (H is the vertical distance between the dune foot elevation and the mean low water) below MLW is used

2 In order to eliminate short-term variability, the mean erosion rate is taken as a mean trend over ten years of yearly surveys.

3. LARGE SCALE LABORATORY EXPERIMENTS

In this part, two large-scale flume experiments have been performed including beach and dune profile evolution in the GrossenWellenKanal (GWK) in Hannover, Germany and sediment transport measurements of graded sediments in the Large Oscillating Water Tunnel (LOWT) in de Voorst, The Netherlands.

3.1 Beach and dune profile evolution in the GWK

The hydrodynamic and sediment dynamic processes and their interactions between natural dune and beach with beach nourishment have been investigated under controlled environmental conditions as part of a series of tests initiated several years ago in the GWK (Peters et al, 1996). The objectives of these experiments were to assess the potential of beach nourishment techniques in tidal seas and to provide a suitable data set for validation purposes of coastal profile models developed in topic D. The flume is 350 m long, 5 m wide and 7 m deep. Random waves with a mean period of 5.5 sec and significant wave heights of 0.65 and 1.2 m have been used in these experiments together with a normal water level at +4 m over the bottom of the flume and a storm surge level at +5 m. The experiments have been divided into two major test phases:

In test phase I, an equilibrium profile corresponding to the median diameter of the sand placed into the flume (d_{50}=0.3 mm) was built until the mean sea level and four different plane beache slopes ranging from 1:5 to 1:20 were built over the mean sea level (see figure 1).

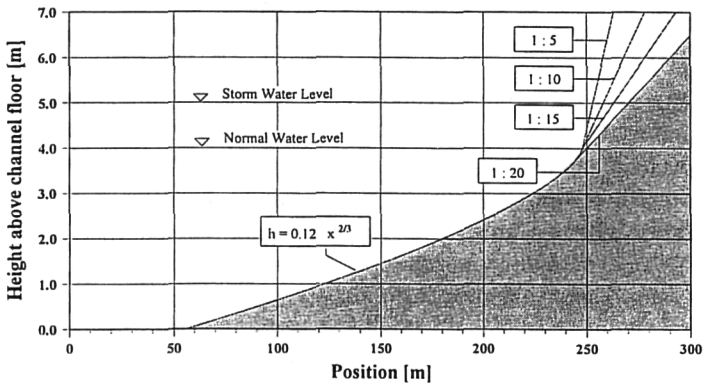


Figure 1: Tests in the GWK - phase I: Initial beach profiles

Each profile was then subjected to normal and storm wave and level conditions. The following measurements have been performed for each test:
- water level measurements along the flume to define the wave characteristics and wave set-up/set-down

- velocity measurements to define the velocity profiles in the surf zone and collect velocity-time series at these measuring points
-underwater bed-profile measurements
-suspended sediment measurement in the surf zone, involving OBS-sensors, multi-frequency sonar sensor, suction-tube sampler
-video records of the swash zone
A first analysis of these experiments has been reported by Peters et al (1997)

In test phase II, attention was drawn on beach and dune stability protected by barriers placed at different positions (in front of the dune or at the seaward face of the bar) in order to check if such barriers could reduce the erosion rate of the dune (see figure 2)

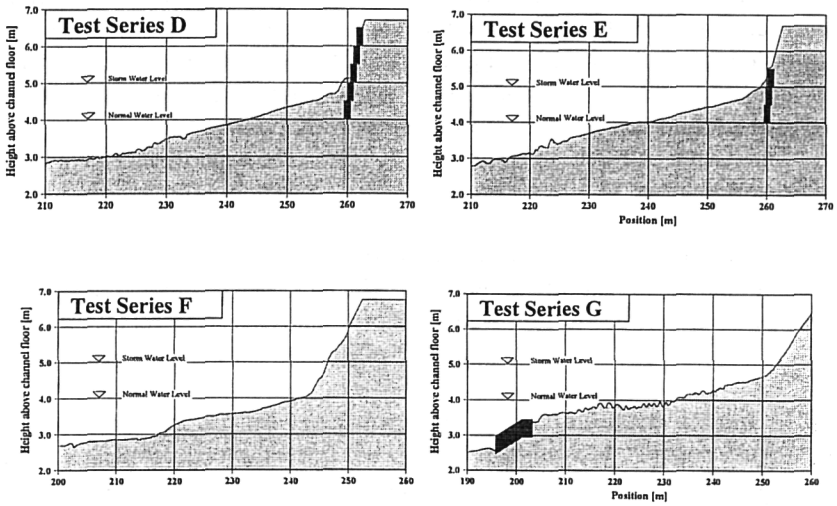


Figure 2: Tests in the GWK - phase II: Initial beach profiles

In addition, a new technique to measure the concentration of heavy minerals in natural sand has been tested in the flume during test F. This concentration is determined by measuring radiometric properties of the sediment with a γ-ray detector (named MEDUSA) that is towed over the seabed. This determination employs the differences in concentrations of natural radionuclides within minerals, where heavy minerals are characterized by a high natural radioactivity (de Meijer et al., 1996). A calibration of these characteristics with a few sediment samples establishes a linear relation between radiometry and heavy mineral content.

Futhermore, the sound level has also been measured. It reflects the noise generated when the detector is towed over the bottom, and is measured by a microphone within the detector. It is independent of tow direction and gives an impression of the bottom roughness (e.g. ripple structures, grain size, bioturbation) of the bed. Which type of roughness is actually measured is not yet understood but corresponding distribution patterns of heavy mineral concentrations and bottom roughness was observed. That is, a maximum in heavy mineral content coincides with a minimum in seaward increasing sound level. The experiments shows that these distributions can be purely the result of cross-shore hydrodynamic processes. Heavy minerals

tend to be concentrated seawards of the bar system in a region of fine-grained sediments and seawards of this region, grain size increases.

The technique of deriving grain size by measuring the towing noise of the MEDUSA detector seems promising and would allow a synoptical, in-situ measurement of the two sedimentological parameters causing selection in sediment transport and offers a handle to study these in more detail in laboratory experiments and in the field.

3.2 Sediment transport measurements in the LOWT

The objectives of this experiment are :1) to increase our present understanding and physical insight in the basic mechanisms of bed-load and suspended load transport in oscillatory flow conditions when graded sediments are present in the bed and 2) to obtain a dataset of sediment transport rates, sediment concentrations and velocity profiles per sediment fraction which can be used for the development of mathematical model formulations for sediment transport.

The LOWT enables experiments at full scale including oscillatory flows with superimposed currents. The test section is 14 m long, 1.1 m high and 0.3 m wide. Most of the research in the tunnel during the last decade was carried out using unsieved sand dune with a median diameter of 0.21 mm and a narrow size distribution (Ribberink and Al-Salem, 1995, Katopodi et al., 1994). Two types of oscillatory flow conditions were generally used, namely regular second-order Stokes waves and sinusoidal waves with superimposed net currents. In the majority of the experiments the plane-bed regime with sheet-flow conditions was observed. Since three years, specific attention is paid to the influence of the grain size in combined wave-current conditions (Janssen and Ribberink, 1996). Experimental programmes were carried out with median diameters of 0.13 mm and 0.32 mm keeping the geometric standard deviation unchanged. The flume has also been used recently to study sediment transport with sands containing up to 20% heavy minerals which are naturally found in the field. These tests show that these heavy minerals, with a density >2.9 kg/l, have clearly different transport properties than light minerals (Tánczos et al., 1997) and induce armouring effects.

In the present experiments, two series of tests have been performed as part of the Training Mobility Program of the European Union. Several participants of the SAFE projects took part of this experiment and used the measured data to analyse sediment transport processes.

In Series K, a mixture of the two sand types has been used and the hydrodynamic conditions have been chosen in order to obtain a close connection with previous experimental series in the tunnel. This makes comparisons with available data possible and increases the scope and possibilities of the present work. Flow conditions included as previously second-order Stokes waves (2 cases) and sinusoidal waves with superimposed net current (2 cases). The measurement program included :

- Measurement of the net, time-averaged sediment transport rate and the evolution of the

composition of the bed for the four hydrodynamic conditions. Mass conservation technique and sampling of the bed and of the sediment traps have been used for that purpose.

- Detailed time dependent measurements of the suspended load inside and outside the sheet-flow layer and the velocity profiles over the vertical will be performed for two hydrodynamic conditions.

In both cases each condition was repeated two or three times in order to increase the reliability of the results.

In Series L, the previous experiments of Tánczos et al. (1997) were completed by using mixtures of light sand and zircon with the same grain size but distinctly different density. This condition allows measuring selective transport due to density effects only. In addition to a higher density (~4.6 kg/l), zircons contain several orders of magnitude more uranium and thorium than light sand and can therefore be "traced" by their natural radioactivity. During the experiments, the bed compositon and the thickness of the active layer has been measured in situ by a X-ray detector, whereas the suspended transport has been determined using a transverse suction system. The samples collected by the transverse suction system provided information on the composition of the suspended sediment.

4. NUMERICAL MODELLING

The modelling part of the project includes the development of process-based cross-shore models, beach nourishment modelling and oscillatory coastal behaviour.

4.1 Process-based cross-shore modelling

The developments under this task are focusing on improvements and extensions of the cross-shore profile models developed under MAST I and II, in as far as they are considered relevant to nourishment behaviour. Three key process-elements which are missing sofar concern the inner surf zone and the swash dynamics, the incorporation of cross-shore sediment gradation and developments of the concept of (quasi-) dynamic equilibrium.

At present, most of cross shore profile models used for modelling profile evolutions have difficulties in dealing with the innersurf and the swash zones. It concerns the hydrodynamics part i.e.wave height decay, wave kinematics, run-up and down as well as the sediment transport. Several approaches are presently under investigation to get a proper description of these processes in view of their incorporation into a morphodynamic model and first results concerning the wave kinematics have been published (Hamm, 1996 and Bosboom et al, 1997).

Gradation is also a very relevant topic when dealing with beach nourishment as well as natural beaches. Intensive measurement campaigns at Terschelling have shown that selective transport leads to grain-size profiles following closely the bathymetric profile (Guillen and Hoekstra, 1996). Efforts have put here on the analysis of experimental laboratory data for the

Large Oscillating Water tunnel. Furthermore, the selective transport of heavy minerals is also a new aspect of gradation which is under study in the project (see par. 3.). Additional small-scale beach evolution measurements are also scheduled. Such analysis also require proper theoritical formulation of sediment transport and mass conservation equations which are also under development in the project.

Finally, the beach equilibrium concept developed by Bruun and Dean in the surf zone is being now extended to the non-breaking zone. Several behaviour-oriented models describing long-term profile evolution as a dynamic process around an equilibrium profile function of wave conditions, water levels and sediment properties are under development in the project.

4.2 Beach nourishment modelling

Under this task the potential of process-based and behaviour-oriented models to hindcast and forecast subareal and subaquaous nourishments is assessed by comparison with field data and behaviour tests. The field cases selected are Malagueta and Rosslare Strand which are monitored during the project and Sylt and Ocean city, Maryland. This assessment includes the use of existing models with improvements implemented in the course of the project. It includes cross-shore profile models as discussed above as well as one-line models and behaviour-oriented three dimensional models. One-line models are widely used as a design tool to predict the planform evolution of a nourishment. Improvements underway include attempts to simulate seasonal variations by cross-shore transport (Hanson et al, 1997). 3D models are more recent. They aim at including both longshore and cross-shore approaches in a coupled way in a simple manner in order to be used as a design tool and not only a research tool (Larson and Hanson, 1996).

4.3 Oscillatory coastal behaviour

This task explores those larger-scale and longer-term aspects of coastal behaviour which are considered relevant either for the nourishment behaviour itself or for the autonomous (background or natural) behaviour of the coast. It consists mainly of an inventory of identified cases displaying relevant spatial and temporal behaviour. It is foreseen that while structural erosion or accretion of a coastal stretch is of primary concern to coastal management, knowledge of coastline oscillations on larger time scales relative to the erosional or accretional trend would allow for a more efficient management practice. Particularly, the possibility to evaluate time scales and amplitude of oscillation could help designing protection plans. Several documented sites have already been identified in The Netherlands (Stive et al, 1996), Germany (Dette,1997) and France. Modelling efforts will also be devoted to these processes. First results concerning the modeling of longshore sand waves into a one-line model have been published by Hanson et al (1996).

5. CONCLUSIONS

Starting from the 80's, after the failure of many "hard" measures for protecting sandy beaches (like groins, breakwaters or sea-walls) become evident from both the technical and economic

point of view, the interest of using "soft" remedial measures like beach nourishment has largely increased. Once the beach erosion phenomenon has been defined, by identifying both the causes (through a study on morphological processes) and the local interests (evaluating the different aspects related to safety, recreation, environment and economy), the careful selection of the protective measures to be adopted is of primary interest. Nowadays beach nourishment, eventually integrated with some "supporting structures", is an increasingly important option (Capobianco and Stive, 1997)

Available experiences suggest that consistent evaluation criteria for design and for the subsequent accreditation of nourishment projects are however needed and a number of questions on technical and public policy issues must be addressed for the development of such evaluation criteria. Technical issues identified include design frequency and life, pre- and post-fill erosion rates, post-fill profile equilibration, project length, volumetric requirements, grain size compatibility, protective dunes, long-term sand resources, placement location, "hybrid" projects, and downdrift impacts. Public policy issues include monitoring, periodic renourishment, and maintenance, rehabilitation, environmental permitting.

Some issues, such as renourishment frequency, have both technical and public policy implications, reflecting the fact that beach nourishment is far from being a simple technical exercise.

The exchange of experience between the various participants of this project belonging to various institutes which combine research activities with consultancy services and field monitoring in the field of coastal engineering has already led to the recognition of the present diversity of coastal environments, engineering practices and legal constraints. On the other hand, they all noted that the use of shore nourishment and dune restoration for coastal hazards management will likely increase significantly in the European Union over the next decades. It is therefore prudent for coastal management authorities and the European Commission to begin to consider fundamental design, maintenance, periodic nourishment and performance assessments necessary for objective evaluation of such nourishments. In this project, a contribution towards a european approach of the design and the evaluation of nourishment measures is looked for and the mixing between field-oriented and modelling tasks has already shown its efficiency. The project has just completed its second year and entered its last year focussing on final outputs which will include a large range of results as described in this paper.

Acknowledgements

This project is carried out as part of the MAST III programme , partly funded by the European Commission (Directorate of Science, Research and Development (DG-XII), contract MAS3-CT95-0004) and by national bodies including the Service Technique des Ports Maritimes et des Voies Navigables (France) , the French Ministère de l'Equipement, des Transports et du Tourisme, the Rijkswaterstaat (Netherlands) and the Ministerio de Obras Publicas y Transportes (Spain)

References

Aarninkhof, S. and Stive, M.J.F. (1998). Monitoring the nearshore zone with the ARGUS video system: A tool for Coastal Zone Management. Abstract for Third European Marine Science and Technology Conference, Lisbon, May 1998.

Aarninkhof, S.G.J., Janssen, P.C. and Plant, N.G. (1997). Quantitative estimations of bar dynamics from video images. Coastal Dynamics Conference, Plymouth, June 1997 (in press)

Bosboom, J., Klopman, G., Roelvink, J.A. and Battjes, J.A. (1997). Boussinesq modelling of wave-induced horizontal particle velocities, Coastal Engineering 32 (1997) 163-180

Capobianco, M. and M.J.F. Stive (1997). Soft protection technologies as a tool for integrated coastal zone management. MEDCOAST'97, Malta, november 11-14.

Dette, H.H. (1997). Evaluation of longterm dune recession data. Proc. Coastal Dynamics' 97, Plymouth, UK, June 23-27, ASCE (to appear).

Guillen, J. and P. Hoekstra (1996). The equilibrium distribution of grain size fractions and its implications for cross-shore sediment transport: a conceptual model. Marine Geology, 135, 15-33

Hamm, L. (1996). Computation of the near-bottom kinematics of shoaling waves. Proc. 25th ICCE, Orlando Florida, ASCE, 537-550.

Hanson, H, Larson, M., Kraus, N.C., and Capobianco, M. (1997). Modeling of Seasonal Variations by Cross-Shore Transport Using One-Line Compatible Methods. Proc. Coastal Dynamics' 97, Plymouth, UK, June 23-27, ASCE (to appear).

Hanson, H., M.M. Thevenot and N.C. Kraus (1996). Numerical simulation of shoreline change for longshore sand waves at a groin field. Proc. 25th ICCE, Orlando, Florida, ASCE,4024-4037.

Janssen, C.M. and J.S. Ribberink (1996). Grain-size influence on sand transport in oscillatory sheet flow. Proc. 25th Int. Conf. on Coastal Engng., Orlando, FL, USA, ASCE, in press.

Katopodi, I., J.S. Ribberink, P. Ruol and C. Lodahl (1994). Sediment transport measurements in combined wave-current flows. Proc. Coastal Dynamics'94 Conf., Barcelona, Spain, ASCE, 837-851.

Larson, M, Kraus, NC, Hanson, H, and Gravens, MB. (1997). Beach Topography Response to Nourishment Operations at Ocean City, Maryland. Proc. Coastal Dynamics' 97, Plymouth, UK, June 23-27, ASCE (to appear).

Larson, M. and H. Hanson (1996). Schematized numerical model of three-dimensional beach change. Proc. 10th congress of APD-IAHR, Langkawi island, Malaysia (in press).

Lechuga, A.(1997). Una Estrategia de Defensa de Playas. Algunos Ejemplos Internacionales. IV Jornadas españolas de Ingenieria de Costas y Puertos. Cadiz (Spain), May, 1997.

de Meijer, R.J. and Tánczos, I.C. and Stapel, C. (1996). Radiogenic heavy minerals as tools in selective transport, in: Geology of siliciclastic shelf seas, De Batist, M. and Jacobs, P. (eds.), Geological Society special publication 117, 289-297.

Nourtec (1997). Innovative Nourishment techniques evaluation. Final Report. Coord. Rijkswaterstaat/ RIKZ, The Hague, The Netherlands.

Peters K., J. Newe and H.H. Dette. (1997). On beach nourishment design. Proc. Coastal Dynamics' 97, Plymouth, UK, June 23-27, ASCE (to appear)

Peters, K., J. Newe and H.H. Dette (1996). Development of underwater beach profile by monochromatic and random waves. Proc. 25th ICCE, Orlando, Florida, ASCE.

Ribberink, J.S. and A.A. Al-Salem (1995). Sheet-flow and suspension of sand in oscillatory boundary layers. Coastal Engineering, 25, 205-225.

Santas, J.C. et al. (1997). Monitorización de la nueva playa de la Zurriola, Gros, en San Sebastian. IV Jornadas españolas de Ingenieria de Costas y Puertos. Cadiz (Spain), May, 1997.

Spanhoff, R., E.J. Biegel, J. Van de Graaff and P. Hoelstra (1997). Shoreface nourishment at Terschelling, the Netherlands: feeder berm or breaker berm ? Proc. Coastal Dynamics'97, Plymouth, june 23-27, ASCE (to appear).

Stive, M.J.F., J. Guillen and M. Capobianco (1996). Bar migration and dune face oscillation on decadal scales. Proc. 25th ICCE, Orlando, Florida, ASCE, 2884-2896.

Tánczos, I.C., de Meijer, R.J., Ribberink, J.S., Janssen, C.M. (1997)."Selective transport of heavy and light minerals under asymmetric waves", Submitted to Sedimentology

TITLE: Probabilistic Design Tools for Vertical Breakwaters (PROVERBS)

CONTRACT NO: MAS3-CT95-0041

COORDINATOR:

Prof. H. Oumeraci (Coordinator)
TU Braunschweig
Leichtweiß-Institut für Wasserbau
Abteilung Hydromechanik und Küsteningenieurwesen
Beethovenstr. 51a
DE-38106 Braunschweig/Germany
Phone: +49 531-391-3930
Fax: +49 531 391-8217
Email: h.oumeraci@tu.bs.de

PARTNERS:

Prof. N.W.H. Allsop (Task 1 Leader)
HR Wallingford Ltd.
Howbery Park
GB-Wallingford OX 10 8BA / UK
Phone: +44 1491 822 230
Fax: +44 1491 825 539
Email: nwha@hrwallingford.co.uk

Dr. R.S. Crouch (Task 3 Leader)
Dept. of Civil & Structural Engineering
University of Sheffield
Mappin Street
GB-Sheffield S1 3JD / UK
Phone: +44 114 222 5716
Fax: +44 114 222 5700
Email: r.crouch@sheffield.ac.uk

M.B. De Groot (Task 2 Leader)
Delft Geotechnics
P.O. Box 69
NL-2600 AB Delft / The Netherlands
Phone: +31 152 693 787
Fax: +31 152 610 821
Email: dgo@delftgeot.nl

Prof. J.K. Vrijling (Task 4 Leader)
Delft University of Technology
Faculty of Civil Engineering
Stevinweg 1
NL-2628 CN Delft / The Netherlands
Phone: +31 15 278-5278
Fax: +31 15 278-5124
Email: a.ramdjan@tudelft.nl

ASSOCIATED PARTNERS:

Prof. H.F. Burcharth
Aalborg University
Department of Civil Engineering
Sohngaardsholmsvej 57
DK-9000 Aalborg / DENMARK
Phone: +45 9635 8482
Fax: +45 9814 2555
Email: burcharth@civil.auc.dk

Prof. D.H. Peregrine
University of Bristol
Department of Mathematics
University Walk
GB-Bristol BS8 1TW / U.K.
Phone: +44 117 928-7971
Fax: +44 117 928-7999
Email: d.h.peregrine@bristol.ac.uk

B.G. Madrigal
Centro De Estudios De Puertos Y Costas
c./ Antonio López 81
ES-28026 Madrid / SPAIN
Phone: +34 1 335 7625
Fax: +34 1 335 7622
Email: braulio.g.madrigal@cedex.es

Dr. M. Van Gent
Delft Hydraulics
Marine and Coastal Infrastructure
P.O. Box 177
NL-2600 MH Delft / THE NETHERLANDS
Phone: +31 15 285 8846
Fax: +31 15 285 8582
Email: marcel.vangent@wldelft.nl

Prof. L. Franco
Politecnico di Milano
Dipartimento di Ingegneria Idraulica
32 Pzz. Leonardo da Vinci
IT-20133 Milano / ITALY
Phone: +39 2 2399 6297
Fax: +39 2 2399 6298
Email: leofranc@fenice.dsic.uniroma3.it

P.J. Hewson
University of Plymouth
School of Civil and Structural Engineering
Palace Street
GB-Plymouth PL1 2DE / U.K.
Phone: +44 1752 233652
Fax: +44 1752 233658
Email: phewson@civ.plym.ac.uk

Prof. A. Lamberti
Università degli Studi di Bologna
Dipartimento di Ingegneria delle Strutture
Viale del Risorgimento 2
IT-40136 Bologna / ITALY
Phone: +39 51 644-3749
Fax: +39 51 644-8346
Email: alberto@idraulica.ing.unibo.it

Prof. W. Richwien
Universität Gesamthochschule Essen
Institut für Grundbau und Bodenmechanik
Universitätsstr. 15
DE-45117 Essen / GERMANY
Phone: +49 201 183-2857
Fax: +49 201 183-2870
Email: igb010@sp2.power.uni-essen.de

Prof. M. Bélorgey
Université de Caen
Centre de Géomorphologie
Laboratoire de Mécanique
Rue de tilleuls 24
FR-14000 Caen / FRANCE
Phone: +33 231 565 711
Fax: +33 231 565 757
Email: belorgey@meca.unicaen.fr

A. Martinez
Sogreah Ingenierie SNC
Rue de Lorraine 6
FR-38130 Echirolles / FRANCE
Phone: +33 47633 4079
Fax: +33 47633 4296
Email: martinez@sogreah.fr

Dr. K.H. Andersen
Norwegian Geotechnical Institute
P.O. Box 3930 Ullevaal Hageby
N-0806 Oslo / NORWAY
Phone: +47 220 23035
Fax: +47 222 30448
Email: kha@ngi.no

T. Bruce
University of Edinburgh
Department of Mechanical Engineering
The King's Buildings
GB-Edinburgh EH9 3JL / U.K.
Phone: +44 131 650 8701
Fax: +44 131 667 3677
Email: tom.bruce@ed.ac.uk

Dr. I.J. Losada
Universidad de Cantabria
Departamento de Ciencas y Technicas del Agua
Grupo de Ingenieria Oceanografica y de Costas
Avda. de los Castros S/N
ES-39005 Santander / SPAIN
Phone: +34 42 201810
Fax: +34 42 201860
Email: inigo@puerhp1.unican.es

G. Müller
Queens University of Belfast
Department of Civil Engineering
Stranmills Road
Belfast BT7 1NN / NORTHERN IRELAND
Phone: +44 1232 274517
Fax: +44 1232 663754
Email: g.muller@qub.ac.uk

Prof. E. Benassai
Università degli Studi di Napoli "Frederico II"
Dipartimento di Idraulica
Via Claudio n. 21
IT-80125 Napoli / ITALY
Phone: +39 81 7683444
Fax: +39 81 5938936
Email: benassai@ds.unina.it

D. Berdin
Bureau Veritas
Direction Téchnologique Océanique
17 bis Place des Reflets
FR-92400 Courbevoie / FRANCE
Phone: +33 1 4291 5291
Fax: +33 1 4291 5345
Email: dberdin@bureauveritas.com

J.-B. Kovarik
Service Technique Central
B.P. 53 - boulevard Gambetta 2
FR-60321 Compiègne / FRANCE
Phone: +33 344 926027
Fax: +33 344 200675
Email:
jb.kovarik@stcpmvn.equipement.gouv.fr

M. De Gerloni
ENEL Società per Azioni
Direzione Studi e Ricerche
Centro di Ricerca Idraulica e Strutturale
Via Ornato 90/14
IT-20162 Milano / ITALY
Phone: +39 2 7224 8534
Fax: +39 2 7224 8430
Email: degerloni@cris.enel.it

Probabilistic Design Tools for Vertical Breakwaters PROVERBS

H. Oumeraci / A. Kortenhaus
Leichtweiß-Institut, TU Braunschweig
Beethovenstr. 51a, 38106 Braunschweig, Germany

SUMMARY

The paper attempts (i) to briefly outline the main objectives, issues and motivations as well as the organisation and participation structure of PROVERBS on probabilistic design of vertical breakwaters; and (ii) to present some selected findings of this project related to the use of probabilistic design methods for caisson breakwaters.

