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THIRD EUROPEAN MARINE SCIENCE AND TECHNOLOGY CONFERENCE

Lisbon, 23-27 May 1998

PROJECT SYNOPSES
Volume I: Marine Systems

EUR 18220



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 I: Marine Systems

EUR 18220 EN

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

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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 92-828-2898-0 (Volume I)

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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.

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[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

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Marine Systems

I.1. Marine systems research

I.1.1. Circulation and exchange of water masses

TITLE: **OBSERVATIONS AND MODELLING OF EDDY SCALE GEOSTROPHIC AND AGEOSTROPHIC CIRCULATION: THE OMEGA PROJECT**

CONTRACT NO: MAS3-CT95-0001

COORDINATOR:

Joaquín Tintoré
IMEDEA (CSIC-UIB)
Edifici Mateu Orfila, Campus UIB
E-07071 Palma (Balears)
Spain
Tel: +34-71-173227 Fax: +34-71-173426
email: dfsjts0@ps.uib.es
http://campanilla.uib.es/Omega/

PARTNERS:

John T. Allen
Southampton Oceanography Center (SOC)
(James Rennell Division)
Empress Dock
Southampton, Hamsphire SO14 3ZH
United Kingdom
Tel: +44-1703-596429
Fax: +44-1703-596204
email: jta@soc.soton.ac.uk

Jordi Font
Institut de Ciències del Mar (CSIC)
Grup d'Oceanografia Física
P. Joan de Borbó s/n
E-08039-Barcelona
Spain
Tel: +34-3-2216450
Fax: +34-3-2217340
email: jfont@icm.csic.es

Jean Marie Beckers
GHER, B5 Sart Tilman
Université de Liège
B-4000-Liège, Belgique
Tel: +32-4-3663358
Fax: +32-4-3662355
email: beckers@segi.ulg.ac.be

Giovanni Corsini
Università degli Studi di Pisa
Dipartimento Ingegneria della Informazione
Via Diotisalvi, 2
I-56126-Pisa, Italy
Tel: 39 (0) 50 568511 Fax: 39 (0) 50 568522
email: gcorsini@iet.unipi.it

Jean Claude Gascard
LODYC, Université Paris VI - CNRS,
Tour 26, 4 Place Jussieu
75252 Paris
France
Tel: 33 1 44277070. Fax: 33 1 44273805
email: gascard@lodyc.jussieu.fr

Jaime Rodríguez
Dept. de Ecología
Universidad de Málaga
Campus Universitario de Teatinos
E-29071-Málaga, Spain
Tel: 952 -13 18 50 Fax: 952-13 20 00
email: jaime@uma.es

OBSERVATIONS AND MODELLING OF EDDY SCALE GEOSTROPHIC AND AGEOSTROPHIC CIRCULATION

Tintoré J.; Vélez P., Gomis D., Monserrat S., Allen J., Guymer T., Roe H., Smeed D., Cipollini P., Font J., Ruíz, O. Chic, S., Beckers J.M., Rixen, M., Corsini G., Diani M., Baldacci A., Rodriguez J., Blanco, F. Jimenez, J.M., Echevarría, F., A. Corzo, Ruíz J., Gascard J.C. and OMEGA Group collaborators

SUMMARY

The importance of *three-dimensional ageostrophic motion* in mesoscale oceanic features such as fronts, meanders, eddies and filaments has been established in recent years in a number of areas of the world's oceans. Vertical velocities found in these features are of the order of several tens of meters per day, this is an order of magnitude higher than the largest vertical velocities usually observed in upwelling areas. The relevance of the ageostrophic motion comes from the fact that it conects the deep ocean to the upper layer. OMEGA is an *interdisciplinary process oriented study* of general scientific interest for marine sciences that could be carried out in any ocean area characterised by sharp density gradients and significant mesoscale variability.

The major *objectives* of this project are (1) to determine the spatial and temporal variability of the three-dimensional ageostrophic circulation in an intense mesoscale upper ocean front (upper 300 m), (2) to understand the relationship between biological variability and mesoscale physics and (3) to provide the scientific community with a new and useful tool for computation of vertical motions from routine CTD and ADCP data, using an interdisciplinary theoretical and experimental (in situ and remote) approach. Understanding and quantifying vertical velocities in front/eddy systems represents a continuation of our previous studies (Tintoré et al. 1991; Pollard and Regier 1992; Allen et al. 1994; Allen and Smeed 1996), and has the ultimate aim of quantifying the net importance of ageostrophic circulations in the world's oceans.

Physical forcing at the mesoscale has clear biological implications such as the enhancement of primary production and patchy biomass accumulations of large phytoplankton cells. Usually this is explained as the result of nutrient transport into the euphotic zone and phytoplankton growth, but there is also the possibility of a direct effect of vertical motions on the size structure of phytoplankton. Flow cytometry and image analysis permit a fast description and size-spectrum modelling of the phytoplankton community (Rodríguez and Li, 1994), and were applied to the analysis of macroscale features in the Alboran Sea (Rodríguez et al., in press). Recent studies using acoustic techniques have also demonstrated that biological patchiness of zooplankton may be closely coupled with hydrographic variability and that distributions that are seemingly inexplicable on behavioural grounds are related to the vertical circulation in the upper ocean. Understanding the interactions between physical, chemical and biological systems and their inherent scales of variability is a necessary prerequisite for predicting the ways that the ocean responds to environmental change.

The field work was completed in the Alborán Sea during October (BIO Hesperides) and December (R/V Discovery) 1996. Data obtained in 4 consecutive samplings of the same area included Seasoar, ADCP, fluorescence, acoustic backscatter, nutrients, flow-cytometry, lagrangian floats, etc. Preliminary analysis of these data show the existence of significant temporal variability and also variability at scales of the order of the internal Rossby Radius and also indirect evidences of vertical motions. On board flow cytometry analyses and size-fractionated chlorophyll have demonstrated the existence of strong mesoscale biological patchiness along the fronts. Patchiness variability between consecutive surveys illustrate the relevance of frontal activity, advective transport and fast water-mass changes in the region. Dynamic models and diagnostic methods are being used to interpret the observations and to diagnose the dynamically balanced mesoscale circulation, including the vertical velocity. These methods include quasigeostrophic (QG), semigeostrophic (SG) and iterated geostrophic (IG) models, as well as the primitive equations based method of digital filter initialization (DFI). Results obtained with all these different methods are presented here and discused.

1. INTRODUCTION

General perspective

The significance of the ageostrophic circulation in mesoscale ocean structures such as eddies, filaments or meanders has been clearly established in different regions of the world's oceans in recent years. More specifically, the understanding of vertical motions -which are purely ageostrophic- and their biological implications has motivated several recent studies (Woods et al. 1986; Leach 1987; Tintoré et al. 1988; Pollard and Regier, 1992, Prieur and Sournia, 1994). In the Coastal Transition Zone (CTZ) off the California coast, mesoscale filaments are characterised by vertical motions up to 40 m/day that force nutrient-rich coastal waters to sink along the filaments (Dewey et al. 1991; Haidvogel et al. 1991). In Gulf Stream meanders, several authors also found vertical velocities of several/many tens of meters per day from both experimental and numerical studies (Bower and Rossby 1989; Onken 1992; Lindstrom and Watts 1994).

Mesoscale structures and computation of vertical velocity

The vertical velocity component of mesoscale circulation is a critical dynamical variable for identifying the important scales of physical balance in the ocean and the marine ecosystem. However, this is a variable which cannot be directly measured in routine studies, and indirect techniques are required for its estimation. Some early estimation of vertical motion was carried out by Chew et al. (1985) who used a temperature conservation equation to show that significant vertical motions could occur within frontal Gulf Stream meanders.

The Omega equation is a diagnostic method for estimating vertical motion based on quasi-geostrophic balance, without any stationarity assumption (Hoskins et al. 1978), and that has proved to be a useful tool for mapping the atmospheric vertical velocity field. Its reliability for ocean studies was first established by Leach (1987). A similar application of the Omega equation to hydrographic data collected in the Alborán Sea was carried out by Tintoré et al. (1991) who diagnosed vertical velocities up to 50 m/day. At a Sargasso Sea front, Pollard and Regier (1992) applied a 2-D version of the Omega equation to SeaSoar undulating CTD data and shipboard ADCP data to estimate vertical motions. Their calculations showed that vertical velocities in excess of 40 m/day could be found in intense frontal regions.

A major result of these studies is the dependence of the vertical velocity magnitude on the scale of the considered horizontal motion. Fiekas et al. (1994) diagnosed vertical motions around 5 m/day, due to instabilities of around 85 km wavelength at the North Atlantic Intergyre Front. Tintoré et al. (1991) and Viúdez et al. (1996a) experimentally found that the vertical velocities associated with frontal waves of the western Alboran gyre were one order of magnitude higher than the ones diagnosed in the large scale gyre itself. In the Sargasso Sea, Pollard and Regier (1992) observed that maximum vertical velocities (40 m/day) were associated with small surface-trapped frontal eddies (~40 km). Allen and Smeed (1996) have recently diagnosed vertical velocities in excess of 90 m/day in an Omega equation analysis of SeaSoar and ADCP data from an experimental observation of (20-30 km scale) eddies and meanders at the Iceland Færœs Front. Estimates made from three data sources (RAFOS floats, current meters and IES) by Lindstrom and Watts (1994) also asesed the occurrence of intense vertical motions at short scales.

Computation of vertical velocity using numerical models

Numerical studies actually clarified this dependence of the vertical velocity on the horizontal scale considered. Realistic simulations of the mesoscale circulation in the CTZ indicated that strong downwelling (40 m/day) could take place at the edge of narrow filaments (Haidvogel et al. 1991). The results of high resolution modelling of frontogenesis (Wang 1993) showed that vertical velocities up to 100 m/day could be expected at Rossby deformation radius scale meanders due to frontal baroclinic instability. Allen et al (1993) compared the results obtained from the IGM (Iterative Geostrophic Method) method to those in PE simulations, showing that the IGM method gives a simple but acurate aproximation. Barth (1994) found that rapidly growing frontal instabilities were associated with vertical motions much larger than those associated with long-wavelength modes. Strass (1994) carried out numerical simulations of mesoscale instabilities at fronts and also found the largest vertical velocities at highest wavenumbers. Primitive equation models also provide a useful mean of objectively

determining errors involved in vertical velocity diagnosis (Fiekas et al. 1994). Viúdez et al. (1996b) used a data assimilation technique with a primitive equation model to obtain consistent three-dimensional ageostrophic velocity fields in the Alborán Sea. Pinot et al (1996) used results obtained from a primitive equation model as observations and compared the results obtained computing vertical velocity using QG and semi geostrophic theory. They found that SG results were closer to PE model results but recent work carried out by Pedder (1998, personal comunication) indicates that SG has to be used with great care due to the geometrical transformations involved.
However, it is known that primitive equation models may produce noisy vertical velocities, especially when the internal radius of deformation is poorly resolved. Furthermore, vertical velocities are the result of divergence in the ageostrophic, generally weaker, component of the horizontal velocity field and are therefore sensitive to small changes in balance of the flow, as well as model boundary conditions and numerical resolution. Care must be taken that the vertical velocities predicted by a primitive equation model are accurate if they are to be used to drive a biological model.

Vertical exchanges and biochemical implications
Several interdisciplinary studies suggested that vertical advection can have a net effect on the vertical exchanges of properties and hence a determinant impact on the marine ecosystem. Simple models of eddies observed at the Iceland Færœs Front (Allen et al. 1994) showed that salt and heat transports across the front due to the formation and breaking of unstable meanders can be significant, drawing warm high salinity water up and over cold dense water. It is now well known that fronts are places of enhanced biological activity and that, from the biological point of view, vertical circulation is of great significance to primary productivity and may explain its patchiness in the surface layers of the ocean and the patchiness of nutrient distributions (Strass, 1992). This patchiness echoes the identification of the mesoscale as a critical scale for physical variability.
The transport of phytoplankton across the thermocline and the phytoplankton growth in the euphotic zone have been studied by a number of authors, among others and initially by Woods et al. (1986) and Leach (1987). The upward transport of nutrient-rich subsurface waters into the surface layer is one possible mechanism for enhancing primary production. In a Mediterranean eddy/front system, Pinot et al. (1995) found a significant relationship between an upwelling pattern at the cold side of the front and coincident maxima of nitrate and chlorophyll concentrations. On ecophysiological grounds, abundance of nutrients would explain why phytoplankton is dominated by large cells storing large amounts of chlorophyll. Under nutrient-limiting conditions, small size (higher surface/volume ratio) would be advantageous (see Chisholm, 1992 for a revision). On strictly physical grounds, the persistence of large cells in the upper layer against their tendency to sink was directly related to upward motion and turbulence (Semina, 1971; Peña et al., 1990; Ruíz et al., 1996a). Conversely, streamers of phytoplankton have been observed being drawn down to depths of 350 m in areas of high vertical velocities (Pollard et al., 1991). In any case, cell size appears as a relevant variable in the analysis of physical and biological coupling and vertical fluxes in the pelagic ecosystem.
The analysis of the size structure of plankton was a theoretical subject until Rodriguez and Mullin (1986) described the first complete size spectrum in the North Pacific Central Gyre. More recently, the development of techniques like flow cytometry and image analysis permitted a much more efficient way of describing size-biomass spectra (Rodríguez and Li, 1994) and, consequently, the possibility of applying the size-based aproach to the analysis of physical - biological interactions at different scales in the ocean (Ruíz et al., 1996b; Rodríguez et al., in press). In particular the small sample volume needed, the short-time required for analysis and the large population sizes obtained, make flow cytometry an extremely useful technique to study biological patchiness at the mesoscale.
Similar arguments can be applied to zoopankton, that may actively make use of the presence of local water transports to find and successfully exploit patches of phytoplankton. Bioacoustic measurements form the basis for promising modern methodologies using ADCPs and multi frequency echo-sounders to provide high resolution data for the vertical distribution of zooplankton in the water column. Since these are non-intrusive underway measurements, they provide biological information on small time and space scales and therefore allow the

investigation of mesoscale bio-physical interactions. The current use of ADCP data for biological observations with detailed SeaSoar hydrography has been demonstrated by Roe and Griffiths (1993). Roe et al. (1994) showed how the movement and distribution of zooplankton correlate with mesoscale eddies and fronts. Most previous authors used ADCP data to provide relative acoustic backscatter which can only give a qualitative view of the behaviour and patchiness of zooplankton. Roe et al. (1996) used in situ temperature and salinity profiles to calculate the vertical sound absorption profile to calculate absolute backscatter. As a result quantitative comparisons can be made across mesoscale fronts and eddies. Additionally the use of a well calibrated multi-frequency split beam echo-sounder has provided higher resolution acoustic backscatter measurements which can resolve individual targets and estimate zooplankton size classes.

In essence therefore, the importance of the ageostrophic circulation in mesoscale features has been shown to be important for different areas of marine sciences. From the basic physics, to the more applied character of the effects on the biogeochemical cycle in the euphotic zone.To understand the complex interaction between theses different fields, an interdisciplinar study such as the OMEGA project is needed.

2. OBJECTIVE

The main objectives of this project are (1) to establish the spatial and temporal variability of the three-dimensional ageostrophic circulation in an intense mesoscale oceanic upper ocean front (upper 300 m), (2) to evaluate the impact of the ageostrophic vertical motion on the biogeochemical properties in the upper 200 m layer and (3) to provide the scientific community with a new and useful tool for computation of vertical motions from routine CTD and ADCP data, using an interdisciplinary theoretical and experimental (in situ and remote) approach. In other words, the OMEGA project combines an observational strategy of remote sensing and *in situ* high resolution and repeated physical, chemical, biological and meteorological measurements with a numerical modelling/data assimilation strategy, to compute the vertical motion, quantify the errors involved in the diagnostic analysis of observational data and understand the global interdisciplinary characteristics of the upper ocean. Mesoscale eddies are ubiquitous in the ocean and the conclusions from OMEGA will be relevant to all ocean regions.

3. METHODOLOGY

In this section we introduce the interdisciplinary methodology used in the different field studies (3.1) followed by the different specific methodologies used for quantitative estimation of vertical velocity (3.2 to 3.5).

3.1 Field studies

In this project, *in situ* and satellite observations complement numerical models' results to provide a wealth of data for studying the relationship between surface and sub-surface signatures and its relation with the vertical velocity. The OMEGA field studies were designed in two specific frontal zones of the western Mediterranean: the northern edge of the western gyre in the Alboran Sea, and the Almeria-Oran front. Both regions are characterized by strong vertical shear and intense mesoscale circulation, and are usually identified by strong gradients in satellite infrared imagery.

Two cruises were carried out during autumn 1996: in October the Spanish BIO Hésperides sampled the western Alboran gyre (OMEGA-1) and in December the UK RRS Discovery, the Almeria-Oran frontal region (OMEGA-2), Figures 1a and 1b. In both cruises, data obtained in 3-4 consecutive samplings of the same area included Seasoar (undulating CTD + optical sensors), ADCP, in conjunction with differential and 3D GPS navigation, as well as meteorological information. The effects of mesoscale circulation on biological populations were also studied using novel underway sampling techniques including flow cytometry,

optical plankton counting, continuous net recording and near-IR light scattering. High frequency biological sampling of the near surface layer was carried out following the path of the SeaSoar undulating CTD. Samples were taken every hour or half an hour along the SeaSoar path, this giving a total of more than 60 points in OMEGA-1 and 90 in OMEGA-2, regularly distributed. On average, the resulting distance between sampling stations was 14-15 km, which permits to capture the mesoscale biological patchiness. Phytoplankton cell populations in the size range between 0.6 and 30 μm approximately were analysed through on board flow cytometry, which pemits the quantitative monitoring of different functional and taxonomic categories. Simultaneous analyses of in vitro chlorophyll and particles between 3 and 40 μm approximately (resistive particle counter) permitted to obtain a rather complete picture of mesoscale phytoplankton and seston patchiness. Additional small water samples were taken from the CTD-rosette for the laboratory image analysis of cells larger than 30 μm (microplankton).
Backscatter data from ADCP and EK500 echosounder, were taken concurrently with hydrography via SeaSoar, and in the case of ADCP data the backscatter were corrected for absorption coefficient, using SeaSoar temperature and salinity, and for non linearity in range. In addition the study offered an opportunity to synchronise the acquisition of near real time satellite data from several new sensors with high resolution in-situ surface and upper ocean measurements. Acoustic, optical and direct sampling techniques were therefore used to observe and quantify biological distributions both at the surface and in vertical profile to over 350 m.

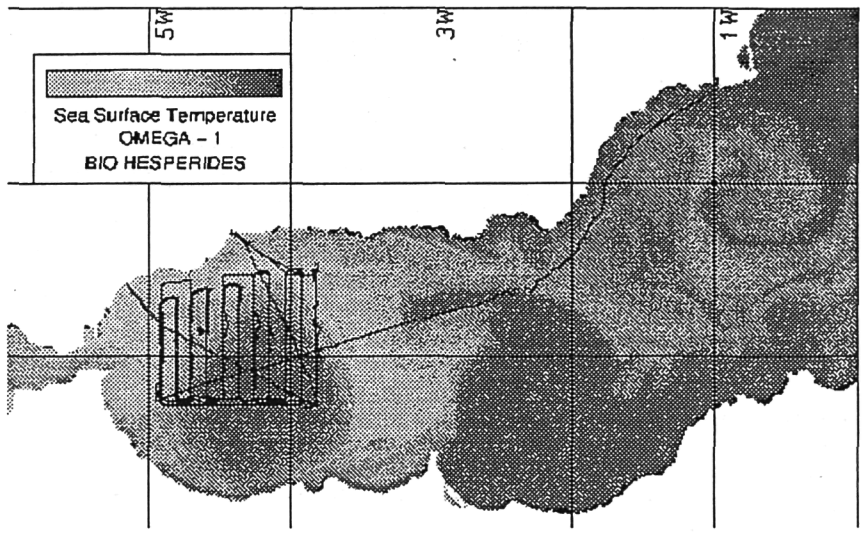


Figure 1a: Cruise tracks for BIO Hesperides

During the first OMEGA-1 survey, neutrally buoyant Lagrangian floats were deployed at the depth where maximum vertical motion was expected (100 m) providing direct estimates of the vertical velocity. The floats were tracked by 6 acoustic receivers previously moored in the area, and recovered 50 days after the deployment.

During OMEGA-2 some ship tracks were aligned along ERS-2 and Topex-Poseidon satellite tracks so that the combination of altimeter data and in situ SeaSoar and ADCP vertical profiling can be used to derive the along track geoid. Knowledge of the geoid will allow long term monitoring of the cross-track surface geostrophic currents and their temporal variations over the lifetime of the ERS satellites. An aircraft made meteorological and radiometric measurements during this second cruise.