1. INTRODUCTION

Due to the growing pressure exerted by human activities and needs in the industrial and amenity sector within the coastal zone, interest in protective structures against the hydrodynamic actions of the sea is expected to increase. A further important reason supporting this expectation is the increase of the strength and frequency of storm surges observed in the last decades.

On the other hand, the construction of coastal structures is still essentially based on empirical design methods, as well as on trial and error approaches, thus making any optimisation almost impossible. The latter statement is particularly supported by the fact that most of the catastrophic failures experienced by coastal structures could not be predicted at the design stage and cannot yet be satisfactorily explained by present design methods and analyses. In fact, most of the failure modes which have been identified to date are associated with the dynamic nature of the wave-loads and the highly transient phenomena involved, suggesting an urgent need for the development of integrated rational design approaches based on an increased understanding of the hydrodynamic, geotechnical and structural processes involved in the wave-structure-foundation interaction.

With this background an extensive research programme, which also includes coastal structures, has been initiated by the European Union (EU) within the Marine Science and Technology (MAST), and one of the research projects within this phase deals with "Probabilistic Design Tools for Vertical Breakwaters (PROVERBS)". In the following a short presentation of PROVERBS is given, followed by a brief outline of some selected key findings and their practical importance.

2. BRIEF PRESENTATION OF PROVERBS

(A) MAIN OBJECTIVES

PROVERBS is a research project involving 23 institutes from 8 European countries and different disciplines (fluid mechanics, applied mathematics, soil mechanics, structural dynamics, hydraulic and coastal engineering).

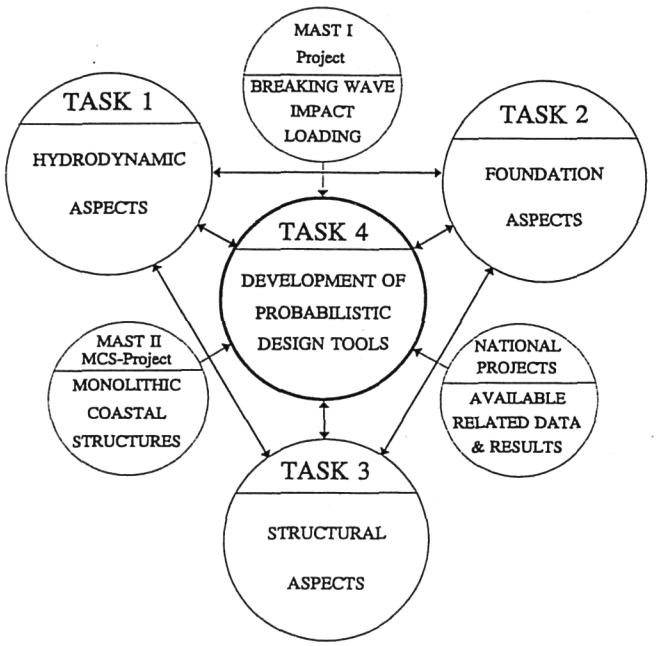


Fig. 1: Implementation of existing and new knowledge in probabilistic based design framework (PROVERBS)

The main objective of PROVERBS is to develop and implement new rational probability based methods for the design of monolithic coastal structures and breakwaters subject to sea wave attacks, and then demonstrate their advantages as compared to existing conventional design methods. This will be achieved by enhancing the knowledge in various aspects associated with hydrodynamic, geotechnical and structural processes involved in the wave-structure-foundation interactions and in the associated failure mechanisms. In addition, the results gained in previous MAST and national research projects will also be linked together with the new knowledge generated in PROVERBS and implemented for the development of the probabilistic design tools (Fig. 1).

These new design tools are intended to supplement/replace the existing conventional design approach and to build a solid scientific basis for any future authoritative European design guidelines and codes (see e.g. *Burcharth et al., 1994*). Some of the monolithic structures/breakwaters addressed in PROVERBS are schematically shown in Fig. 2.

(B) GENERAL MOTIVATIONS

The major reasons why monolithic structures and why probabilistic design methods have been selected as candidate research topics for a large European project are outlined below.

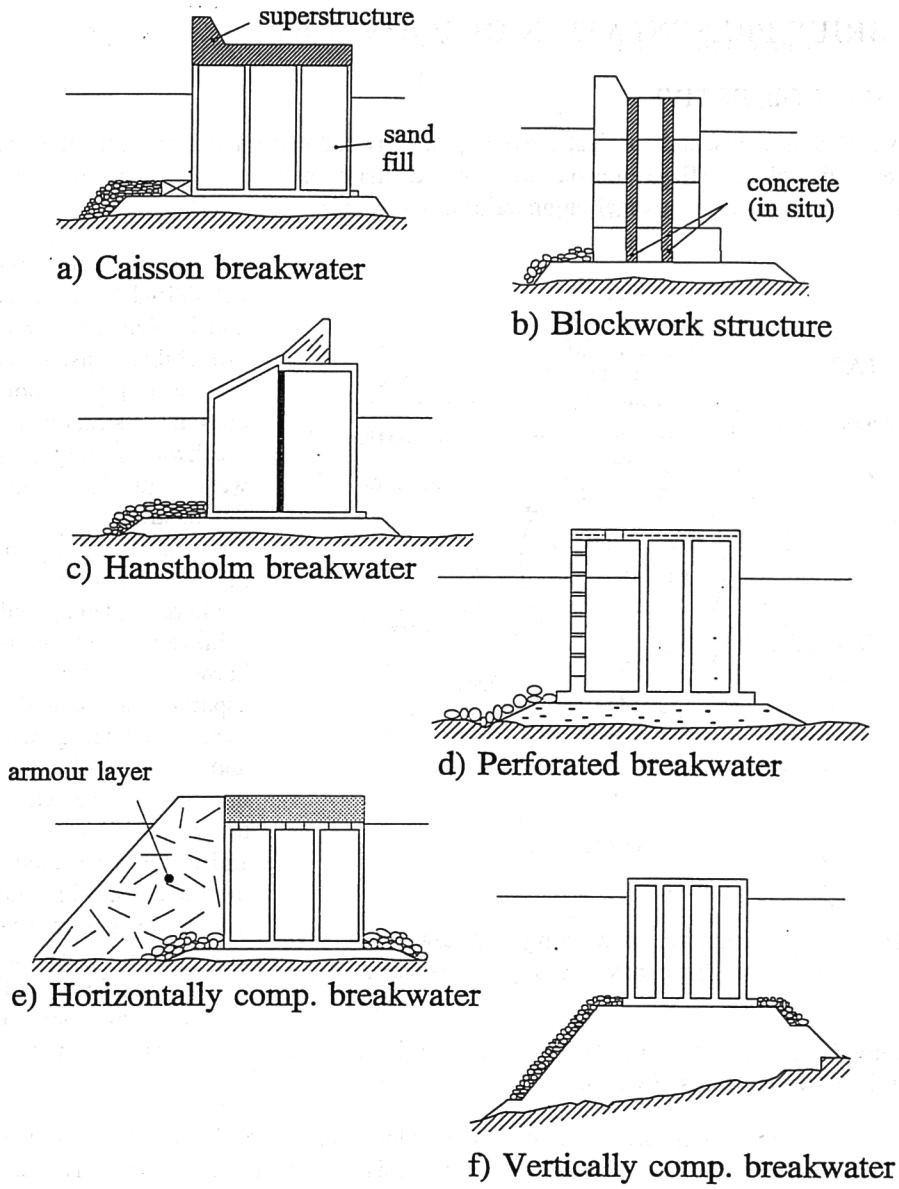


Fig. 2: Main types of monolithic structures/breakwaters

MOTIVATIONS FOR MONOLITHIC COASTAL STRUCTURES

Catastrophic failures: Numerous severe and catastrophic failures were experienced by vertical breakwaters in the 1930s. It should be stressed that major failures may cost 2-3 times more to re-build than the original construction costs. As a conse-

quence, the vertical breakwater type was almost abandoned - except in some few countries - in favour of the rubble mound breakwater type (*Oumeraci, 1994*). After a series of catastrophic failures experienced by large rubble mound breakwaters at the end of the 1970s and the beginning of the 1980s, a number of actions were started to promote the revival of vertical breakwaters and the developments of new breakwater concepts (*Oumeraci et al, 1991*). In this respect extensive research efforts at interdisciplinary and multinational level were urgently required.

- *Need for breakwaters at greater depth*: To suit the increasing draught of large vessels, breakwaters should be founded in increasingly deeper water, thus making the cost of such structures more prohibitive. Construction costs of 100 to 350 million ECU/km breakwater are not seldom. In this respect, a type of structure is needed which represents a better alternative not only in terms of technical performance and total costs, but also in terms of standardization, quality control, environmental aspects, construction time and maintenance. Moreover, more focus than in the past must be put on the optimisation of the design.

- *Need for environmently friendly structures*: Monolithic structures can easily be given any shape, perforations and any further constructional features to reduce the impact on the environment. Moreover, less material and less energy for material transportation than for further traditional breakwater types is required for construction. In fact, most of the material involved in a caisson breakwater is sand - dredged from deeper sea, thus minimizing the energy required for transportation and maximising the conservation of scarce construction material.

- *Need for multi-purpose structures*: Due to the inherent considerable public investments, it is expected that the objective of coastal structures will not solely be limited to the damping of wave action. Taking the opportunity of such expensive structures, facilities for amenity and wave power extraction might also be integrated in the structure (cost sharing, acceptance by society etc.). In this respect, caisson structures are suited for this purpose, because of their flexibility to adapt to any requirements related to their shape, size etc.. Although not yet based on rational design methods, the caisson type structures have already demonstrated their capability because they can easily be adapted to meet also:
  - further purposes like amenity, wave power extraction and further industrial needs;
  - environmental requirements by providing a suitable shape and further interesting features to reduce wave reflection, to increase the water exchange between open sea and protected area, to minimize the disturbance of the ground and to fit into the maritime scenery.

Examples from Japan (*Tanimoto et al., 1994*), Monaco (*Bouchet et al., 1994*) and Korea (*Lee et al., 1994*) have already shown that the potential of adapting caissons type structures to meet any requirement of technical, social and ecological nature is higher than for any other traditional type of structure. This however, requires a high level of knowledge and technology. PROVERBS is expected to contribute to bringing the European maritime construction industry in a world leading position in this field.

- *Potential large-scale application for sea-walls*: Because of the competitiveness of caisson structures in terms of technical performance, total costs, environment, quality control, construction time and standardization, it is believed that there is also a large potential for their use as sea walls to respond to the increase of storminess and sea level rise. This will help to react more rapidly and better protect the coastal zones of high economic, social and environmental values.

MOTIVATIONS FOR PROBABILISTIC DESIGN METHODS

- *Need for more and better optimisation*: Breakwaters and coastal structures represent considerable public investments (in the range of 1 billion US$ for a 5 km long breakwater in deep water) which encounter less and less acceptance by government and local authorities, due to the decreasing availability of fundings for this kind of large projects and the increasing awareness of environmental impacts by governments and society. Beside the need to diversify the use of such structures (see multi-purpose use as described above), there is an urgent need to use more rational methods for design and more sophisticated tools for the optimisation of such structures. It is obvious that such methods can only be developed in an integrated manner, requiring a multi-national framework and a multi-disciplinary research strategy.

- *Complexity of physical problems involved*: The results of previous MAST-projects have highlighted the complexity and the integrated nature of the problems related to breakwater stability and design, including the considerable importance of the three-dimensional and stochastic nature of the processes involved in the wave-structure-foundation interactions (wave loading and dynamic response) as well as the large number of possible failure mechanisms and their complex interaction. This necessarily prescribes the use of probability-based analysis methods as the sole alternative for the design. In fact, this is the only alternative which may provide a systematic and comprehensive framework not only for optimisation procedures but also for the application of engineering judgement.

- *Stimulating aspects*: Since the prospective probability based design methods will essentially be based on the feedback from prototype experience, the results are expected to stimulate a rapid and continuous feedback between researchers and practioners, thus enhancing the worldwide applicability of these tools. This will also actively stimulate the collection of more and better data, because it is the essence of probability based tools to use more and better information.

(C) ISSUES / TASKS ADDRESSED BY PROVERBS

As already illustrated by Fig. 1, four main issues are addressed by PROVERBS: hydrodynamic, foundation, structural and probabilistic design aspects. Each of these aspects is dealt with in a sub-project called "Task".

- *Task 1: Hydrodynamic Aspects*: Hydrodynamic inputs will be provided by focusing on wave loadings, including associated uncertainties and statistical distributions required to implement the probabilistic design tools in Task 4. Prototype measurements

and 3D-hydraulic model tests will form the major part of this work, supplemented by further physical and numerical modelling.

- *Task 2: Foundation Aspects*: Beside the development of new knowledge related to failure mechanisms and dynamic soil properties, information will be generated on probability, partial safety factors and uncertainties for soil parameters and models, making them readily applicable for the implementation of probabilistic design tools in Task 4. Analysis, numerical modelling and laboratory tests will build the major means for the investigations, supplemented by centrifuge modelling and prototype measurements.

- *Task 3: Structural Aspects*: This task will provide the methods to assess the structural strength of breakwater walls under pulsating and extreme impact loading, as well as their durability. Uncertainties in the loading and resistance parameters will be accounted for as needed for the implementation of the probabilistic design tools. Finite element analysis will principally be used for the investigations.

- *Task 4: Probabilistic Design Tools*: In a first preparatory phase a probabilistic framework will be developed by linking together all above aspects by describing the failure modes, by establishing the fault trees, by evaluating the associated uncertainties and developing a reliability design philosophy. In a second phase, probabilistic design tools will be developed. Based on reliability calculations at Level II and III, on the analysis of case studies and involvement of practitioners, a method to assess the overall reliability of vertical breakwaters will be developed and applied to a set of selected representative structures.

The organisation structure showing the Coordinator, the Management Committee Meeting and the Task Leaders is given in Fig. 3.

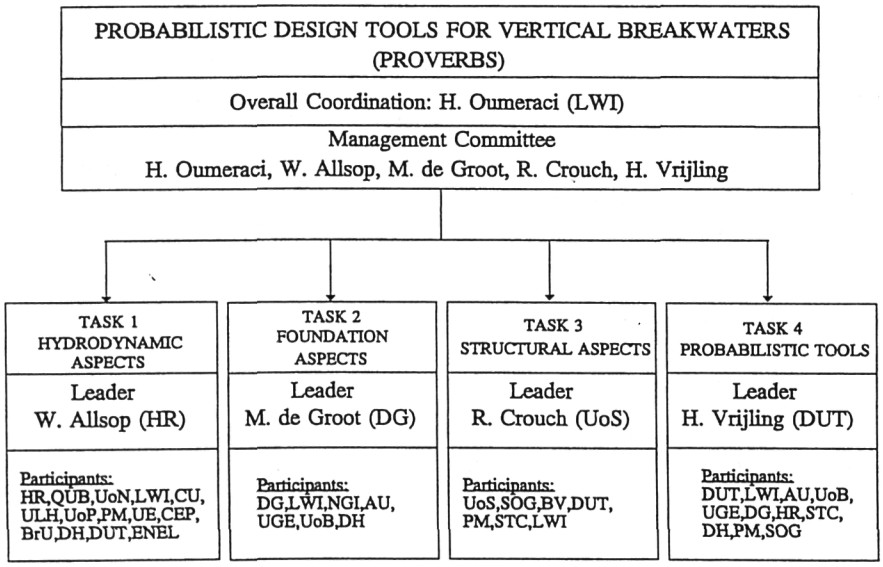


Fig. 3: Organisation structure of PROVERBS

3. TASK 1 - HYDRODYNAMIC ASPECTS

(A) BACKGROUND

Many port or coastal structures, including breakwaters, are formed with vertical, near-vertical or steeply sloping faces. The prediction of wave forces on such structures is complicated, and predictions of forces and pressure often have very high uncertainties. Simple prediction methods for pulsating wave loads usually predict average pressures of about $p_{av} = 2\,\rho \cdot g \cdot H_s$, where H_s is the incident wave height. Recent research studies under PROVERBS have measured pressures up to or greater than $p = 40\,\rho \cdot g \cdot H_s$, much higher than would be predicted by simple design methods.

Problems due to wave impacts may appear comparatively small. Vertical breakwaters are massive structures, and the incidence of failure of existing structures is relatively low. Quays or sea walls ure usually backed by ground or fill, and will not therefore fail in the direction of the principal wave loading. Unfortunately, recent failures of vertical breakwaters in Uk, Japan and Italy has demonstrated that design methods are unsufficient, and studies in UK and Germany have demonstrated that wave impacts may have considerable influence on design loadings (*Allsop et al., 1996*).

The present stock of vertical breakwaters, many in Europe constructed after about 1830, are subject to continuing deterioration, so their safety reduces with time. In some areas, both sea levels and storminess have increased over the last 10-20 years, and show every sign of continuing to reduce safety margins.

(B) OBJECTIVES

Within the PROVERBS project, the primary objective of Task 1 is to supply essential datas and prediction methods to Task 2-4 on hydro-dynamic loadings on vertical and composite structures. The second objective is to develop new prediction tools and data to be used more widely by consulting engineers, contractors, and owners in the analysis of performance and safety of such structures. Task 1 is led by HR Wallingford, and is divided into 3 sub-Tasks, each contributing to overall analysis and integration:

Task 1.1	Field Measurements	co-ordinator University of Plymouth
Task 1.2	Hydraulic model studies	co-ordinator HR Wallingford
Task 1.3	Numerical Modelling	co-ordinator Delft Hydraulics

(C) TECHNICAL PROGRESS

FIELD MEASUREMENTS

Wave pressures are being measured on breakwaters at four different sites in Europe. The measurements in the field reflect the complexities of real seas; provide supplementary information to the laboratory tests, and are intended to provide data for improved scale correction methods.

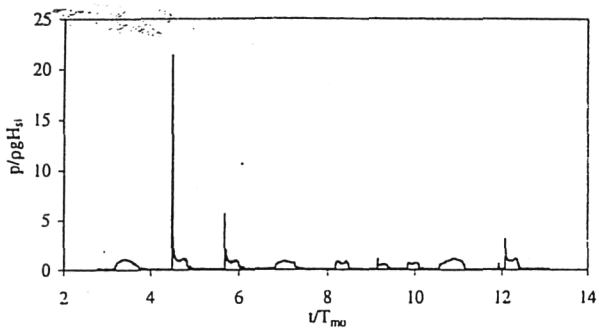


Fig. 4: Typical pressure time series under impact conditions (*Allsop et al., 1996*)

Hydraulic model tests have been used widely to measure wave forces, and/or wave pressures, on sections of simple vertical or composite breakwaters (see example results in Fig. 4). Most tests have been conducted in narrow 2-dimensional wave flumes with normal wave attack, but some studies have also used large 3-dimensional wave basins with short-crested and/or oblique wave attack. Much of the effort in the first year of the project was devoted to substantially extending the analysis of data from laboratory studies completed under national funding.

This initial analysis confirmed that most wave forces under "pulsating wave" conditions on many structures were much as expected in simple prediction methods. But that analysis work also demonstrated that "wave impacts" by wave breaking against structures are also very important in the design of some structures. Previously felt to be only of very short duration, or very rare in occurrence, wave impacts have been shown to have caused failure in a number of breakwaters. The major results of the first part of the project have therefore been:

- new methods to predict that conditions give rise to wave impacts, see example parameter map in Fig. 5;
- methods to predict the magnitude and duration of impacting wave forces.

Other results are standardised response parameters coverage and measurements; new data for the performance of perforated caissons; identification of effects of steep bep slopes; new scaling approaches for hydraulic model studies; and new data on wave induced pressures in rubble foundations. New work in 1997 has included supplementary model tests to fill gaps, and integration of new test data from outside PROVERBS.

4. TASK 2 - FOUNDATION ASPECTS

(A) BACKGROUND

Several geotechnical aspects may complicate the foundation design for vertical breakwaters, like:

- Elastic response yielding dynamic effects under wave impact loading;
- Irregular pore pressure distribution in the bedding layer or rubble mound due to uneven grainsize distributions or elastic storage or wave induced movements of the caisson;
- Excess pore pressures due to compression of the soil under suddenly increasing wave loads or induced by repetitive wave loading;
- Negative pore pressures due to dilation under suddenly increasing wave loads;

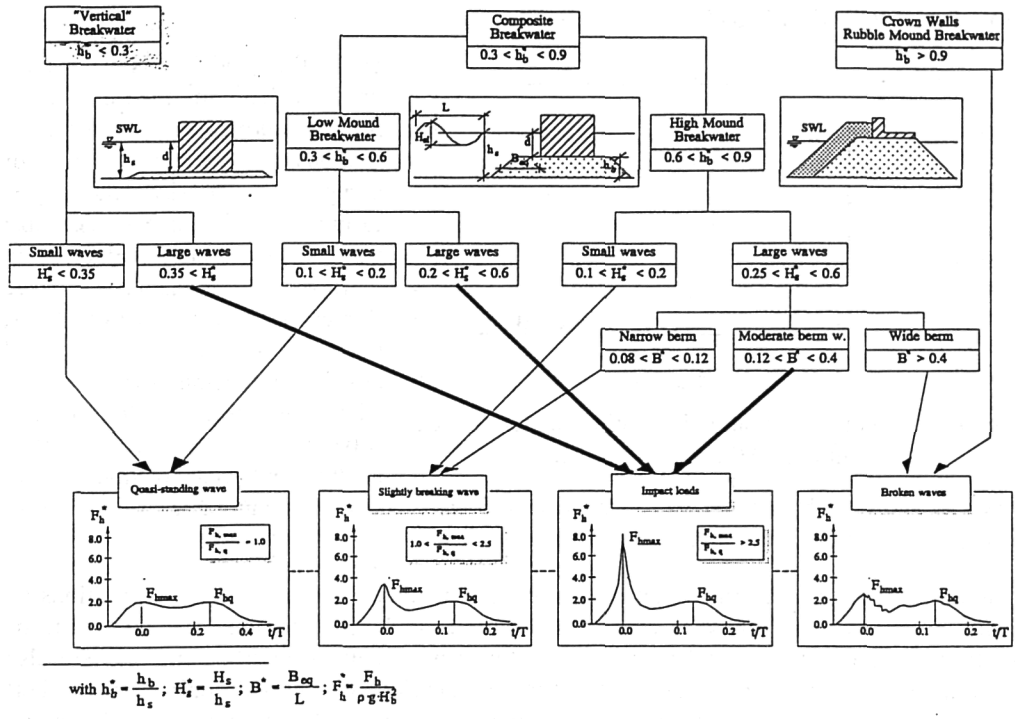


Fig. 5: Parameter map of PROVERBS (*Allsop and McConnell, 1998*)

- Degradation under repetitive loading;
- No clear boundary between failure and no-failure, but small residual deformations under repetitive high loads.

The interaction with wave loading and the inherent uncertainty of the soil properties at each site means a further complication. Task 2 is quantifying all these effects with the help of systematic soil sample tests, sophisticated calculation models, laboratory tests with a centrifuge and the measurement of the vibration response of some existing caisson breakwaters. In view of the complexity of mechanisms leading to geotechnical and further failure modes, conventional stationary methods like for common bearing capacity calculations are of limited use to explain the actual damages. More reliable models have been/are being developed. The interaction between the different models, including the required input and the expected outcome is examplarily shown in Fig. 6 (*De Groot et al., 1996*).

(B) OBJECTIVES

The aim of all this work is to find the phenomena being relevant for each type of vertical breakwater, the prevailing conditions and to formulate a basis for engineering guidelines:

- studies needed to judge the feasibility of a caisson breakwater in a specific case within a reasonable time;
- relatively simple methods to be applied for a preliminary design; quantification of the most relevant phenomena in an approximate way for each variable of the selected structure;

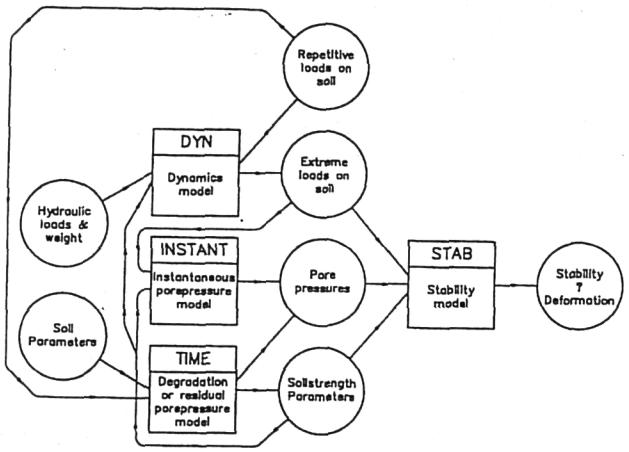


Fig. 6: Inputs, models and expected outputs at high design level (*De Groot, 1998*)

- studies needed for a detailed design; relevant requirements for soil data, hydraulic data, calculation models and/or laboratory studies;
- dealing with uncertainties concerning soil, hydraulic loads, structural strength and the applied models.