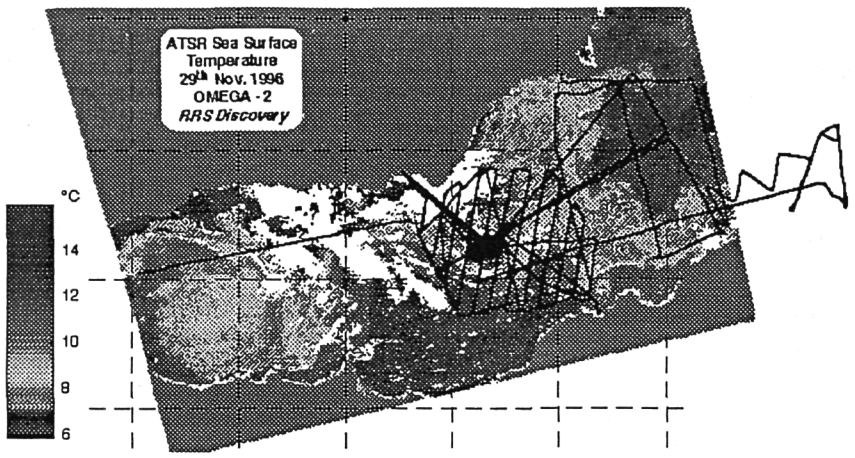


Figure 1b: Cruise tracks for RVS Discovery

During the period from September to December 1996, AVHHR data were acquired to investigate the Sea Surface Temperature (SST) temporal and spatial variability on the area. More than 40 cloud free images were selected and processed. TM (Thematic Mapper) and MOS (Modular Optical Scanner) multispectral images were also acquired and processed to investigate the relationship between biological activity and mesoscale circulation from the ocean colour analysis. Satellite data were used to complement the ship measurements by providing detailed spatial information on surface signature associated with mesoscale features, thus giving a synoptic context for the sub-surface data.

For the first time, in the OMEGA study we were able to combine an almost continuous size spectrum of biological activity, from dissolved organic material to shrimps and small fish a few cms in length, with simultaneous physical data (*in situ*, lagrangian and remote) at similar temporal and spatial resolutions. The different OMEGA data reports are available in the OMEGA WWW server, http://campanilla.uib.es/Omega/.

3.2 QG Computation of vertical velocity

The vertical velocity field is computed from the diagnostic quasi-geostrophic omega equation which is directly obtained by eliminating the time derivatives from the quasi-geostrophic vorticity and thermodynamic equations (Hoskins et al. 1978):

$$f^2 \frac{\partial^2 w}{\partial z^2} + \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \left(N^2 w \right) = \nabla_h \mathbf{Q}$$

where $\mathbf{Q} = \left[2f \left(\frac{\partial V}{\partial x} \frac{\partial U}{\partial z} + \frac{\partial V}{\partial y} \frac{\partial V}{\partial z} \right), -2f \left(\frac{\partial U}{\partial x} \frac{\partial U}{\partial z} + \frac{\partial U}{\partial y} \frac{\partial V}{\partial z} \right) \right]$ and (U, V) are the geostrophic velocity components. The important significance of this equation is that given suitable boundary conditions we can diagnose the vertical velocity field, w, from knowledge of the geostrophic velocity shear in all three dimensions. After breaking the omega equation down into a set of simultaneous finite difference equations, we can solve these equations for suitable boundary conditions (Leach 1987; Tintoré et al. 1991; Pollard and Regier 1992, Allen and Smeed 1996).

3.3 Computation of vertical velocity from PE models using DFI

Through density dynamical assimilation in a primitive equation (PE) model, the 3D velocity field can be diagnosed (Viudez et al., 1996b). Digital Filter Initialization (DFI) is a dynamically based method in which we use a multilevel PE model with real initial data to diagnose the vertical velocity. We integrate the model forward and backward and apply a filter to remove near inertial waves generated in the initial adjustment process between density and velocity field obtaining then the slow mode.

The major interest of this method is that since it is based on PE dynamics it does not require the internal Rossby radius being smaller than 1 (Ro<1) as does require Quasi-Geostrophy.

3.4 Computation of vertical velocity from lagrangian observations

Moorings were deployed in an aray of six accoustic beacons, three in the east and three in the western Alborán basin. Nine floats were launched on October 5, 1996 from BIO Hesperides, near 4.9 W , slighly north of 36,1 N, at the jet. each one 1 mile apart using the methodology described in Gascard et al (1994). Floats were balasted to be in equilibrium at a depth of approximately 100 m and drifted during 40 days when a weight was released and the floats came to the surface and started to transmit through the ARGOS system. It was the first time we used this type of floats in a stratified environment and they ended up having a mixed isopycnal/isobaric behaviour, and not the usual isobaric one that is usually recorded in deep convection studies. Two floats (numbers 8 and 15) went ashore the Morrocan coast and the data were lost, while another one was tracked in Rabat, and the data recovered. These 9 floats have been located 60 times per day (very 24 minutes) during the following 40 days (until November 14, 1996). In addition floats were measuring in situ (and recording internally) temperature, pressure (indicating the entrainment vertical velocity) and float rotations (indicating the relative vertical velocity) .

3.5. Laboratory image analysis and size-spectra modeling of phytoplankton

Microplankton cells (>30 μm) were measured and enumerated through a video-interactive image analysis system. A data base comprising flow cytometry and image analysis size-abundance distributions was developped to fit the normalised biomass spectra function and the biomass density function. This can be integrated in any particular size range to give biomass of that size compartment (Blanco et al., 1994; Vidondo et al., 1997).

3.6. Ocean colour satellite images

Statistical distribution of (Optically Active Parameters) OAPs were derived from in situ data collected during the cruises. Then an ocean colour model was used to derive robust regional algorithms to retrieve the concentration of chlorophyll-a and phaeopigments in the phytoplankton and the concentration of non-chlorophyllous particles from reflectance data integrated on the bands of the satellite sensor. The Empirical Orthogonal Function (EOF) analysis was used to decompose space- and time- distributed data set into an uncorrelated linear combination of separate functions of the original variables. This methodology allows a modal expansion ranked by their spatial and/or temporal variance, thus identifying the dominant temporal and spatial patterns.

4. RESULTS

The different sensors and sampling methodologies used during the OMEGA cruises have highlighted the presence of active frontal zones in both study areas. Preliminary analysis of the data show the existence of significant variability at scales of the order of the internal Rossby Radius and also indirect evidences of vertical motions.

The combined in situ and remotely sensed datasets have enabled a detailed description of the surface water types, the fronts that separate them, the bio-optical properties, and the associated changes around the time of the cruises. Shipborne measurements indicate that the surface signatures visible from remote sensed data are indicative of circulation to a depth of more than one hundred metres. The results of the merging and interpretation of such a comprehensive dataset show the potential and capabilities of the combined satellite/in situ approach in rendering a picture of the relationship between the physics of frontal zones and bio-optical variability at the mesoscale with an unprecedented degree of accuracy. Particular attention is given to the relationship of the observed biological variability to the 3-D circulation at the front and to assessing the influence of sub-surface patchiness in the interpretation of ocean colour data from satellites.

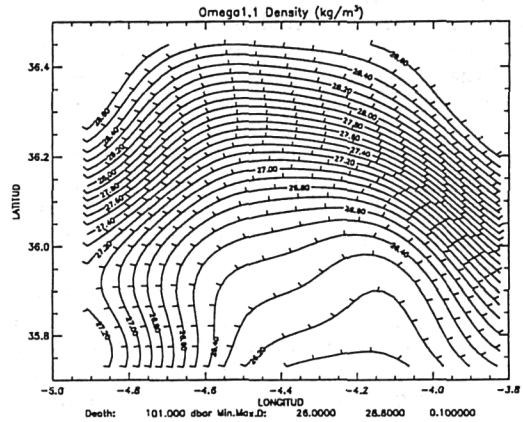
To describe the existing mesoscale structures and their spatial and temporal variability, a classical univariate analysis has been used from the Seasoar data. Figure 2a, b and c show the existence of a significant temporal variability between the three surveys. This variability affects the whole upper 300 m and appears to be mostly associated with changes in the jet location in the western boundary of the study area. Quasi-geostrophic computation of vertical velocity from the data recorded during the first sampling on OMEGA-1, Figure 3, shows that as it might have been expected, upward motion exists upstream of the ridge and downward downstream, with maximum values reaching 50 m/day. The successive samplings on the same area allow an evaluation of the temporal evolution of the mesoscale structures. Preliminary analysis of the flow cytometry measurements indicate a clear relationship between phytoplankton size class distribution and vertical motion in areas of intense mesoscale circulation.

A more elaborated method of multivariate analysis is being developped in OMEGA to be able to take advantage of the existence of ADCP data for the reconstruction of a regular density field, the input data needed for QG computation of vertical velocity. The method is based on multivariate optimal statistical interpolation of SeaSoar and ADCP data, allows to separate the non-divergent and irrotational contributions of the motion field, as well as the geostrophic and ageostrophic contributions of the streamfunction field. Results indicate that this analysis not only allows to estimate the relative contribution of ageostrophic processes, but can lead also to a better resolution of the geostrophic component of mesoscale circulation features than an analysis based only on hydrographic observations. In other words, the use of ADCP data modifies the density field and, therefore, the resulting vertical velocities. Generally speaking, the main pattern can be recognized in both analisis. However, multivariate analysis clearly adds strong shears in small domains, resulting in vertical velocity fields with smaller scale structures and higher values.

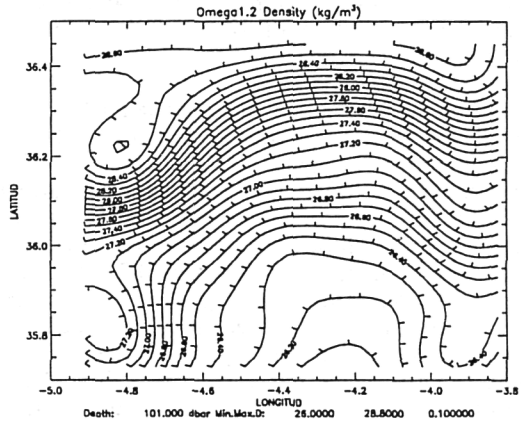
The floats recorded temperature, pressure and vertical velocity. We can observe departures of the order of 50 m and superimposed on this, higher frequency tidal motions. Floats number 10 and 11 drifted eastward though the two gyres. Overlying temperature and pressure signals shows that the float goes up when temperature decreases, therefore suggesting that the float is crossing the front at a certain angle (i.e. they are not exactly isopycnal). This behaviour is general for the whole operation. If we derive the filtered in situ pressure, we obtain the entrainment vertical velocity. The other velocity component is estimated by the number of turns (1 turn being approximately equivalent to 1m). All floats seem to show a downward motion except float 11. Overlying the two velocity components of the vertical velocity we find that the pressure part dominates and adding the two, we see a large upward motion at the begining of the period, in all floats, from 50 to 100 m/day (not shown in this paper).

All this physical varibility has obvious biological effects. Detailed analysis of the mesoscale surface distribution of several fundamental biological descriptors such as fluorescence, chlorophyll, phytoplankton cell populations and total seston particles shows the existence of a nucleus of phytoplankton and particle accumulation in the northwest part of the study area. This seems to be part of the coastal upwelling area in the northwestern Alboran Sea. Also evident are a series of mesoscale patches all along the front, patches that can be explained by the biological response to local physical and chemical inputs or by advection from the western

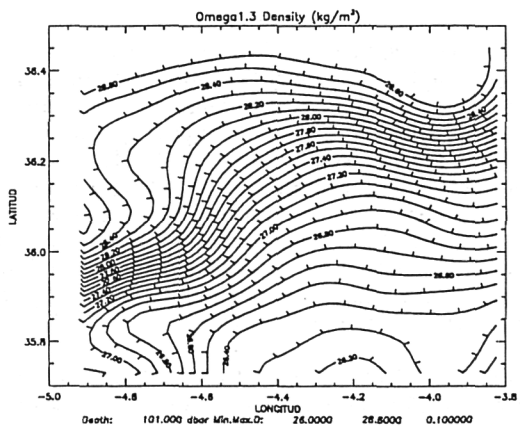
main nucleus. A large area south to the front is characterised by very low values of chlorophyll, cell and particle abundance. This area is part of the large-scale anticyclonic gyre in the western Alboran Sea. A simlar large scale structure, along the front, was visually observed with seabird and cetacean distributions. Chlorophyll patchiness and subsurface maxima can be clearly observed in OMEGA-1 and OMEGA-2, the fluorescence signal



a



b



c

Figures 2a,2b and 2c. density distribution at 100 m in surveys 1,2 and 3 from OMEGA-1

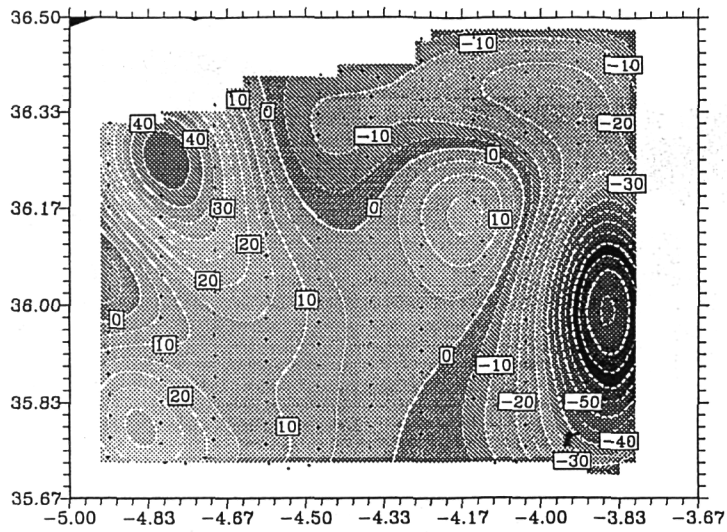


Figure 3: QG vertical velocity at 100 m from survey 1, OMEGA-1

measured by the fluorometer on SeaSoar. Figure 4 shows clear evidence of fluorescence and IR backscatter extending in a tongue along isopycnals down to 200 m. Figure 5a shows nanoplankton distribution during the first survey of OMEGA-1. Tongues coincides with the frontal zone defined by SeaSoar temperature and salinity. This is in good agreement with the findings by Strass (1992) that chlorophyll patchiness can be due to the vertical circulation at fronts.

In OMEGA-2 cruise in the Almeria-Oran front area, similar features were observed, though the physical processes are different from the ones described before. The Almeria-Oran front forms at the eastern end of the Alboran Sea where much of the Atlantic inflow leaves the gyre system and forms a tight, unstable, jet along the Algerian coast. The general circulation in the area is again characterised by intense vertical shear; near surface currents in excess of 1 ms^{-1} are not evident below 150 m. Below the pycnocline, conservation of potential vorticity appears to be achieved through conservation of vertical stratification. Above 150 metres strong horizontal shear on the cyclonic side of the front creates significant cyclonic relative vorticity on the north east edge of the main jet. In the pycnocline, isopycnal maps of potential vorticity (IpPV maps) clearly demonstrate the instructive balance between vertical stratification and changes in rotation as potential vorticity is conserved following the fluid motion. At the mesoscale, such fundamental analysis is essential to verify the vertical motion diagnosed from the observed frontogenesis. In quasi geostrophic (QG) theory vertical velocities, as part of an ageostrophic flow, are required to achieve geostrophic balance in the presence of horizontal advection of vorticity and steeply sloping density surfaces. These vertical motions are on timescales that are significant to biological processes and their net vertical excursion is as much as three times larger than the depth of the euphotic zone at the Almeria-Oran front.

Three repeat fine scale surveys of the Almeria-Oran front show streamers of high fluorescence and light backscattering along sloping density surfaces in the pycnocline. This indicates the vertical transport of phytoplankton both along and across the front to depths exceeding 200 m. This vertical transport is confirmed by the entrainment of Mediterranean Surface Water into the northern end of the frontal jet, its subduction to a depth of around 130 m along and across the front and subsequent entrainment into the Algerian current. Vertical velocities estimated from these direct observations agree with those diagnosed from solution of the QG omega equation, Figure 6. The high frequency repetition of the surveys is sufficient to observe the propagation of regions of vortex stretching (compression) downstream (upstream) of vorticity advection along the front. These processes are characteristic of baroclinic instability and, allowing for

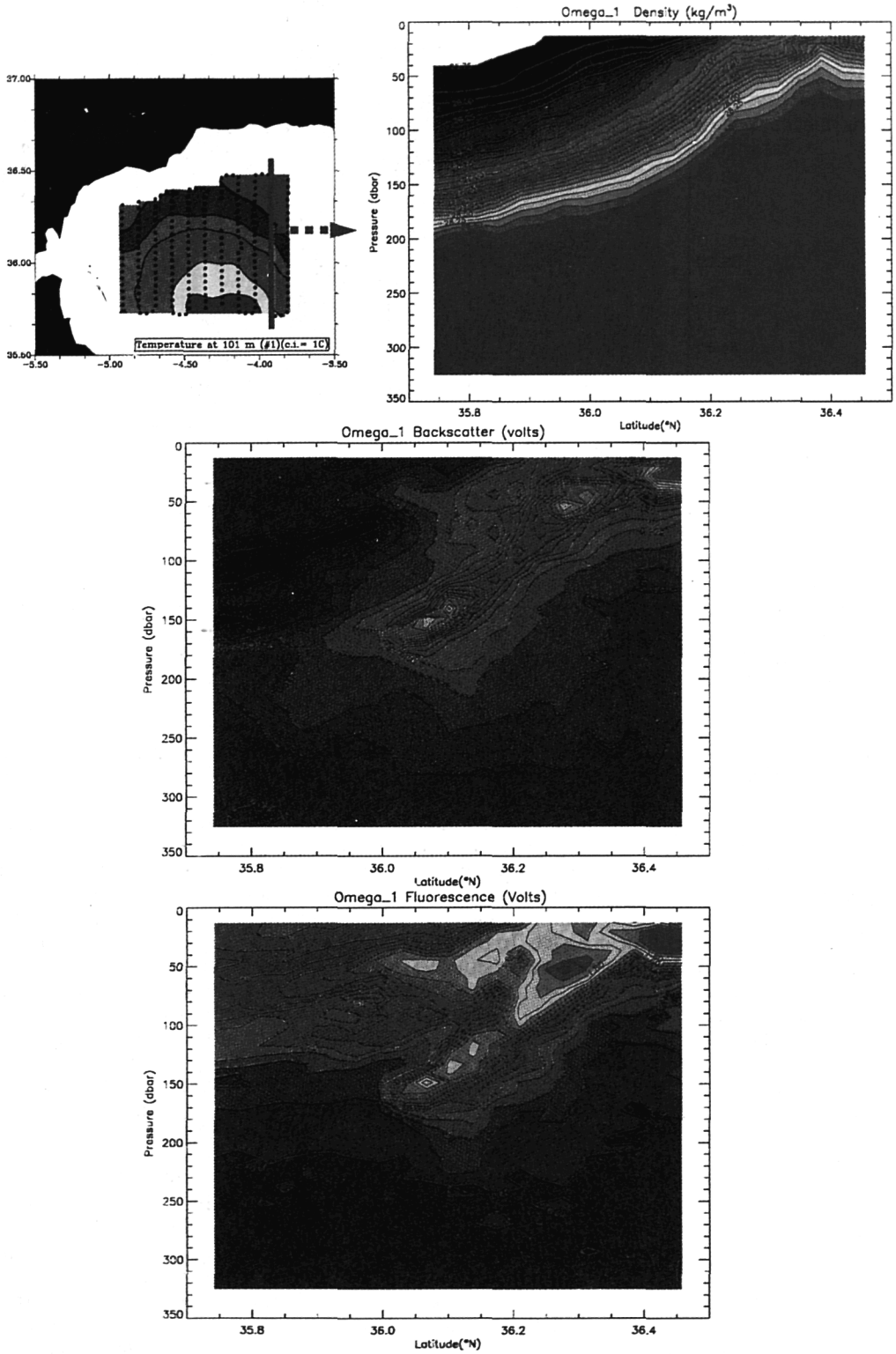
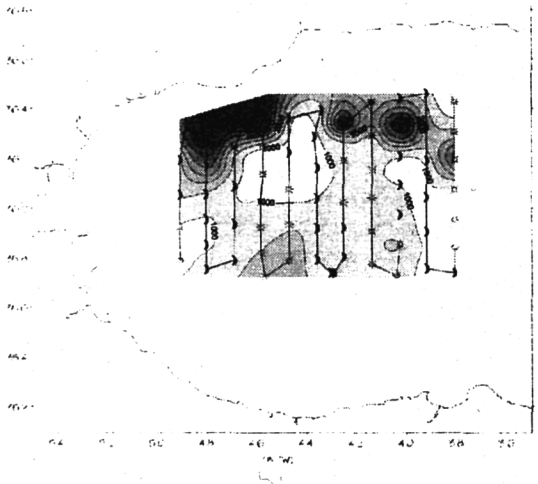


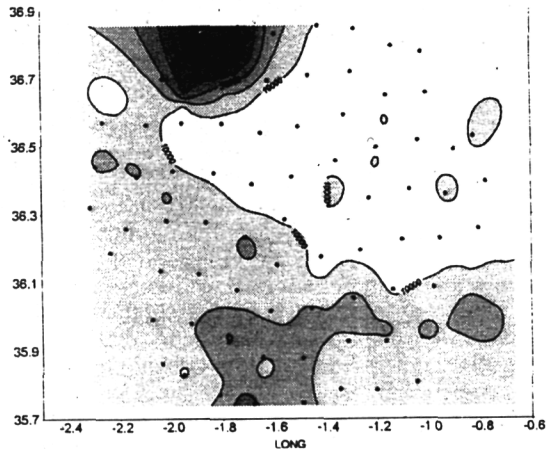
Figure 4: Evidence of downward motion along isopycnal from fluorescence and backscatter data in survey 3 from OMEGA–1

temporal asynopticity of each survey, they exhibit a wavenumber between 0.5 and 1.0 along the ~150 km length of the front.