An example for the development of one of the engineering models is presented in the following section.

(C) ENGINEERING MODELS FOR DYNAMIC STRUCTURE BEHAVIOUR

Simple engineering models have been developed and calibrated by large-scale model tests to simulate both oscillatory motions and permanenent displacements of a breakwater subject to impact loading induced by breaking waves (*Oumeraci and Kortenhaus, 1994*). The models can also be used to reproduce the cumulative effect of repetitive impacts.

Both models can be used together to study the stepwise failures which were neglected in the past. In fact, the displacements induced by a single impact may be too small and non relevant for the stability, but the cumulative effect resulting from repeated impacts may lead to the collapse of the structure. These models have already been successfully applied to reproduce some Japanese prototype failures which otherwise could not be explained by existing standard formulae (*Oumeraci et al., 1995*). This results in safer design over the lifetime of the structure.

5. TASK 3 - STRUCTURAL ASPECTS

(A) BACKGROUND

The failure of caisson breakwaters may be brought about not only by the rigid body motion of the structure resulting from deformations in the foundation or soil-structure interface, but also as a consequence of the rupture of structural elements. Local structural failures may render the caisson unfit for its original purpose without necessarily leading to loss of tranquil water in the harbour. For example, chloride ingress into the front wall may be sufficient to induce corrosion leading to a loss of bond, anchorage and reinforcement area and concrete cracking in the cover zone, all of which significantly reduce the mechanical integrity of the section. If under-designed, a weakened structural element may rupture under repeated storm wave slamming resulting in loss of fill material. Without a regular programme of inspection, diagnosis and repair, progressive deterioration and collapse of a wall panel might occur. This could remove support for the top slab and crown wall. The consequent reduction, or loss, of vehicle access over the structure may signifi-

cantly restrict harbour operations. Coastal engineers need guidance on how to assess the likelihood of a chain of such events and how to avoid them.

Before detailed calculations are made, a series of plausible failure scenarios need to be identified. Possible local and global collapse modes should include those related to the transportation, during the placing operation and those occurring during the service life of the structure. By directly considering many of these issues, Task 3 provides new design aids for coastal engineers.

(B) OBJECTIVES

The principal goal of the Task 3 Team is to identify (and develop where necessary) a set of reliable tools which can accurately predict the structural safety levels associated with vertical breakwaters. Limit State Functions are to be generated for critical failure modes for inclusion in the Task 4 probabilistic design models.

A review of existing design codes of practice, national standards and guideline documents for caisson structures has been undertaken. These studies to-date have highlighted key omissions and inconsistencies in existing documents. The early findings coupled with the practical experience of the team and information on construction and maintenance costs for large structures have helped guide work on other topics within Task 3.

Delft University of Technology and Sheffield University have been working on the development of analytical tools (mathematical models) which describe the deformation response of cellular caissons subjected to a variety of loadings. Durability and fatigue aspects are also addressed by the latter group.

(C) ANALYTICAL MODELS FOR CAISSON RESPONSE

A hierarchy of models with increasing numbers of degrees-of-freedom have been examined within Task 3. Analytical studies into the floating stability (associated with rigid body pitching, rolling and heave motions) of cellular caissons have been made by Delft University to investigate the likelihood of accidental sinking. Other models examining the degree of structural distress caused by local overload during towing have been considered as have the effects of bedding down onto an uneven foundation. The latter has been studied in a rectangular multi-cell caisson using a 3-d finite element approach with shell elements (Fig. 7).

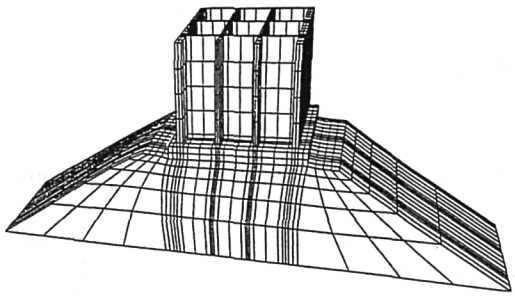


Fig. 7: 3D finite element model of a typical rectangular unit (*Crouch, 1998*)

Work has also concentrated on the caisson behaviour under severe wave slamming once sited on the foundation. Design models ranging from (i) simple (horizontal) continuous beam idealisations spanning between the cross walls on the front face, (ii) front-to-back beam-on-elastic-foundation models for the base slab which include vertical loads from the front, back and cross walls as well as the pressure load from the fill, (iii) supported rec-

tangular Mindlin plate, closed-form linear transient analysis models which apply an idealised church-roof wave pressure-time history and return the transient bending moment distribution; (iv) a layered, curved shell explicit transient dynamic non-linear finite element analysis approach and (v) a full 3-d continuum non-linear implicit transient dynamic finite element analysis code (with capability to include dynamic fluid-structure interaction effects).

Although much progress has been made on modelling progressive fracturing in reinforced concrete structures using finite element techniques, further development of robust constitutive models for concrete and provision of efficient, accurate solution algorithms dedicated to caisson structures is under way.

(D) TASK 3 OUTPUT

By the end of the project Task 3 will have delivered the following:

- A critique of existing codes appropriate for the structural design of cellular reinforced concrete caissons. The final report will not only highlight areas where greater clarity is required but also provide recommendations (based largely on EC principles) on the framework and detail of the PROVERBS design model.
- Identification of the dominant structural failure modes in pre-cast cellular caissons and an assessment of the consequences of such failure on the overall function of the breakwater.
- Guidance on appropriate analytical approaches to treat the structural behaviour of cellular caissons during the transportation and placing stages together with associated Limit State Functions for key loading events.
- A catalogue of, and comparisons between, different analysis methods for the static and dynamic response of cellular caissons under severe wave slamming together with associated Limit State Functions. Guidance on undertaking the finite element analysis (linear and non-linear) of reinforced concrete caissons together with examples of analyses on three representative structures (rectangular multi-cell, highly perforated structure and cylindrical shell caisson). New shell and 3-D continuum non-linear dynamic finite element codes specifically written for caissons with dedicated pre-processors.

A review of existing quantitative models for durability service-life assessments (including chloride ingress models in particular) and guidance on how to incorporate these models into a structural integrity management programme.

6. TASK 4 - PROBABILISTIC ASPECTS

(A) PROBABILITY OF FAILURE

Several methods exist to calculate the probability of failure. These methods are identified and will be used in a risk analysis to show their advantages and disadvantages. Approximating methods have in general lower calculation times than exact methods. However, in some cases approximating methods fail to give reliable results in which case exact methods have to be used (Fig. 8).

(B) DEFINITION OF THE ACCEPTABLE PROBABILITY OF FAILURE

When designing a structure using probabilistic tools a way to accept or reject the calculated probability of failure has to be found. Generally, codes of practice are not necessarily applicable to solve this problem. The acceptable (target) probability of failure can however be defined in different ways. In PROVERBS several methods are investigated, like economical optimization (Fig. 9) and comparison to similar structures.

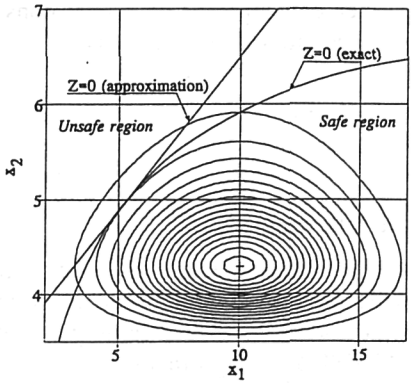


Fig. 8: Fictitious simultaneous distribution of two random variables with exact and approximating failure boundary

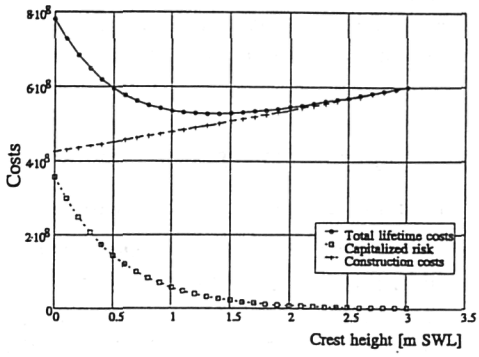


Fig. 9: Example of economical optimization of the probability of failure (*Voortman et al., 1998*)

(C) INVENTORY OF FAILURE MODES

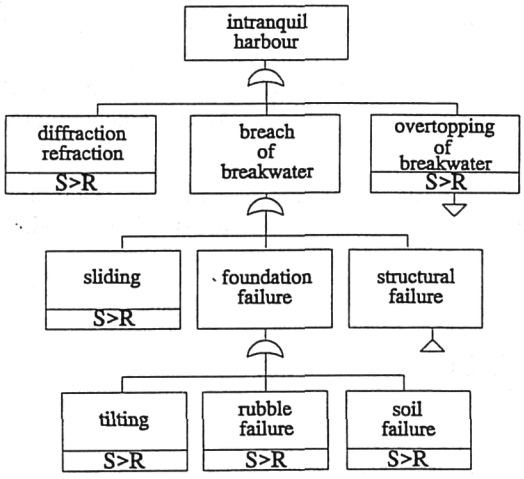


Fig. 10: Simplified fault tree for vertical breakwaters (*Vrijling and Voortman, 1998*)

Experience has shown that coastal structures do not fail because of mistakes in the description of the failure modes, but because of neglecting an important mode of failure. Therefore a project should start with identifying all relevant failure modes of the various alternative designs.

Structures may fail in many different ways. An inventory of all possible failure modes of vertical breakwaters has been made for use in further analysis. For each failure mode the probability of failure will be calculated.

The fault trees which represent the possible paths of the selected failure modes to be dealt with in PROVERBS have been established at various levels of detail for a set of different typical structures. An example fault tree is shown in Fig. 10.

Using the fault tree the probabilities of failure of the different failure modes can be combined into the overall failure probability.

These results build the basis for the identification of the models which are required to describe the failure modes, including their interaction. They also provide the basis for the implementation of these models into probabilistic design tools.

CONCLUDING REMARKS

The integrated character of the research strategy which is being particularly pursued in PROVERBS as well as the multi-disciplinary research efforts to link together the hydrodynamic, geotechnical, structural and probabilistic design aspects represent a substantial departure from the existing, essentially empirical approach, and thus constitutes a very important step towards a largely rational discipline. In this respect, the results will not only enable to lay down the scientific basis for authoritative design guidelines for coastal structures, but also constitutes a scientific platform for continuous improvements, even after completion of the MAST Programme.

The process oriented research adopted in PROVERBS will also provide a physically sound departure and scientific basis for the development of innovative alternative constructions which can fulfil technical, economical and ecological criteria.

ACKNOWLEDGEMENTS

The author would like to thank the Task Leaders and all other partners of PROVERBS for their valuable contributions and for the new and enjoyable research atmosphere they created within PROVERBS. Thanks are also due to the European Unions for the support of this project. The nice cooperation with the EU representative C. FRAGAKIS is also acknowledged. The support of national research projects by the respective national research foundations and governments which largely contributed to the success of PROVERBS is also gratefully acknowledged.

REFERENCES

ALLSOP, N.W.H.; MCKENNA, J.E.; VICINANZA, D.; WHITTAKER, T.J.T. (1996): New design methods for wave impact loadings on vertical breakwaters and seawalls. *Proceedings International Conference Coastal Engineering (ICCE)*, ASCE, Orlando, Florida, USA, no. 25, Volume 2, Chapter 194, pp. 2508-2521.

ALLSOP, N.W.H.; VICINANZA, D.; MCKENNA; J.E. (1996): Wave forces on vertical and composite breakwaters. *Strategic Research Report. Hydraulic Research Wallingford*, SR 443, Wallingford, U.K., 94 pp.

ALLSOP, N.W.H.; MCCONNELL, K. (EDS.) (1998): PROVERBS flyer, Task 1 insert sheet. *Flyer, MAST III, PROVERBS-Project: Probabilistic Design Tools for Vertical Breakwaters*, Wallingford, U.K., 2 pp.

BOUCHET, R.; CELLARIO, P.; ISNARD, J.L. (1994): New types of breakwater: two projects in Monaco. *Proceedings International Conference on Hydro-Technical Engineering for Port and Harbor Construction (Hydro-Port)*, Yokosuka, Japan, vol. 1, Part 1, pp. 581-592.

BURCHARTH, H.F.; SØRENSEN, J.D.; CHRISTIANI, E. (1994): On the evaluation of failure probability on monolithic vertical wall breakwaters. *Proceedings International Workshop Wave Barriers in Deepwaters*, PHRI, Yokosuka, Japan, pp. 458-517.

CROUCH, R.S. (1998): PROVERBS flyer, Task 3 insert sheet. *Flyer, MAST III, PROVERBS-Project: Probabilistic Design Tools for Vertical Breakwaters*, Sheffield, U.K., 2 pp.

DE GROOT, M.B. ET AL. (1996): Foundation design of caisson breakwaters. *Norwegian Geotechnical Institute*, no. 198, 2 volumes, Oslo, Norway, 126 pp; 9 Appendices.

DE GROOT, M.B. (1998): PROVERBS flyer, Task 2 insert sheet. *Flyer, MAST III, PROVERBS-Project: Probabilistic Design Tools for Vertical Breakwaters*, Delft, The Netherlands, 2 pp.

LEE, D.S.; HONG, G.P. (1994): Korean experience on composite breakwaters. *Proceedings International Workshop Wave Barriers in Deepwaters*, PHRI, Yokosuka, Japan, pp. 172-183.

OUMERACI, H.; PARTENSCKY, H.-W.; TAUTENHAIN, E.; NICKELS, H. (1991): Large-scale model investigations: a contribution to the revival of vertical breakwaters. *Proceedings of the Conference on Coastal Structures and Breakwaters*, ICE, London, U.K.: Thomas Telford Ltd., pp. 207-220.

OUMERACI, H. (1994): Review and analysis of vertical breakwater failures - lessons learned. *Coastal Engineering, Special Issue on 'Vertical Breakwaters'*, Eds.: Oumeraci, H. et al., Amsterdam, The Netherlands: Elsevier Science Publishers B.V., vol. 22, nos. 1/2, pp. 3-29.

OUMERACI, H.; KORTENHAUS, A. (1994): Analysis of dynamic response of caisson breakwaters. *Coastal Engineering, Special Issue on 'Vertical Breakwaters'*, Eds.: Oumeraci, H. et al., Amsterdam, The Netherlands: Elsevier Science Publishers B.V., vol. 22, nos. 1/2, pp. 159-183.

OUMERACI, H.; KORTENHAUS, A.; KLAMMER, P. (1995): Displacement of caisson breakwaters induced by breaking wave impacts. *Proceedings of the International Conference of the Institution of Civil Engineers - Advances in coastal structures and breakwaters*, Clifford, J.E., London, U.K.: Thomas Telford Ltd., Paper 3, pp. 50-63.

TANIMOTO, K.; TAKAHASHI, S. (1994): Japanese experience on composite breakwaters. *Proceedings International Workshop Wave Barriers in Deepwaters*, PHRI, Yokosuka, Japan, pp. 1-24.

VOORTMAN, H.G.; KUIJPER, H.K.T.; VRIJLING, J.K. (1998): Economic optimal design of vertical breakwaters. *Proceedings International Conference Coastal Engineering (ICCE)*, ASCE, Copenhagen, Denmark, no. 26, 2 pp.

VRIJLING, J.K.; VOORTMAN, H.G. (1998): PROVERBS flyer, Task 4 insert sheet. *Flyer, MAST III, PROVERBS-Project: Probabilistic Design Tools for Vertical Breakwaters*, Delft, The Netherlands, 2 pp.

TITLE: Scour Around Coastal Structures (project **SCARCOST**)

CONTRACT NO: MAST3-CT97-0097

COORDINATOR:

B. Mutlu Sumer
Technical University of Denmark,
Department of Hydrodynamics and Water Resources (**ISVA**),
Building 115
DK-2800, Lyngby, Denmark
Tel: +45 45 25 14 23, Fax: +45 45 93 28 60 and +45 45 93 63 28 (loc.)
e-mail: sumer@isva.dtu.dk

PARTNERS AND CONTACT PERSONS:

Richard Whitehouse
HR Wallingford (**HR**)
Howbery Park
Wallingford, Oxon OX10 8BA UK
Tel (direct): + 44 1491 822434 (switchboard) 835381, Fax (local): + 44 1491 825743
email: rjsw@hrwallingford.co.uk

F. Jorge Seabra-Santos
IMAR, Department of Civil Engineering
University of Coimbra, (**IMAR**)
3049 Coimbra Codex, Portugal
Tel: +351 39 410678, Fax: + 351 39 22833 and +351 39 410678 (local)
e-mail: fseabra@gemini.ci.uc.pt

Alf Tørum
SINTEF Civil and Environmental Engrg.,
Department of Coastal and Ocean Engrg. (**SINTEF**)
N-7034 Trondheim, Norway
Tel: +47 73 59 23 68, Fax : +47 73 59 23 76
e-mail: Alf.Torum@civil.sintef.no

Agustin Sanchez-Arcilla / Francisco Rivero
Laboratori d'Enginyeria Maritima
Universitat Politecnica de Catalunya (**CIIRC-UPC**)
Gran Capita, s/n (modul D-1)
08034 Barcelona, Spain
Tel : + 34 3 280 64 00 (A. Sanchez-Arcilla) and +34 3 401 73 94 (F. Rivero), Fax : +34 3 401 73 57
e-mail: rivero@etseccpb.upc.es

Mathieu Mory
Laboratoire des Ecoulements Geophysiques et Industriels (**LEGI**)
BP 53
38041 Grenoble Cédex 9, France
Tel: +33 4 76 82 50 60, Fax: +33 4 76 82 50 01
e-mail: mory@hmg.inpg.fr

Gilliane Sills
Department of Engineering Science
University of Oxford (**UOX**)
Parks Road
Oxford OX1 3PJ, UK
Tel: + 44-1865-273164, Fax: + 44-1865-273907
e-mail: Gilliane.Sills@eng.ox.ac.uk

Neil MacDonald
Department of Civil Engineering
University of Liverpool (**UL**)
PO Box 147
Liverpool L69 3BX, UK
Tel: +44 151 794 5242, Fax: +44 151 794 5218
e-mail: n.j.macdonald@liverpool.ac.uk

Øivind Arntsen
NTNU, Coastal and Ocean Engrg. (**NTNU**)
Rich., Birkelands vei 1a
7034 Trondheim, Norway
Tel: + 47 73 59 47 00, Fax: + 47 73 59 45 35
e-mail: Oivind.Arntsen@bygg.ntnu.no

SCOUR AROUND COASTAL STRUCTURES (SCARCOST)

B. M. SUMER
Technical University of Denmark,
Department of Hydrodynamics
and Water Resources (ISVA),
DK-2800, Lyngby, Denmark

R. WHITEHOUSE
HR Wallingford
Howbery Park
Wallingford,
Oxon OX10 8BA UK

A. TØRUM
SINTEF Civil and Environmental
Engrg., Department of Coastal
and Ocean Engrg.
N-7034 Trondheim, Norway

SUMMARY

This MAST project started on 1 September 1997, and runs for 3 years. The main aims of the project are described, and the work plan is summarized. No results are yet available from the project.

1. INTRODUCTION

When a structure is placed in the coastal environment, it will change the flow pattern in several respects, some examples of which are given below:

- Reflection of waves, leading to increased wave action in front of the structure.
- Diffraction of waves around the structure.
- Formation of horseshoe vortices at the heads and vortex shedding behind the structure.
- Contraction of currents (like a tidal current in front of a breakwater).
- Breaking of waves at the sloping walls of the structure.

These changes usually lead to the scouring of sediment from around the structures. The scouring of sediment poses a threat to the stability of the structure.

The objectives of the project are

- To study the potential risk for scour in the vicinity of coastal structures; and
- To prepare and disseminate practical guidelines, to be developed from the research programme and also taking into account all "state-of-the-art" knowledge.

To achieve these objectives, the study will concentrate on obtaining a profound understanding of the physical processes involved. This will include 1) the flow processes in the overlying water, and 2) the behaviour of the sediment bed.

Laboratory measurements of flow, sediment and scour processes will be carried out, using sophisticated measurement and flow-visualization techniques, on a wide variety of coastal structures such as detached breakwaters, submerged breakwaters, individual piles, vertical large cylinders (such as platform legs and bridge piers) and pile groups. The objectives of these experiments are to unveil the mechanisms responsible for scour. These experiments will be

complemented by field experiments, and limited mathematical modelling efforts on issues related to wave-induced excess pore pressure in the soil in conjunction with the processes of scour and sinking of armour blocks.

The structures specifically covered in this project and the approach taken is indicated in Table 1. The new findings will be collated with existing available information when formulating the guidelines.

Table 1. Summary of the structures and the contributing partners in the project.

Structure	Participants								
	ISVA	HR	SINTEF	LEGI	UL*	IMAR	CIIRC-UPC	UOX	NTNU*
Detached breakwater		L						L	
Detached submerged breakwater							L,T		
Vertical pile	L					L			
Large vertical cylinder	L								
Pile groups	L			L		L			
Breakwater element, small-height vertical cylinder			L,T,F					F	
Extent of scour protection		L		L		L	L,T		
Filters			T					T	
Penetration and stability of armour blocks, and protection edges	L,T							F	

Legend: * UL and NTNU studying the processes, not structure specific.
L: Laboratory study, T: Theoretical/numerical study, F: Field study

The project is organized in two main tasks: Task 1. Flow and scour processes, and Task 2. Sediment behaviour close to the structure and scour.

2. FLOW AND SCOUR PROCESSES (TASK 1)

The work in this part of the project (Task 1) concentrates on the interaction between the water flow and the sediment at the toe of the structure. This task is led by HR. The work is sub-divided into four topics each of which is intended to provide new understanding or insight for the way waves and currents scour sediment from around structures. The results obtained from these investigations will contribute knowledge to an improved understanding of the physical processes of scour, and the counter-measures that can be taken to reduce scour. Wherever it is practical to do so, measurements of the pressure field at the seabed will be made to enable the transfer of results to Task 2 (discussed below). The data will be input to the project database, and the key results will provide input to the design guidelines. The four topics are as follows:

Topic 1.1. Flow and scour processes around vertical cylinders
Topic 1.2. Scour around detached breakwaters
Topic 1.3. Scour around submerged breakwaters, and
Topic 1.4. The effect of turbulence on sediment transport/scour

TOPIC 1.1. FLOW AND SCOUR PROCESSES AROUND VERTICAL CYLINDERS

The participants of this topic are ISVA, IMAR and LEGI. Each will study a different aspect of this important canonical case. The planned work covers both single slender circular piles, large diameter cylinders, and pile groups. Tests will include wave-only conditions, waves and currents and some tests will be carried out with breaking waves.

ISVA will perform wave-basin experiments to investigate the flow and scour processes around a large vertical cylinder exposed to wave action. The cylinder is so large that the flow is in the unseparated flow regime. Hence, the vortex mechanisms (the key elements for scour in the case of slender piles, Sumer, Fredsøe & Christiansen, 1992) do not exist. The objective here is to establish the link between the flow produced by waves (i.e., the steady streaming) and the associated scour development. Two kinds of experiments will be performed: rigid bed experiments (particle tracking and velocity measurements), and mobile bed experiments (measuring the bed topography as the bed develops). Complementary experiments around single slender piles will be utilised to examine possible influence of scale effects.

IMAR will perform a flume investigation of the wave-related scour around a single cylinder. The main issues to be investigated are (1) the flow modifications induced by the obstacle (reflection, diffraction, contraction), (2) the streaming effects induced by the non-uniformity in the wave boundary layer (linear and non-linear waves) and (3) the role of the horseshoe vortex and vortex shedding. The influence of the Ursell number on the hydrodynamics will be investigated in tests with values of the Keulegan-Carpenter KC = O(3) and KC = O(10) giving contrasting conditions of streaming versus vortex regimes, akin to the cases of a large cylinder and a single pile, respectively.

Tests by IMAR will also examine the flow processes for a pile group under wave-only and combined wave-current forcing. The ratio of wave to current strength will influence the way in which the flow interacts with the pile group. For these tests the ratio of steady current speed to

wave orbital velocity amplitude will be less than unity. Complementary investigations of the scour development at the pile group and counter-measures for scour will be investigated with LEGI during the wave basin experiments (see below). As many structures are built in the surf zone, the influence of breaking waves on scour development will also be examined through tests by LEGI and IMAR.

In complementary measurements ISVA will do experiments with 2 and 3 pile arrangements, as an extension to their earlier published work on single piles. The influence of the gap size G between piles, and the angle of attack of the waves on the flow processes and scour development will be examined. The experiments will concentrate on observing the physical processes in regular waves using the bed shear stress measurements from hot-film probes in a small-scale facility, and the scour processes using a mini underwater video camera in a medium-scale facility.

Finally, LEGI, in cooperation with ISVA and IMAR, will make scour measurements in a 3D wave basin at Laboratoire d'Hydraulique de France with pile-groups of various configurations with a range of gap settings. Around 10 or 20 piles will be placed in a sand-pit with pile-gap to pile diameter ratios G/D 0(1) and 0(2), some tests at a single pile will provide comparative results. Tests will be done for both regular and irregular waves without a current, with KC number larger than 6 to ensure vortex action. The counter-measures against scour will also be tested. Complementary data on the flow field and turbulence levels over an artificially stabilised scour hole will be obtained with a Laser Doppler Velocimeter (LDV).

TOPIC 1.2. SCOUR AROUND DETACHED BREAKWATERS

The scour around surface-piercing breakwaters will be examined by HR. This series of experiments is intended to examine with a mobile bed model the scour development around the periphery of the breakwater due to the combined action of waves and currents. The equilibrium scour depth and time development of scour will be examined as well as scour protection measures. Previously published experimental studies have largely concentrated on the 2D scour in front of seawalls (e.g. Powell & Carpenter, 1997) and the 3D scour at the breakwater tip (Sumer & Fredsøe (1997), and Fredsøe & Sumer (1997)). One of the aims of this experiment is to examine the transition from a 2D to 3D scour pattern, and another will be to consider the influence of breaking waves (surf zone). The experiment will be designed, based upon previous experience at HR and a review of published work, as well as knowledge gained from other partners during the first year of the project. The experiments will be conducted in the UK Coastal Research Facility - a large 3D coastal basin at Wallingford.

The waves and currents will be monitored with 3D acoustic current meters and the development of the scour profile will be measured. During tests UOX will make measurements of the pressure field on the seabed and in the sediment, thus formalising the link between Task 1 and Task 2 of the project.

TOPIC 1.3. SCOUR AROUND SUBMERGED BREAKWATERS

CIIRC-UPC will concentrate on large-scale 2D wave flume experiments to examine the scour

development at the toe of submerged breakwaters under different wave conditions and varying freeboard. Both the local hydrodynamics and pore pressures in the bed will be measured as well as the evolution of the bed (sand). As part of the experiment a Particle Image Velocimetry (PIV) system will be used to map the flow field in part of the water column. The counter-measures for scour in front of the breakwater will also be studied. CIIRC/UPC will contribute the results of some detailed hydrodynamic experiments on submerged breakwaters (national and EC - HCM funding).

In parallel, CIIRC-UPC will undertake mathematical modelling of the wave hydrodynamics and morphodynamics around the submerged breakwater. The model will use a phase-averaged linear wave transformation model (including interaction with reflected waves), a non-linear mild slope model, a 2DV model (using sigma co-ordinates), a turbulence model (k-epsilon) and a bottom evolution module. The differences between the flow patterns generated in the 2D flume and the 3D prototype case will be addressed.

TOPIC 1.4. THE EFFECT OF TURBULENCE ON SEDIMENT TRANSPORT

The participating institutes in this topic are ISVA, HR and UL.

In the vicinity of structures the turbulence levels are high and the shear stress vector is highly variable in time. Recent research has shown that there are some shortcomings with using traditional bed shear-stress driven sediment transport formulae (e.g. Meyer-Peter and Müller) when predicting sediment transport in these highly turbulent flows. One of the topics being investigated by HR and UL within SCARCOST is the effect of turbulence on sediment transport, with the purpose of refining existing sediment transport models. HR will investigate a number of possibilities for improvements to be made over the existing approaches, including a method for entraining the sediment into the flow based upon turbulent kinetic energy instead of shear stress. In addition the research will consider whether the suspended load should be prescribed in terms of a near-bed reference concentration or a sediment pick-up rate. The aim is to devise an approach that is applicable for inclusion in numerical models. The methods devised will be compared with data collected by ISVA (see below).

The UL approach will be to take the commercially available CFD code (FLUENT) which will be modified to include waves. A 1DV model will be compared with the FLUENT results and will be used to generate suspended sediment profiles for varying levels of turbulence. An existing sediment transport model (O'Connor and Nicholson, 1992) will be modified to be able to account for the turbulence levels in the flow. This will be incorporated in an existing 2DH morphodynamic model which can be applied to predict the bed evolution around (e.g.) a detached breakwater thus allowing a comparison with the results from Topic 1.2.

The experimental work by ISVA will provide underpinning or validation data for the theoretical work by HR/UL. A steady current flume channel will be used for (1) measurements of the bed shear stress (hot-film probe) and flow/turbulence levels over a rigid bed and (2) measurements of the sediment transport rate over a mobile bed (sediment trap). The experiments will be carried out with the time-averaged bed shear stress just in excess of the value for initiation of sediment transport (fine sand) to maintain a flat bed during the course of the experiments.

Additional turbulence will be generated by a pipe placed at a distance from the bed across the flume width, or by the introduction of a series of surface-piercing grids. The time-averaged shear stress will be matched for the 'normal' and 'turbulent' cases. The measured sediment transport rates will be compared for 'normal' boundary layer flow and flow with 'enhanced' turbulence levels.

3. SEDIMENT BEHAVIOUR CLOSE TO THE STRUCTURE AND SCOUR (TASK 2)

Clearly, the processes associated with the sediment are also important in scour. This is directly related to the wave-generated pore pressure in the sediment bed. The work in this part of the project (Task 2) concentrates on these processes. This task is led by SINTEF. The work is sub-divided into six topics:

Topic 2.1. Wave-generated pore pressure and scour around breakwater elements
Topic 2.2. Non-linear modelling of wave-induced pore pressures
Topic 2.3 Wave bottom pressures and wave kinematics in the surf zone
Topic 2.4. Sediment transport/scour by accounting for the effect of momentary liquefaction
Topic 2.5. Penetration of blocks into the bed in the absence of filters
Topic 2.6. Cyclic stiffness of loose sand

TOPIC 2.1. WAVE-GENERATED PORE PRESSURE AND SCOUR AROUND BREAKWATER ELEMENTS

UOX will carry out field measurements on wave generated pore pressures in a sand seabed.

UOX has already designed and built an instrument package with four pressure transducers mounted on a vertical pipe with a distance of 20 mm apart in vertical direction. A similar test set-up will be used for the planned SCARCOST field measurements of the pore pressures in the upper layers of a seabed. The instruments will be attached to a tripod/quadruped. There will also be instrumentation to monitor the seabed elevation during the experiment.

Since the vertical gradients of the pore pressures at the seabed surface is most important from the scour point of view, the pressure transducers will be spaced over 0 to 0.6 m bed depth.

The breakwater element of a rubble mound stone will be simulated with a truncated cylinder placed on the seabed with the axis vertical. Wave induced pressures will be measured on the cylinder as well as in the seabed. There will also be an altimeter and an inclinometer to monitor the scour at the cylinder as well as the tilt of the cylinder.

UOX has planned to make the initial field measurements on the English/Welsh coastline. The measurements will be carried out on a sand bed with the cylinder on the seabed with some skirts as a scour protection. It will also be considered to include a field measurement campaign with the cylinder buried.

TOPIC 2.2. NON-LINEAR MODELLING OF WAVE INDUCED PORE PRESSURES

The non-linear modelling of wave induced pore pressures will include:

- Plane strain modelling with non-linear soil
- 3D case with linear soil

using

- finite element methods
- varying soil properties
- surf zone waves

The modelling of the UOX field tests (see Topic 2.1) will be carried out to get an improved understanding of sand behaviour through numerical modelling. The model can then be used to analyse the more extreme cases that it is hoped will occur during the UOX field measurements.

TOPIC 2.3. WAVE BOTTOM PRESSURES AND WAVE KINEMATICS IN THE SURF ZONE

The planned work will include experimental work on wave-induced bottom pressures and wave kinematics in the surf zone to provide information on more extreme cases and also on a larger variety of cases with respect to what is expected from the UOX field measurement program.

The planned work contemplates to implement a viscous-flow model for the breaker transformation and to validate it with respect to the wave kinematics and to the wave-induced pressures measured both in laboratory-scale experiments (NTNU, SINTEF), and in full-scale experiments (UOX).

Two computer codes will be considered: RIPPLE, a model for transient, two-dimensional flows of incompressible fluids with surface tension on free surfaces of general shape. RIPPLE is developed by the Fluid Dynamics Group T-3 Los Alamos National Laboratory. The RIPPLE code is available at NTNU, and will be considered for this project. An alternative approach is to use the FIRAM code. FIRAM, developed at NTNU, is a numerical model for computation of incompressible turbulent flow, based on finite element formulation and a (k,ϵ,L) turbulence model. Today FIRAM does not include a general free surface. One approach will be to try the Arbitrary Lagrangian Formulation for an efficient free surface modelling.

TOPIC 2.4. SEDIMENT TRANSPORT/SCOUR BY ACCOUNTING FOR THE EFFECT OF MOMENTARY LIQUEFACTION

The objective of this subtask is to modify an existing sediment transport model to account for the effects of wave-induced pore pressures.

The Terzaghi equation will be used to determine the pore pressures in the seabed. This equation

(model) will be validated against the available data.

The next step will be to modify an existing sheet flow model to account for the additional forces due to wave induced pore pressures and to validate the model against available data sets.

This modified sheet flow model is then used to generate data sets of suspended sediment concentration and bed load. These data sets will be used as a basis for modifying the O'Connor and Nicholson (1992) sediment transport model to account for pore pressures. Finally the modified model will be validated against available data sets.

TOPIC 2.5. PENETRATION OF BLOCKS INTO THE BED IN THE ABSENCE OF FILTERS

The objective of this subtask is to study on a laboratory model scale the penetration of marine objects such as armour blocks in the bed due to the buildup of pore pressures by waves in a silt bed. The experiments will be carried out in a wave flume, 26.5 m long, 0.6 m wide and 0.8 m deep. The silt will be placed in a box which is part of the flume bed. The model objects (a circular pipe (2D), a sphere and a cube) will be mounted on a frame which is free to move in the vertical direction. The model objects will initially be on the bed or buried in the silt.

During the experiments the waves and the pore water pressures at several points across the soil depth with and without the object will be measured. The vertical displacement of the object will also be measured.

The experimental results will give information on the following items:

- the penetration distance
- the influence of the initial position of the object on the penetration
- the influence of the specific gravity of the object on the penetration
- the influence of the soil layer thickness on the penetration
- the influence of the wave height and -period on the penetration
- the time scale of the penetration process
- comparison with the UOX field experiment results.

TOPIC 2.6. CYCLIC STIFFNESS OF LOOSE SAND

A limited set of laboratory experiments will be carried out on samples of sand (40 -45 % porosity) built into a conventional triaxial cell for soil testing. The samples will be tested in the low stress region (cell pressures 10 - 30 kPa). The type of experiments will be stress controlled cyclic triaxial tests on cylindrical samples of disturbed sand. The built-in porosity shall be known, and corresponds to loose conditions. The degree of saturation of the sample is a key parameter to the understanding of the cyclic stiffness and should be controlled in the tests. The degree of saturation will also be varied in the test program to elucidate the effect of this parameter on the cyclic stiffness of the soil.

Cyclic deviatoric stresses with known and constant amplitude over a number of cycles shall be

applied in the tests. The stress amplitude will correspond to those produced in situ stress by wave patterns, and can be varied from test to test, and also during a test (several blocks, each with constant stress amplitude).

In the cyclic tests, axial (and radial) deformations, pore pressure (undrained cyclic tests) and water expulsion from the sample during testing (drained tests) will be measured.

The compressibility of the pore water is controlled by the degree of saturation. To investigate the role of pore water compressibility, the degree of saturation will be controlled and will be in the range of 90 %-99.5 %. The saturation degree will be determined from measurements of test sample total volume, its sand volume and the volume of water added. The accuracy of this method is judged to be (0.5 % of the saturation degree.

REFERENCES

Fredsøe, J & Sumer, B. M. (1997): "Scour at the round head of a rubble-mound breakwater". Coastal Engineering, vol. 29, pp. 231-262.

O'Connor B. A. & Nicholson J. (1992). "An estuarine and coastal sand transport model. In: Coastal and estuarine studies". Dynamics and exchanges in estuaries and the coastal zone. Ed. D. Prandle, Am. Geophys. Union, pp. 507-526.

Powell K. A. & Carpenter K. (1997). "Toe scour at vertical seawalls. Mechanisms and prediction methods". HR Wallingford Report SR 506, Wallingford, UK.

Sumer, B.M., Fredsøe, J. & Christiansen, N. (1992). "Scour around a vertical pile in waves". Proc. ASCE Journal of Waterway, Port, Coastal and Ocean Engineering, Vol. 117, No. 1, pp. 15-31, 1992.

Sumer, B.M. & Fredsøe, J. (1997): "Scour at the head of a vertical-wall breakwater". Coastal Engineering, vol. 29, pp.201-230.

INTERNET ADDRESS OF THE PROJECT

http://www.isva.dtu.dk/Scarcost/scarcost.html

Title: **Validation of Low Level Ice Forces on Coastal Structures LOLEIF**

Contract No. **MAST III - CT97-0098**

Partcipants:

Technical Research Center of Finland
Dr.-Tech. T Kärnä **(VTT)**
Kemistintie 3
SF-02044 Espoo
FINLAND
Tel. +358-9-4566945
Fax +358-9-4567003
tuomo.karna@vtt.fi

Cambridge University Engineering Department
Prof. A.C. Palmer **(CU)**
Trumpington Street
GB-Cambridge CB2 1PZ
GREAT BRITAIN
Tel. +44-1223-332718
Fax +44-1223-332662
acp24@eng.cam.ac.uk

Helsinki University of Technology
Prof. M. Määttänen **(HUT)**
Otakaari 1 M
SF-02150 Espoo
FINLAND
Tel. +358-9-4513440
Fax +358-9-4513443
mauri.maattanen@hut.fi

Luleå University of Technology
Prof. L. Fransson **(LUT)**
S-97187 Luleå
SWEDEN
Tel. +46-9-2091102
Fax +46-9-2091913
frans@ce.luth.se

University of Trondheim
The Norwegian Institute of Technology
Prof. S. Løset **(NTNU)**
Høgskderingen 1
N-7034 Trondheim
NORWAY
Tel. +47-7-3394-700
Fax +47-7-3594-535
sveinung.loset@ktek.unit.no

Laboratoire de Glaciologie
et Geophysique de l'Environment
Dr. P. Duval **(LGGE)**
BP 96
F-38402 Saint-Martin-d''Hères-Cedex
FRANCE
Tel. +33-476-824200
Fax +33-476-824201
jacques@alaska.grenet.fr

Hamburgische Schiffbau-
Versuchsanstalt GmbH
Dr.-Ing. J. Schwarz **(HSVA)**
Bramfelder Straße 164
D-22305 Hamburg
GERMANY
Tel. +49-40-69203-428
Fax +49-40-69203-345
schwarz@hsva.de

Validation of Low Level Ice Forces on Coastal Structures

LOLEIF

by Dr.-Ing. Joachim Schwarz
Hamburgische Schiffbau-Versuchsanstalt GmbH
Bramfelder Straße 164
D-22305 Hamburg

Summary

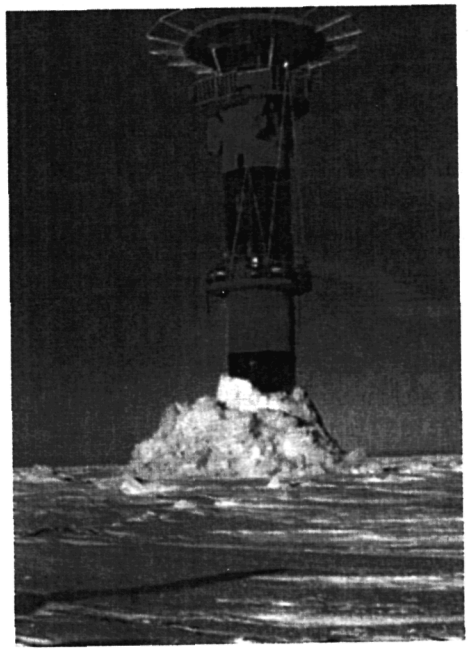
The prediction of ice forces on vertical coastal and offshore structures has been subject to research for more than 25 years. The forces resulting by the various methods scatter however by a factor up to 15.

Low ice forces have been predicted by small scale tests and have been verified by some full scale measurements. Nevertheless, they have not gained acceptance from industry and governmental authorities, because the majority of researchers have predicted much higher ice forces.

Recent findings in Canada by full scale tests indicate, however, that the ice forces on vertical structures are indeed 10 times smaller than they have been used in the design of structures in recent years. This means, that marine structures like bridge piers, coastal protection and offshore structures are most likely significantly overdesigned against ice forces.

In order to save multimillion Dollars in future marine constructions researchers from Great Britain, France, Sweden, Norway, Finland and Germany in cooperation with scientists from USA, Canada and Russia are carrying out a research project with the objective to validate low ice forces on vertical marine structures by full scale measurements and numerical modelling. The paper describes the research program, and its present status.

The project is sponsored by the European Union (MAST III-Programme) and by multinational oil companies.



Introduction

Coastal structures in northern and central European waters as well as offshore structures for exploration and production of hydrocarbons from the European Arctic have to be designed to withstand the forces applied by moving ice. Ice forces govern the design in most cases where ice is present. The largest ice forces are caused by pressure ridges and by level and rafted ice on vertical structures.

About these ice forces there exist an extraordinary uncertainty between the predictions of scientists around the world; the predictions scatter for the same conditions by a factor of 10 to 15.

Attempts for consensus on ice forces by Shkhinek at al. (1994) did show the wide scatter but can not recommend design ice loads on vertical structures.

Recent full scale measurements by Fritzpatrick (1994), Kennedy (1996) and by Wessels and Jochmann (1991) indicate that the ice forces on vertical structures are much smaller than presently being used for the design of structures.This situation - the wide scatter of ice force predictions and the latest full scale measurements - has stipulated a group of scientists from six European countries to carry out a research project on the „Validation of Lower Level Ice Forces on Coastal Structures". A proposal for funding was submitted to the European Commisson (MAST-Programme). After successfull evaluation of the proposal the contract for funding was signed in August 1997 by the Commission and the LOLEIF-consortium.

Scope of Work

The overall objective of the project is to prove the validity of lower ice forces, and to have the results accepted by authorities and users, and ultimately incorporated into an EUROCODE. This will only be successful if the research is technically and scientifically of highest standard without leaving any doubts in the results.

In order to achieve this goal, the following research program will be executed:

- Evaluation of existing ice force prediction methods, including theoretical ice force models and identification of possible reasons for the wide scatter of predicted ice forces

- Full scale measurements of forces of level ice and ridges at the lighthouse KEMI 1 (Gulf of Bothnia) by panels of different pressure areas. Accurate and complete characterization of the ice features (level ice and ridges) which are interacting with the lighthouse. This includes the fracture toughness of level ice, the strength of the consolidated and unconsolidated part of ridges and the documentation of the ice failure process.

- Development of new theoretical ice force models on the basis of the results of the previous tasks. Particular emphasis will be given to fracture mechanics and fracture characterization of the complex systems generated by the repeated

fracture, and to constitutive modelling of ice rubble in pressure ridges and its progressive failure modes.

- Recommendations of ice forces on vertical structures from level ice and ridges in consultation with the classification societies.

The features that distinguish the present research project from previous work are:

- More sophisticated determination of the level ice properties by laboratory tests on compressive strength, tensile strength, E-modulus and fracture toughness, the later one being of great importance to the formulation of theoretical prediction models. In-situ determination of the compressive strength of the consolidated layer of pressure ridges as well as the shear strength of unconsolidated ridge material (broken ice).

- Close-up measurement of ice thickness (level ice as well as ridges) in front of the lighthouse.

- Determination of the ice failure process when interacting with the lighthouse.

Determination of the effect of non-simultaneous failure of the ice when interacting with the lighthouse by using 10 force measuring panels, instead of 3 to 5 as has been used in previous full scale measurements.

The achievements of the research project are expected to result in

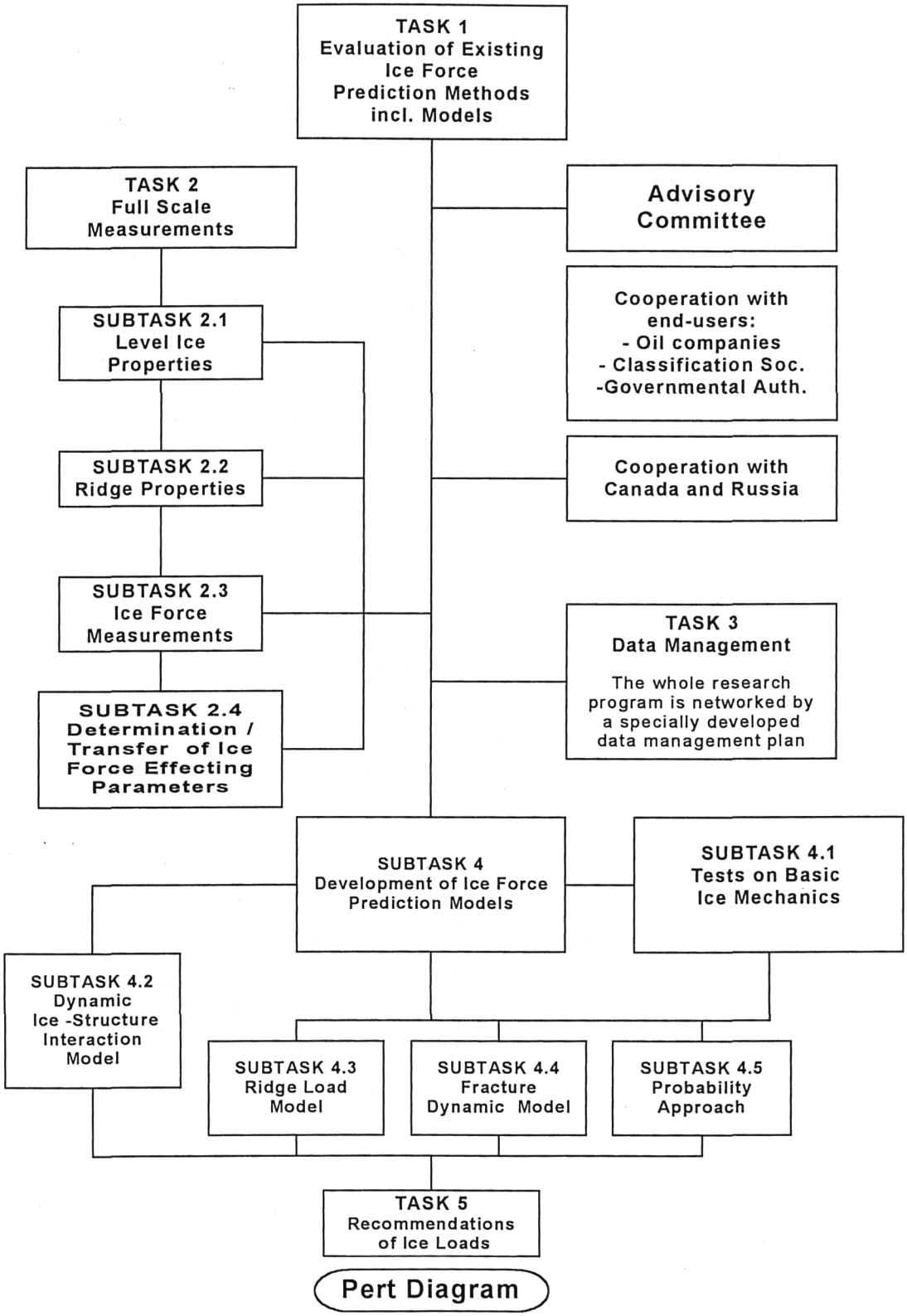
- a fundamental insight into the problem of ice-structure interaction,
- ice force prediction models based on most extensive field and laboratory studies,
- the elucidation of the controversy on ice forces,
- validation of low ice force levels for the case of ice breaking against vertical structures.

The results will

- provide governmental authorities and classification societies with substantial information on ice forces on coastal, offshore and structures on inland waters (estuaries, rivers, lakes),
- provide the basis for the development of EUROCODES for ice forces,
- drastically reduce the costs for structures which are to be designed to withstand ice loads,
- open new possibilities for technical and scientific developments.

TASK STRUCTURE OF THE PROJECT

Task	Sub-Task	Title	Taskleader	Partner
1		**EVALUATION OF EXISTING ICE FORCE PREDICTION METHODS**	NTNU	CU
2		**FULL SCALE TESTS**		
	2.1	**Level Ice Properties**	LUT	HSVA, LGGE
	2.2	**Ridge Mechanical Properties**	HUT	VTT, LUT, NTNU
	2.3	**Ice Force Measurements at Lighthouse**	HSVA	LUT
	2.4	**Determination and Transfer of Ice Force Affecting Parameters**	HSVA	HUT, LUT
3		**DATA MANAGEMENT**	HSVA	Sub-contractor HYDROMOD
4		**DEVELOPMENT OF ICE FORCE PREDICTION MODELS**	VTT	CU, HUT, NTNU, LGGE
	4.1	**Investigations on Special Ice Mechanics Problems Related to Numerical Modelling**	LGGE	VTT
	4.2	**Dynamic Ice-Structure Interaction Model**	VTT	HUT
	4.3	**Ridge Load Model**	HUT	VTT, NTNU
	4.4	**Fracture Dynamics Model**	CU	LGGE
	4.5	**Probability Approach**	NTNU	VTT, CU
5		**RECOMMENDATION OF ICE FORCES ON COASTAL STRUCTURES**	HSVA	VTT, CU, HUT, LUT, NTNU, LGGE
6		**PROJECT MANAGEMENT**	HSVA	



Pert Diagram

C:\EUVORHAB\MAST\LOLEIF2\PERT2.CFL

Short Description of Individual Tasks and Present Status

Task 1: Evaluation of Existing Ice Force Prediction Methods (NTNU)

Objectives:
The purpose of this task is to review the existing methods and models for ice force prediction and to identify possible reasons for the wide scatter of predicted ice forces. This will provide the basis for the detailed approaches taken in subsequent tasks of the project.