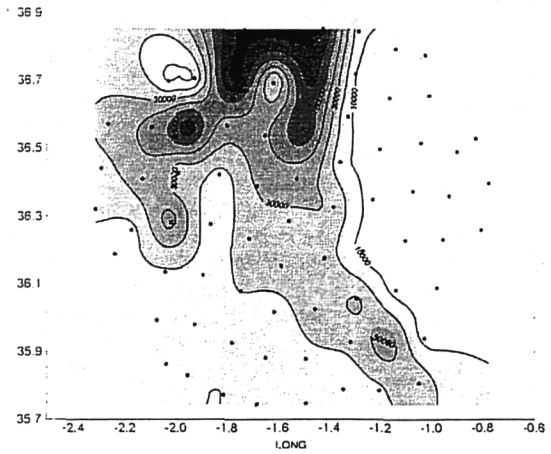
Resolution and quantification of mesoscale spatial and temporal biological variability is a fundamental part of the proposal objectives. Results from underway flow cytometry measurements of the surface water, Figures 5b and 5c, illustrate the short-term variability of the mesoscale patchiness of Prochlorophytes, a group of very small (μm <1) photosynthetic picoplankters still poorly known in the Mediterranean. Surface mesoscale variability is strong both at the physical and biological levels. On average, prochlorophyte concentrations show a 5 fold increase in the region between the first and third fine scale surveys. At the beginning, gradients are smooth and the front can be roughly defined by the isoline of 10,000 cells/ml. Concentrations are slightly lower on the "Mediterranean" rather than the "Atlantic" side of the front, where a patch with >20,000 cells/ml is found. During the second and particularly the third fine scale surveys, Mediterranean Surface Water, with salinity in excess of 37.70, occupied the northeastern region of the fine scale survey area. This water had advected from further east in the western Mediterranean and could be characterised biologically by concentrations of more than 70,000 prochlorophyte cells per ml. ADCP current measurements showed that until reaching the Almeria-Oran frontal jet, the flow associated with this advection of surface water was slow. This may help to enhance cell populations but at this stage the difference in cell populations between water masses may purely be due to differences in origin.



a



b



C

Figure 5a:Nanoplankton distribution during the first survey of OMEGA-1, 5b and 5c: Short-term variability of the mesoscale surface patchiness of Prochlorophytes

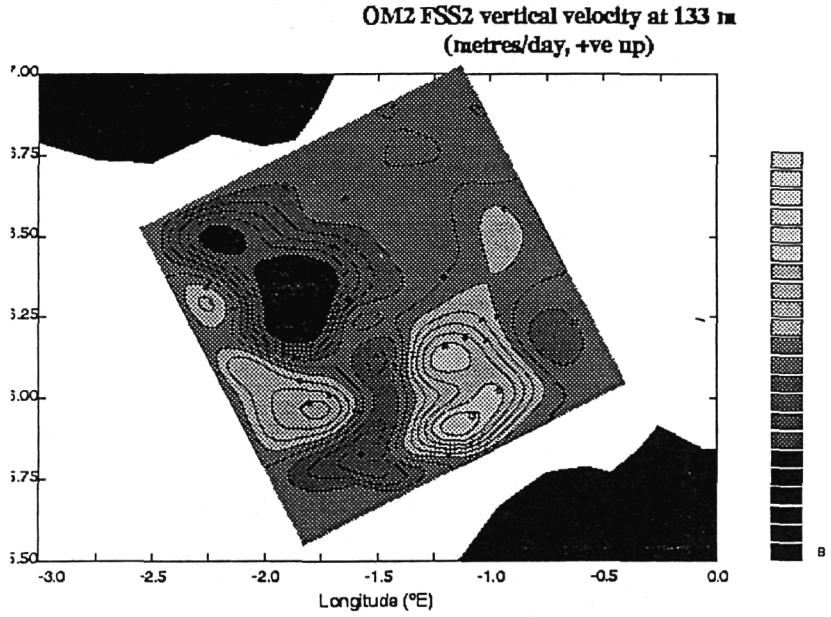


Figure 6. Vertical velocity in the Almería-Orán front area

Prognostic analyses using DFI, Figure 7, show very similar results to those obtained using QG theory, with maximum vertical motion in the range of 40-60 m/day. The differences obtained betweeen these two methods are now being studies, with special attention to the boundary conditions used in the open boundaries PE model.

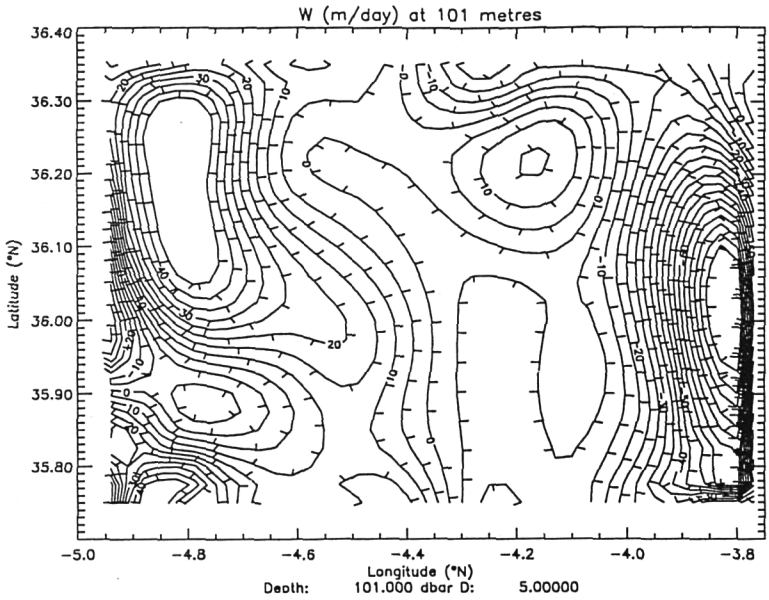


Figure 7: vertical velocity diagnosed using DFI at 100 m.

5. DISCUSSION AND CONCLUSIONS

Physical analyses are underpinned by an essential and thorough interpretation of the three dimensional hydrographic field through the calculation of Rossby-Ertel potential vorticity (PV) and the mapping of PV and its planetary and local components on isopycnal surfaces. Isentropic PV (IPV) maps, or in this case their oceanographic equivalent, isopycnal PV (IpPV) maps, were introduced by Starr and Neiburger (1940). Hoskins et al. (1985), discussed the importance of IPV maps at length and demonstrated the use of them as complete pictures of the dynamics of a mesoscale system. Locally the conservation of PV requires a balance between relative vorticity and water mass stratification. Changes in stratification in order to achieve that balance imply vertical motion and they result in vortex stretching and compressing. By mapping the vortex stretching term on density surfaces, Allen and Smeed (1996) showed how vortex compression (stretching) on the downstream (upstream) side of a cyclonic meander, where there are upward (downward) vertical velocities, were associated with a strong PV gradient across a front. However, on deeper surfaces they showed how vortex stretching (compression) on the downstream (upstream) side of the cyclonic meander was consistent with conservation of PV following water particles influenced by the passage of a cyclonic vortex above. This fundamental approach is not only essential as a precursor to diagnosing vertical motion, it also helps to explain the biophysical processes. For example, differential stretching and compression of the water column associated with a propagating cyclonic vortex may not only bring high nutrient concentrations up into a shallow thermocline and trigger a local phytoplankton bloom. Equally dramatically this system may stretch the mixed layer below the euphotic zone and increase the phytoplankton mortality.

During both observational experiments, the circulation in the Alboran Sea was shown to be characterised by intense vertical shear in the upper 250-300 metres of the water column. As a consequence early results show that both univariate (using only the SeaSoar derived hydrography) and multivariate (using a combination of hydrography and underway VM-ADCP data) analysis schemes result in similar IpPV maps and diagnosed vertical circulations; there is no significant barotropic component to the flow and any fluid motion is slow below 150-250 m. Horizontal shear in the upper water column creates significant relative vorticity on the cyclonic side of the main current jets. Repeated fine scale surveys allow us to observe the

advection of vorticity by baroclinic instability and thus propagating regions of steepening and slumping of the isopycnal surfaces at the front. However the magnitude of the vertical motion diagnosed in the western Alboran Gyre surveys is around twice that diagnosed in the Almeria-Oran front surveys. This was expected; the near surface horizontal velocities in the Western Alboran gyre are around twice the magnitude of those observed at the Almeria-Oran front while the local Rossby number in the two regions is probably similar.

The synopticity of the surveys might be, as usually recognised but not usually addresed, a source of error and precisely for this reason, different surveys were planed in OMEGA project. As a simple approximation, the ratio of the propagation speed of baroclinic instabilities to the effective speed of the ship in the along front direction may be as high as 0.25-0.5, resulting in an underestimation of vertical motion and baroclinic wavenumber by a factor of 1.33-2.00. Advection velocities are even greater than the phase speeds of baroclinic instabilities and therefore the question of synopticity may be a greater problem for the interpretation of biological distributions and therefore biophysical processes. The problem has been addresed from two different perspectives. A novel technique may be used to correct the reconstructed field by actively using the horizontal velocity fields to relocate the data stations. Using a suitable velocity field we can integrate a lagrangian motion equation. By downstreaming (upstreaming) stations sampled before (after) a mean cruise time, we obtain a more synoptic data set relative to the fluid flow. Early results (Rixen and Beckers, 1998) using previous data sets and model flow fields are encouraging. A different method has been also used to try to establish the adequacy of considering the Seasoar surveys as synoptic. In this statistical method, a 'synoptic' survey has been prepared using the linear time trend estimated from two consecutive surveys. The overall distribution of vertical velocity obtained is practically the same, although local values might be different by a factor of 2. These results are consistent with those obtained by Allen (personal comunication) who used a numerical model to analyse the effects of upstream or downstream sampling.

According to expectations, we have found an accumulation of phytoplankton along the frontal structures. The substantially higher values of chlorophyll and biomass in the western Alboran front are being analysed in the context of differential physical forcing. Frontal patches of phytoplankton are dominated by large, microplanktonic cells, in coherence with our previous macroscale observations in the Alboran Sea (Rodríguez et al., in press), whereas small picoplanktonic cells are widely distributed and show much less clear spatial patterns. The patchiness and short-term variability of Prochlorophytes observed in the Eastern Alboran front appear to derive from both frontal dynamics and different water mass transport, and indicate that these organisms are adapted to very different environmental conditions (Vaulot et al., 1990). Though the strong horizontal velocities found imply that a careful analysis of the descriptions of mesoscale biological patchiness is needed, the synopticity analysis described before suggests that the overall pattern can indeed be considered quasi-synoptic and is threfore encouraging.

We have just passed the half way stage in the lifetime of the OMEGA project. Therefore, this paper presents a snap-shot of on-going research. Most of the observational data from the two experimental cruises are now fully calibrated and processed. The joint analysis of physical and biological data is well underway and the challenging task of examining and quantifying biophysical processes has shown a promising start.

ACKNOWLEDGMENTS

This is a contribution to the European Union Marine Sciences and Technology Programme, under contract MAS3-CT95-0001. The authors are gratefull to the masters and crews from BIO Hespérides and RRS Discovery for their enthusiastic colaboration, and to the Spanish (grant AMB95-0901-C02-02) and British agencies that funded the ship time.

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TITLE: Climatic variability of Mediterranean paleo-circulation
CLIVAMP

CONTRACT NO: MAS3-CT95-0043

COORDINATOR:

Michel Crépon
Université Pierre et Marie Curie - Paris VI
Laboratoire d'Océanographie Dynamique et de Climatologie
Place Jussieu 4
F - 75252 Paris
Tel.: +33 1 44277174, fax: +33 1 44277159
E-mail: mc@lodyc.jussieu.fr

PARTNERS:

J.P. Bethoux
Centre National de la Recherche Scientifique
URA 353 - Laboatoire de Physique et Chimie Marines
F - Villefranche-sur-Mer

M. Paterne
Commissariat à l'Energie Atomique
Direction des Sciences de la Matière
Centre des Faibles Radioactivités
F - Gif-sur-Yvette

W. Roether
Universität Bremen
Institut für Umweltphysik
Fachgebiet Fernekundung
D - Bremen

R. Williams
University of Liverpool
Department of Earth Sciences
UK - Liverpool

E.J. Rohling
University of Southampton
Department of Oceanography
UK - Southampton

F. Martel
Centre d'Etudes Techniques Industrielles et d'Innovations Scientifiques SA
F - Aix-en-Provence

A. Lascaratos
National and Kapodistrian University of Athens
Department of Applied Physics
GR - Athens

K. Haines
University of Edinburgh
Department of Meteorology
UK - Edinburgh

V. Artale
ENEA - Ente per le Nuove Tecnologie, l'Energia e l'Ambiente
Task Force Ambiente Globale e Cambiamenti Climatici
I - Roma

(no manuscript submitted)

TITLE: Tracing the Water Masses of the North Atlantic and the Mediterranean (**TRACMASS**)

CONTRACT NO: MAS3-CT97-0142

COORDINATOR:

Kristofer Döös
Meteorologiska Institutionen Stockholms Universitet (MISU)
S-10691 Stockholm
Sweden
Tel.: + 46-8-161734, Fax: + 46-8-157956
E-mail: doos@misu.su.se

PARTNERS:

Vincenzo Artale
Email:vincenzo@canaletto.casaccia.enea.it
Tel: + 39 630483096
Salvatore Marullo
Email: salva@gorgona.casaccia.enea.it
Tel: + 39 630486652
Volfango Rupolo - Subproject C coordinator
Email:volfango@canaletto.casaccia.enea.it
Tel: + 39 630484988
Ente per le Nouve technologie, l'Energia et l'Ambiente (ENEA)
Centro Ricerche Casaccia
Via Anguillarese 301
00060 S. Maria di Galeria (Roma)
Italy

Rosalia Santoleri
Email: lia@oceano.ifa.rm.cnr.it
Tel:+39 6 59293073
Istituto Fisica dell'Atmosfera - Consiglio Nazionale delle Ricerche (IFA-CNR)
Piazza Luigi Sturzo 31
00144 Roma
Italy

Sybren Drijfhout - Subproject A coordinator
Email: drijfhou@knmi.nl
Tel: +31 30 2206682
Koninlijk Nederlands Meteorologisch Instituut (KNMI)
P.O. Box 201
3730 AE De Bilt
The Netherlands

Bruno Blanke - Subproject D coordinator
Email:Bruno.Blanke@deneb-gw.univ-brest.fr
Tel:+ 33-298016702
Sabrina Speich
Email:Sabrina.Speich@deneb-gw.univ-brest.fr
Tel:+ 33-298016511
Laboratoire de Physique des Océan (LPO)
UFR Sciences et Techniques
6, avenue Le Gorgeu - B.P. 809
29285 Brest CEDEX
FRANCE

Peter Killworth
Email:Peter.D.Killworth@soc.soton.ac.uk
Andrew C. Coward
Email:Andrew.Coward@soc.soton.ac.uk
Robert Marsh
Email: Robert.Marsh@soc.soton.ac.uk
Mei-Man Lee
Email: Mei-Man.Lee@soc.soton.ac.uk
Tel:+44-1703-595000
Fax:+44-1703-596204
Southampton Oceanography Centre (SOC)
European Way
Southampton
SO14 3ZH
UK

Tracing the Water Masses of the North Atlantic and the Mediterranean

Vincenzo Artale[1], Bruno Blanke[2], Andrew C. Coward[3], Kristofer Döös[4], Sybren Drijfhout[5], Peter Killworth[3], Mei-Man Lee[3], Robert Marsh[3], Salvatore Marullo[1], Volfango Rupolo[1], Rosalia Santoleri[6], Sabrina Speich[2]

[1]Istituto Fisica dell'Atmosfera - Consiglio Nazionale delle Ricerche, Rome, Italy; [2]Laboratoire de Physique des Océan, Brest, France; [3]Southampton Oceanography Centre, U.K.; [4]Meteorologiska Institutionen Stockholms Universitet, Sweden; [5]Koninlijk Nederlands Meteorologisch Instituut, The Netherlands; [6]Ente per le Nouve technologie, l'Energia et l'Ambiente, Rome, Italy,

Abstract

TRACMASS will use a new method that employs Lagrangian trajectories to investigate the North Atlantic and Mediterranean water mass circulation as they result from numerical simulations of the global ocean. Specifically, the major goals of the project are:
A. The origin and formation of the North Atlantic Deep Water (NADW).
B. The fate and transformation of the North Atlantic Deep Water.
C. The Mediterranean Water (MW) mass circulation.
D. Theoretical studies of the trajectory methods.

Simulations from four different general circulation models will be used. Two high resolution Cox-Bryan type (OCCAM and MEDMOM), one C-grid model with depth coordinates (OPA) and one isopycnic model (GIM). They are all global except MEDMOM, which is only applied over the Mediterranean. The project is divided into 4 parallel sub-projects, which are all linked and dependent on each other.
Qualitative and quantitative studies of the formation and transformation of the NADW and its origins will be performed in subprojects A and B. The NADW is probably the most important water mass the ocean produces in terms of impact on the world ocean thermohaline circulation and the climate. The NADW forms the deep part of the World Thermohaline Conveyor Belt that redistributes the heat and salt in the ocean on a global scale.
Both the conditions of NADW formation and its deformation will be traced. It is unclear whether the NADW is transformed into other water masses by ventilation along isopycnals in the Southern Ocean or by diffusion through the thermocline in the tropics and other upwelling areas.

The mass circulation in the Mediterranean, its time dependence and the MW influence on the formation of the North Atlantic Deep Water will be studied in subproject C. The MW influence on the NADW is both studied in subproject A and C; the difference is that in C, it is seen from the Mediterranean perspective, and in A from the North Atlantic perspective. The two subprojects remain fundamentally linked.
In subproject D a study of the trajectory methods themselves will be carried out. This will include examination of time dependence, and evaluation and exploitation of the bolus velocity.

1) Objectives and Methodology

TRACMASS will use a new method that employs Lagrangian trajectories to investigate the North Atlantic and Mediterranean water mass circulation as they result from numerical simulations of the global ocean. Specifically, the major goals of the project are:

A. The origin and formation of the North Atlantic Deep Water (NADW).

- Study of the conditions of its formation.
- Quantitative tracing of the path of the suspected water mass sources of the NADW (the "cold" and "warm" water paths, the impact of the Mediterranean water outflow and the newly proposed "two cells" scenario, ...).
- Determination of the impact of time dependent processes as seasonal and interannual variability.

B. The fate and transformation of the North Atlantic Deep Water.

- Provide Lagrangian evidence of the structure of its southward displacement.
- Qualify, localise in time and space, and quantify the transformation in other water masses.

C. The Mediterranean Water (MW) mass circulation.

- The water mass circulation in the Mediterranean basin.
- Its time variability.
- Its significance on the North Atlantic water mass circulation.

D. Theoretical studies of the trajectory methods.

- Further development of the Lagrangian trajectory methods.
- Investigate the possibility of having time dependent trajectories.
- Investigate the properties of the Bolus transport.

2) Task structure of the project

2.1 Overview

The project is divided into 4 parallel sub-projects, which are all linked and dependent on each other. In subprojects A and B both qualitative and quantitative studies of the formation and transformation of the NADW and its origins will be undertaken. The NADW is probably the most important water mass the ocean produces in terms of impact on the world ocean thermohaline circulation and the climate. The NADW forms the deep part of the World Thermohaline Conveyor Belt that redistributes the heat and salt in the ocean on a global scale.
The conditions of the NADW formation and deformation will be studied. It is unclear whether the NADW is transformed into other water masses by ventilation along isopycnals in the Southern Ocean or by diffusion through the thermocline in the tropics and other upwelling areas.
In subproject C, the circulation in the Mediterranean will be studied and the MW influence on the formation of the North Atlantic Deep Water. The MW influence on the NADW is both studied in subproject A and C; the difference is that in C, it is seen from the Mediterranean perspective, and in A from the North Atlantic perspective. The two subprojects remain fundamentally linked.
In subproject D, the trajectory methods themselves will be investigated. This will include examination of time dependence, and evaluation and exploitation of the bolus velocity.

For the Lagrangian trajectories, the full three-dimensional velocity fields from the models are used. The computations are made both with stationary and time varying fields. The results obtained are compared with existing data and theoretical models. Temperature and salinity budgets will be calculated along trajectories. These budgets will be chosen to be a representative set of trajectories which constitute the Conveyor Belt in the three different models. These calculations will enable us to describe the water mass transformation of Conveyor Belt water in the three models and to delineate the different processes which are responsible for this water mass transformation.