Task Description:
The interaction of ice with coastal structures is a complex process involving several possible modes of failure and deformation behaviour of ice, and is influenced by numerous factors related to the structure, to the ice and the physical environment. A considerable amount of work has been done to measure and predict the forces which ice features can exert on a structure. There have been several approaches to this problem including analytical and numerical predictions, and laboratory and field studies. Both deterministic and probabilistic approaches have been used and they have been integrated together in certain cases.

It is the purpose of this task to review critically both pioneer and recent approaches to the estimation of global forces on fixed structures during ice-structure interaction. The task will consider ice-structure interactions such as limit momentum, limit force, limit stress and limit fracture as limiting global ice load scenarios. The task will investigate the reasons for the large scatter of the prediction methods.

Present Status:
The evaluation is in progress and will continue with the assistance of Canadian experts, who have been involved in full scale tests on the exploration platform MOLIKPAQ.

Task 2: Full Scale Tests (HSVA)

Sub-Task 2.1: Level Ice Properties (LUT)

Objectives:
Establish a database of accurate ice properties which correlates in time and space with measured full scale ice loads. The result should be used in numerical modelling of ice/structure interactions.

Task Description:
The brackish sea ice found in the Gulf of Bothnia is typically thick level ice and wind generated pressure ridges. The origin of the level ice can be pack ice, crushed ice, snow or frazil frozen together under various thermal and dynamic conditions. Most of the ice properties that are important to ice force calculations can thus be coupled to the weather situation during ice formation. Statistics on wind, precipitation and temperature are also needed to estimate the size and resistance of the total ice cover. Ice thickness and mechanical properties over a control area will be directly measured in connection with extreme ice load events at the lighthouse. The parameters to be obtained are:

1. Ice morphology (ice type, thickness, cracks, floe size, inhomogeneity)
2. Physical ice properties (internal structure, brine, air bubbles, sediment, pollution)
3. Mechanical properties (ultimate strength, elastic modulus, viscosity)
4. Fracture mechanical parameters (fracture energy, propagation rate)

Status:
Preliminary tests on fracture toughness are being carried out in order to define the correct test method which provides scale independent results.

Sub-Task 2.2: Ridge Mechanical Properties (HUT)

Objectives:
The ridge mechanical properties will be determined by on-site measurements of internal shear stress of unconsolidated ridge material

- ice block size
- thickness of consolidated ice layer
- bending, compressive and shearing strength of consolidated layer

If additional industrial money is available new scanning radar tomography will be tested to find out the internal structure of ridges, and new full scale ridge loading set ups will be realized in order to measure ridge full scale strength data.

Task Description:
The present ridge keel load design is based on soil mechanics limit load analysis. It assumes simple simultaneous failure planes inside the keel and balances internal friction and cohesion shear forces with the total ridge load. In reality failure will be progressive along 3-dimensional failure surfaces which will result in smaller loads. The ice rubble friction and cohesion is known only through scale model tests. In other instances ice properties exhibit strong size effect.

Another feature in the pressure ridge is the consolidated layer. After the ridge has been formed loose ice floes start to adfreeze to each others at layers above and close to the waterline. Depending on the ambient temperatures also water filled cavities freeze. Thus, as time passes, an adfrozen consolidated layer forms. Its thickness depends on the cumulative freezing index..

Status:
Preliminary full scale tests are being carried out for ridge mechanical properties in the Gulf of Bothnia in order to check the test set-up and make sure all equipment is ready for the main test phase (winter 1998/1999).

Sub-Task 2.3: Ice Force Measurements at KEMI-Lighthouse (HSVA)

Objectives:
In order to meet the main objective, i.e. the validation of low ice forces, full scale measurements of ice forces on the KEMI-lighthouse will be carried out during two winter seasons.

Task Description:
The KEMI-lighthouse in the north-east corner of the Gulf of Bothnia has been chosen for measuring the forces of the drifting ice, i.e. level ice, pressure ridges and rubble ice.

During summer 1998 a steel shield will be mounted to the 5.8 m diameter vertical shaft of the lighthouse, to which 10 ice force panels will be mounted. Eight panels of them will be mounted in the upper level, side by side half around the south-western surface of the lighthouse, from where the ice movement predominantly does occur.

The panels, each having a load surface of 200 cm (length) by 80 cm (width) are working according to the electrical strain gauge load cell principle (s. Fig. 2).
In addition to the ice force measurements, information will be obtained on

- ice drift velocity
- ice thickness
- ridge ice profile
- overall ice situation

The winter season 1997/1998 will be used to install one pilot ice force measuring panel at the lighthouse in order to secure its and the entire measuring systems quality and realibility. The main ice force measurement campagne will be in the winters 1999 and 2000.

Status:
Most of the equipment for measuring the ice forces has been purchased. One panel has been built and the data aquisition system compiled (incl. video transmission between lighthouse and the partners) which is beeing tested for its functionallity and reliability. Only after this information is satisfactory the other 8 panels will be manufactured and installed in summer 1998 at the lighthouse.

Sub-Task 2.4: Determination and Transfer of Ice Force Affecting Parameters (HSVA)

Objectives:
Determination of parameters influencing the ice structure interaction such ice drift velocity and direction, ice thickness, surface and subsurface geometry of ice formations, meteorological and hydrological data, and overall ice scenario.

Task Description:
In order to evaluate the measured ice forces correctly, it is necessary to determine those parameters, which are directly influencing the total load on a marine structure. To fulfill this requirements extensive field measurements of the influencing parameters will be carried out simultaneously with the collection of ice force data.

Status:
Necessary instrumentation for

- determining ice thicknesses
- profiling subsurface geometry of ice ridges
- ice drift velocity

have been purchased and pretested in the laboratory.

Task 3: Data Management (HSVA, sub-contractored to HYDROMOD)

Objectives:
The general purpose of the project-accompanying data and information management comprises comprehensive and competent services to ensure focal collection, distribution, dissemination, publication, archiving, and final banking of data, results, miscellaneous information, and documents acquired and produced within the project by the different research institutions and scientific teams.

Task Description:
The data management system comprises the following work packages:

- Data management set-up
- Accompanying data management
- Data merging and archieving with data base on CD-ROM.

Status:
Basic understanding has been achieved between partners concerning data, information, document exchange. An inventory has been submitted to the project teams aiming on the development of a consistent project data and information catalogue. Agreement has not yet been achieved on what is mandantory and what is just „nice to have". It was concluded that the Data Management should be not exessively sophisticated and user friendly!

Task 4: Development of Ice Force Prediction Models (VTT)

Introduction

While the aim of the field test program of Task 2 is

- to measure the forces of drifting ice (level ice and ridges) against a marine structure,
- to show the effect of various parameters on these forces, and
- to elucidate the fracture mechanisms of the ice during the failure process

in Task 4 the necessary theoretical ice force prediction models are to be developed. This dual approach - full scale measurements and theoretical modelling of the force problem - is the most promising way in providing reliable methods to predict the ice forces on marine structures for most general application.

Task 4 comprises of the following sub-tasks:

Sub-task 4.1:	Investigations on Special Ice Mechanics Problems Related to Numerical Modelling
Sub-task 4.2:	Dynamic Ice-Structure Interaction Model
Sub-task 4.3:	Ridge Load Model
Sub-task 4.4:	Fracture Dynamics Model
Sub-task 4.5:	Probability Approach

The work on Task 4 has just started.

Sub-Task 4.1 Investigations on Special Ice Mechanics Problems Related to Numerical Modelling (LGGE)

Objectives:
To investigate the fracture mechanisms involved at small scale ice deformation as basic ingredients of numerical modelling of the ice-structure interaction.

Sub-Task Description:
Experiments will be carried out on:

- Micro-mechanisms responsible for crack nucleation at grain scale
- Mechanical behaviour of undamaged ice
- Mechanical behaviour of damaged ice

Sub-Task 4.2 Dynamic Ice-Structure Interaction Model (VTT)

Objectives:
The first objective of this Sub-task will be to develop a new numerical model for dynamic ice-structure interaction. The model will be applicable for any forms of vertical structures. The ice features to be considered include level ice, rafted ice, ice ridges, rubble fields and icebergs. Such a unifying model is not existing at present. The second objective will be to derive a new load combination formula for probabilistic analysis. This will help in obtaining one of the main aims of the project: justification for a substantial decrease in the global ice load estimates.

Sub-Task Description:
A new numerical model will be developed which is based on old dynamic ice-structure interaction models developed by VTT and HUT. The old physical model used in these numerical solutions will be replaced by the new physical model. The quality and reliability of the computer program will be tested by comparisons to all available laboratory- and field data. Then, it will be possible to design structures that are safe from severe ice induced vibrations.

Sub-Task 4.3 Ridge Load Model (HUT)

Objectives:
Existing ridge load models are based on soil mechanics bearing capacity approach. They can observe only simple failure planes and simple vertical structure shapes. By the present project a new numerical analysis procedure will be developed that allows to model real 3-dimensional structural shapes and ridge profiles in which complicated failure surfaces are progressively developing. No known analytical method can solve this problem. Also approximate plastic limit analysis approaches fall short of describing the real geometry of the problem.

Sub-Task Description:
The finite element method is today the most versatile tool in continuum mechanics. An analysis procedure based on the finite element method will be developed to numerically simulate ridge interaction with real structures. An adaptive material and geometric non-linear 3-D finite element model that is capable to observe localized failure development is needed. Consolidated

layer strength data will be used for determining the size of its failure surface. Two material models will be considered for the consolidated layer. An ideal elastic-plastic model will be used as a first approach in the FE-model. Second, a non-linear material model that considers the macro-scale voids and damage evolution within the material will be developed.

Sub-Task 4.4 Fracture Dynamics Model (CU)

Objectives:
The objective of this task is to consider fracture as a failure mode, and to identify parameter ranges in which it is the critical mode, so that they can be used in models.

Sub-Task Description:
In the past most research on ice loading has considered crushing or flaking as the dominant ice failure mode. This is justified by the fact that this failure mode appears to provide the highest global loads. However, full-scale experience shows that besides crushing there are other failure modes such as splitting, spalling, and large-scale transverse fracture of ice floes, and that those alternative modes may govern.

The objective is to extend fracture mechanics solutions to the splitting and crushing problem, to provide a more realistic and complete description of the problem, and to provide information that can be incorporated into design load calculations.

A final objective is once and for all to resolve the much-disputed question of "scale effects", which has bedeviled ice force research for many years. Scale effects in other areas of mechanics and physics have always responded to a more complete physical understanding, and there is no reason why this should not also apply to ice.

Sub-Task 4.5 Probability Approach (NTNU)

Objectives:
The central objective of this task is to assemble a systematic probabilistic model and evaluate its reliability, including sensitivity to inaccurate knowledge about transition parameter values, where the ice failure mode changes.

Sub-Task Description:
To apply the probabilistic approach, a probabilistic description of the ice conditions near the structure is needed first. The parameters of the probabilistic model will include at least ice thickness, ice strength, temperature, ice velocity, salinity, porosity, direction of ice movement and also different forms of ice features, such as level ice, rafted ice, ridged ice, etc. Probabilities of encountering these features will be incorporated as well.

Task 5: Recommendation of Ice Forces on Coastal Structures (HSVA, Coordinator)

Objectives:
Combine all findings of the entire project and recommend design ice loads for future marine structures. Initiation of the development of an EUROCODE for Ice Forces.

Task Description:
The Advisory Committee, which will include representatives of Governmental authorities of the EU countries, European classification societies, European Oil Companies and at least one representative from Russia will evaluate the results of the research and will participate in the formulation of final recommendations. The results of the research project including the recommendations, will be presented to users from industry and science at a special conference. This conference will be organized by the LOLEIF consortium.

The recommendations on ice forces on vertical structures could be the basis for the new EUROCODE on Ice Forces.

List of References

Fritzpatrick, J. (1994): State-of-the-Art of Bottom-Founded Arctic Steel Structures, Canadian Marine Drilling, Calgary, Alberta.

Kennedy (1996): Personal communication.

Shkhinek, K.; Blanchet, D.; Croasdale, K. (1994): Comparison of the Russian and Foreign Codes and Methods for Global Load Estimations. Proceeding of the 13th OMEA Conference, 1994.

Wessels, E.; Jochmann, P.: Model-Full Scale Correlation of Ice Forces on a Jacket Platform in Bohai Bay, Proc. of 9. Intern. Conference on Port and Ocean Engineering under Arctic Conditions, POAC, St. John's, 1991.

TITLE: The optimisation of crest level design of sloping coastal structures through prototype monitoring and modelling

CONTRACT NO: MAS3-CT97-0116

COORDINATOR:
Prof. Dr. ir. J. De Rouck / ir. P. Troch
University of Ghent, Department of Civil Engineering
Technologiepark 9, B-9052 GENT / Belgium
Tel. (Fax) : +32 9 264 54 89 (58 37)
E-mail : peterb.troch@rug.ac.be

PARTNERS:

ir. L. Van Damme
Ministry of the Flemish Community
Coastal Division
Vrijhavenstraat 3
B-8400 OOSTENDE / Belgium
Tel. (Fax) : +32 59 55 42 11 (50 70 37)

ir. F. Wens / ir. B. Eelen
Flanders Hydraulics
Berchemlei 115
B-2140 BORGERHOUT / Belgium
Tel. (Fax) : +32 3 236 18 50 (235 95 23)
E-mail : flanders.hydraulics@watlab.be
bart.eelen@lin.vlaanderen.be

Prof. Dr. Techn. H.F. Burcharth
Ass. Prof. Peter Frigaard
Aalborg University, Dept of Civil Eng.
Sohngaardsholmsvej 57
DK-9000 AALBORG / Denmark
Tel. (Fax) : +45 96 35 80 80 (98 14 25 55)
E-mail : peter.frigaard@civil.auc.dk

Dipl.-Ing. H. Schüttrumpf
Leichtweiss Institut für Wasserbau
Dept. of Hydromechanics and Coastal Eng.
Beethovenstrasse 51A
D-38106 BRAUNSCHWEIG / Germany
Tel. (Fax) : +49 531 391 39 32 (82 17)
E-mail : h.schuettrumpf@tu-bs.de

Dr. A. Lewis / Dr. J. Murphy
University College Cork
Hydraulics and Maritime Research Laboratory
IE-CORK / Ireland
Tel. (Fax) : +353 21 90 21 65 (34 35 80)
E-mail : t_lewis@ucc.ie

Dr. M. R. A. van Gent
Delft Hydraulics, Marine and Coastal Infrastructure
PO Box 177
NL-2600 MH DELFT / The Netherlands
Tel. (Fax) : +31 15 285 85 85 (261 96 74)
E-mail : marcel.vangent@wldelft.nl

ir. J. G. de Ronde
Rijkswaterstaat / RIKZ
Kortenaerkade 1 - PO Box 70904
NL-2500 EX THE HAGUE / The Netherlands
Tel. (Fax) : +31 70 3114 208 (321)
deronde@rikz.rws.minvenw.nl

Dr. J. R. Medina
Universidad Politecnica de Valencia
Departamento Transportes / ETSI Caminos
Camino de Vera s/n
E-46022 VALENCIA / Spain
Tel. (Fax) : +34 6 387 73 75 (79)
E-mail: jrmedina@tra.upv.es

Dr. C. Miguel Lemos
Instituto Hidrografico
Rua das Trinas 49
P-1200 LISBOA / Portugal
Tel. (Fax) : +351 1 395 51 19 (05 15)
E-mail: clemos@mail.telepac.pt

THE OPTIMISATION OF CREST LEVEL DESIGN OF SLOPING COASTAL STRUCTURES THROUGH PROTOTYPE MONITORING AND MODELLING

(OPTICREST)

R. VERDONCK, P. TROCH, J. DE ROUCK

University of Ghent, Faculty of Applied Sciences, Department of Civil Engineering
Technologiepark 9, B-9052 Ghent, BELGIUM

SUMMARY

The aim of the OPTICREST project is to optimise the design of the crest level of sloping coastal structures. Thereto, a rubble mound breakwater and a seadike will be monitored (full scale) during storm events and will be studied in laboratory tests (scale models). The results from in-situ and laboratory tests will be used to optimise numerical models and design rules for the crest level of sloping coastal structures.

1 INTRODUCTION

Sloping coastal structures, such as breakwaters, are used world-wide for coastal protection and harbour sheltering. Despite extensive research, some aspects of their design still remain unsolved. One of these aspects is the design of the optimum crest height. The OPTICREST project will study the phenomena of wave run-up, overtopping and spray on sloping coastal structures, in order to find better design rules for the crest level.
Prototype measurements on a rubble mound breakwater and visual observations by harbour authorities at various locations world-wide, have shown that quantities of overtopping water and spray are clearly higher than expected during design. Large quantities of overtopping water may cause serious damage to the landward side of a structure and spray may be very annoying for harbour activities. Thus the social and economical ambitions of the hinterland are endangered. The crest level is one of the most important aspects in the design of sloping coastal structures.
First a brief discussion of the background leading to the project is given. Next, the tasks of the project are explained in more detail. There are three major tasks: prototype measurements, laboratory measurements and numerical modelling. Finally, an outlook of the research results is briefly summarised.

2 BACKGROUND

During the MAST II - 'Full scale dynamic load monitoring of rubble mound breakwaters' project (MAS2-CT92-0023), wave run-up was measured on the NW rubble mound breakwater of the Zeebrugge harbour (Belgium). These measurements were compared with run-up levels measured on three scale models of the breakwater cross-section. The run-up levels measured in the different scale models all fit well with experimental design curves. The prototype measurements, however, are approximately 50% higher (Figure 1). This difference confirms

the practical experience in many harbours that wave overtopping is higher during exploitation than expected during design.
All the prototype results were obtained during one storm event. The range of Iribarren numbers for the prototype results is small due to the observed wave and breakwater characteristics.
Nowadays crest level design is based on model tests and on empirical formulae, based on such tests. So, if this trend for higher prototype run-up levels would be confirmed by future prototype measurements (in a wider range of Iribarren numbers), the consequences on breakwater design would be tremendous. Therefore further research is necessary. The foregoing was the immediate cause for the OPTICREST project.

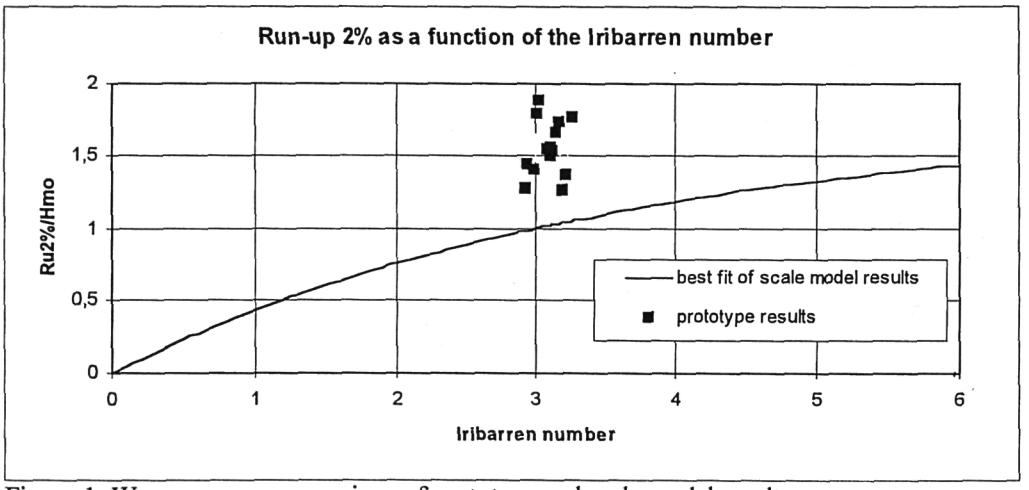


Figure 1. Wave run-up: comparison of prototype and scale model results.

Extensive laboratory testing on wave run-up has been carried out by Van der Meer, Losada, Allsop and others, leading to design rules used today.

The formula for run-up on rough slopes, proposed by Van der Meer [6] has the form:
$Ru_{x\%}/H_s = a \cdot \xi_m$ for $\xi_m < 1.5$
$Ru_{x\%}/H_s = b \cdot \xi_m^c$ for $\xi_m \geq 1.5$
For permeable structures, the value of $Ru_{x\%}/H_s$ does not exceed a certain value d.
in which $Ru_{x\%}$ is the run-up level with x% exceedance probability
ξ_m is the surf similarity parameter, based on the mean period
a,b,c,d are experimental coefficients

The run-up on smooth slopes is described by Van der Meer & Janssen [5]:
$Ru_{x\%}/H_s = a \cdot \xi_m$
$Ru_{x\%}/H_s \leq b$
in which a and b are experimental coefficients

Van der Meer & Janssen also studied the effects of a berm, a shallow foreshore, slope roughness and oblique wave attack on wave run-up. They give formulae for reduction factors, based on laboratory tests.

For the run-up on rough slopes, the formula by Losada & Gimenez-Curto [3] is also widely used:

$Ru_{x\%}/H_s = a \cdot (1 - \exp(b \cdot \xi_m))$

in which a and b are experimental coefficients

These formulae have been derived on the basis of laboratory experiments. In these experiments only simple geometries and bathymetries can be tested. Therefore, these tests can not simulate the complexity of run-up on real structures in real sea conditions.

3 PROTOTYPE MEASUREMENTS

In order to establish better design rules for the crest level of sloping coastal structures, the information that is lacking are prototype run-up measurements. Within the OPTICREST project, major attention is paid to the collection of full scale data.

Prototype measurements will be carried out at two different locations: at the NW breakwater of Zeebrugge (Belgium) and at an impermeable sea dike in Petten (the Netherlands).

In Zeebrugge, measurements of wave run-up levels will be carried out and the breakwater will be further instrumented to measure overtopping and spray.
Run-up is measured using six stepgauges, placed along the slope of the breakwater. At the bottom, the stepgauges are attached to an armour unit. At the top they are supported by a jetty that is constructed above the breakwater. Each stepgauge contains a number of electrodes, spaced vertically at 20 cm distances. Each submerged electrode produces an output voltage. The summation of these voltages leads to an output signal that contains the information about the water level with a 20 cm resolution. Specially developed software computes the instantaneous water surface profile on the slope.
Overtopping will be measured by a screen catching the overtopping water which is collected in a container. The volume of water in the container will be monitored by a continuous measurement of the water level in the container. To increase accuracy, a device to damp the movements of the water surface will be installed in the container. When the container is full, a mechanism (syphon, weir or valve) will allow to empty it very quickly.
Spray will be measured at various distances behind the breakwater. The sea water droplets will be caught at ground level, and the total volume will be measured using for instance tipping bucket gauges. The measured quantities will be compared to measurements of rain, that will be carried out far enough away from the breakwater to avoid any influence of spray. The wind will be measured by two wind meters placed on the jetty. The wind data will be used to analyse the spray data.
Wave data are obtained from two waverider buoys close to the breakwater (at 165 m and at 215 m in front of the breakwater) and from waverider buoys located at 5 km, 30 km and 45 km from the structure.

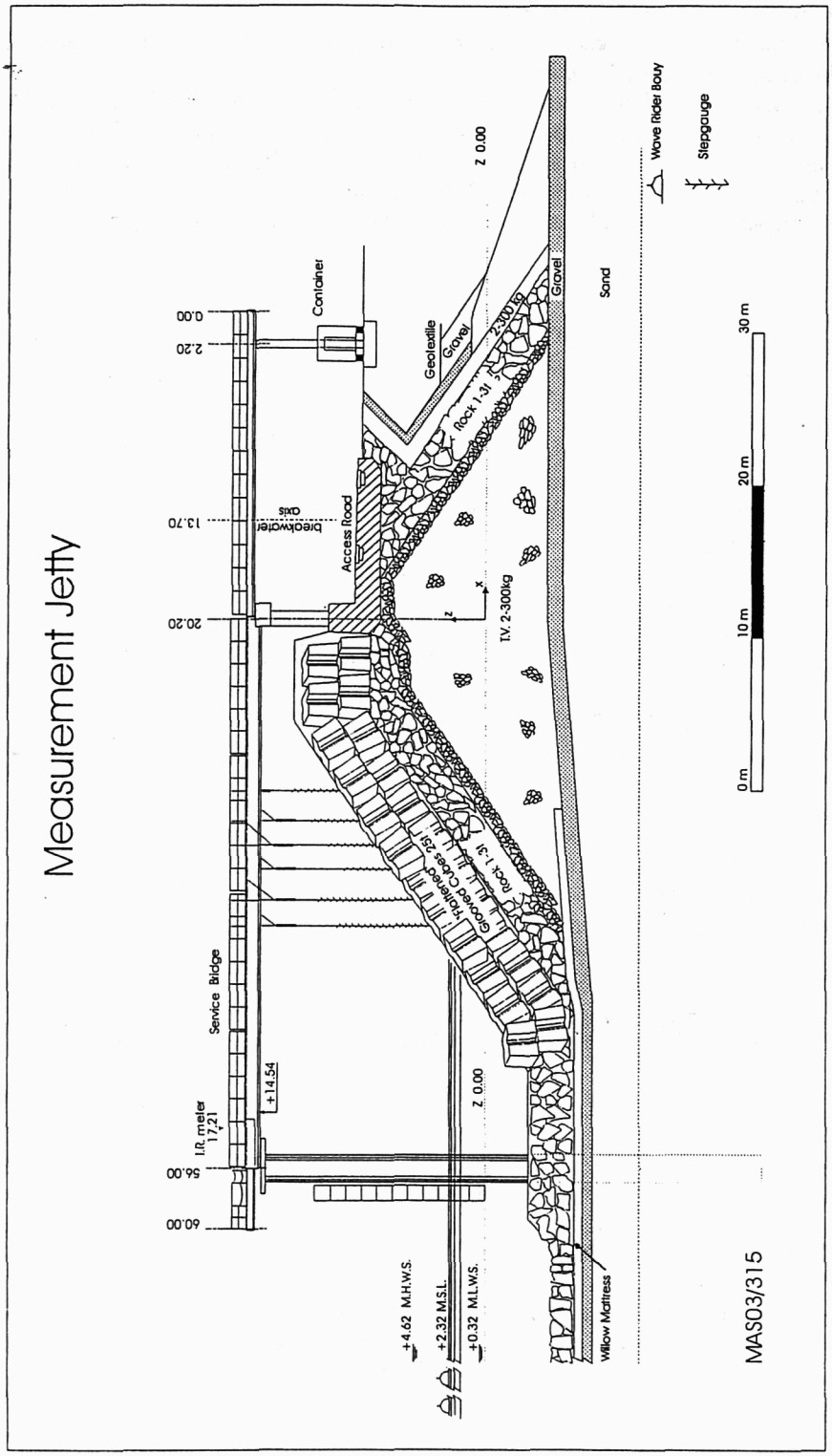


Figure 2. Cross section of the Zeebrugge breakwater with the instrumentation (early 1998)

In Petten, wave run-up will be measured.
The Petten coastal region is characterised by nearly straight iso-baths with a bar and trough and a dike onshore (Figures 3 and 4).
Data about the wave climate are collected by waverider buoys (MP2 and MP4) and by directional waveriders (MP1 and MP5). Just in front of the bar, a wave staff and a water level meter (MP3) are used to measure incoming waves. In front of the dike the waves are measured by a wave staff and a pressure transducer (MP6 and Mb6).
The wave run-up is measured, using a staff gauge placed along the slope of the sea dike (MP7).

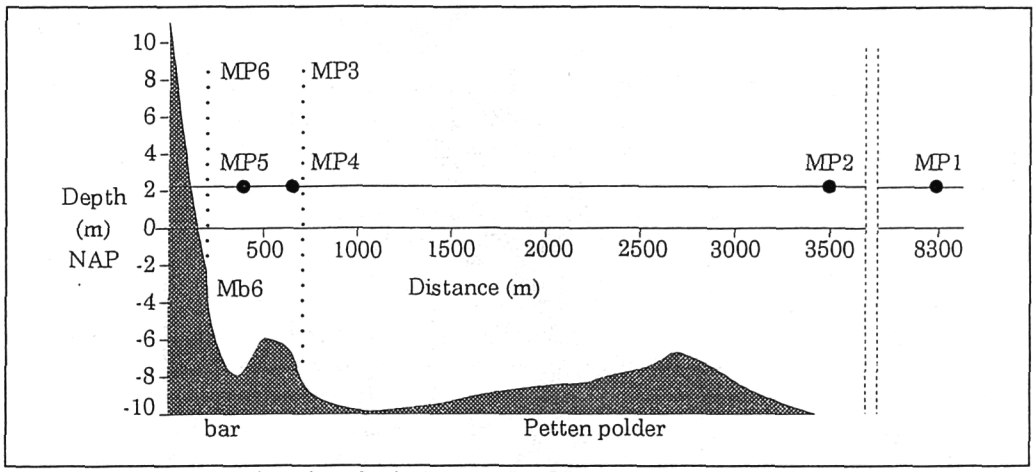


Figure 3: Wave sensor locations in the Petten coastal area.

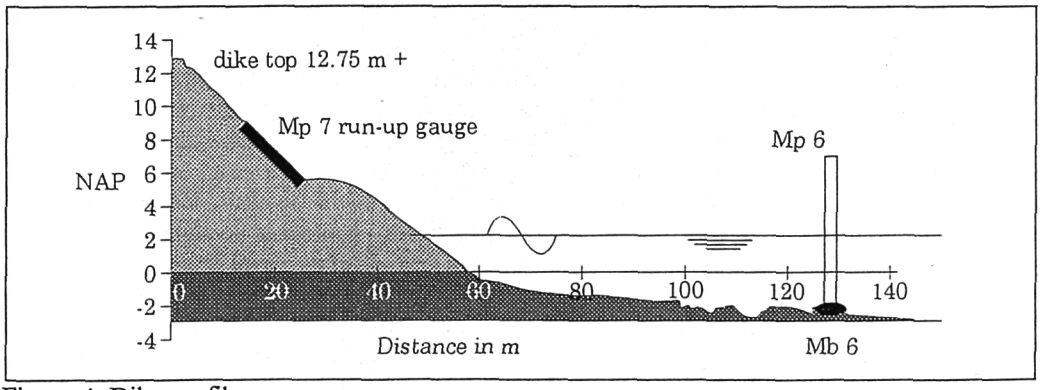


Figure 4: Dike profile.

Tide and wind data are available through a nationally funded project.

4 LABORATORY MEASUREMENTS

Both the Zeebrugge and the Petten site will be modelled in scale model tests. Run-up levels and overtopping volumes will be measured. In the scale model tests, both in-situ measured spectra and standard spectra will be used. Special attention will be paid to the influence of the foreshore bathymetry.
Two dimensional and three dimensional tests will be carried out. Furthermore a special series of two dimensional tests will investigate the crest stability of a heavily overtopped sloping structure.

4.1 Two dimensional testing

Deviations between the scale model results and the prototype measurements will be determined and the influence of different scale effects will be investigated. This may lead to changes in the models from the two sites. The models will then be re-built and the tests will be repeated.
Apart from the classical wave flume tests, a series of tests in a wind-wave flume will also be performed. The influence of wind on run-up, overtopping and spray will be studied in these experiments. Therefore tests with different wind velocities will be carried out.

4.2 Three dimensional testing

Three dimensional tests will be carried out for models of the Zeebrugge and the Petten site. The scaling will be as close as possible to the scales used in the two dimensional tests.
These tests will attempt to validate the prototype results and continue to investigate the influence of such parameters as wave height, period, water depth, angle of wave attack, directional spreading, currents, foreshore bathymetry and structure geometry.

4.3 Scale model testing to assess the stability of the crest

Failure of a dike is often initiated by damage to the crest, caused by overtopping. Overtopping as such can not be avoided, due to uncertainties in the prediction of the design water level, the design wave and the run-up phenomenon.
If large quantities of water overtop a structure, the velocity field of downrushing water at the landward side of the structure will be considerable. This downrushing water may lead to failure of the structure.
Two dimensional model tests will be carried out on a sloping structure with a common seaward slope and a common landward slope. The layer thickness and the water velocity of the overtopping water will be measured at different points on the structure. The result of this investigation will help in a better assessment of the crest stability of overtopped structures.

4.4 Link between prototype and scale model results

One of the conclusions from the MAST II 'Full scale dynamic load monitoring of rubble mound breakwaters' project, was that wave run-up and overtopping are not well predicted in scale models. This bad prediction is due to several factors, such as: measuring systems, wind, roughness, randomness of sea conditions, ... The purpose of the comparison between prototype and scale model results is to quantify these effects in order to allow a better predictions of run-up levels and overtopping discharges from laboratory tests. This will be done by a systematic procedure of feed-back between the prototype measurements and the laboratory experiments.

5 NUMERICAL MODELLING

Before and within the MAST-programmes, several numerical models for the description of wave action on and in coastal structures have been developed, both engineering tools (ODIFLOCS, IBREAK, RBREAK, FLO_X, ...) and research tools (SKYLLA, VOFbreak^2, 2D-HYDROTUR).
It has to be expected that these numerical models will play a very important role in future research and design of coastal structures. Therefore, it is of paramount importance that these models are as reliable as can be achieved. Up to now, these models have been calibrated against scale model test results only. In the OPTICREST project, they will also be calibrated with the results of the prototype measurements.

In a first stage, an existing code will be refined. New modules with a detailed calculation of some physical phenomena (such as: a turbulence model, a porous flow module, ...) will be

implemented. In a second stage, the prototype measurements will be used to calibrate the model. The results from the prototype measurements will also give a better insight in the capacities and the limitations of numerical modelling.

6 OUTLOOK

Existing design techniques for sloping coastal structures, which include the use of mathematical and physical models have not prevented severe failures. Such failures have disastrous consequences, such as loss of life, damage to property, loss of business, economic ruin, ... Reliable design methodologies are essential.
To the knowledge of all partners involved, a consistent, widely accepted design methodology for the crest level does not exist. This is the consequence of a lack of prototype measurements and leads to either an overdesign or an underdesign of the crest level.
The OPTICREST project will provide a better insight in the run-up phenomenon, optimised and calibrated numerical models and better scale modelling techniques. Furthermore, better design rules will be formulated. This will lead to a better design method of the crest of sloping coastal structures. With our coasts being used more than ever before, these results will be very valuable and important.

7 REFERENCES

[1] Andorka Gal, Verification set Petten, Ministry of Transport, Public Works and Water Management, Directorate-General for Public Works and Water Management, National Institute for Coastal and Marine Management, RIKZ, 1996

[2] De Rouck, J., Troch, P., MAST II project MAS2-CT92-0023: Publishable Synthesis of Scientific Results MAS02/1-892/JDR

[3] Losada, M.A., Gimenez-Curto, L.A., Mound breakwaters under oblique wave attack; a working hypothesis, Proc. 18th Coastal Eng. Conf., 6, pp. 83-92, 1982

[4] Troch, P., De Somer, M., De Rouck, J., Full scale dynamic load monitoring of rubble mound breakwaters, Proceedings Second MAST days and EUROMAR market, 7-10 Nov. 1995, Sorrento

[5] Van der Meer, J.W., Janssen, J.P.F.M., Wave run-up and wave overtopping at dikes, Published in ASCE, Wave forces on inclined and vertical wall structures, 1994

[6] Van der Meer, J.W., Stam, C.J., Wave run-up on smooth and rock slopes of coastal structures, Journal W'way, Port, Coastal and Ocean Eng.,ASCE, Vol. 118, No. 5, Sept./Oct. 1992

II.2.2. Remote sensing

TITLE: Establishment of an Airborne Geoid Mapping System for Coastal Oceanography (**AGMASCO**)

CONTRACT NO: MAS3-CT95-0014

COORDINATOR:

Dr. L. Timmen
GeoForschungsZentrum Potsdam (GFZ)
Div. 1: "Kinematics and Dynamics of the Earth"
Albert-Einstein-Strasse (Telegrafenberg)
D-14473 Potsdam, Germany
Tel.no. (Fax): +49 331 288 1132 (1169)
E-mail: timmen@gfz-potsdam.de

PARTNERS:

Dr. L. Bastos
University of Porto, Obs. Astronomico
Monte Virgem
P-4430 Vila Nova de Gaia, Portugal
Tel.no. (Fax):+351-2-782-0404 (7253)
E-mail: lcbastos@ncc.up.pt

Dr. R. Forsberg
National Survey and Cadastre
Rentemestervej 8
DK-2400 Copenhagen NV, Denmark
Tel.no. (Fax): +45-35-87-5319 (5052)
E-mail: rf@kms.min.dk

Dr. A. Gidskehaug
University of Bergen
Institute of Solid Earth Physics
Allegaten 41
N-5007 Bergen, Norway
Tel.no. (Fax): +47-55-58-3399 (9669)
E-mail: arneg@ifjf.uib.no

Dr. K. Hehl
Technische Fachhochschule (TFH) Berlin
Luxemburger Strasse 10
D-13353 Berlin, Germany
Tel.no. (Fax): +49-30-4504-2611 (2632)
E-mail: 100736.1345@compuserve.com

Mr. U. Meyer
Alfred-Wegener-Institut für Polar und
Meeresforschung
Columbusstrasse
D-27568 Bremerhaven, Germany
Tel.no. (Fax): +49-471-4831-550 (149)
E-mail: umeyer@awi-bremerhaven.de

ESTABLISHMENT OF AN AIRBORNE GEOID MAPPING SYSTEM FOR COASTAL OCEANOGRAPHY (AGMASCO)

L. TIMMEN
GeoForschungsZentrum Potsdam, Telegrafenberg A17, D-14473 Potsdam, Germany
L. BASTOS
Univ. of Porto, Obs. Astronomico, Monte da Virgem, P-4430 V. N. Gaia, Portugal
R. FORSBERG
National Survey and Cadastre, Rentemestervej 8, DK-2400 Copenhagen NV, Denmark
A. GIDSKEHAUG
University of Bergen, Inst. of Solid Earth Physics, Allegaten 41, N-5007 Bergen, Norway
K. HEHL
Technische Fachhochschule Berlin, Luxemburger Strasse 10, D-13353 Berlin, Germany
U. MEYER
Alfred-Wegener-Institut, Columbusstr., D-27568 Bremerhaven, Germany

SUMMARY

Within the EU MAST-III project AGMASCO (start: Jan. 1996, end: Febr. 1999), an airborne gravimetry/altimetry system has been established to determine geoid and sea surface topography in coastal and shelf areas. First demonstration projects (Skagerrak/1996, Fram Strait/1997) and a full application project (Azores/1997) have been performed. The AGMASCO system and the objectives are described and the performance of the flight campaigns with the obtained results is outlined.

1. INTRODUCTION

To study the dynamic sea surface topography (SST) large progress has been achieved with the performance of satellite missions like ERS-1 and ERS-2. But there are still deficiencies: in coastal areas (islands, shoals, local tides etc.), and in the polar regions (covered by sea ice and only partly covered by satellite observations). To overcome this drawback an additional flexible, fast and cost saving system has become necessary. The AGMASCO system is based on most advanced sensor technology (accelerometer, laser and radar altimeter, GPS, INS) for gravity and sea surface height data acquisition and new data processing methods to deliver most accurate products. The hardware can be operated over sea as well as over land, therefore coastline transition zones (e.g. plate boundaries) may be covered which bridges important gravity data gaps. Because of the homogeneity of these data, they are well suited for assimilation with satellite data to develop more detailed geoid and sea surface models in regions of interest.

GPS technology is one of the main components of the airborne gravity/sea surface height determination system. Gravity information is obtained from differencing accelerations observed by a gravity meter (gravity and aircraft accelerations) and derived from GPS observations (aircraft accelerations). The recent accuracy increase in airborne gravimetry is achieved due to large improvements in kinematic GPS data processing (cf Gumert 1995, Harrison et al. 1995, Klingelé et al. 1997, Olesen et al. 1997, Wei and Schwarz 1995, Xu et al. 1997). The progress becomes obvious in the gravity accuracy as well as in the spatial resolution of the gravity

field. In addition, GPS combined with altimetry allows the determination of the instantaneous sea surface height and topography with the demanded accuracy in the order of ±10 cm (results from first investigations). Therefore, the AGMASCO system can be a useful tool for oceanography. From the "measured" SST the ocean current may be determined based on the geostrophic assumption.

2. AGMASCO SYSTEM OUTLINE

The basic concept is illustrated with Fig. 1. Geoid information are derived from accelerations measured by a gravimeter which is operated on a gyro-stabilized inertial platform. The seperation between airplane acceleration and gravity is achieved by subtracting the GPS derived airplane acceleration from the gravimeter signal. Simultaneously, the ocean surface is observed by altimeter measurements. By combining geoid, altimetry and GPS the sea surface topography is given through the equation:

$$SST = h - N - A$$

(h: ellipsoidal height of airplane, N: geoid height, A: airplane height above sea surface).

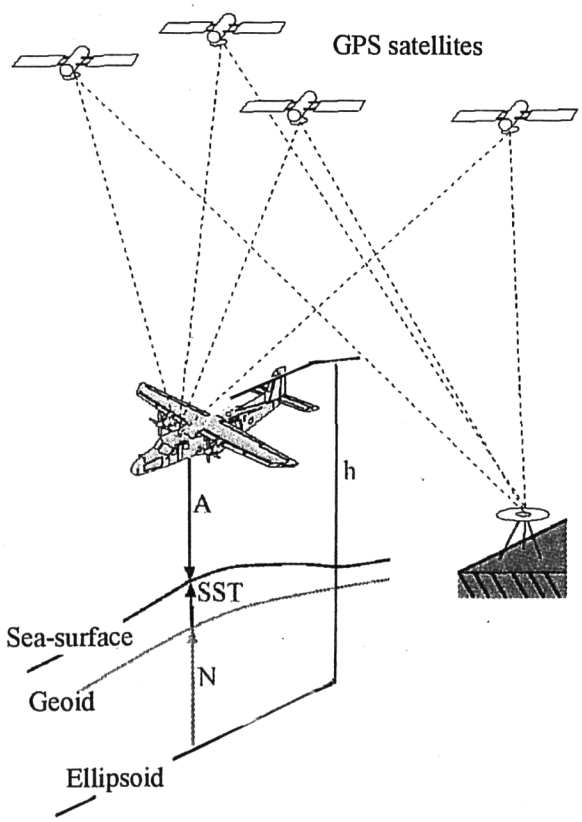


Fig. 1: The AGMASCO airborne geoid and sea surface mapping system for coastal oceanography

The system involves the integration of available hardware components as well as of hard- and software which have been developed within the project (see Fig. 2).
The gravity sensor is the LaCoste&Romberg (LCR) S99 air/sea gravity meter (University of Bergen) specially upgraded by ZLS Corp. (Austin, Texas) for airborne application. The kinematic positioning and the airplane attitude determination are based on GPS (Trimble SSI, Ashtech Z12) and INS (Honeywell Lasernav, others). Two rover GPS receivers were installed during the first flight campaigns (Skagerrak 1996, Fram Strait 1997), an additional receiver was attached to one of the wings in the Azores (1997). Up to 5 GPS reference stations were employed during one campaign. An Optech 501 SX laser altimeter and a special prototype radar altimeter (developed at the University of Stuttgart, Germany) are operated to observe the sea surface. During the Azores campaign, a strap-down accelerometer system has been employed as a supplement to the obtained LCR system. This sensor block consists of three QA-3000-030 accelerometers produced at AlliedSignal Aerospace (Redmond, Washington) which are mounted orthogonally in an aluminium block. The mounting device including the electronics has been designed by the Bavarian Academy of Science (Munich, Germany, cf Boedecker et al. 1994). A central data logging unit has been developed within a contract between GFZ Potsdam and KADSOFT (Dresden, Germany). This ensures time synchronization and adequate data storage. The data records are mainly based on a 1 Hz sampling rate. INS and altimetry data acquisition are performed with frequencies of up to 200 Hz.
For AGMASCO two different airplanes are available now: a Dornier 228 from AWI, Bremerhaven (Skagerrak, Fram Stait), and a CASA Aviocar C212 from the Portuguese air force (Azores). The airplane flight velocities varied between 200 and 250 km/h (depends on wind) with altitudes of about 400 m and 250 m (Azores). The use of autopilot ensured an appr. constant engine speed and a horizontal airplane orientation.

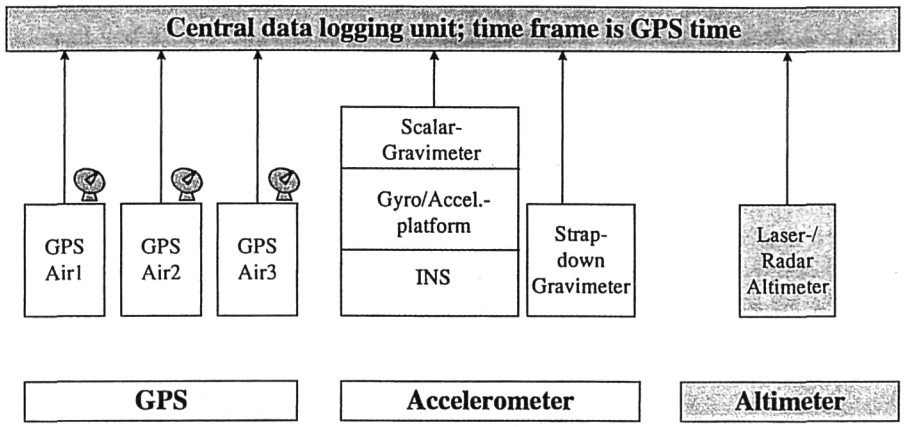


Fig. 2: AGMASCO hardware architecture

3. SYSTEM VALIDATON AND GROUND-TRUTH

For validation of the system two short inital test flights ($2x3^h$) have been performed in northern Germany in June 1996. Profiles over land as well as over the North Sea have been flown at different altitudes to check the radar and the laser altimeter. The gravity meter behaviour was checked by passing over well known gravity anomalies.
In Sept. 1996 a demonstration project was performed in the Skagerrak region to show the operationality and reliability of the system. The gravity anomaly field of the region is well

known from earlier 1960's-vintage marine and land gravimetry. There is a large, localized 50 mgal gravity anomaly (traditionally interpreted as a buried Tertiary volcano) south of the Norwegian coast. Well defined gravity anomalies associated with salt domes exist on the Danish side of the Skagerrak. The oceanography shows a varying pattern, with fairly strong currents, and an oceanographic "front" created from mixing of the more brackish Baltic water with the saltier North Sea water. This front is known to yield a sea surface topography in the order of 10 cm.

In addition to the already existing data, the R/V Hakon Mosby (University of Bergen) was employed for ground-truth measurements during the Skagerrak and the Azores campaign. This has been done immediately after the airborne measurements and partly simultaneously with the flights. ADCP (Acoustic Doppler Current Profiler) and CTD (Conductivity, Temperature, Depth) data were acquired as well as sea gravity data. GPS was used for positioning. The SST derived from ADCP and/or CTD data can be compared with the AGMASCO airborne method.

A few airplane and ship profiles coincide with satellite tracks (Topex/Poseidon, ERS-1/2) which allows a direct comparison between the different data sources.

4. FLIGHT CAMPAIGNS AND RESULTS

The Skagerrak campaign was performed from 13 to 23 of September, 1996. Fig. 3 shows the airplane trajectories. The profile A corresponds to a Topex/Poseidon track, and line M is observed by ERS-2. The flight track separation is 15 km. In total, the area was observed in 42 flight hours. Immediately after finishing the airborne survey the gravimeter was moved from the airplane Polar4 (Do228) to the R/V Hakon Mosby to avoid larger delays between the airplane and ship data collection. On the research vessel gravimetric profile data were acquired over 1400 km.

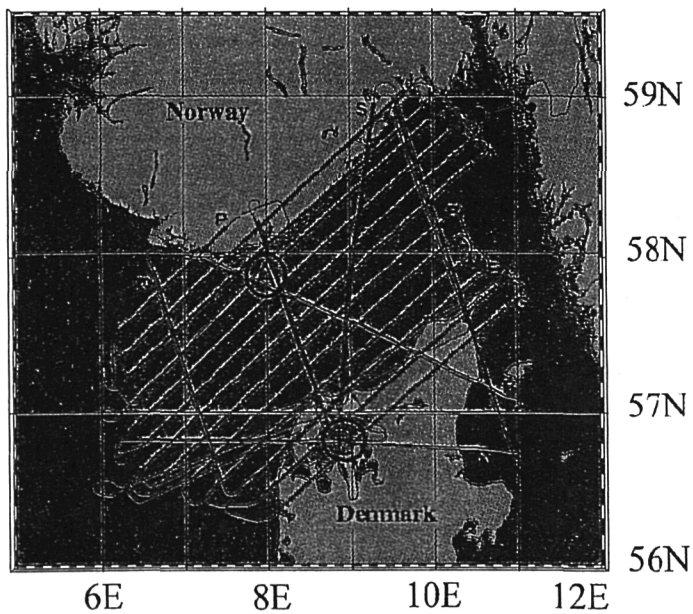


Fig. 3: The AGMASCO profiles of the Skagerrak campaign in 1996. The positions A and B are the locations of a buried volcano and a salt dome, respectively.

After filling some gaps with the Hakon Mosby gravity data the model of the gravity field has been improved. This serves as a reference (ground-truth) for assessing the airborne gravity results. In Fig. 4 airborne free air anomalies are depicted derived from the profiles passing the two density/gravity anomaly features in the Skagerrak area. The upper part shows the anomaly of the salt dome in northern Jutland (peak at km 115) compared with the upward continued gravity ground-truth. The lower figure comprises a comparison for the buried volcano (peak at km 85). For geophysical interpretation the amplitude and the half-width are a measure of the extension of such phenomena (e.g. oil/gas/salt deposits).
There is good agreement between ground-truth and airborne results. Only a small discrepancy in the amplitude of the volcano amplitude can be realized. The assumed spatial resolution of appr. 6 km (low pass filtering, 0.005 Hz cutoff frequency) is confirmed in both examples. For the whole Skagerrak campaign the general agreement between ground-truth and airborne gravity anomalies is within ±2.7 mgal (r.m.s. difference). Considering a small uncertainty for the reference model (land/marine data) an achieved overall accuracy of ±2 mgal can be claimed for the Skagerrak campaign.