Representative subsets of trajectories from the three models are needed which describe the Conveyor Belt. These subsets consist of sets of three-dimensional fields of coordinates as a function of time [x(t),y(t),z(t)], which define the various trajectories.

2.2 Detailed workplan

A. The origin and formation of the North Atlantic Deep Water

The NADW is formed in the northern regions of the North Atlantic Ocean. In order to understand the three-dimensional time varying ocean thermohaline circulation, the mean

state of the global circulation will first be identified. This will let us qualify the variability compared with this state in the following step.

The NADW is characterised by a deep salinity maximum in a large part of the World Ocean, and by relatively high temperatures. The source of the high temperature and salinity is the warm and salty water of the NADW return flow in the thermocline. Up till now it has been unclear: (a) whether these high temperature and salinity water mass characteristics are imported into the Atlantic from outside (Indian Ocean/Agulhas Current); or (b) whether they are acquired by mixing along trajectories in the Atlantic itself (mixing with Caribbean or Mediterranean Water); or (c) whether they result from air/sea interaction with that part of the NADW return flow which resides in the ocean's mixed layer. Budgets for the salinity and temperature will be calculated, i.e. comparing the storage, forcing and mixing along the trajectories. These calculations will enable us to describe the water mass transformation of Conveyor Belt water in the models and to describe the different processes which are responsible for this water mass transformation. In particular, focus will be made on the role of Agulhas, Caribbean and Mediterranean water in the salt budget of the Conveyor Belt, the interconnection of the advective paths of the Mediterranean water and the upper branch of the Conveyor Belt, the amount of ventilation of Conveyor Belt water along its path in the Atlantic, and the way Conveyor Belt water is transformed in to North Atlantic Deep Water in the convective areas in the North Atlantic.

Evaluation will be made of the links between mass, heat and buoyancy fluxes on the upper branch of the thermohaline circulation as well as the reservoir of modal waters and their export by intermediate and deep currents. In fact, both modal waters and the waters advected in the dense currents near the sills between Greenland and the Shetlands Islands, transport surface signals into the intermediate and deep layers of the ocean. Modal waters (e.g., the water of the Greenland Sea and the Labrador water) are formed during winter with their characteristics varying from one year to the other. They remain insulated from the shallow layers for a time scale of years before surfacing again, in different regions of the ocean. Therefore, a study on this water formation, spreading path and associated time is of primary importance for the structure of the Conveyor Belt to be established.

B. The fate and transformation of the North Atlantic Deep Water

The North Atlantic Deep Water can convert into shallower warm water either by isopycnic ventilation in the Southern Ocean, which is then converted into warmer water in the northward Ekman transport, or by tropical upwelling through the thermocline. A quantification of the transport and time scale of these two water conversions will be made.

The path of the Conveyor Belt will be traced and estimations of the relative importance of the Cold vs. the Warm Water Path will be made both qualitatively and quantitatively. It is impossible at this stage to be too precise about the path of this work as it will depend on the findings made.

C. The Mediterranean Water (MW) mass circulation.

By now different GCM models are available that reproduce the main features of the Mediterranean general circulation well. The Lagrangian scheme will be implemented into the MEDMOM (Roussenov et al., 1995) and OPA Mediterranean GCM models. The Lagrangian diagnostics will allow us to trace the thermohaline circulation and to discriminate among the different involved mechanisms. In particular it will possible to detect the relative importance of the internal mixing in the different subbasins and how this mixing affects the hydrological properties of the Gibraltar outflow. A detailed study of the seasonal variability of the Mediterranean circulation and of the salt and heat transport of the Gibraltar outflow will be made with the techniques of forward and backward particle integration.

Moreover, computer resources will let us also perform different sensitivity studies of the Mediterranean circulation. Lagrangian diagnostics will be applied to several runs (MEDMOM GCM) with different vertical diffusion coefficients and with different surface fluxes, varying from different climatological data to actual data from remote sensing. This Lagrangian approach will facilitate the study of the response of the marine system to the variability of the atmospheric forcing and of the internal mixing, considerably improving knowledge of the dynamics of the Mediterranean Sea and of the processes involved in the formation of Mediterranean Water.

Although the Gibraltar outflow of salty and warm Mediterranean water is small (about 1 Sv) compared with North Atlantic oceanic currents, its role is significant for the NADW formation and meridional overturning. The isopycnal layer within which the core of the Mediterranean outflow resides intersects the ocean surface within the Labrador and Norwegian-Greenland Sea. This import of salty water at the surface reduces the stability of the water column making the occurrence of deepening events easier (Hecht et al., 1996, Reid 1976). In this context it is an important scientific task to evaluate the influence of the MW in the NADW formation using Lagrangian diagnostics. Here this problem will be studied from a 'Mediterranean' point of view. The results of subproject A will be fulfilled by a more detailed knowledge of the processes involved in the formation of the MW and of the interannual and climatic variability of the Gibraltar outflow.

This subproject embraces the dynamics of two very different ocean systems as well as two different numerical approaches (global and regional models). Only the combination of the competencies and resources of the laboratories involved will let us address this scientific task.

D. Theoretical studies of the trajectory methods.

The methods to calculate the Lagrangian trajectories used to trace the water masses will also be developed further and validated. The results from this will provide the tools needed for the 3 other sub-projects (A, B and C).

Our Lagrangian tool has several advantages with respect to a more traditional model for transport of tracers, for which passive quantities are advected and diffused with sophisticated (and expensive) numerical schemes, and makes use of the fields (velocity, diffusivity) produced by an ocean GCM. Some of the strong points of the approach are: speed and accuracy in the computation of the trajectories, access to estimates of directional transports (for water flowing from one given oceanic section to another); and to backward integrations (for tracking water masses in the past). Various exciting studies have recently illustrated the power of the approach (Döös 1995, Blanke and Raynaud 1997).

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TITLE **Demonstrator for Interoperability of Oceanographic Catalogues (DINOCAT)**

CONTRACT N° **MAS3-CT970123**

COORDINATOR

Arnaud de Villeneuve
OCI Services
3, avenue de l'Europe
31400 Toulouse, FRANCE
Phone: 33 + 5 61 00 30 80 - Fax: 33 + 5 61 00 30 85
E-Mail : adeville@oci.fr

PARTNERS

Henrik Berle
TERMA Elektronik
Bregnerodvej 144, DK-3460 Birkerod, Denmark
Tel. : +45- 45949675
Fax. : +45- 45949699
E-mail: hkb@terma.com

David Curé
IFREMER - DITI/IDT/ISI - Centre de Brest
P.O. Box 70 - 29280 Plouzané - FRANCE
Tel. :+33-298224279
Fax. :+33-298224644
E-mail: david.cure@ifremer.fr

Jones Meirion
British Oceanographic Data Centre (BODC)
Bidston Observatory, Birkenhead - Merseyside L43 7RA
UNITED KINGDOM
Tel. :+44-1516538633
E-mail: bodcmail@pol.ac.uk

Dir. D.M.A. Schaap
MARIS
P.O. Box 5807 - 2280 HV Rijswijk - THE NETHERLANDS
Tel. :+31-703366707
E-mail: maris@xs4all.nl

Demonstrator for Interoperability of Oceanographic Catalogues

DINOCAT

Henrik Berle, David Nodar, Arnaud de Villeneuve

1. INTRODUCTION

Oceanographic Data Observations are basically organised in databases containing catalogues and archives containing datasets. Catalogues and data archives are distributed on different European Oceanographic Data Centres. Oceanographic Researchers need tools to easily access the catalogues and archives.

In order to improve and to simplify the access to the data, the DINOCAT (Demonstrator for Interoperability of Oceanographic Catalogues) project aims at building a demonstrator which can search on multiple oceanographic database catalogues, where the databases are geographically distributed and heterogeneous.

2. OBJECTIVES

The purpose of this project is to build a demonstrator, which provides a uniform query facility, to search on multiple oceanographic database catalogues, where these databases are geographically distributed and heterogeneous. i.e. each of the databases has its own query interface which may or may not be available from the World Wide Web.

The uniform query interface is provided to the user through a standard WWW browser.

The uniform query interface will enable a scientific user to search for data, located at the different data centres without having any knowledge of the individual query languages and/or the organisation of the data centres which holds the data.

The uniform query interface will make it possible for the scientist to search for data based on the data type, geographical location and time together with other relevant parameters.

The Demonstrator is developed by using the capabilities of the INTERNET (WWW Browser, HTTP Servers), and the existing architecture of the involved Data Centres.

It is seen as very important that the data centres should not convert their data to a common format but rather continue to use their existing format.

The chosen approach could later be extended towards an operational system including other types of oceanographic Catalogues and other oceanographic Data Centres.

The methodology to be applied is divided into three main phases :

1. **Definition of the General System Architecture in collaboration with the Data Centres,** Catalogues to be concerned by the demonstration, tools and software to be used.
2. **Design and implementation of the software** by OCI/TERMA
3. **Installation of the developed software at the Data Centres and the Focal Point,** for presentation of the Demonstrator during two month, with application of the exploitation and dissemination plan.

3. ARCHITECTURE OVERVIEW

As the project is in the specifications stage, the overall architecture is the only result the DINOCAT partners may present.

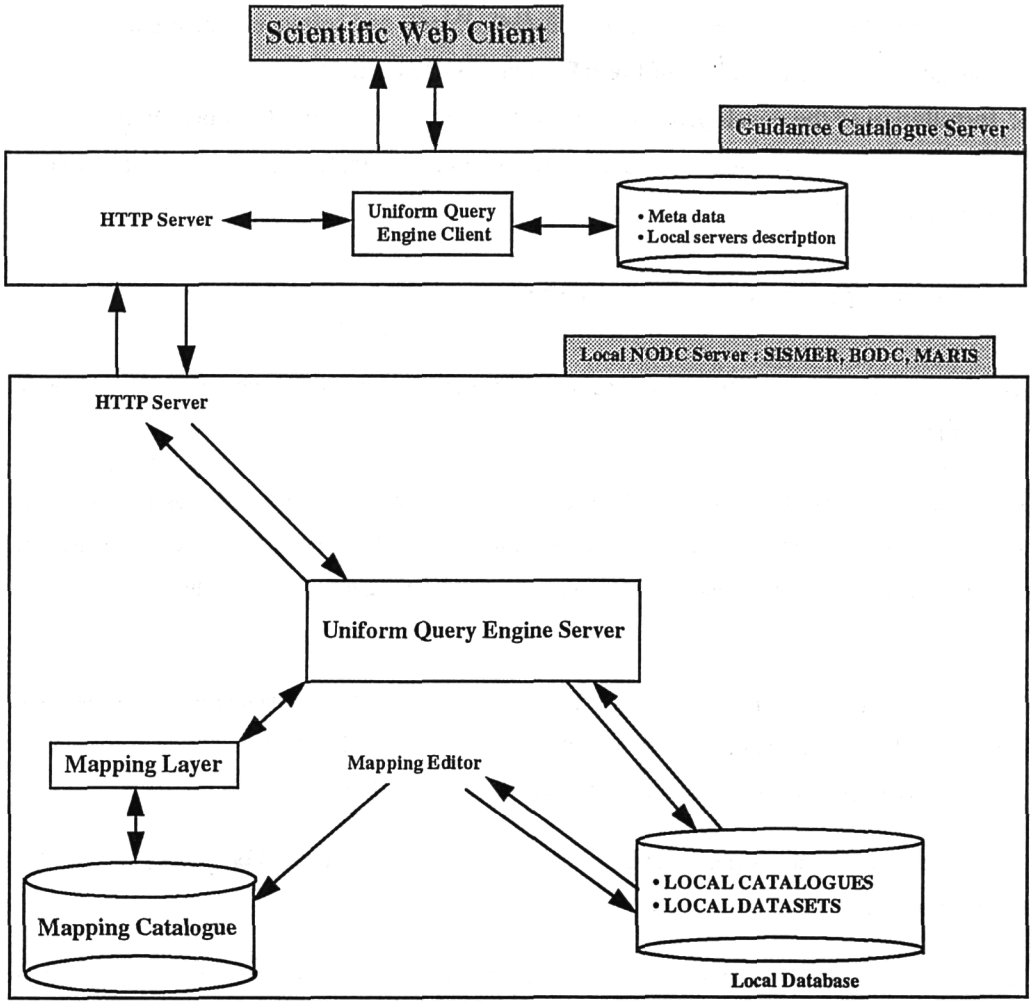
The main idea behind the architecture is that a scientific user can use a web browser to perform a uniform query on a number of heterogeneous catalogues. The following top level architectural presentation shows how a Scientific client can create a uniform query by the means of the Guidance catalogue server.

The Guidance catalogue server contains a Uniform Query Engine Client which uses a local meta data catalogue to help the scientific client to formulate a query. The local meta data catalogue contains top level meta data information and not information about individual data sets.

When the scientific user has created a uniform query it is submitted to the Uniform Query Engine Client for processing.

The Query Engine Client submits the query to the Uniform Query Engine Server installed at the Data Centres. The Uniform Query Engine Server converts the uniform query to a local query by means of the mapping layer. The local query is now executed against the local catalogues/datasets. The result of the local query is send back to the Uniform Query Engine Client, which collects the results from the different Data Centres and returns the result to the scientific user.

Architecture figure



The Architecture of the Demonstrator includes :

- **Three data centres** with associated catalogues : BODC, MARIS, SISMER.
- **A focal point** for hosting the "Guidance-Catalogue" and the Front-End Facility, for the duration of the demonstration : SISMER.

I.1.2. Integrated ecosystem studies

TITLE: Impact of a Climatic Gradient on the *P*hysiological *E*cology of a *P*elagic Crustacean

(project PEP)

CONTRACT NO: MAS3-CT95-0013

COORDINATOR:

Prof. Dr. F. Buchholz
Biologische Anstalt Helgoland
Meeresstation/Marine Station
D 27483 Helgoland
Tel.: +4725 819 -352; Fax: -311
E-mail: fbuchhol@x4u2.desy.de

PARTNERS:

Dr. P.M. David
Centre d'Océanologie de Marseille (COM)
Faculté des Sciences de Luminy
Université de la Méditerranée
F-13009 Marseille
Tel. +4 91 82 91 38; Fax +4 91 82 91 94
E-mail: david@com.univ-mrs.fr

Prof. Dr. J. Matthews
The Scottish Association for Marine Science (SAMS)
Dunstaffnage Laboratories
PO-Box 3
GB-PA34 4AD Oban, UK
Tel. +1631567 853 ; Fax +16315 65518
E-mail: jama@dml.ac.uk

Dr. P. Mayzaud
Observatoire Océanologique
Laboratoire d'Océanographie Biochimique et Ecologie (LOBE)
Quai de la Darse
B.P 28
F-06230 Villefranche-sur-mer
Tel. + 4 93 76 38 28; Fax +4 93 76 38 48
E-mail: mayzaud@ccrv.obs-vlfr.fr

Dr. T. Patarnello
University of Padova (UP)
Department of Biology, Section of Genetics
Via Trieste 75
I-35121 Padova
Tel. +498 276 218; Fax +498 276 209
E-mail: patarnel@cribi1.bio.unipd.it

IMPACT OF A CLIMATIC GRADIENT ON THE *P*HYSIOLOGICAL *E*COLOGY OF A *P*ELAGIC CRUSTACEAN (PEP)

F. BUCHHOLZ[1], P. DAVID[2], J. MATTHEWS[3], P. MAYZAUD[4] and T. PATARNELLO[5]

1) Biologische Anstalt Helgoland (BAH), Marine Station at Helgoland, Germany
2) Centre d'Océanologie (COM), Université de la Mediterranée, Marseille, France
3) The Scottish Association for Marine Science (SAMS), Dunstaffnage Laboratories, Oban, Scotland
4) The Observatoire Océanographique, Laboratoire d'Océanographie Biochimique et Ecologie (LOBE), Villefranche sur mer, France
5) University of Padova (UP), Department of Biology, Section of Genetics, Padova, Italy

SUMMARY

The MAST III project PEP aims at studies on functional marine biodiversity as a basis for understanding ecosystem structure, dynamics and resilience, and is focused on the Northern krill, the euphausiid *Meganyctiphanes norvegica,* as a pelagic model in zooplankton. The patterns of diversity in this species - an important component of Atlantic communities - is being investigated at specific locations in the north-eastern Atlantic, the Kattegat and the Mediterranean. Physiological performance and capacity as well as populational traits will be related to the genetic repertoire with respect to the prevailing thermal and trophic regimes. The project was started on 1 February 1996 and runs for 36 months. An overview on the project's central approaches and some specific results is given.

1. INTRODUCTION

Within its extraordinarily wide range of occurrence from the Arctic to the Mediterranean, the Northern krill, *Meganyctiphanes norvegica* are exposed to a variety of environmental conditions. With respect to the thermal regime they are able to cope with low as well as high temperatures. This property makes krill a suitable organism to study the potential for eco-physiological optimisation in different climatic as well as trophic environments. The project has brought together a multidisciplinary group of physiologists, ecologists, acousticians, and geneticists to study the ways the species has adapted itself to such a range of conditions.

The project considers abiotic and biotic conditions at three selected study sites, the Atlantic off Scotland and the Clyde sea, the Mediterranean in the Ligurian sea, and the Kattegat at the Alkor-Deep. The adaptive capacity of *M. norvegica* in terms of the rates, ranges and limits of physiological performance in relation to the differing climatic conditions will be compared. Particularly, the study of physiological capability and linkage to and between processes of

nutrition, energy-storage (e.g. lipids, carbohydrates), reproduction, and overall metabolism are objectives.
Parallel, the genetic differentiation in *M. norvegica* with respect to physiological function and the contrasting properties of the ecosystems are investigated.
Adaptive features are sought which give clues towards the extent of eurythermy vs. stenothermy in the species. The differing climatic regimes at the three locations are considered as parameters of a "natural experiment". The results of the comparison will help in determining the capacity of *M. norvegica* to cope with short- and long-term changes in sea-temperatures.
In all three areas krill crosses different water strata during regular vertical migration. The influence of the different conditions, with special regard to temperature, on the physiology of the migrating specimens are analysed, in order to identify causes and effects of this characteristic behaviour.
Numerous vertebrates depend on *M. norvegica* as a food source. The role of krill in the food chains of the ecosystems will be defined and compared at the three study sites. The results will be usable for further approaches in fishery-biology.

2. MATERIAL AND METHODS

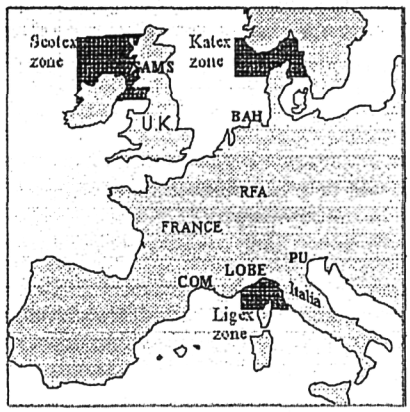
Sea-Experiments comprise the central approach of the project. The pelagic populations of *M. norvegica* are studied and compared using a modern research vessel especially equipped for laboratory studies on board. RV "Heincke" (55m, 1000tn, built 1990, BAH) is not only the central instrument but also the platform for direct cooperation and scientific exchange of approaches, methodology, and results. Maintenance experiments with live specimens subjected to controlled conditions are conducted during the cruises. The team has spent 20 weeks on board during summer and winter cruises of three weeks duration to the three locations in 1996 and 97 (LIGEX, SCOTEX, KATTEX I&II) .

- Existing data sets on population characteristics are re-analysed and improved using modern methods of quantitation with respect to biomass, vertical distribution/migration, and population structure. An Optical Plankton-Recorder (laser-beam, with fluorescence and TS-sensors), Dual-Frequency-Sonar and two Multinets (MOCNESS, 9 nets, 330 and 2000µ) in conjunction with modern computational methods of data-evaluation are applied.

- Adaptive processes linked to nutrition, reproduction, metabolism, behaviour, and genetic differentiation are studied on the basis of modern techniques. Among other equipment and methods available, an Oxy-Stat-respirometer, a 6-chamber (Clarke electrodes), closed circuit respirometer, Fast Protein Liquid Chromatography (FPLC) to isolate enzymes for in-vitro studies of temperature-related properties, radio-tracer-techniques in nutrition studies in conjunction with a set of specialised chromatography-systems for lipid- and fatty acid-analysis, and state of the art- methodology for mtDNA, and nuclear microsatellite-analysis are applied. The latter techniques are flanked by karyological analysis of the populations.

3. RESULTS AND DISCUSSION

In the following, some highlights of current results are presented, and shortly discussed in order to outline some objectives of the PEP-project. A full overview on a comparative basis of the Climatic Triangle can not yet be given, because data evaluation is still in progress.



The main working areas (Fig. 1) are close to the respective laboratories of the partners, and previous data on local krill populations as well as seasonal biotic and abiotic conditions exist and can be built upon. The cruises may be considered as „snapshots" of three weeks duration each, in summer and winter.

Fig. 1 Main working areas of the PEP-project

TEMPERATURES

Comparative measurements were carried out by CTD at several specific locations. In the French Ligurian Sea the temperatures are relatively constant (12 to 13°C) within the normal vertical migration range of krill, which lies between 700 m and the near-surface. Temperatures in the Scottish Clyde Sea (130 m) are colder but also relatively stable with depth (7 - 9°C) and only change slightly between seasons. Temperatures in the Danish Kattegat vary greatly with season (4 - 20°C) and areas rich in krill as the Alkor Deep (140 m), variability with depth is also significant as a result of stratification (Buchholz et al. 1998)

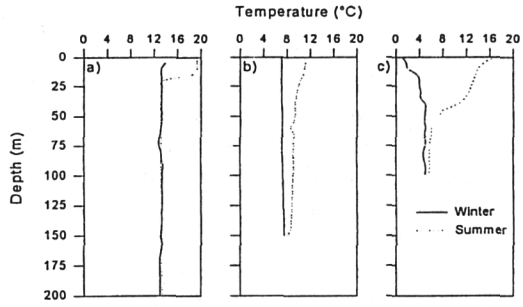


Fig. 2 Sea temperatures measured by CTD in a) the Ligurian Sea, b) the Clyde Sea, and c) the Kattegat

TROPHIC ENVIRONMENT

The trophic environments of the Climatic Triangle were studied by using an Optical Plankton Counter (OPC) with parallel Chl a and TS measurement, alternatively by CTD, as well as multiple plankton nets for zooplankton (MOCNESS). In the Ligurian sea, krill associated with a semi-permanent frontal system where catches coincided with a local high biomass area in terms of Chl a and zooplankton-counts located near the top of a salt-dome. This situation varies with season. Fig. 2 depicts the situation in September 1997.

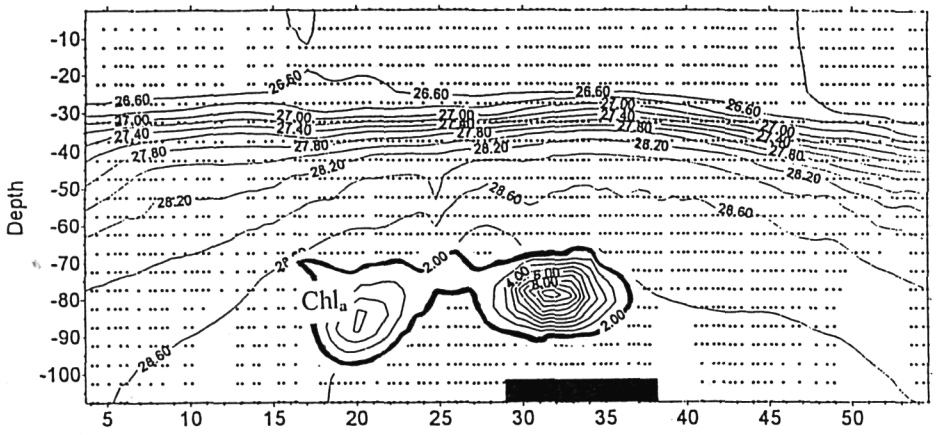


Fig. 3 OPC - data in September 1997, along a transect from Cap Ferrat towards Calvi (Ligurian sea, distance from Cap Ferrat is shown at the abscissa). Averaged data point localisations are shown. The isolines are Sigma-t (kg/m^3) - values, overlaid with Chl a - data (mg/m^3). The area of highest krill catches (MOCNESS) is indicated.

The highest gut pigment contents in krill was found in the Clyde sea. In the Kattegat, krill relied strongly on zooplankton resources. Experiments on board and stomach analyses underlined the opportunistic feeding behaviour in krill.

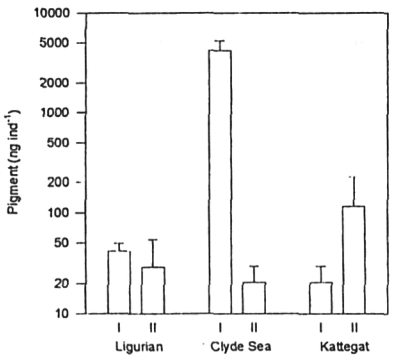


Fig. 4 Mean maximum gut pigment content (expressed as ng eq. Chl a per individual) at each site during summer and winter expeditions

POPULATIONS

Population studies and biomass estimates were carried out by multi-net sampling, bi-frequency sonar, and acoustic doppler profiling (ADCP). Vertical migration velocity of the Ligurian population was up to 500 m within two hours (Tarling et al. 1998b).

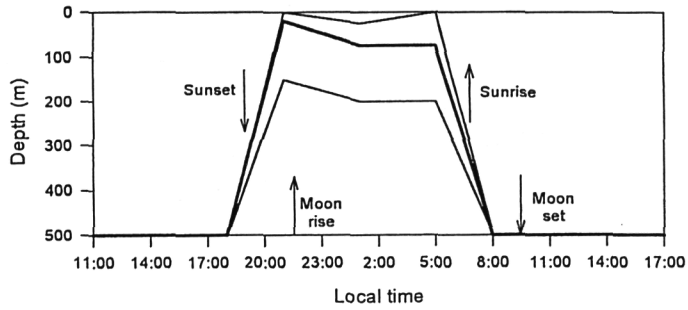


Fig. 5 Relative backscatter measured by ADCP at 150 kHz during upward and downward vertical migration phases in LIGEX II (19-20/9/1997).

Time course studies on the spatial distribution of krill within the Alkor-Deep (Kattegat) revealed that krill concentrated regularly during the night and dispersed while migrating upward during day time (Tarling at al. 1998a). The patterns of vertical migration differ greatly between sites and depend on hydrographical and morphological conditions in the areas. An optimization model of vertical migration is planned to be established.

Based on acoustic estimations at 38 and 120 kHz, the biomass of the geographically well defined Kattegat population was assessed to be 75 tons. Such estimates will be related to concurrent ones at the other sites.

Morphometric measurements were performed on samples from the three sites, and seasonal population development derived. These data will be referenced to published earlier results.

PHYSIOLOGY

Respiration rates (Saborowski and Buchholz 1998) increased exponentially with temperature (4-16°C). However, rates were similar at each of the respective ambient temperatures, indicating a compensatory effect of overall metabolic processes to different temperatures regimes.

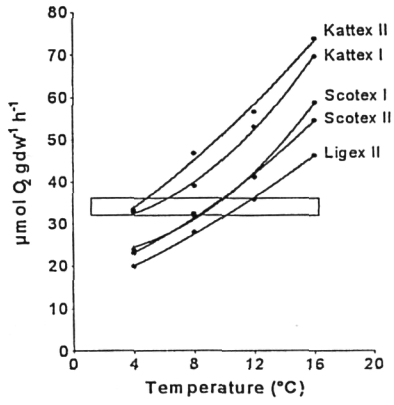


Fig. 6 Respiration rates of *M. norvegica* from the three sites in summer and winter in relation to ambient temperature. Ligex I samples will be verified during a land based experiment in spring 1998. In order to emphasise general patterns, error bars are not included in the graphs (Std. Dev. Max. 20% of the respective means: n= 6-10). The box indicates the respiration of krill at the respective ambient temperatures of the study sites.

The metabolic key enzyme citrate synthase showed increased substrate affinity at ambient temperatures but maximum reaction velocities, temperature profiles, and thermal stability did not differ significantly between populations.

Lipid stores and structures differed greatly between sites and seasons. Extensive maintenance experiments served to analyse adaptive features in gut transit, biochemical storage and (enzymatic) digestion (data not shown). Such data will be integrated into a model of digestion for krill.

Reproductive strategies basically relied on physiological plasticity which allows a flexible response to widely diverse environmental conditions. Reproduction is limited to the period of maximum food availability (phyto- and zooplankton) for the offspring. Egg maturation and release, however, are closely linked to the moult cycle which is temperature dependent (Cuzin-Roudy and Buchholz 1998).

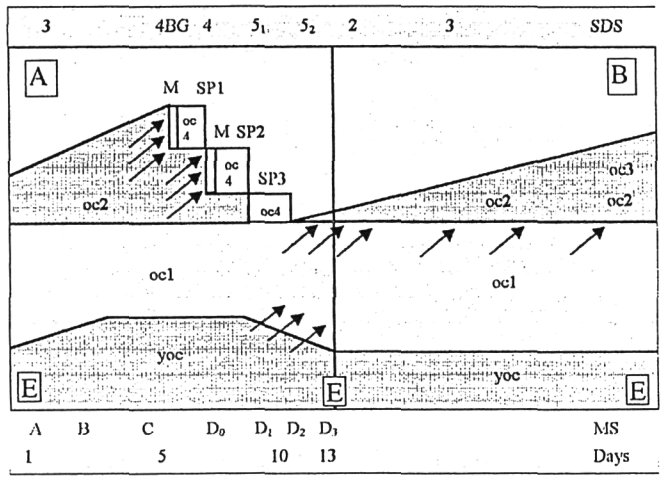


Fig. 7 Ovarian development and spawning are related to moult preparation in Northern krill. In the ovary, production of new young oocytes (yoc) and first phase of yolk accumulation (previtellogenesis: ocl) are going on during the whole reproductive season, but eggs are produced cyclically and released in multiple spawning events. One cycle of egg production corresponds to 2 successive moult cycles as illustrated for the Kattegat krill during the reproductive season.
A: „Spawning moult cycle" of 13 days corresponds to the maturation (M) and the release of a batch of eggs in 1 to 3 spawns (SP1,...SP3), during premoult. The 2 main spawns are synchronised with moult stages D0 and D1, the third one is residual.
B: „Vitellogenic moult cycle" corresponds to lipidic yolk accumulation (vitellogenesis: oc2 and oc3) for the next batch of eggs, coming from developed previtellogenic oocytes (ocl).
The model is valid for the other two populations, taking into account that timing of the cycles is temperature dependent.
E: ecdysis (moult); MS: moult stages; SDS: sexual development stages.

GENETICS

Our mtDNA data indicated a clear differentiation between the Atlantic and the Mediterranean population. The Alboran Sea is geographically part of the Mediterranean basin but belongs to the Atlantic hydrological system. The genetic homogeneity of the Alboran population with the Atlantic ones and its significant differentiation from the Ligurian population suggests that the

current systems play a major role in determining the population structure of *M. norvegica*. The Alboran population, however, showed haplotype frequencies which are intermediate between the Atlantic and the Mediterranean.

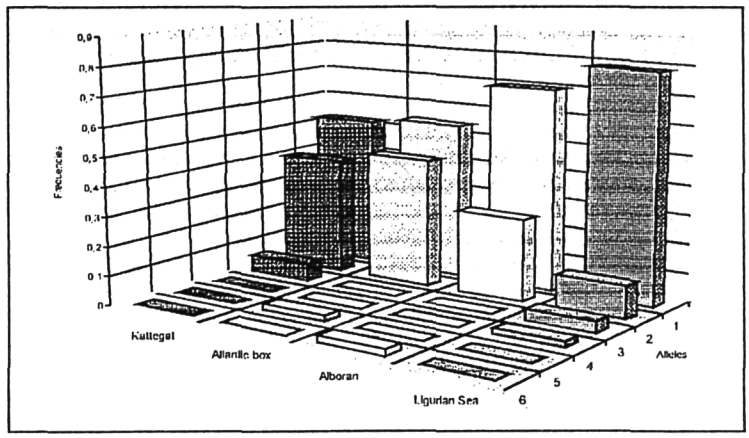


Fig. 8 Mitotypes frequencies

Population structure was also investigated by analysing two nuclear microsatellites loci (Mn-DiC7 and Mn-Dio8). The Mn-DiC7 locus is consistent with the mtDNA data and indicated a genetic divergence between the Mediterranean and the Atlantic population. However, the Mn-Dio8 locus suggests a differentiation between the Atlantic off Scotland and the Kattegat population.

4. CONCLUSIONS

The Atlantic species *Meganyctiphanes norvegica* is characterised by high physiological plasticity, in terms of metabolic and reproductive adaptation, and biochemical composition (e.g. lipids). Opportunistic, omnivorous feeding matches with the krill's occurrence in high production areas, i.e. the Atlantic shelf break, the at least eutrophic Clyde estuary, the Alkor-Deep location - which is a „plankton-oasis" inside the salt-depleted Kattegat -, and the Ligurian frontal system. The molecular genetic approach gives a first indication of a possible separation of krill stocks.

5. ACKNOWLEDGEMENTS

The PEP-Team includes E. Albessard, A. Bedo, S. Bröhl, J. Cuzin-Roudy, P. David, S. Dallot, O. Guerin-Ancey, J-P. Labat, S. Lass, D. Müller-Navarra, L. Ostellari, S. Sabini, R.Saborowski, M. Salomon, P. Schumann, E. Seris, G. Tarling, C. Thiriot-Quiéreux, P. Virtue,. who contributed their ideas, cooperation and results for the above overview and will publish these in refereed journals.

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T. Patarnello presented a paper and abstract at the 4th International Conference on Marine Biotechnology including first results on the genetic analysis in *Meganyctiphanes norvegica*. J. Matthews and F. Buchholz also attended this conference (Sorrento, Italy, Sept. 1997)

TITLE: **Microbial Ecosystem Dynamics (project MEDEA)**

CONTRACT NO: **MAS3-CT95-0016**

COORDINATOR: **Univ. of Bergen, Dept. of Microbiology,**
N-5020 Bergen, Norway
Telephone: +4755212683; Fax: +4755323962;
Email: frede.thingstad@im.uib.no
Principal scientist: T.Frede Thingstad

PARTNERS:

Station Zoologique, Villefranche-s-Mer
Observatoire des Sciences de l'Univers
URA CNRS 716
Université P & M Curie (Paris VI)
BP 28, 06230 Villefranche sur Mer, France
Telephone:+33-4-93763821; Telefax:+33-93763834; Email rassoul@ccrv.obs-vlfr.fr
Principal scientists: Fereidoun Rassoulzadegan and John Dolan

National Environmental Research Institute, Roskilde
Fredriksborgv.399, BP358, DK-4000, Roskilde, Denmark
Telephone: +45-46301200; Telefax:+45-46301114; Email: ake@dmu.dk
Principal scientist: Åke Hagström

Station Biologique, Roscoff
CNRS SBR (UPR 9402 CNRS)
Centre National de la Recherche Scientifique, UPR 9402
Université Paris VI, Pierre et Marie Curie
BP 74, 29682 Roscoff Cx, FRANCE
Telephone:+33 98 29 23 23; Telefax: +33 98 29 23 24; Email: Daniel.Vaulot@univ-rennes1.fr
Principal scientist: Daniel Vaulot

Institute for the Water Environment, Hørsholm
VKI, Hørsholm, Denmark
Agern Allé 11, DK-2970 Hørsholm, Denmark
Telephone: +45 45 16 92 00; Telefax::+ 45 45 16 92 92; Email: hha@vki.dk
Principal scientist: Harry Havskum

Institut de Ciències del Mar, Barcelona
Passeig Joan de Borbó, s/n
08039 Barcelona, Spain
Telephone: +34-32216416; Telefax:+34-32217340; Email: celia@cucafera.icm.csic.es
Principal scientist: Celia Marrasé

FUNCTIONING OF THE PHOTIC ZONE MICROBIAL FOOD WEB. CONCEPTS, MODELS AN EXPERIMENTS IN THE MEDEA PROJECT.

T. Frede Thingstad[1], John Dolan[2], Åke Hagstrøm[3], Harry Havskum[4], Celia Marrasé[5], Fereidoun Rassoulzadegan[2] and Daniel Vaulot [6]

[1]Dept. of Microbiology, University of Bergen, Jahnebk. 5, N-5020 Bergen, Norway.
[2]Station Zoologique, BP 28, 06230 Villefranche sur Mer, France
[3]Danish Environmental Research Institute, Fredriksborgv.399, BP358, DK-4000 Roskilde, Denmark.
[4] VKI, Hørsholm, Agern Allé 11, DK-2970 Hørsholm, Denmark
[5] Institut de Ciències del Mar, Passeig Joan de Borbó, s/n , 08039 Barcelona, Spain
[6]Station Biologique, BP 74, 29682 Roscoff Cx, FRANCE

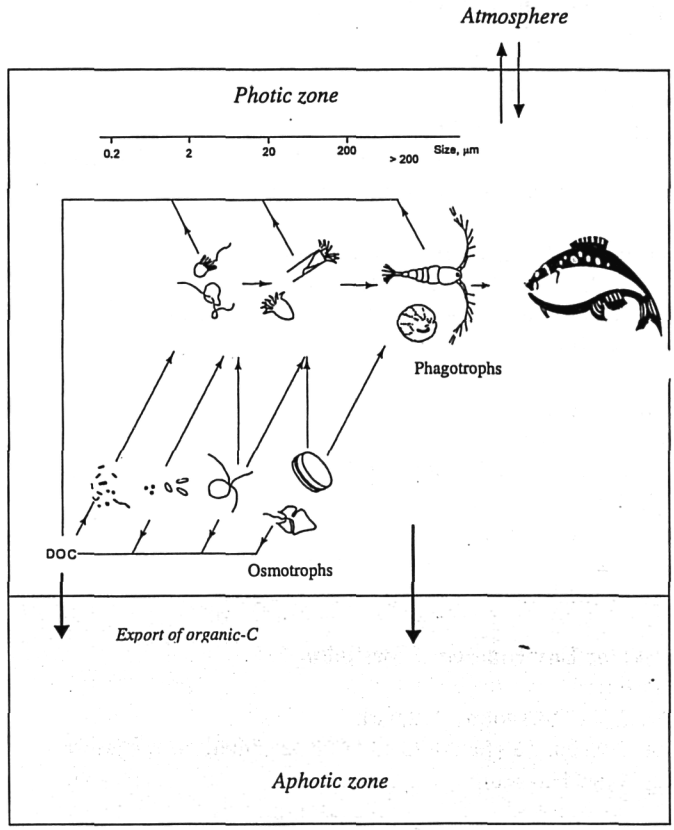


Figure 1. Illustration of the present paradigm of C-flow in the pelagic photic zone. Carbon fixed by phytoplankton of different cell-size is transported upwards in the food chain towards larger predators, but also 'lost' to the pool of dissolved organic matter (DOC). Via the 'microbial loop', part of the DOC is re-incorporated into the particulate food chain by uptake into heterotrophic bacteria. Via export through sinking of large particles or by downwelling or diffusion of dissolved DOC, carbon is transferred to the ocean's interior (Modified from a figure by T. Fenchel).

SUMMARY
MEDEA is a study of the microbial part of the photic zone food web combining experimental research on the different functional groups, with exploration of the limits to which simple, unifying models can be used to combine such knowledge into an understanding of the mechanisms controlling structure and function the food web. Observations and experimental studies in MEDEA are performed in a variety of natural environments and under different experimental conditions. With a food web of organisms possessing an almost infinite variety in trophic strategies, an environment subject to continuos water movement and more or less 'catastrophic' events in meteorological forcing, the attitude is often met that the photic zone is a system in which little is to be gained from simple and generic conceptual models. Our experience is contrary to such an attitude, a large range of the properties of the system seems amenable to analysis within simple models based on nutrient flow through the food web.

INTRODUCTION

Over the last two decades, the general view of carbon flow through the photic zone food web has changed drastically. Up to the end of the seventies, the dominating (but not single) idea was that a reasonable understanding of the marine pelagic food web could be obtained by assuming a simple linear food chain from relatively large phytoplankton, via copepods, to fish. Smaller phytoplankton, protozoa, bacteria and viruses where thought to have only modest roles in this play. In particular, with the methods of detection then available, bacteria seemed to be few , no methods were available to estimate their activity, and the dominating food chain concept seemed perfectly consistent with estimates suggesting that copepods were capable of doing the main job of mineral regeneration in the photic zone. In the wake of new techniques leading to new observations, this view has changed drastically. If one, today, should extract a similar kind of 'generally accepted' food web, comprising the main (but far from all) ideas about carbon flow through the photic zone, there seems to be a consensus merging around structures of the type illustrated in Fig.1. Here, the 'classical' food chain (to the right in Fig. 1) has been expanded into a kind of 'ladder-like' food web structure with a very strong element of size-dependent relationships: A series of osmotroph organisms (the term is here used for an organism taking up dissolved nutrients, organic or inorganic, through the membrane), ranging in size from heterotrophic bacteria to large diatoms, are preyed upon by a series of increasingly larger protozoa and metazoans, eventually producing food for fish. The carbon fixed in photosynthesis by the phytoplankton is thus transported upwards into larger particles through this predatory food chain. Organic carbon is, however, also lost from this upwards transport through a series of processes such as excretion, egestion, sloppy feeding, and viral lysis releasing material to the pool of dissolved organic material. Parts of this 'lost' material is re-assimilated into the particulate food chain by uptake into heterotrophic bacteria (lower left corner of the food web in Fig. 1), a cycle often termed the 'microbial loop'. In the classical picture, this system would transport carbon to the aphotic zone via sinking of copepod fecal pellets and large phytoplankton cells from the right side of Fig. 1. In the last years this has been supplemented by a possible export where diffusion and downwelling transport undegraded DOC from the left 'microbial' side.