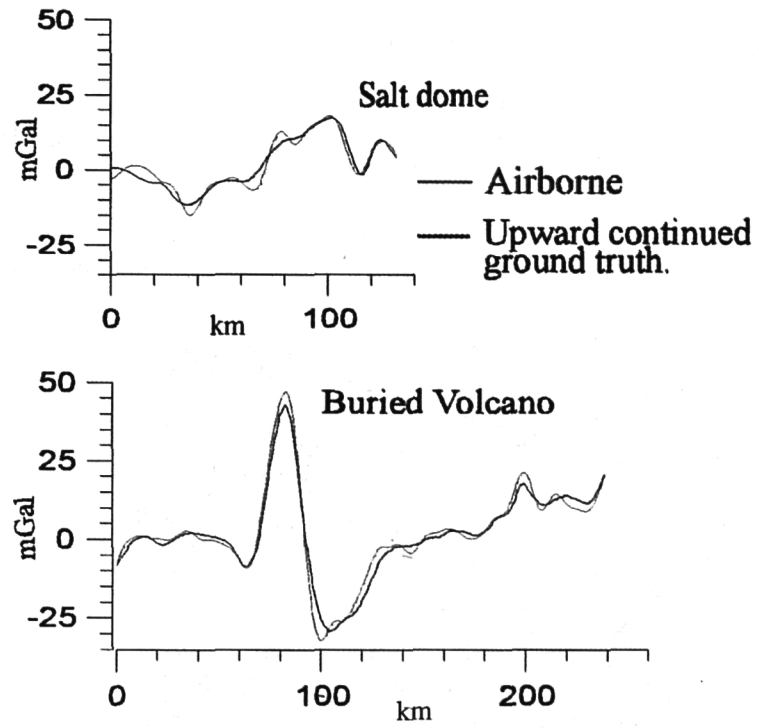


Fig. 4: Airborne free air anomalies compared with upward continued marine/land gravity. The anomalies from the buried volcano and the salt dome are well seen by the airplane measurements.

To estimate the quality of the combined airborne results from GPS and altimetry, first comparisons have been performed with the Topex/Poseidon satellite altimetry. In Fig. 5 the airborne determined sea surface height (Sept. 17) is compared with the two satellite passes (Sept. 12 and 22). Both results are corrected for tidal effects by applying the AG95 tidal

model, with elastic loading. The agreement between the spaceborne and airborne method is in the order of 10 cm.
A pointwise control has been performed by passing the tide gauge in Hanstholm harbour during one flight track. The comparison with the available ground truth shows an agreement of 8 cm which suits well the AGMASCO error estimates.
Further investigation has to be done to sustain the above mentioned accuracy quantities.

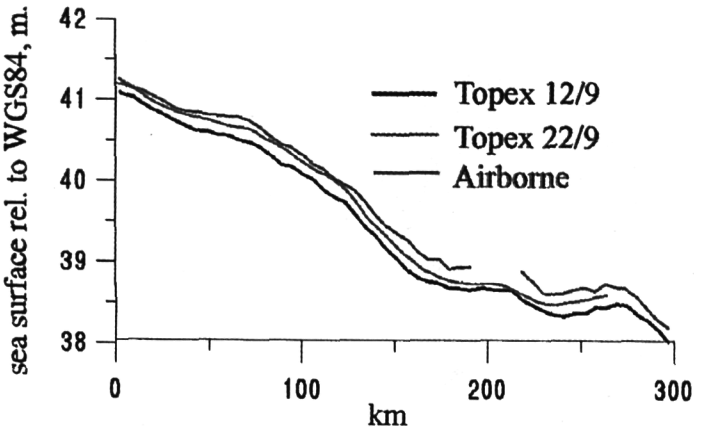


Fig. 5: Comparison of satellite and airplane altimetry along the Skagerrak profile A.

In connection with the NORDGRAV aerogravity and magnetics program (Boebel et al. 1998) AGMASCO flights have been performed between Greenland and Svalbard in August 1997, see Fig. 6. NORDGRAV is a direct spin-off project from the successful Skagerrak campaign. The Fram Strait between the Artic Ocean and the Norwegian-Greenland Sea is an important region for studying the Arctic Ocean water exchange, notably the outflow of Arctic Ocean pack ice and surface waters along the East Greenland coast. The goal of the Fram Strait campaign is to gain a first insight into the unknown gravity field of the region, and to gain a first-hand experience with airborne altimetry over a partially ice-covered region. The Fram Strait program (28 flight hours) includes 5 parallel East-West profiles with a double flight along the 79°N latitude. A pointwise control has been performed by helicopter gravimetry.
After the completion of the Skagerrak data processing the evaluation of the Fram Strait measurements will follow.

In October 1997, an airborne gravimetry/altimetry campaign has been realized in the Azores region which is lying in the confluence of three main tectonic plates, the Azores triple junction. This area is considered as a natural laboratory for earth sciences research. The sea bottom topography shows peculiar features with active volcanism. From the oceanographic point of view the region presents very interesting characteristics which are not yet well known.
Within 54 flight hours the whole area has been covered with profiles perpendicular to the Mid-Atlantic Ridge (12 km seperation) and with additional tracks coinciding with ERS-2 and Topex/Poseidon tracks, see Fig. 7. The R/V Hakon Mosby was involved to perform the hydrographic (ADCP, CTD) and gravimetric ground truth measurements (about 4000 km profiles). Because a second LCR gravimeter/platform system (owned by AWI) is available for AGMASCO since the summer of 1997, the airplane and the ship were employed simultaneously for gravity measurements.

The results from satellite altimetry, and shipborne and airborne measurements will be compared and combined to improve the geoid and SST determination in this region.

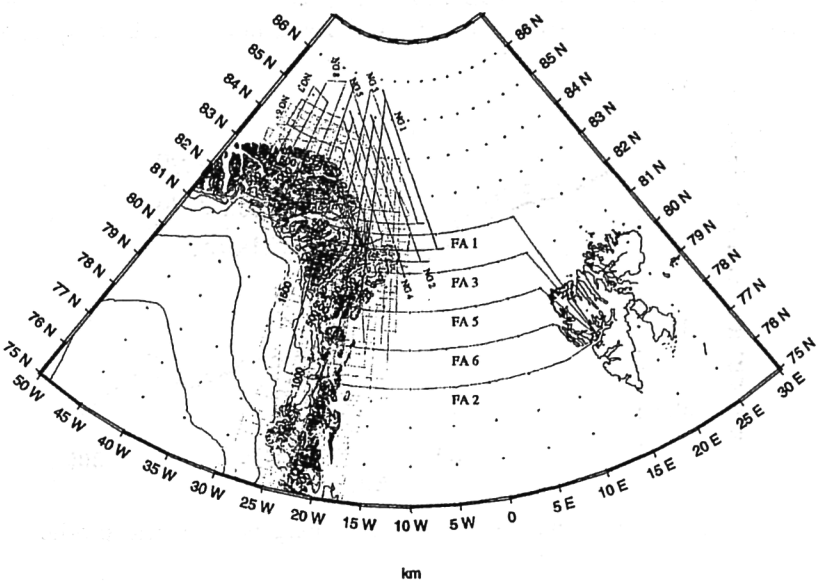


Fig. 6: The AGMASCO flight tracks crossing the Fram Strait in East-West direction. This project was coordinated with the NORDGRAV campaign in July/August 1997 (Boebel et al. 1998)

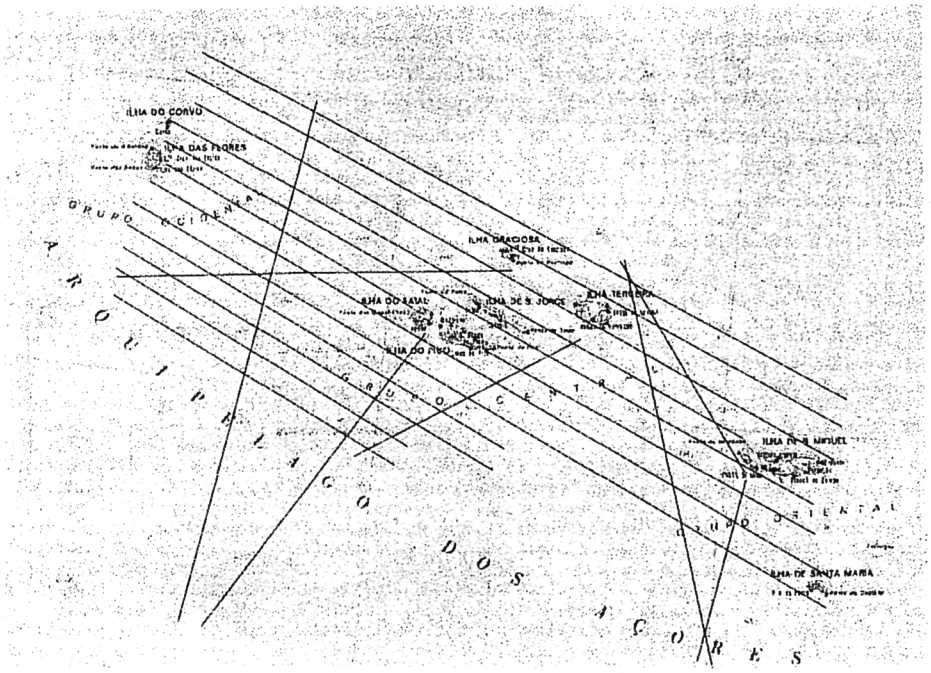


Fig. 7: The AGMASCO profiles during the Azores campaign Oct. 1997.

5. CONCLUSIONS

The already obtained results from the still ongoing data processing reveal accuracies at the 10 cm level regarding geoid and sea surface heights. This is derived from a comparison with available data, and simultaneous shipborne ground-truth measurements (gravity, ADCP, CTD, by R/V Hakon Mosby). The airborne and shipborne measurements along the ERS-2 and Topex/Poseidon tracks allow a direct comparison of the different techniques and will show the advantages of each system.
After the development and establishment of the AGMASCO system, an integration in larger application projects has to be striven for. This is a requirement to improve continually the system efficiency (smaller hardware components, more automatic data acquisition and processing) and to adapt it to future demands and available sensor technology. To increase the number of potential users, the AGMASCO group can as a technology spin-off offer the employment of their airplane based system for geophysical objectives in the field of geodynamics research or resource exploration.

6. ACKNOWLEDGEMENTS

This project is funded by the European Commission under the contract no. MAS3-CT95-0014. This support is gratefully acknowledged.

7. REFERENCES

Boebel, T., Bastos, L., Cunha, S., Forsberg, R., Gidskehaug, A., Meyer, U., Miller, H., Nesemann, M, Olesen, A. V., Timmen, L. and Xu, G., 1998: Airborne gravimetry and altimetry in North Greenland and Fram Strait - NORDGRAV'97. Presentation at the EGS General Assembly in Nice, France, April 1998, published in EGS Annales Geophysicae (Abstract).

Boedecker, G., Leismüller, F., Sponholtz, T., Cuno, J. and Neumeyer, K., 1994: Accelerometer/GPS integration for strapdown airborne gravimetry: first test results. Proc. IAG Symp. 113 Gravity and Geoid, 177-186, Springer, Berlin, Heidelberg, etc.

Gumert, W. R., 1995: Third generation aerogravity system. Proc. IAG Symp. Airborne Gravity Field Determination. Special Report No. 60010, Dept. of Geomatics Engineering, Univ. of Calgary, 153-161.

Harrison, J. C., MacQueen J. D., Rauhut, A. C. and Cruz, J. Y., 1995: The LCT Airborne Gravity System. Proc. IAG Symp. Airborne Gravity Field Determination. Special Report No. 60010, Dept. of Geomatics Engineering, Univ. of Calgary, 163-168.

Klingelé, E., Cocard, E., M. and Kahle, H.-G., 1997: Kinematic GPS as a source for airborne gravity reduction in the airborne gravity survey of Switzerland. J. Geophys. Res., 102, 7705-7715, 1997.

Olesen, A. V., Forsberg, R, and Gidskehaug, A., 1997: Airborne gravimetry using the La-Coste & Romberg gravimeter - an error analysis. In: M.E. Cannon and G. Lachapelle (Conveners): Proc. Int. Symp. Kin. Syst. in Geodesy, Geomatics and Navigation, Banff, Canada, 613-618.

Wei, M., K.-P. Schwarz 1995: Analysis of GPS-derived acceleration from airborne tests. Proc. IAG Symp. Airborne Gravity Field Determination. Special Report No. 60010, Dept. of Geomatics Engineering, Univ. of Calgary, 175-188.

Xu, G., Bastos, L. and Timmen, L., 1997: GPS kinematic positioning in AGMASCO campaigns - Strategic goals and numerical results. Proc. ION GPS-97, 1173-1183, Kansas City, USA.

Index of Contact Persons (Volumes I - IV)

Coordinators	Contract No. (Acronym)	Page
Akkerman R.J.	ERBMAS3CT960057 (MMS 2000+)	851
Amann Hans	ERBMAS3CT970102 (HYACE)	1529
Anagnostou Christos	ERBMAS3CT960049 (METROMED)	795
Bach Friedrich-Wilhelm	ERBMAS3CT970084 (EURODOCKER)	1403
Barstow Stephen Farley	ERBMAS3CT970109 (EUROWAVES)	911
Bergamasco Alessandro	ERBMAS3CT970145 (F-ECTS)	859
Berlamont Jean	ERBMAS3CT970082 (COSINUS)	585
Best Angus Ian	ERBMAS3CT950038 (POSEIDON)	1183
Bokn Tor Lauritz	ERBMAS3CT970153 (EULIT)	871
Buchholz Friedrich	ERBMAS3CT950013 (PEP)	39
Burt Richard	ERBMAS3CT970077 (HYTOV)	1095
Cammann Karl	ERBMAS3CT970138 (MASTOC)	1541
Cappenberg Thomas E.	ERBENV4CT970582 (ISLED)	741
Cervenka Pierre	ERBMAS3CT970090 (COSMOS)	1287
Chelazzi Guido	ERBMAS3CT950012 (EUROROCK)	361
Clero J.-P.	ERBMAS3CT950036 (MAUVE)	1367
Conradsen Knut	ERBMAS3CT950026 (BIOSONAR)	1171
Costello Mark J.	ERBMAS3CT970146 (MARINE SPECIES)	199
Cowling Michael	ERBMAS3CT950028 (BROS)	1471
Crépon Michel	ERBMAS3CT950043 (CLIVAMP)	23
Dalsgaard Tage	ERBMAS3CT960048 (NICE)	779
Dando Paul	ERBMAS3CT950021 (AG-HY-FL)	225
de Baar Hein	ERBMAS3CT950005 (MERLIM)	209
De Lange Gert-Jan	ERBMAS3CT970137 (SAP)	303
De Leeuw Gerardus	ERBENV4CT970526 (ANICE)	721
De Rouck Julien	ERBMAS3CT970116 (OPTICREST)	987
De Vriend Huib	ERBMAS3CT950002 (PACE)	487
de Wit Rutger	ERBENV4CT960218 (ROBUST)	687
Desbruyères Daniel	ERBMAS3CT950040 (AMORES)	287
Doeskeland Stein Ove	ERBMAS3CT970156 (CYANODRUGS)	1267
Döös Kristofer	ERBMAS3CT970142 (TRACMASS)	25
Du Buf Hans	ERBMAS3CT970122 (ADIAC)	1071
Dubelaar George B.J.	ERBMAS3CT950030 (CYTOBUOY)	1499
Duwe Kurt	EUROMAR EU 0429 (OPMOD)	1435
	ERBMAS3CT970089 (OPCOM)	907
Dyer Keith	ERBMAS3CT950022 (INTRMUD)	521
Elbaz-Poulichet Françoise	ERBENV4CT960217 (TOROS)	669
Favali Paolo	ERBMAS3CT950007 (GEOSTAR)	1321
Foote Kenneth	ERBMAS3CT950031 (BASS)	1011
Frankignoulle Michel	ERBENV4CT960213 (BIOGEST)	621
Fredsoe Joergen	ERBMAS3CT970081 (SASME)	575
Gasparini Otello	ERBMAS3CT970107 (SWAN)	1121
Geider Richard John	ERBMAS3CT970080 (AIMS)	1027
Gensane Marc	ERBMAS3CT950009 (DEO)	1139
Gieskes Winfried	ERBMAS3CT960050 (ESCAPE)	811
Goni Raquel	ERBMAS3CT970155 (ECOMARE)	139
Gorsky Gabriel	ERBMAS3CT980161 (EURAPP)	131

Granéli Edna	ERBMAS3CT970103 (NUTOX)	99
Gray John S.	ERBMAS3CT970148 (KEYCOP)	865
Graziottin Flavio	ERBMAS3CT950033 (VAMP)	1513
Gundersen Jens Kristian	ERBMAS3CT950029 (MICROMARE)	1487
	ERBMAS3CT970078 (MICRO-FLOW)	1381
Hamm Luc	ERBMAS3CT950004 (SAFE)	931
Henriet Jean-Pierre	ERBMAS3CT950045 (CORSAIRES)	239
Herman P.M.J.	ERBENV4CT960216 (ECOFLAT)	655
Hinton Oliver Richard	ERBMAS3CT970099 (LOTUS)	1109
Höfle Manfred	ERBMAS3CT970125 (MARGENES)	1245
Hovem Jens	ERBMAS3CT950046 (ISACS)	1275
Howarth Michael John	ERBMAS3CT970159 (PROVESS)	117
Jansen Eystein	ERBMAS3CT950015 (ESOP 2)	329
Kilpatrick Iain	ERBMAS3CT970091 (Composite Pressure...)	1411
Lane David	ERBMAS3CT950024 (AMADEUS)	1347
Lange Manfred A.	ERBENV4CT970637 (BASIS)	757
Launiainen Jouko	ERBMAS3CT970117 (BALTEX-BASIS)	353
Le Beux Yves	ERBMAS3CT970110 (ROBLINKS)	1133
Lefeuvre Jean-Claude	ERBENV4CT970436 (EUROSSAM)	715
Lehucher Pierre Marie	ERBMAS3CT960051 (MATER)	393
Leviandier Luc	ERBMAS3CT950027 (MORSE)	883
Lucas James	ERBMAS3CT970105 (DEBYE)	1045
Luyten Patrick	ERBMAS3CT970088 (COHERENS)	85
Maestrini Serge Y.	ERBMAS3CT970149 (DOMTOX)	867
Maier-Reimer Ernst	ERBMAS3CT970141 (SINOPS)	253
Marsset Bruno	ERBMAS3CT970121 (VHR3D)	1301
Martin Jean-Marie	ERBENV4CT960286 (EROS21)	703
Meincke Jens	ERBMAS3CT960070 (VEINS)	345
Mienert Jürgen	ERBMAS3CT950003 (ENAM II)	229
Miles Peter Raymond	ERBMAS3CT970101 (SEISCAN)	265
Mill Peter John	ERBMAS3CT950042 (AMBIOS)	194
Moelenberg Flemming	ERBMAS3CT960053 (PHASE)	835
Moore Peter Geoffrey	ERBMAS3CT950020 (BIOMAERL)	169
Müller Werner	ERBMAS3CT970118 (BIOMARK)	1567
O'Connor Brian	ERBMAS3CT970106 (INDIA)	601
Olsen Yngvar	ERBMAS3CT960052 (COMWEB)	823
Oost Wiebe	ERBMAS3CT950044 (ASGAMAGE)	211
Oumeraci Hocine	ERBMAS3CT950041 (PROVERBS)	945
Pacyna Jozef Marian	ERBENV4CT960214 (POPCYCLING)	633
Parker Eric J	ERBMAS3CT970119 (GOPAL)	1299
Parrilla Barrera Gregorio	ERBMAS3CT960060 (CANIGO)	433
Partensky Frederic	ERBMAS3CT970128 (PROMOLEC)	105
Pascoal António	ERBMAS3CT970092 (ASIMOV)	1413
Patching John W.	ERBMAS3CT970085 (BIOCOLOR)	77
Paterson David M	ERBMAS3CT970158 (BIOPTIS)	377
Pedersen Poul Moeller	ERBMAS3CT980160 (BIOBASE)	877
Pedros-Alio Carlos	ERBMAS3CT970154 (MIDAS)	195
Plaisant Alain	ERBMAS3CT950008 (PROSIM)	1077
Poertner Hans-Otto	ERBENV4CT970596 (CLICOFI)	747
Prandle David	ERBMAS3CT950025 (PROMISE)	533

Prendin Walter	ERBMAS3CT970083 (ARAMIS)	1391
Priede Imants	ERBMAS3CT950010 (ALIPOR)	1335
Prieur Daniel	ERBMAS3CT950034 (Microorganisms thermophiles biomolecular...)	1231
Provost Christine	ERBMAS3CT970130 (YOYO 2001)	1429
Rice Anthony Leonard	ERBMAS3CT950018 (BENGAL)	271
Riska Kaj	ERBMAS3CT950006 (ICE STATE)	315
Rosenthal Harald	ERBMAS3CT970111 (HARMFUL SHIPS)	919
Sanchez-Arcilla Agustin	ERBMAS3CT950037 (FANS)	561
Schmidt Heinar	ERBMAS3CT970157 (SOFIE)	1559
Schwarz Joachim	ERBMAS3CT970098 (LOLEIF)	973
Send Uwe	ERBMAS3CT970147 (OCTOPUS)	1553
Sinha Martin	ERBMAS3CT970120 (ISO-3D)	1069
Soulsby Richard Leslie	ERBMAS3CT970086 (COAST3D)	591
Stackebrandt Erko	ERBMAS3CT960047 (CHABADA)	763
Stal Lucas J.	ERBENV4CT970571 (BASIC)	727
Stanislas Gaetan	ERBMAS3CT970123 (DINOCAT)	33
Stips Adolf	ERBMAS3CT970114 (MITEC)	1057
Sumer B. Multu	ERBMAS3CT970097 (SCARCOST)	963
Tande Kurt	ERBMAS3CT950039 (TASC)	61
Thingstad Tron Frede	ERBMAS3CT950016 (MEDEA)	49
Thomas Gareth	ERBMAS3CT950011 (KADWCI)	503
Timmen Ludger	ERBMAS3CT950014 (AGMASCO)	997
Tintoré Joaquin	ERBMAS3CT950001 (OMEGA)	5
Valero Myriam	ERBMAS3CT950019 (BIOGAP)	153
Van Biesen Leo	ERBMAS3CT970100 (SIGMA)	1037
Van Rijn Leo Cornelis	ERBMAS3CT970115 (SEDMOC)	611
Van Soest Robertus W. M.	ERBMAS3CT970144 (SYMBIOSPONGE)	1253
van Velzen Kees	EUROMAR EU 0493 (ELANI)	1443
Vander Donckt Emile	ERBMAS3CT970143 (MEMOSEA)	1547
Verbist Jean-François	ERBMAS3CT950032 (Bioactive marine natural products)	1215
Vincent Christopher	ERBMAS3CT950017 (TRIDISMA)	1155
von Bodungen Bodo	ERBMAS3CT960058 (BASYS)	415
Watson Andrew	ERBMAS3CT950023 (IMCORP)	1459
Watson John	ERBMAS3CT970079 (HOLOMAR)	1197
Wensink Geert J.	ERBMAS3CT950035 (C-STAR)	549
Williams Allan Thomas	ERBENV4CT960215 (DUNES)	641
Wollast Roland	ERBMAS3CT960056 (OMEX II)	451
	ERBMAS3CT970076 (OMEX II -PHASE II)	469
Zibordi Giuseppe	ERBMAS3CT970087 (COLORS)	901

Index of Contracts (Volumes I - IV)