While the main structure illustrated in Fig.1 by now seems more or less accepted, our understanding of how this structure is controlled, the mechanisms shifting the balance between the right 'classical' side and the left 'microbial' side, and the mechanisms regulating the activity of the organisms involved, is by far less developed. This lack of a generic theoretical foundation is not a mere academic problem of importance only to a closed field of marine microbiologists; a correct

Table 1. Examples of related sciences and management aspects influenced by the concepts of how the microbial part of the photic zone food web is regulated.

Fisheries science and management.
Production of food for harvestable marine resources.
- *How much of the primary production reaches harvestable levels?*

Sanitary microbiology and management of tourist areas
Aesthetic and hygienic qualities of coastal waters.
- *Survival of pathogenic micro-organisms.*
- *Turbidity and colour of surface waters.*

Waste-water management and biogeochemistry
Fate and effect of organic and inorganic pollutants.
- *What do we need to remove from waste water discharges?*
- *What particle surface area is there for adsorption of surface-active compounds?*
- *What is the fate of polluted particles (bio-accumulation, sinking?)*

Climatic change and biogeochemistry.
Atmospheric CO_2.
- *What regulates the export of C via the particulate and dissolved routes to the ocean's interior?*

Biodiversity and diversity conservation.
- *How does the interactions between organisms in Fig. 1 create niches for different functional groups and species ?*

understanding of how this system responds to anthrophogenic inputs and to variable hydrographical, meteorological, and climatic conditions, is important to a series of related disciplines and to the management of coastal and open oceans (Table 1).

Medea is a project centred around the idea that quite a large range of important properties of the structure illustrated in Fig. 1 can, at least qualitatively, be understood from (amazingly) simple models integrating the various functional groups. The main uniting theme of the MEDEA project is thus to explore the theoretical, experimental, and observational foundations for such a unifying description of the photic zone food web. Being perfectly aware of the inherent dangers of using over-simplified models, Medea has balanced this approach with strong components focusing research on parts of the microbial food web where we feel that our present knowledge may be insufficient to formulate such simplified models in a correct manner. This article focuses on the philosophy and present status of this work, and is not a review of all the work taking place within the MEDEA project.

MATHEMATICAL IDEALIZATIONS OF FIG.1

Based on the philosophy that modelling is the art of balancing on the edge between removal of as much unnecessary detail as at all possible, and the retention of a maximum of essential features, we have been exploring the steady states of simple box models of the type illustrated in Fig. 2. Although appearing almost ridiculously over-simplified when considering the immense biological detail of the real system, we have found analysis of this structure to produce,

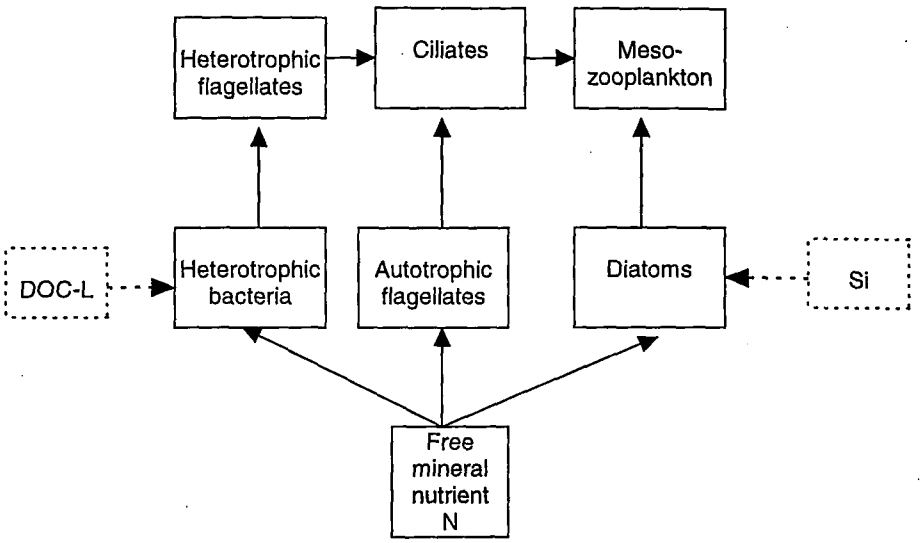


Figure 2. Idealization of the food web structure in Fig. 1 into a box-model allowing analytical solutions for different steady states. Here, the C-flow through the food web is driven by the mechanisms distributing the limiting mineral element (usually N or P) between the functional groups of organisms.

not only qualitative understanding of how size-dependent predation and competition shape the pelagic food web, but even to produce useful numerical predictions and reproductions of actual micro- and mesocosm experiments.

Mere inspection of Fig.2 reveals that there is a kind of basic configuration of the flow structure when [1)]there is a supply of degradable organic carbon exceeding that used by the bacteria (i.e. the bacterial growth grate is mineral nutrient limited), and [2)]there is a supply of silicate exceeding the diatom need. In this case, all the osmotrophs are limited by the same mineral nutrient (in our case normally N or P). If the sum of allochthonous and autochthonous supply of degradable DOC is less than the bacterial carbon demand of the basic configuration, nutrient flow through the left side will be reduced, if Si supply does not meet the diatom demand of the basic configuration, nutrient flow through the right 'classical' side will be reduced. In this perspective, degradable DOC and silicate have a kind of symmetric roles in regulation of the flow structure of mineral nutrients.

To analyze the mechanisms creating the structure of the basic configuration, we have used models where analytical expressions for biomasses and rates can be obtained from [1)]physiological parameters such as affinities, clearance rates and yield coefficients, [2)]the total amount of nutrient available to the system and [3)]the distribution of the available nutrient between the microbial part of the food web and the mesozooplankton predators.

The processes of metazoan reproduction, loss and migration, and the processes importing and exporting nutrients (N, P and Si), and DOC to the photic zone, are of course very variable in time and space, and the manifestation of the generic structure in Fig.2 under different natural and experimental conditions would be expected to vary considerably.

AN EXAMPLE OF FOOD WEB CONTROL: THE EFFECT OF PROTOZOA ON BACTERIAL PRODUCTION.

Since, in the simple framework of Fig.2, ciliates are assumed to prey on both the competitors (autotrophic flagellates) and the predators (heterotrophic flagellates) of bacteria, increased ciliate biomass should stimulate bacterial production. In the case where there is no silicate, while L-DOC is in excess, bacterial production should increase at the square of ciliate biomass ($BP \propto C^2$; Thingstad et al. 1997). The model in Fig.2 can then be used to interpret experimental results such as those shown Fig.3 (Dolan and coworkers, unpublished): Addition of glucose (+N) to water from the P-deficient surface waters of Villefranche Bay (NW Mediterranean) has no effect because the bacteria are P, rather than C-limited. The addition of PO_4 stimulates bacterial production, but with a lag needed for the added P to be transferred via phytoplankton into ciliates. If the model is correct, however, the addition of P stimulated bacterial consumption of L-DOC more than it stimulated the system's production of organic bacterial substrates. After approximately 2 days of P-addition, the system thus shifts from P- to C-limitation of bacterial growth rate. Adding glucose in addition to PO_4 therefore allowed another day of rapid increase in bacterial production before bacterial consumption increased beyond the supply of organic-C (autochthonous production + glucose addition). As the system turns into C-limitation of bacterial growth rate, a main deviation occurs from the $BP \propto C^2$-relationship (Fig.3, right panel). The simplicity of these models allow simulations of such experiments to be run in Excel spreadsheets, thus greatly facilitating the use of such models in the planning of new experiments.

THE SYSTEM'S BEHAVIOUR IN OLIGOTROPHIC WATERS

When the total nutrient N_t available to the microbial system decreases, such models predict the larger osmotrophs to disappear. Qualitatively, this explain not only the dominance of small organisms in the phytoplankton community, but also the increasing relative dominance of heterotrophic bacteria, relative to phytoplankton, in oligotrophic waters. At some extreme degree of oligotrophy, however, these models predict phytoplankton biomass (and thus the primary production of carbon) to become so low, relative to bacterial biomass, that bacterial growth rate becomes C-limited (Thingstad et al. 1997). Whether natural systems experience an oligotrophy so extreme that this theoretical flip into bacterial C-limitation occurs, remains a question open to investigation. If the interpretation of the experiment above is correct, it seems, however, that also eutrophication (adding mineral nutrients) may flip the system into C-limitation of bacteria (at least over short time scales). The meager information so far available thus indicates that, at both extremes in oligo- and eutrophy, the mineral nutrient flow through the left-, 'microbial', side of Fig.2 is restricted by the system's production of degradable DOC. At least some natural systems, seem, however, to be in the intermediate range where production of labile DOC is in excess, and bacterial growth rate is mineral nutrient limited (Thingstad et al., in press).

Focusing on the importance of understanding the growth conditions for the heterotrophic bacteria, the MEDEA project has also studied the elemental composition of heterotrophic bacteria in diverse environments (Heldal et al.1996).

THE NICHE FOR AUTOTROPHIC PICOPLANKTON.

In the basic configuration of the system in Fig.2, it is the size selectivity of the predators which allow coexistence of the three competing osmotrophs. An important conceptual consequence of this is that the classical Hutchinson paradox theoretically can be resolved without necessarily invoking inhomogeneities in time or space as main mechanisms for maintenance of

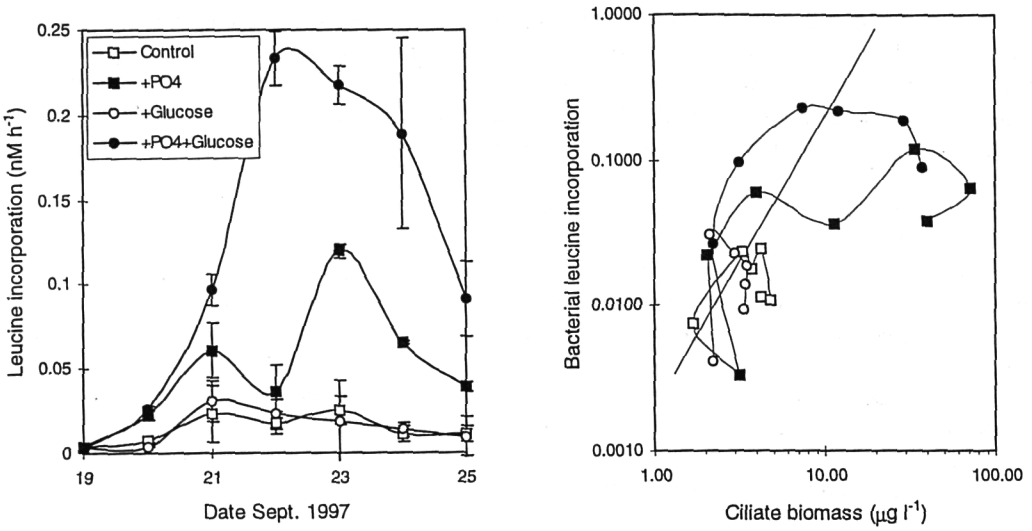


Figure 3.

Left panel: Bacterial production estimated as incorporation of ^{14}C-leucine in 20 l carboys containing the natural plankton community from 'point B' Villefranche Bay. Incubated with daily additions of PO_4 (■),glucose (O), or both (●). All carboys, including controls (□), received nitrate to maintain P-deficiency. Error bars indicate range between two parallell carboys.

Right panel: Leucine incorporation plotted against ciliate biomass in log-log plot. The straight line is the relationship $y=0.002 C^2$ where C is ciliate biomass, as predicted from the assumption of stady state in the system of free mineral nutrients, bacteria, and hetero- and auto-trophic flagellates. (Dolan et al. unpublished).

microbial diversity. The minimum concentration (N_C) of free limiting nutrient at which an osmotrophic organism can maintain a stable population in the photic zone, is when diffusion transport of nutrient towards the cell exactly balances the nutrient loss by sinking cells. If there is no compensating mechanisms like floating, swimming, etc., this gives an expression for a spherical cell where N_C is proportional to the fourth power of cell radius ($N_C \propto r^4$; Thingstad in press). With such a strong 'penalty' for being large, one might argue for a large dominance of very small phytoplankton.

This also means, however, that if a photosynthetic cell gets small enough, it will be subject to predation from predators preying in the size range of heterotrophic bacteria. Two organisms limited by the same substrate can not stably coexist in these models if they have the same specific loss rate. This suggests a possible problem in explaining coexistence of picoplanktonic osmotrophs all limited by one nutrient and preyed upon at the same rate.

Investigations in Medea have established the important role of autotrophic picoplankton in diverse environments (Jacquet et al. subm. a; Marie et al. 1997; Vaulot and Marie subm.). New findings (Neveux and Lantoine, subm.) also suggest that picoplanktonic diversity is even larger than so far assumed. Field investigations has also given data indicating a similar loss

rate for different taxa, and thus suggesting that that there is no size-selectivity in grazing (Yahel, et al. in press).

In laboratory experiments, however, with the bacterivorous ciliate *Uronema* and the algivorous ciliate *Strombidium*, different predatory loss rates for the small picoplanktonic phytoplankters *Prochloroccus* and *Synechococcus* was found (Christaki et al. subm.). Feeding these ciliates microspheres in the size-range 0.5-1.0 μm, a strong dependency on prey size was found for the clearance rate of *Strombidium*, less so for *Uronema* (Christaki et al., in press a).

DIVERSITY MAINTAINING MECHANISMS.

Within the conceptual framework of models such as the one in Fig.2, diversity can be reformulated as being the degree to which the total nutrient available to the microbial community is divided between functional groups and between species within these groups. In addition to the diversity maintained by size-selectivity of predators discussed above, diversity can be increased further if there are additional mechanisms selectively 'killing the winner' in the community inside one of the 'black boxes' designating functional groups in Fig.2. As one such mechanism, we have suggested viral lysis (Thingstad , in press). Since viruses are host-specific, down to the level of species, they can, at least in theory, increase the loss rate of the most successful species within one functional group, and thus allow coexistence of several species, even if these feed on the same food and have the same metazoan or protozoan predator.

Within the MEDEA project, we have used DNA-hybridization to study the relative contribution of bacteria, previously isolated on agar plates, to the total bacterial community in natural samples. The 48 specific bacteria studied comprised up to 69% of the total count, or up to 111% of the nuceoid-containing cells of the natural community (Pinhassi et al. 1997). Theoretical estimates based on the virus-hypothesis suggest that there should be room for something in the order of 50 simultaneously dominant species of heterotrophic bacteria.

The occurrence of bacterial viruses has also been shown in the extreme environment of the Dead Sea (Oren et al. 1997) and we have isolated viruses of phytoplankton for further laboratory studies (Jacobsen et al. 1996).

THE PRODUCTION OF DISSOLVED ORGANIC CARBON.

With the importance suggested by this analysis of the L-DOC 'switch' on the left side of Fig.2, a correct understanding of the mechanisms producing carbon substrates for the bacteria become central to our understanding of how the whole system works.

In addition to the role of viruses in controlling diversity, the process of viral lysis has been speculated to release the content of the infected cell into the surrounding water. Within MEDEA, we have studied this process by using a model system where photosynthetic algae (*Phaeocystis*) were infected by virus in laboratory cultures. The growth of heterotrophic bacteria could then be used to demonstrate how the lysate serves as organic substrate (Bratbak et al. unpublished).

Within MEDEA, we have also developed a method whereby the release of DOM during protozoan grazing on bacteria can be studied, despite the problem that the remaining bacterial prey normally will consume the DOM produced through sloppy feeding, egestion, etc. (Pelegri et al., subm).

MIXOTROPHIC PROTISTS.

The scheme in Fig.2 may convey the impression that any organism in the food web can be unambiguously classified as either osmotroph or phagotroph, autotroph or heterotroph. This

is not the case. In particular there are protists with both photosynthetic and phagotrophic abilities. I.e. organisms combining the functions of the phytoplankton and the protozoan predators in Fig.2. In MEDEA, we have found these organisms to play a role In environments as diverse as the brackish layer of Norwegian fjords (Havskum and Hansen, 1997) and the eastern Mediterranean (Christaki et al. in press b). As shown using models of the same type as discussed above, the effect can theoretically be quite substantial because mixotrophs can gain from the double effect of both removing their predator, and at the same time obtain in a pelleted form the mineral nutrient already harvested by the competitor.

DIEL CYCLES.

In our analyses, we have assumed that a reasonable approximation to the real state of the system could be obtained by assuming parts of the food web in Fig. 2 to have a dynamics fast enough to reach a steady state within the time scale between observations. If the frequency of observation is increased above 1 d^{-1}, one would expect the diurnal variation in light to perturbate the system and induce fluctuations around the steady state. In such a perspective, the study of diel fluctuations becomes a kind of nature's own perturbation experiments, where studies of the system's fluctuations should provide information on the mechanisms controlling the dynamics of the system.

Within MEDEA, extensive studies have been performed on the diel cycles of the photosynthetic picoplankton. Such studies have required the development of new sampling equipment (Jacquet et al., subm b) and flowcytometric techniques (Marie et al. 1996, 1997) allowing high-frequency, high precision measurements. Using this, the synchronised cycle of division of these small phytoplankters has been well documented (Jacquet et al., subm. a; Vaulot and Marie, subm.).

Within MEDEA, extensive studies have also documented cycles in bacterial production, dissolved and particular organic-C, and inorganic nutrients (Hagstrøm et al. unpublished). Whether these fluctuations are driven by trophic couplings to the fluctuations in cell size, abundance, and activity of the photosynthetic organisms, or whether there are additional points in the food web where external forces drive the observed cycles, is however, still poorly understood.

TURBULENCE.

The structure of the mineral nutrient flow through the microbial community in Fig.2 depends upon how 'clever' the organisms are to collect food at low food concentrations. In the mathematical formulation, this ability is contained in the affinity constants of the osmotrophs, and the clearance rates of the predators; both expressing the volume cleared for food per unit time per unit biomass. We denote both by the symbol α. If the relative movement between an organism and its food is increased, these α-parameters should increase. Turbulence, if acting differently on the different α's, should therefore potentially shift the steady state structure of the microbial community. According to theory, the Kolmogorov length scale at natural turbulence level is in the order of 1 mm (Peters and Redondo 1997). Since water movement below Kolmogorov scale is dominantly laminar, turbulence would in theory be expected mostly to influence the α's of the larger organisms. Contrary to what perhaps may be the intuitive feeling, our models predict the steady state in the lower left, bacterial, corner of Fig.2, to be highly dependent upon properties in the 'classical' side of the food web ($BP \propto \left(\frac{\alpha_M}{\alpha_D}\right)^2$ where subscripts D and M denote diatoms and mesozooplankton, respectively).

Within MEDEA, we have studied the effects of turbulence in microcosms incubated under still and turbulent conditions. Clear effects at the bacterial level has been found (Peters et al. subm.).

CONCLUSION

We have been able to use simple models to create an integrated framework within which the expertise of the MEDEA partners on different aspects of the microbial food web can be linked, and thereby improve our understanding of the pelagic microbial food web as a whole. In particular, we feel that the approach has proven successful for processes taking place over the time scale of days. MEDEA has also made important contributions to our knowledge on the variations taking place over the time scale less than one day, but the linkages between food web processes at this time scale are still poorly understood.