Contract No. (Acronym)	Coordinator	Page
ERBENV4CT960213 (BIOGEST)	Frankignoulle Michel	621
ERBENV4CT960214 (POPCYCLING)	Pacyna Jozef Marian	633
ERBENV4CT960215 (DUNES)	Williams Allan Thomas	641
ERBENV4CT960216 (ECOFLAT)	Herman P.M.J.	655
ERBENV4CT960217 (TOROS)	Elbaz-Poulichet Françoise	669
ERBENV4CT960218 (ROBUST)	de Wit Rutger	687
ERBENV4CT960286 (EROS21)	Martin Jean-Marie	703
ERBENV4CT970436 (EUROSSAM)	Lefeuvre Jean-Claude	715
ERBENV4CT970526 (ANICE)	De Leeuw Gerardus	721
ERBENV4CT970571 (BASIC)	Stal Lucas J.	727
ERBENV4CT970582 (ISLED)	Cappenberg Thomas E.	741
ERBENV4CT970596 (CLICOFI)	Poertner Hans-Otto	747
ERBENV4CT970637 (BASIS)	Lange Manfred A.	757
ERBMAS3CT950001 (OMEGA)	Tintoré Joaquin	5
ERBMAS3CT950002 (PACE)	De Vriend Huib	487
ERBMAS3CT950003 (ENAM II)	Mienert Jürgen	229
ERBMAS3CT950004 (SAFE)	Hamm Luc	931
ERBMAS3CT950005 (MERLIM)	de Baar Hein	209
ERBMAS3CT950006 (ICE STATE)	Riska Kaj	315
ERBMAS3CT950007 (GEOSTAR)	Favali Paolo	1321
ERBMAS3CT950008 (PROSIM)	Plaisant Alain	1077
ERBMAS3CT950009 (DEO)	Gensane Marc	1139
ERBMAS3CT950010 (ALIPOR)	Priede Imants	1335
ERBMAS3CT950011 (KADWCI)	Thomas Gareth	503
ERBMAS3CT950012 (EUROROCK)	Chelazzi Guido	361
ERBMAS3CT950013 (PEP)	Buchholz Friedrich	39
ERBMAS3CT950014 (AGMASCO)	Timmen Ludger	997
ERBMAS3CT950015 (ESOP 2)	Jansen Eystein	329
ERBMAS3CT950016 (MEDEA)	Thingstad Tron Frede	49
ERBMAS3CT950017 (TRIDISMA)	Vincent Christopher	1155
ERBMAS3CT950018 (BENGAL)	Rice Anthony Leonard	271
ERBMAS3CT950019 (BIOGAP)	Valero Myriam	153
ERBMAS3CT950020 (BIOMERLE)	Moore Peter Geoffrey	169
ERBMAS3CT950021 (AG-HY-FL)	Dando Paul	225
ERBMAS3CT950022 (INTRMUD)	Dyer Keith	521
ERBMAS3CT950023 (IMCORP)	Watson Andrew	1459
ERBMAS3CT950024 (AMADEUS)	Lane David	1347
ERBMAS3CT950025 (PROMISE)	Prandle David	533
ERBMAS3CT950026 (BIOSONAR)	Conradsen Knut	1171
ERBMAS3CT950027 (MORSE)	Leviandier Luc	883
ERBMAS3CT950028 (BROS)	Cowling Michael	1471
ERBMAS3CT950029 (MICROMARE)	Gundersen Jens Kristian	1487
ERBMAS3CT950030 (CYTOBUOY)	Dubelaar George Bavo Joseph	1499
ERBMAS3CT950031 (BASS)	Foote Kenneth	1011
ERBMAS3CT950032 (Bioactive marine prod)	Verbist Jean-François	1215
ERBMAS3CT950033 (VAMP)	Graziottin Flavio	1513
ERBMAS3CT950034 (Microorganisms therm)	Prieur Daniel	1231

ERBMAS3CT950035 (C-STAR)	Wensink Geert J.	549
ERBMAS3CT950036 (MAUVE)	Clero J.-P.	1367
ERBMAS3CT950037 (FANS)	Sanchez-Arcilla Agustin	561
ERBMAS3CT950038 (POSEIDON)	Best Angus Ian	1183
ERBMAS3CT950039 (TASC)	Tande Kurt	61
ERBMAS3CT950040 (AMORES)	Desbruyères Daniel	287
ERBMAS3CT950041 (PROVERBS)	Oumeraci Hocine	945
ERBMAS3CT950042 (AMBIOS)	Mill Peter John	194
ERBMAS3CT950043 (CLIVAMP)	Crépon Michel	23
ERBMAS3CT950044 (ASGAMAGE)	Oost Wiebe	211
ERBMAS3CT950045 (CORSAIRES)	Henriet Jean-Pierre	239
ERBMAS3CT950046 (ISACS)	Hovem Jens	1275
ERBMAS3CT960047 (CHABADA)	Stackebrandt Erko	763
ERBMAS3CT960048 (NICE)	Dalsgaard Tage	779
ERBMAS3CT960049 (METROMED)	Anagnostou Christos	795
ERBMAS3CT960050 (ESCAPE)	Gieskes Winfried	811
ERBMAS3CT960051 (MATER)	Lehucher Pierre Marie	393
ERBMAS3CT960052 (COMWEB)	Olsen Yngvar	823
ERBMAS3CT960053 (PHASE)	Moelenberg Flemming	835
ERBMAS3CT960056 (OMEX II)	Wollast Roland	451
ERBMAS3CT960057 (MMS 2000+)	Akkerman R.J.	851
ERBMAS3CT960058 (BASYS)	von Bodungen Bodo	415
ERBMAS3CT960060 (CANIGO)	Parrilla Barrera Gregorio	433
ERBMAS3CT960070 (VEINS)	Meincke Jens	345
ERBMAS3CT970076 (OMEX II -PHASE II)	Wollast Roland	469
ERBMAS3CT970077 (HYTOV)	Burt Richard	1095
ERBMAS3CT970078 (MICRO-FLOW)	Gundersen Jens K.	1381
ERBMAS3CT970079 (HOLOMAR)	Watson John	1197
ERBMAS3CT970080 (AIMS)	Geider Richard John	1027
ERBMAS3CT970081 (SASME)	Fredsoe Joergen	575
ERBMAS3CT970082 (COSINUS)	Berlamont Jean	585
ERBMAS3CT970083 (ARAMIS)	Prendin Walter	1391
ERBMAS3CT970084 (EURODOCKER)	Bach Friedrich-Wilhelm	1403
ERBMAS3CT970085 (BIOCOLOR)	Patching John W.	77
ERBMAS3CT970086 (COAST3D)	Soulsby Richard Leslie	591
ERBMAS3CT970087 (COLORS)	Zibordi Giuseppe	901
ERBMAS3CT970088 (COHERENS)	Luyten Patrick	85
ERBMAS3CT970089 (OPCOM)	Duwe Kurt	907
ERBMAS3CT970090 (COSMOS)	Cervenka Pierre	1287
ERBMAS3CT970091 (Composite Pressure...)	Kilpatrick Iain	1411
ERBMAS3CT970092 (ASIMOV)	Pascoal António	1413
ERBMAS3CT970097 (SCARCOST)	Sumer B. Multu	963
ERBMAS3CT970098 (LOLEIF)	Schwarz Joachim	973
ERBMAS3CT970099 (LOTUS)	Hinton Oliver Richard	1109
ERBMAS3CT970100 (SIGMA)	Van Biesen Leo	1037
ERBMAS3CT970101 (SEISCAN)	Miles Peter Raymond	265
ERBMAS3CT970102 (HYACE)	Amann Hans	1529
ERBMAS3CT970103 (NUTOX)	Granéli Edna	99
ERBMAS3CT970105 (DEBYE)	Lucas James	1045
ERBMAS3CT970106 (INDIA)	O'Connor Brian	601

ERBMAS3CT970107 (SWAN)	Gasparini Otello	1121
ERBMAS3CT970109 (EUROWAVES)	Barstow Stephen Farley	911
ERBMAS3CT970110 (ROBLINKS)	Le Beux Yves	1133
ERBMAS3CT970111 (HARMFUL SHIPS)	Rosenthal Harald	919
ERBMAS3CT970114 (MITEC)	Stips Adolf	1057
ERBMAS3CT970115 (SEDMOC)	Van Rijn Leo Cornelis	611
ERBMAS3CT970116 (OPTICREST)	De Rouck Julien	987
ERBMAS3CT970117 (BALTEX-BASIS)	Launiainen Jouko	353
ERBMAS3CT970118 (BIOMARK)	Müller Werner	1567
ERBMAS3CT970119 (GOPAL)	Parker Eric J	1299
ERBMAS3CT970120 (ISO-3D)	Sinha Martin	1069
ERBMAS3CT970121 (VHR3D)	Marsset Bruno	1301
ERBMAS3CT970122 (ADIAC)	Du Buf Hans	1071
ERBMAS3CT970123 (DINOCAT)	Stanislas Gaetan	33
ERBMAS3CT970125 (MARGENES)	Höfle Manfred	1245
ERBMAS3CT970128 (PROMOLEC)	Partensky Frederic	105
ERBMAS3CT970130 (YOYO 2001)	Provost Christine	1429
ERBMAS3CT970137 (SAP)	De Lange Gert-Jan	303
ERBMAS3CT970138 (MASTOC)	Cammann Karl	1541
ERBMAS3CT970141 (SINOPS)	Maier-Reimer Ernst	253
ERBMAS3CT970142 (TRACMASS)	Döös Kristofer	25
ERBMAS3CT970143 (MEMOSEA)	Vander Donckt Emile	1547
ERBMAS3CT970144 (SYMBIOSPONGE)	Van Soest Robertus W. M.	1253
ERBMAS3CT970145 (F-ECTS)	Bergamasco Alessandro	859
ERBMAS3CT970146 (MARINE SPECIES)	Costello Mark J.	199
ERBMAS3CT970147 (OCTOPUS)	Send Uwe	1553
ERBMAS3CT970148 (KEYCOP)	Gray John S.	865
ERBMAS3CT970149 (DOMTOX)	Maestrini Serge Y.	867
ERBMAS3CT970153 (EULIT)	Bokn Tor Lauritz	871
ERBMAS3CT970154 (MIDAS)	Pedros-Alio Carlos	195
ERBMAS3CT970155 (ECOMARE)	Goni Raquel	139
ERBMAS3CT970156 (CYANODRUGS)	Doeskeland Stein Ove	1267
ERBMAS3CT970157 (SOFIE)	Schmidt Heinar	1559
ERBMAS3CT970158 (BIOPTIS)	Paterson David M	377
ERBMAS3CT970159 (PROVESS)	Howarth Michael John	117
ERBMAS3CT980160 (BIOBASE)	Pedersen Poul Moeller	877
ERBMAS3CT980161 (EURAPP)	Gorsky Gabriel	131
EUROMAR EU 0429 (OPMOD)	Duwe Kurt	1435
EUROMAR EU 0493 (ELANI)	van Velzen Kees	1443

CORDIS

The Community Research and Development Information Service

Your European R&D Information Source

CORDIS represents a central source of information crucial for any organisation - be it industry, small and medium-sized enterprises, research organisations or universities - wishing to participate in the exploitation of research results, participate in EU funded science and technology programmes and/or seek partnerships.

CORDIS makes information available to the public through a collection of databases. The databases cover research programmes and projects from their preparatory stages through to their execution and final publication of results. A daily news service provides up-to-date information on EU research activities including calls for proposals, events, publications and tenders as well as progress and results of research and development programmes. A partner search facility allows users to register their own details on the database as well as search for potential partners. Other databases cover Commission documents, contact information and relevant publications as well as acronyms and abbreviations.

By becoming a user of CORDIS you have the possibility to:

- Identify opportunities to manufacture and market new products
- Identify partnerships for research and development
- Identify major players in research projects
- Review research completed and in progress in areas of your interest

The databases - nine in total - are accessible on-line free of charge. As a user-friendly aid for on-line searching, Watch-CORDIS, a Windows-based interface, is available on request. The databases are also available on a CD-ROM. The current databases are:

News (English, German and French version) - Results -
Partners - Projects - Programmes - Publications -
Acronyms - Comdocuments - Contacts

CORDIS on World Wide Web

The CORDIS service was extended in September 1994 to include the CORDIS World Wide Web (WWW) server on Internet. This service provides information on CORDIS and the CORDIS databases, various software products, which can be downloaded (including the above mentioned Watch-CORDIS) and the possibility of downloading full text documents including the work programmes and information packages for all the research programmes in the Fourth Framework and calls for proposals.

The CORDIS WWW service can be accessed on the Internet using browser software (e.g. Netscape) and the address is: http://www.cordis.lu/

The CORDIS News database can be accessed through the WWW.

Contact details for further Information

If you would like further information on the CORDIS services, publications and products, please contact the CORDIS Help Desk :

CORDIS Customer Service
B.P. 2373
L-1023 Luxembourg

Telephone: +352-401162-240
Fax: +352-401162-248
E-mail: helpdesk@cordis.lu
WWW: http://www.cordis.lu/

European Commission

EUR 18220 — Third European Marine Science and Technology Conference — Project Synopses — Volume II: Strategic Marine Research

Luxembourg: Office for Official Publications of the European Communities

1998 — xxx, 523 pp. — 17.6 x 25 cm

ISBN 92-828-2896-4 (Volumes I to VI)
ISBN 92-828-3035-7 (Volume II)

Price (excluding VAT) in Luxembourg (Volumes I to VI): ECU 78

Venta • Salg • Verkauf • Πωλήσεις • Sales • Vente • Vendita • Verkoop • Venda • Myynti • Försäljning

BELGIQUE/BELGIË

Moniteur belge/Belgisch Staatsblad
Rue de Louvain 40-42/Leuvenseweg 40-42
B-1000 Bruxelles/Brussel
Tél. (32-2) 552 22 11
Fax (32-2) 511 01 84

Jean De Lannoy
Avenue du Roi 202/Koningslaan 202
B-1060 Bruxelles/Brussel
Tél. (32-2) 538 51 69
Fax (32-2) 538 08 41
E-mail: jean.de.lannoy@infoboard.be
URL: http://www.jean-de-lannoy.be

Librairie européenne/Europese Boekhandel
Rue de la Loi 244/Wetstraat 244
B-1040 Bruxelles/Brussel
Tél. (32-2) 295 26 39
Fax (32-2) 735 08 60

DANMARK

J. H. Schultz Information A/S
Herstedvang 10-12
DK-2620 Albertslund
Tlf. (45) 43 63 23 00
Fax (45) 43 63 19 69
E-mail: schultz@schultz.dk
URL: http://www.schultz.dk

DEUTSCHLAND

Bundesanzeiger Verlag
Breite Straße 78-80
Postfach 10 05 34
D-50667 Köln
Tel. (49-221) 20 29-0
Fax (49-221) 202 92 78
E-mail: vertrieb@bundesanzeiger.de
URL: http://www.bundesanzeiger.de

ΕΛΛΑΔΑ/GREECE

G. C. Eleftheroudakis SA
International Bookstore
Panepistimiou 17
GR-10564 Athina
Tel. (30-1) 331 41 80/1/2/3
Fax (30-1) 323 98 21
E-mail: elebooks@netor.gr

ESPAÑA

Mundi Prensa Libros, SA
Castelló, 37
E-28001 Madrid
Tel. (34-1) 431 33 99
Fax (34-1) 575 39 98
E-mail: libreria@mundiprensa.es
URL: http://www.mundiprensa.es

Boletín Oficial del Estado
Trafalgar, 27
E-28010 Madrid
Tel. (34-1) 538 21 11 (Libros)/
384 17 15 (Suscripciones)
Fax (34-1) 538 21 21 (Libros)/
384 17 14 (Suscripciones)
E-mail: webmaster@boe.es
URL: http://www.boe.es

FRANCE

Journal officiel
Service des publications des CE
26, rue Desaix
F-75727 Paris Cedex 15
Tél. (33) 140 58 77 01/31
Fax (33) 140 58 77 00

IRELAND

Government Supplies Agency
Publications Section
4-5 Harcourt Road
Dublin 2
Tel. (353-1) 661 31 11
Fax (353-1) 475 27 60

ITALIA

Licosa SpA
Via Duca di Calabria, 1/1
Casella postale 552
I-50125 Firenze
Tel. (39-55) 64 54 15
Fax (39-55) 64 12 57
E-mail: licosa@ftbcc.it
URL: http://www.ftbcc.it/licosa

LUXEMBOURG

Messageries du livre SARL
5, rue Raiffeisen
L-2411 Luxembourg
Tél. (352) 40 10 20
Fax (352) 49 06 61
E-mail: mdl@pt.lu

Abonnements:

Messageries Paul Kraus
11, rue Christophe Plantin
L-2339 Luxembourg
Tél. (352) 49 98 88-8
Fax (352) 49 98 88-444
E-mail: mpk@pt.lu
URL: http://www.mpk.lu

NEDERLAND

SDU Servicecentrum Uitgevers
Externe Fondsen
Postbus 20014
2500 EA Den Haag
Tel. (31-70) 378 98 80
Fax (31-70) 378 97 83
E-mail: sdu@sdu.nl
URL: http://www.sdu.nl.

ÖSTERREICH

Manz'sche Verlags- und Universitätsbuchhandlung GmbH
Siebenbrunnengasse 21
Postfach 1
A-1050 Wien
Tel. (43-1) 53 16 13 34/40
Fax (43-1) 53 16 13 39
E-mail: auslieferung@manz.co.at
URL: http://www.austria.EU.net:81/manz

PORTUGAL

Imprensa Nacional-Casa da Moeda, EP
Rua Marquês de Sá da Bandeira, 16 A
P-1050 Lisboa Codex
Tel. (351-1) 353 03 99
Fax (351-1) 353 02 94, 384 01 32

Distribuidora de Livros Bertrand Ld.ª
Rua das Terras dos Vales, 4/A
Apartado 60037
P-2701 Amadora Codex
Tel. (351-1) 495 90 50, 495 87 87
Fax (351-1) 496 02 55

SUOMI/FINLAND

Akateeminen Kirjakauppa/Akademiska Bokhandeln
Pohjoisesplanadi 39/
Norra esplanaden 39
PL/PB 128
FIN-00101 Helsinki/Helsingfors
P./tfn (358-9) 121 41
F./fax (358-9) 121 44 35
E-mail: akatilaus@stockmann.mailnet.fi
URL: http://booknet.cultnet.fi/aka/index.htm

SVERIGE

BTJ AB
Traktorvägen 11
S-221 82 Lund
Tfn (46-46) 18 00 00
Fax (46-46) 30 79 47
E-post: btjeu-pub@btj.se
URL: http://www.btj.se/media/eu

UNITED KINGDOM

The Stationery Office Ltd International Sales Agency
51 Nine Elms Lane
London SW8 5DR
Tel. (44-171) 873 90 90
Fax (44-171) 873 84 63
E-mail: jill.speed@theso.co.uk
URL: http://www.the-stationery-office.co.uk

ÍSLAND

Bokabud Larusar Blöndal
Skólavördustig, 2
IS-101 Reykjavik
Tel. (354) 551 56 50
Fax (354) 552 55 60

NORGE

NIC Info A/S
Ostenjoveien 18
Boks 6512 Etterstad
N-0606 Oslo
Tel. (47-22) 97 45 00
Fax (47-22) 97 45 45

SCHWEIZ/SUISSE/SVIZZERA

OSEC
Stampfenbachstraße 85
CH-8035 Zürich
Tel. (41-1) 365 53 15
Fax (41-1) 365 54 11
E-mail: uleimbacher@osec.ch
URL: http://www.osec.ch

BĂLGARIJA

Europress-Euromedia Ltd
59, Bld Vitosha
BG-1000 Sofia
Tel. (359-2) 980 37 66
Fax (359-2) 980 42 30

ČESKÁ REPUBLIKA

NIS CR — prodejna
Konviktská 5
CZ-113 57 Praha 1
Tel. (420-2) 24 22 94 33, 24 23 09 07
Fax (420-2) 24 22 94 33
E-mail: nkposp@dec.nis.cz
URL: http://www.nis.cz

CYPRUS

Cyprus Chamber of Commerce & Industry
Griva-Digeni 38 & Deligiorgi 3
Mail orders:
PO Box 1455
CY-1509 Nicosia
Tel. (357-2) 44 95 00, 46 23 12
Fax (357-2) 36 10 44
E-mail: cy1691_eic_cyprus@vans.infonet.com

MAGYARORSZÁG

Euro Info Service
Európa Ház
Margitsziget
PO Box 475
H-1396 Budapest 62
Tel. (36-1) 111 60 61, 111 62 16
Fax (36-1) 302 50 35
E-mail: euroinfo@mail.matav.hu
URL: http://www.euroinfo.hu/index.htm

MALTA

Miller Distributors Ltd
Malta International Airport
PO Box 25
LQA 05 Malta
Tel. (356) 66 44 88
Fax (356) 67 67 99

POLSKA

Ars Polona
Krakowskie Przedmiescie 7
Skr. pocztowa 1001
PL-00-950 Warszawa
Tel. (48-22) 826 12 01
Fax (48-22) 826 62 40, 826 53 34, 826 86 73
E-mail: ars_pol@bevy.hsn.com.pl

ROMÂNIA

Euromedia
Str. G-ral Berthelot Nr 41
RO-70749 Bucuresti
Tél. (40-1) 210 44 01, 614 06 64
Fax (40-1) 210 44 01, 312 96 46

SLOVAKIA

Slovak Centre of Scientific and Technical Information
Námestie slobody 19
SK-81223 Bratislava 1
Tel. (421-7) 531 83 64
Fax (421-7) 531 83 64
E-mail: europ@tbb1.sltk.stuba.sk

SLOVENIA

Gospodarski Vestnik
Zalozniska skupina d.d.
Dunajska cesta 5
SLO-1000 Ljubljana
Tel. (386) 611 33 03 54
Fax (386) 611 33 91 28
E-mail: belicd@gvestnik.si
URL: http://www.gvestnik.si

TÜRKIYE

Dünya Infotel AS
Istiklál Cad. No: 469
TR-80050 Tünel-Istanbul
Tel. (90-212) 251 91 96
Fax (90-212) 251 91 97

AUSTRALIA

Hunter Publications
PO Box 404
3167 Abbotsford, Victoria
Tel. (61-3) 94 17 53 61
Fax (61-3) 94 19 71 54

CANADA

Subscriptions only/Uniquement abonnements:

Renouf Publishing Co. Ltd
5369 Chemin Canotek Road Unit 1
K1J 9J3 Ottawa, Ontario
Tel. (1-613) 745 26 65
Fax (1-613) 745 76 60
E-mail: renouf@fox.nstn.ca
URL: http://www.renoufbooks.com

EGYPT

The Middle East Observer
41, Sherif Street
Cairo
Tel. (20-2) 393 97 32
Fax (20-2) 393 97 32

HRVATSKA

Mediatrade Ltd
Pavla Hatza 1
HR-10000 Zagreb
Tel. (385-1) 43 03 92
Fax (385-1) 43 03 92

INDIA

EBIC India
3rd Floor, Y. B. Chavan Centre
Gen. J. Bhosale Marg.
400 021 Mumbai
Tel. (91-22) 282 60 64
Fax (91-22) 285 45 64
E-mail: ebic@giasbm01.vsnl.net.in

ISRAËL

ROY International
17, Shimon Hatarssi Street
PO Box 13056
61130 Tel Aviv
Tel. (972-3) 546 14 23
Fax (972-3) 546 14 42
E-mail: royil@netvision.net.il

Sub-agent for the Palestinian Authority:

Index Information Services
PO Box 19502
Jerusalem
Tel. (972-2) 627 16 34
Fax (972-2) 627 12 19

JAPAN

PSI-Japan
Asahi Sanbancho Plaza #206
7-1 Sanbancho, Chiyoda-ku
Tokyo 102
Tel. (81-3) 32 34 69 21
Fax (81-3) 32 34 69 15
E-mail: psijapan@gol.com
URL: http://www.psi-japan.com

MALAYSIA

EBIC Malaysia
Level 7, Wisma Hong Leong
18 Jalan Perak
50450 Kuala Lumpur
Tel. (60-3) 262 62 98
Fax (60-3) 262 61 98
E-mail: ebic-kl@mol.net.my

PHILIPPINES

EBIC Philippines
19th Floor, PS Bank Tower Sen.
Gil J. Puyat Ave. cor.Tindalo St.
Makati City
Metro Manilla
Tel. (63-2) 759 66 80
Fax (63-2) 759 66 90
E-mail: eccpcom@globe.com.ph

RUSSIA

CCEC
60-letiya Oktyabrya Av. 9
117312 Moscow
Tel. (70-95) 135 52 27
Fax (70-95) 135 52 27

SOUTH AFRICA

Safto
5th Floor Export House,
CNR Maude & West Streets
PO Box 782 706
2146 Sandton
Tel. (27-11) 883 37 37
Fax (27-11) 883 65 69

SOUTH KOREA

Kyowa Book Company
1 F1, Phyung Hwa Bldg
411-2 Hap Jeong Dong, Mapo Ku
121-220 Seoul
Tel. (82-2) 322 67 80/1
Fax (82-2) 322 67 82
E-mail: kyowa2@ktnet.co.kr.

THAÏLANDE

EBIC Thailand
Vanissa Building 8th Floor
29 Soi Chidlom
Ploenchit
10330 Bangkok
Tel. (66-2) 655 06 27
Fax (66-2) 655 06 28
E-mail: ebicbkk@ksc15.th.com

UNITED STATES OF AMERICA

Bernan Associates
4611-F Assembly Drive
MD20706 Lanham
Tel. (800) 274 44 47 (toll free telephone)
Fax (800) 865 34 50 (toll free fax)
E-mail: query@bernan.com
URL: http://www.beman.com

ANDERE LÄNDER/OTHER COUNTRIES/ AUTRES PAYS

Bitte wenden Sie sich an ein Büro Ihrer Wahl / Please contact the sales office of your choice / Veuillez vous adresser au bureau de vente de votre choix

NB: Country order: EU, EFTA, EU applicant countries, others.

NOTICE TO THE READER

Information on European Commission publications in the areas of research and innovation can be obtained from:

◆ **CORDIS, the Community R & D Information Service**

For more information, contact:
CORDIS Customer Service, BP 2373, L-1023 Luxembourg
Tel. (352) 40 11 62-240; fax (352) 40 11 62-248; e-mail: helpdesk@cordis.lu
or visit the website at http://www.cordis.lu/

◆ **Euroabstracts**

The European Commission's periodical on research publications, issued every two months.
For more information, contact:
RTD help desk, European Commission, DG XIII, L-2920 Luxembourg
Fax (352) 43 01-32084; e-mail: rtd-helpdesk@lux.dg13.cec.be

3 14 15 CG-60-98-002-EN-C

Price (excluding VAT) in Luxembourg (Volumes I to VI): ECU 78

OFFICE FOR OFFICIAL PUBLICATIONS
OF THE EUROPEAN COMMUNITIES

L-2985 Luxembourg

ISBN 92-828-3035-7