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TITEL	Trans-Atlantic Study of *Calanus finmarchicus* **(TASC)**
CONTRACT NO:	MAS3-CT95–0039
COORDINATOR	Dr. K. Tande University of Tromsø Norwegian College of Fishery Sciences 9037 Tromsø, Norway Tel +47 77 64 45 24, fax +47 77 64 60 20 E-mail:kurtt@nfh.uit.no; Web:http://calanus.nfh.uit.no/TASC.HTML

PARTNERS:

Dag Aksnes
Department of Fisheries and Marine Biology
University of Bergen , Bergen High
Technology Center, 5020 Bergen, Norway
Tel +47 55 58 44 78
Fax +47 55 58 44 50
E-mail Dag.Aksnes@ifm.uib.no

Jan Backhaus
Institute fur Meereskunde
Universität Hamburg , Troplowitzstr. 7,
22529 Hamburg, Germany
Tel. +49 40 41 23 26 04
Fax +49 40 560 57 42
E-mail backhaus@dkrz.d400.de

Francois Carlotti
Universite Pierre-et-Marie-Curie
(Paris VI), Laboratorie d'Ecologie du
Plancton Marine, Stationn Zooligique,
P.O. Box 28, 06230 Villefranche-sur-Mer,
France.
Tel + 33 493 76 38 39
Fax +33 493 76 38 34
E-mail carlotti@ccrv.obs-vlfr.fr

Bjørnar Ellertsen
Institute of Marine Research, P.O. Box 1870
Nordnes, 5024 Bergen, Norway
Tel. +47 55 23 84 84
Fax. +47 55 23 85 31
E-mail bjoernar.ellertsen@imr.no

Assthor Gislason
Marine Research Institute , Skulagata 4
121 Reykjavik, Iceland
Tel. +354 55 20 240
Tel +354 56 23 790
E-mail astthor@hafro.is

William Gurney
Department of Statistics and Modelling
Science
University of Strathclyde
Livingstone Tower
26 Richmond Street
Glasgow G1 1 XH, Scotland
Tel. +44 41 552 44 00 ext 3812
Fax +44 41 552 20 79
E-mail bill@stams.strathclyde.ac.uk

Benni Hansen
Life Science and Chemistry,
Roskilde University , P.O. Box 260,
DK-4000 Roskilde, Denmark.
Tel. +45 46 74 24 06
Fax +45 46 74 30 11
E-mail bhansen@virgil.ruc.dk

Roger Harris
Plymouth Marine Laboratory, Prospect Place,
The Hoe, Plymouth, PL1 3DH
United Kingdom
Tel +44 17 52 63 34 00
Fax + 44 17 52 63 31 01
E-mail rph@wpo.nerc.ac.uk

Mike Heath
The Marine Laboratory of the Scottish Office Agriculture and Fisheries Department, P.O. Box 101, Victoria Road
Aberdeen, AB9 8DB, Scotland
Tel. +44 12 24 87 65 44
Fax +44 12 24 29 55 11
E-mail heathmr@31G.dnet.marlab.ac.uk

Hans Jügen Hirche
Alfred-Wegener-Institute für Polar- und Meeresforshung, Colombusstrasse 1,
27515 Bremerhaven, Germany
Tel +49 47 14 83 13 36
Fax +49 47 14 83 11 49
E-mail hhirche@awi-bremerhaven.de

Stein Kaartvedt
Biologisk Instiutt, Departement of Marine Zoology and Marine Biochemistry,
P.O. Box 1064 Blindern,
University of Oslo, Norway
Tel +47 22 85 47 39
Fax. +47 22 85 44 38
E-mail steinka@bio.uio.no

Katherine Richardson
Danish Institute for Fisheries and Marine Research
Charlottenlund Castle
DK-2920 Charlottenlund, Denmark
Tel. +45 33 96 34 00
Fax +45 33 96 34 34
E-mail: kr@dfu.min.dk

Dag Slagstad
SINTEF Civil and Environmental Engineering
Coastal and Ocean Engineering
N-7034 Trondheim, Norway.
Tel +47 73 59 24 07
Fax +47 59 23 76
E-mail dag.slagstad@civil.sintef.no

Subcontractors:

Keith Brander
International Council for the Exploration of the Seas, Palaegade 2, 1261 Copehagen K, Denmark
Tel. +45 33 15 42 25
Fax. +45 33 93 42 15
E-mail keith@ices.dk

Chris Reid
Sir Allister Hardy Foundation for Ocean Science , The Laboratory, Citadil Hill,
Plymouth, PL1 2PB, United Kingdom
Tel. +44 17 52 22 11 35
Fax +44 17 52 22 11 35
E-mail pcr@wpo.nerc.ac.uk

Stig Skreslet
Bodø College, Department of Fisheries and Science, 8002 Bodø, Norway.
Tel. +47 75 51 74 96
Fax. +47 75 51 74 84
E-mail stig.skreslet@hibo.no

Eilif Gard
Fiskarannsoknoarstovau
P.O. Box 3051, Noatun, FR-110 Torshavn, Faroe
Tel. +298 15 092
Fax +298 18 264
E-mail eilifg@frs.fo

WHAT IS TASC?

TASC (Trans-Atlantic Study of *Calanus finmarchicus*) is an international research initiative in plankton ecology. It is a major contribution to the Global Ocean Ecosystem Dynamics project (GLOBEC). TASC build on and integrates three ongoing research programmes: The U.S. GLOBEC Georges Bank program, Canadian GLOBEC activities in the N.W.Atlantic and the EU TASC project.

TASC PHILOSOPHY

The effect of seasonal and long-term variations in physical forcing in the North Atlantic plankton system have demonstrated that lower trophic levels in the pelagic system are strongly influenced by atmospheric and climatic processes. The European TASC focuses on integrated studies of the population dynamics of *C. finmarchicus* in relation to physical processes in the ocean. The project will resolve the mechanisms controlling the large scale demography and generation cycle characteristics of the target species, in particular, the relationship to basin scale circulation features, latitudinal gradients in the abiotic climate, and the interactions with predators and prey.

THE TARGETTED SPECIES

The horizontal distribution of *Calanus* species in the ocean upper layer has been quite intensively investigated. The genus *Calanus* is widely distributed in the northern hemisphere, from the warm waters of the Mediterranean and Black Seas to the cold waters of the central Arctic basin. Although the distributions of *Calanus* species sometimes overlap, distinct species can, in most cases, be related to distinct water masses.

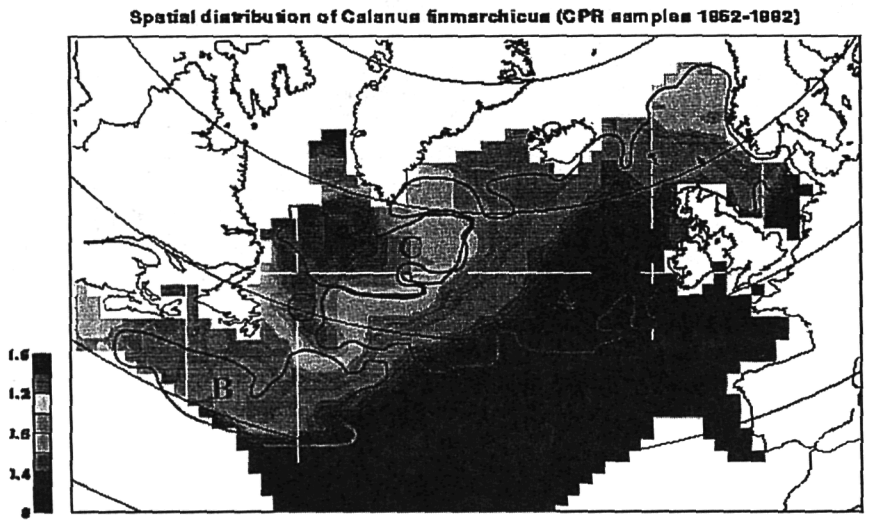


Figure 1. Three areas defined on the basis of the Principal Component Analysis. Area A is characterised by the dominant seasonal cycle of abundance in the North Atlantic region, while in areas B and C the seasonal cycles differ markedly from the dominant patter (Planque, 1996).

In the North Atlantic, the biogeographical boundaries of *C. finmarchicus* is associated with cold temperate water and the species has thus a northerly distribution (Fig. 1). The abundance, as obtained by Continous Plankton Recorder (CPR) surveys, is characterised by the opposition of the northwestern region where the species is abundant and the southeastern region where abundance is low. Three regions of particularly high concentrations are found: Norwegian Sea, Georges Bank, and between southwest Greenland-Newfoundland.

Although the winter and summer distribution patterns are different (vertically and horizontally), they are related through several mechanisms, including the timing of ontogenetic migrating behaviour and of the induction and termination of diapause, the early spring recruitment success, and the vertical and horizontal transport by oceanic currents.

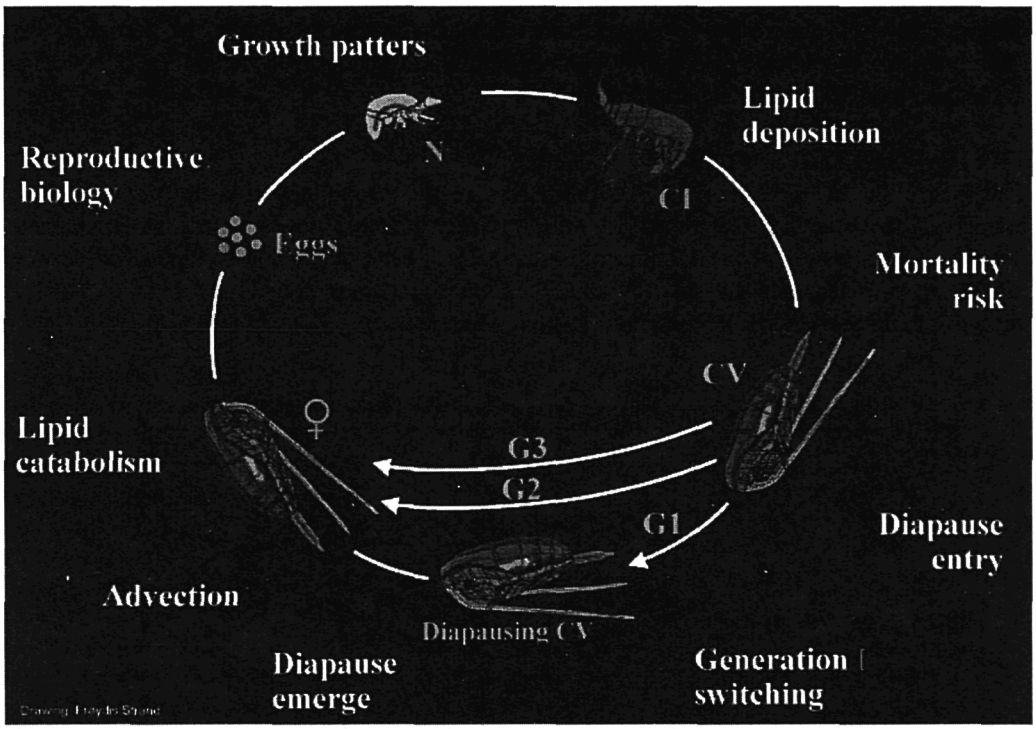


Figure 2. Life cycle of *Calanus finmarchicus* with highlighted topics of study. Number of generations are given as one (G1), two (G2) and three (G3), respectively.

THE LIFE CYCLE

The underlying core question posed by TASC is. Why is this species so successful in the North Atlantic? The European TASC hypothesis is that a core habitat of this species is the large scale gyre in the Norwegian Sea with an annual generation (Fig. 2) as the prevailing pattern. At the continental rim *C. finmarchicus* encounters a wide range of environmental and biological conditions, which determine the number of generations produced.

TASC therefore focuses on factors controlling the life history processes in *C. finmarchicus*, what governs the number of generations produced, and what are the basis and cues whether to prepare for onset of a new generation or whether to prepare for overwintering. What are the roles of the latitudinal differences in light conditions, actual or potential presence of predators and the quantity and quality of food for this decision?

RESEARCH FOCI

The above TASC research are organised in several geographical locations:

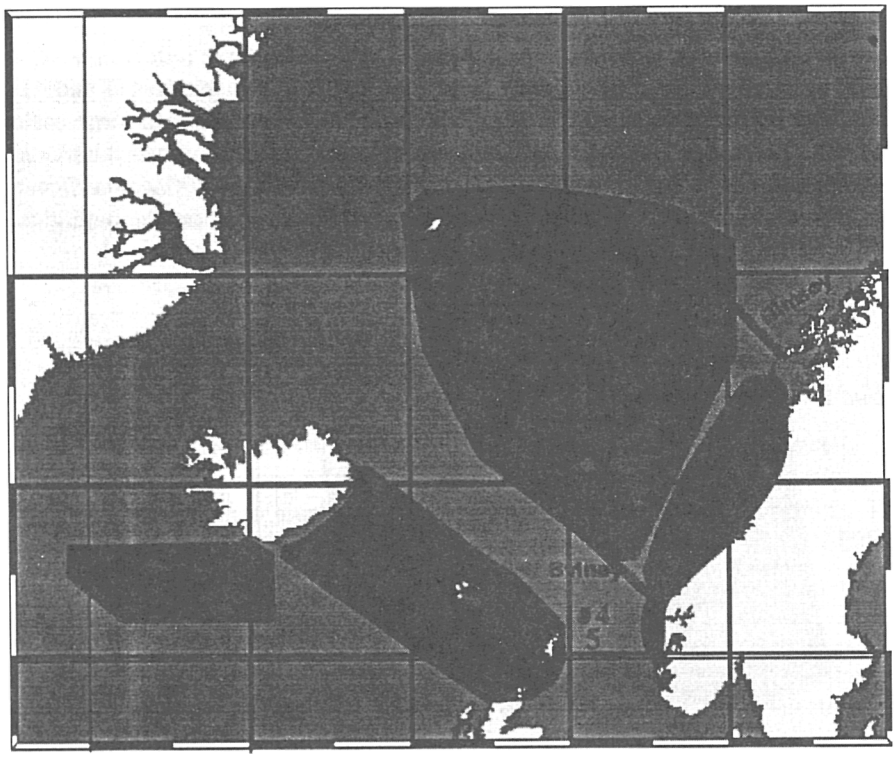


Figure 3. Overview of the EU TASC study regions. Symbols:

1. Cross shelf exchange
2. Generation pattern and switching
3. Predator-prey interactions
4. Comparative time series programme
5. Experiments
6. Large scale field observational programme

RESEARCH STRATEGY

The approach taken by TASC is driven by the extreme complexity of the problems being addressed. Many of the key processes and interactions which determine the generation pattern, the success of their completion and the ultimate fluctuation in stock size, are not yet well understood. TASC combines observational field programmes, laboratory experiments and biological and physical modelling, which will enable us to describe entire populations on spatial scales from kilometres to hundreds of kilometers.

RESEARCH APPROACH

TASC focuses on establishing models of *C. finmarchicus* at each of the three following levels: 1) models of individual physiology, 2) detailed population dynamic models in Od and 1D physical contexts, and 3) simplified biological models designed for coupling to large scale phenomena (3D physical models). TASC has adopted two sets of basic physical model concept (Fig. 4): HAMSOM (Hamburg Shelf Ocean Model) and POM (Princeton Ocean Model), which differ in a number of ways, but form highly detailed forcing for the biological models.

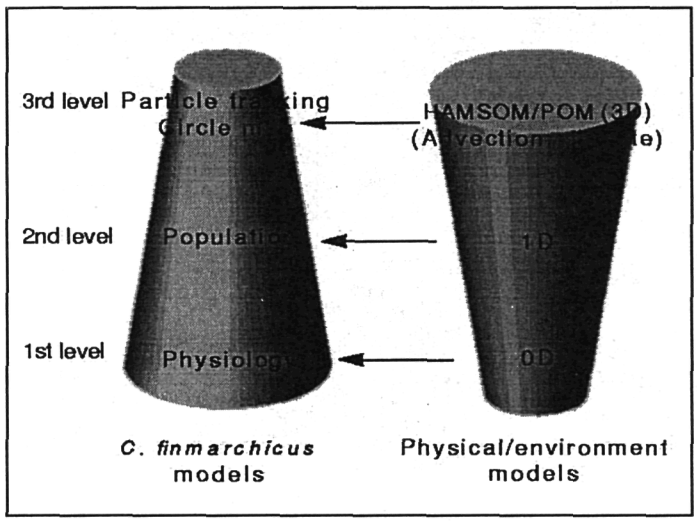


Figure 4. Biological and physical modelling in TASC where the base of the cone represents the highest degree of model complexities.

In order to meet the objectives, TASC has been organised around the following themes:

I. PHYSIOLOGY

TASC experimental studies will combine laboratory and mesocosmos studies to advance quantitative knowledge of the feeding biology, reproductive biology, and key life-cycle phenomena of *Calanus* over the trans latitudinal range. The following experiments are being conducted

* **Station "M" – Norwegian Sea**
  Grazing egg production, hatching viability, and nauplii survival
* **Laboratory**
  TASC has established cultures of *Calanus* at Plymouth Marine Laboratory in order to provide relevant data for modelling physiology and life history
* **Mesocoms**
  Cultivation of *Calanus* from egg to adults are being conducted in order to compare responses in growth patter, developmental and mortality schedules to variations in physical settings along a latitudinal range.

II. POPULATION DYNAMICS

* **Meso and large scale field programme and modelling**
  The objectives are to examine the connections between summer populations of *C. finmarchicus* in the shelf fringing the northeast Atlantic and Norwegian Sea, and the role of deep water circulation feature in this linkage. The aims are to identify behavioural differences in ocean and shelf populations, in particular to understand the mechanisms for the observed alternations between generation patterns in the region. This involves field sampling and modelling.

Predator – prey interaction
TASC will assess mortality risk of *Calanus* with respect to visual predators along a latitudinal (light regime) gradient in the Norwegian Sea and how this impacts plankton vertical distribution and life history traits. TASC will also assess mortality rates for overwintering fjord populations of *Calanus* exposed to visual and non-visual predators, respectively.

Comparative time series
TASC will describe the annual cycle of vertical distribution, generation development and overwintering of *C. finmarchicus* at selected locations in the Nordic Sea and in water south of Iceland. The regional patterns of seasonal migration and generational development will be compared and related to seasonal pattern of hydrography and phytoplankton development.

Exchange of Calanus between ocean basin and shelves
TASC will investigate the connections between overwintering stocks, and shelf summer populations of western, southern and eastern Iceland, at Faroe Plateau, in the Northern North Sea, and along the Norwegian mid-shelf. The correlated trends in each of these systems may be explained in terms of ocean scale circulation patterns. One of the objectives is to identify the physical and biological factors responsible for the switch from a two generation to an annual generation pattern along the Norwegian midshelf sector.

II. RETROSPECTIVE ANALYSIS

* **Long term population changes**
  TASC will explore the data obtained by the Continuous Plankton Recorder survey for the North Atlantic from 1946 onwards, as well as from other sources in Iceland (MRI), the Faroe Islands Fisheries Laboratory, and at PINRO in Murmansk, Russia

RESULTS

Physiology

Calibration of the physiological model of *C. finmarchicus* will be achieved by simulating the results from the experimental work. The knowledge of basic physiologi-cal processes obtained from these studies will be synthesised in a physiological model, the products of which will be tested by comparision with field observations of growth and reproduction collected during the project.

In mesocosm experiments the stage development, somatic growth, lipid storage and population mortality of *C. finmarchicus* (from NI to adult) has been obtained (Fig. 5). These parameters was studied under two different food regimes: *low*, equal to a relatively oligotrophic in situ like situation, and *high*, simulating a bloom situation. The *Calanus* cohort developed rather similarly through all nauplii stages in the two nutrient conditions, but diverged later in the copepodite stages (Fig. 5). The carbon content of adults were significantly higher in the nutrient enriched mesocosms. The results demonstrate for the first time that *C. finmarchicus* are able to close the life circle within 6-7 weeks, in a mesocosm culture facility and these data will, partly form the basis for modelling individual physiology of the species.

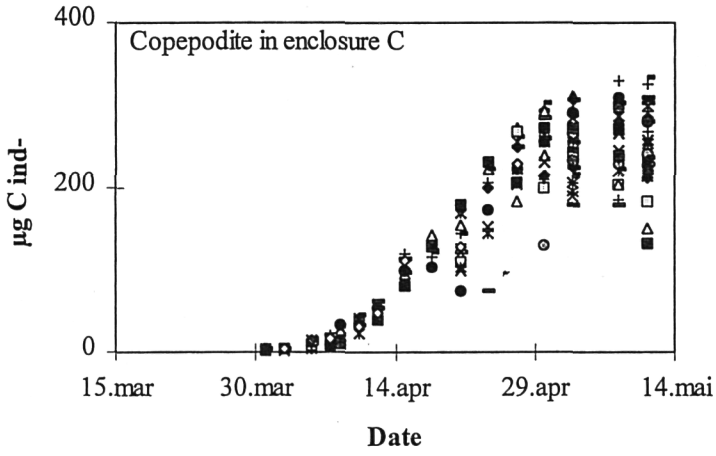


Figure 5 . Growth curves of cohorts of *Calanus finmarchicus* offered enriched fjord water (C) in mesocosms during 1997.

Population Dynamics:

TASC will develop a population model with dynamic responds to environmental conditions (i.e. temperature, food, predators). This will involve stage structured cohorts representing the generation patterns observed in the study area, with growth and development, behaviour, timing of diapause entry and emergence. The life cycle modelled will be compatible with computational demands and will operate in tandem with a particle tracking model.

Behavior: Predator-Prey Interactions

Latitudinal and seasonal gradients in light conditions are fundamental elements of the Norwegian sea ecosystem, probably with profound impact on predator-prey relationships between visual predators (fish) and *Calanus.* Northern stocks of *Calanus* leave, to a large extent, upper layers for overwintering in early summer.

It is **hypothesised** that *Calanus* exhibits flexibility in selection of overwintering depth with respect to presence of prevailing predators. TASC will assess mortality risk of *Calanus* with respect to visual predators along a latitudinal (light regime) gradient in the Norwegian Sea and how this impacts plankton vertical distribution and life history traits. TASC will also assess mortality rates for overwintering fjord populations of *Calanus* exposed to visual and non-visual predators respectively.

Horizontally migrating fish (e.g. herring and mackerel) are major visual predators on *Calanus* during summer. By relying on their schooling behaviour and rapid swimming in predator avoidance, they may forage in upper layers by day. Resident, mesopelagic fish performing diel vertical migrations (*Benthosema glaciale, Maurolicus muelleri*) are major predators on *Calanus* in periods/regions with day/night cycles, but not in periods/regions with mid-night sun. They feed actively on near surface copepod assemblages during short "anti-predatory windows" near sunset and sunrise, and their large eyes possibly also facilitates fairly efficient feeding during night. They do not prey on *Calanus* during day in seasons when the copepods inhabit upper layers. An unprofitable light climate for feeding conditions may reduce the success of mesopelagic fish at high latitudes.

Overwintering in oceanic habitats

In the Norwegian and Greenland Sea, *Calanus* overwinters deeper in regions with upper, Atlantic water masses than where cold water prevails throughout the water column, mainly inhabiting waters with temperatures between -0.5 and +0.5 °C in all parts of the ocean (Fig. 6 upper panel). The temperature is thus a possible ultimate cause governing *Calanus* habitat selection (physiological explanation). However, varying predation pressure represents an alternative explanation, as acoustic studies suggest that the distribution of mesopelagic fish follows warm waters (Fig. 6 lower panel). The Greenland Sea gyres (where *Calanus* overwinters in relatively shallow waters) apparently is almost devoid of these potential

predators. Scattering layers in the Atlantic part are confined to the warm water masses of the upper ~500 m, i.e. above the bulk of the *Calanus* population.

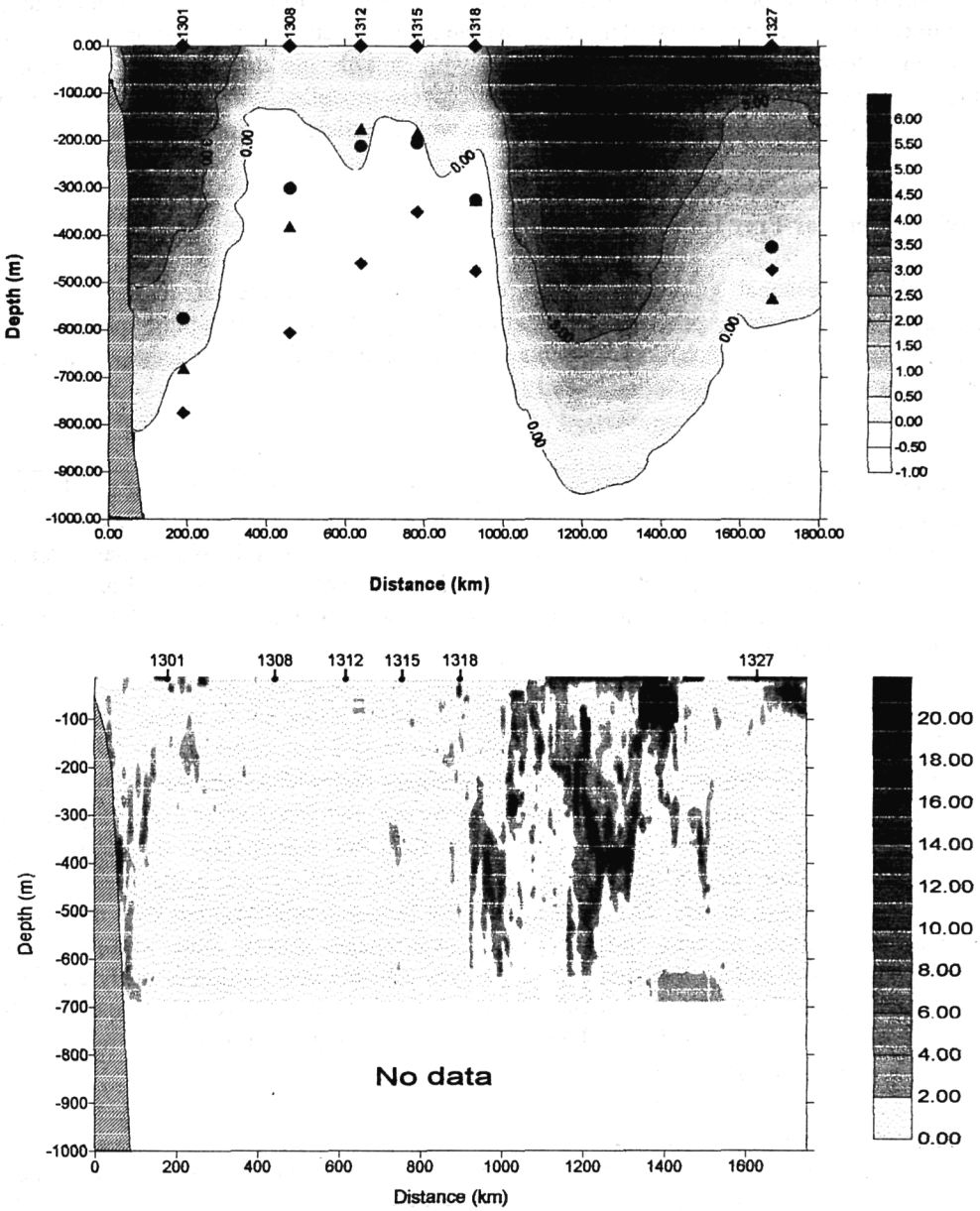


Figure 6. Data from a transect along the Norwegian and Greenland sea showing upper panel: temperatures and median depths of overwintering *Calanus* CIV (◆), CV (●) and females (▲); and lower panel: acoustical backscattering. Stns 1308,1312, 1315 and 1318 are located in cold waters of the Greenland Sea gyres, which is devoid of backscattering (i.e. fish predators on *Calanus*).

Exchange of *Calanus* between ocean basin and shelves

TASC will develop particle tracking concepts which will rely on the detailed physiological data obtained both from field campaigns and experimental studies, where particles have both behavioural and dynamic growth characteristics pertinent to *C. finmarchicus.*

The recent progress incorporates an integrated small scale- and large scale model, where the small scale model domain mainly covers selected parts of the shelf. The resolution of the large scale model is 20x20 km and 4x4 km for the smale scale model. The integration of the two flow fields ensures a more reliable estimate of current and advection in regions with rapidly changing topographic features, like the shelf.

The biology component has been developed to incorporate diffentiated spawning behavior (migration) and delayed spawning in the surface region, along with the stage progression as a function of temperature. The biological model has been developed on the basis of existing field data. The results clearly indicates the possibility of two generations in specific regions.

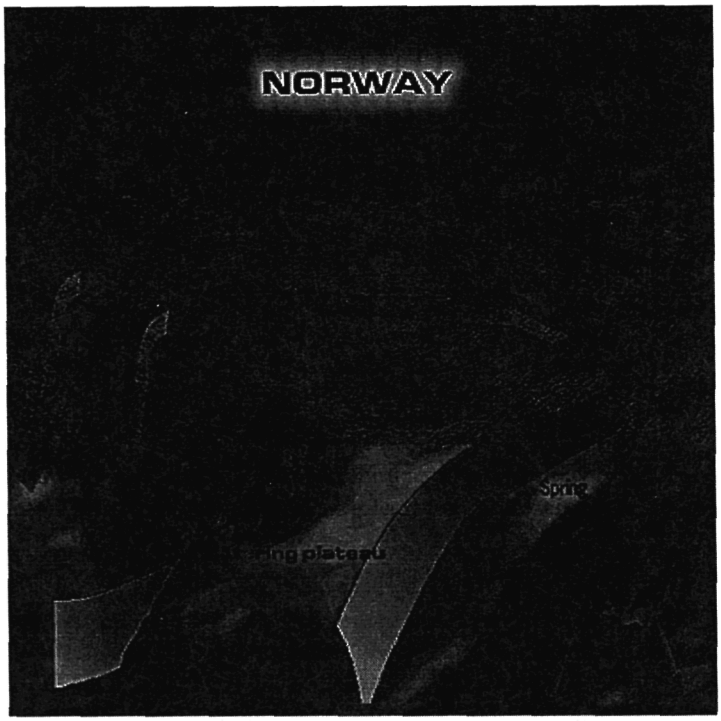


Figure 7. A conceptual draft of the cross-shelf transport between oceanic water and NW European shelves. This example taken from the Norwegian midshelf.

Cross shelf exchange around the Faroe Plateau

The distribution of overwintered *Calanus* in the spring is **hypothesised** to be explained by the distribution and transport at ocean depths of diapause animals during the winter, and their dispersal as they ascend towards the surface in the spring.

The objective of TASC is to test the hypothesis outlined above for shelf areas - in particular the Faeroe Plateau, and southeast Iceland. The model research on the Norwegian midshelf mainly adresses the cross shelf exchange of *Calanus,* and the importance of this advection pattern related to a possible generation switching. See Fig. 7 for a conceptual draft of the advection scheme.

The presented scenario predicts the distribution of animals in the surface waters in spring, which is then be tested on a later cruise in the same area. The approach was to use particle tracking to simulate the horizontal dispersal of concentrations over a period of 120 days, whilst assigning a vertical migration pattern to the particles to mimic the behaviour of *Calanus.*

The initial distribution of concentration (1 December) derived directly from the field data showed an aggregation of animals in the Faeroe-Shetland Channel, and elevated concentrations in the eastern Norwegian Sea (Fig. 8a).

After 60 days (1 February) the particles are at a constant depth of 600m. A band of high concentration is observed along the Atlantic side of the Iceland Scotland Ridge. The model suggests substantial westwards transport of overwintering *Calanus* between December and February. After 100 days (approx. 10 March) the particles reside now at 36 m. The model suggests that high concentrations of animals should be found in the surface waters, amongst others, along the Atlantic side of the Iceland-Scotland Ridge and in the shelf waters along the south coast of Iceland.

After 120 days (1 April), the distribution of concentrations has intensified around the southern part of the Faeroe Plateau whilst the northern part remains less densely populated (Fig. 8d). The concentrations along the south coast of Iceland have spread both east and west along the shelf.

Conclusion: The pattern of invasion of the Faeroe Plateau corresponds with descriptions based on studies carried out by the Faeroese Fisheries Laboratory - that is, invasion takes place first around the southern side of the Plateau and animals are carried clockwise around the Islands by the shelf currents. The extent of overwinter redistribution of concentrations in the Faeroe-Shetland Channel to the west side of the Iceland-Scotland Ridge as far as Iceland is a surprising result which leads directly to a highly distinctive distribution of animals in the surface waters along the Iceland-Scotland Ridge and around Faeroe in the spring.

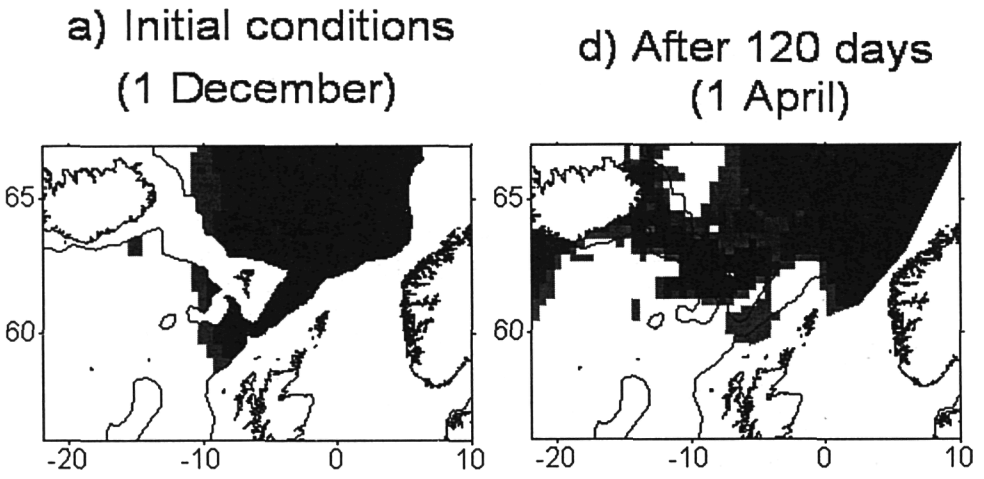


Figure 8. Gridded distribution of *Calanus* concentration as measured by the OPC during Dana cruise in 1996 (a). Simulated distribution of concentrations after120 days with Hellerman winter climatological wind forcing of the HAMSOM model (d).

Life cycle strategies and generation switching

In order to investigate the mechanisms for generation switching in *C. finmarchicus* a particle tracking model with a biological component for the Norwegian Sea and selected adjacent shelves has been developed. The advection of the population, in the present concept is driven by the physical components, while the biological model describes vertical migration and stage development. The work adresses the development and spatial distribution as a function of initial distribution and the current regime along the Norwegian shelf. The model concept has been developed through successive stages along with the refinement of the scientific targets.

Three scenarios has been tested with this model:

1. Passive particle having ontogenetic vertical migration behaviour similar to *Calanus*
2. Spawning when the overwintering generation arrives to the surface without any coupling to phytoplankton production
3. Delayed spawning at the onset of the primary production in oceanic and shelf waters

Vertically, ontogenetic migration particles were advected for 6 years. There was a significant higher loss rate when the animals was in the surface water compared to the period of the year when there was a deep distribution. Annual loss rate was about 45 %, but decreased after a few years to 27% when most of the particles were found in the Norwegian Sea gyre.

Result from Station "M" in the Norwegian Sea showed that spawning of *Calanus* took place well ahead the spring bloom with very low concentration of phytoplankton. In the second scenario particles started to reproduce immediately after arriving to the surface waters. Particles that started to develop this early were able to intiate a second generation over most of the Norwegian Sea, but only a few were able to develop into Stage V and females. Those

who did were all found on or close to the Mid Norwegian shelf and even in the Barents Sea (Fig. 9)

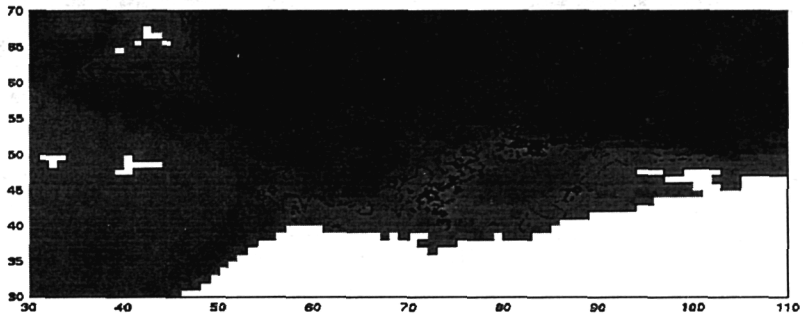


Figure 9. The dots show the geographic distribution of the second generation of CV-CVI in mid July and the isolines show the temperature field.

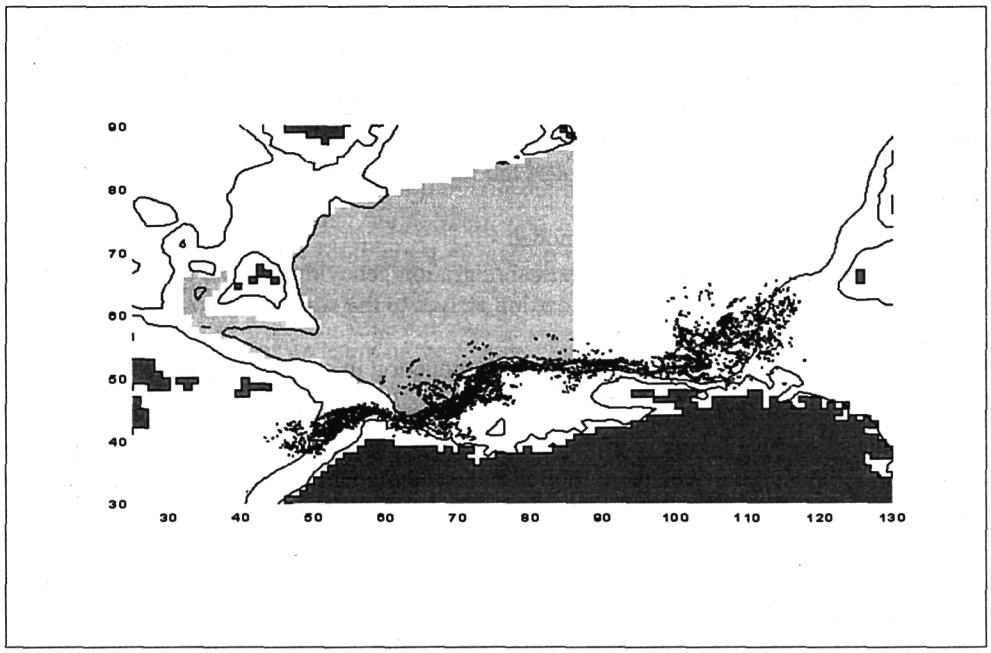


Figure 10. Distribution of eggs hatching to into the second generation. Hatched area identifies the region of release of the first generation.

In the third scenario the overwintering animals were not allowed to produce eggs until the onset of the spring bloom which was specified to May 15.th in oceanic waters and April 1.th on the shelf regions. In this case the spawning for the second generation took place in the Northern North Sea and along the Norwegian shelf break. Spawning of the second generation was possible all the way up to the entrance to the Barents Sea (Fig. 10). On the other hand, very few animals of the second generation were able to develop into stage V. This example proves the potential strength of integrated modelling approaches in order to identify sensitive periods and geographical sites for the formation of the various generations of *Calanus*.

RETROSPECTIVE ANALYSIS

The entire TASC area is now well covered by *Calanus* data of varying spatial and temporal extent/quality and interpretability. The only real void is the Norwegian Basin for which there is currently little available information. It is hoped that more detailed Russian data will become available in the near future.

Phytoplankton Data
A large data-set of chlorophyll-a concentrations (mg-3) in the North East Atlantic has been made available (Platt and Sathyendrenath, 1995) and we have now rendered them into a useful format for analysis. Altogether, there are over 190,000 observations.

Environmental Data
In addition to the zooplankton data we have collected information for the following environmental indices for the entire North Atlantic: (1) The North Atlantic Oscillation Index (1950-1996); (2) sea-surface temperature (1950-1992); (3) wind stress (1950-1992); (4) mean sea- level pressure; and (5) precipitation data (1950-1992). These data have been subjected to some rudimentary exploratory analyses and are proving useful in attempting to understand some of the long-term seasonal and spatial variations evidenced in the zooplankton data.

Results summary
We have made a number of interesting observations across the North -East Atlantic: (1) In the shelf areas of the North Sea and around Iceland the abundance of *C. finmarchicus* fell overall between 1958 and 1996. (2) In the region of the Fair Isle current and areas adjacent to Scotland's East Coast there was a dramatic change in the level of *C. finmarchicus* abundance in 1967 which was also accompanied by a change in the shape of the seasonal cycle; (3) In the northern North Sea the abundance of *C. helgolandicus* also declined between the 1960s and 1980s, since when it increased while *C. finmarchicus* abundances fell; (4) North and North-East of Iceland the proportion in samples of the Arctic calanoid, *C. hyperboreus*, has increased while that of the more Atlantic *C. finmarchicus* has declined; (5) South of Iceland the abundance of *C. finmarchicus* appears to have increased slightly (1958-1996) according to the CPR data, in spite of the fact that this area has witnessed the greatest increases in wind stress over the same period. This is a finding of particular interest since it contradicts certain well accepted ideas which suggest that the abundance of *C. finmarchicus* is retarded by high wind levels (Fig. 11).

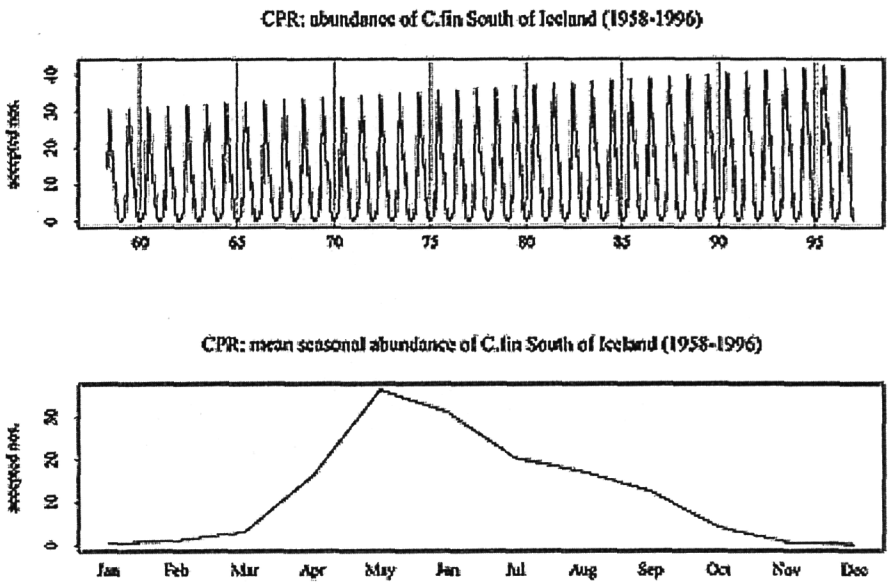


Figure 11. Mean abundance (accepted numbers) south of Iceland of *Calanus finmarchicus* estimated using the Multinomial Logit Model based on 12 monthly periods per year. The seasonality is slightly dependent on long-term trend which was (statistically) adequately represented with a straight line.

This indicate that it is unlikely to find any uniform response pattern in biomass formation of *Calanus* throughout its range of distribution for the time periods covered by the data. Some of the underlying mechanisms for this will hopefully be disclosed by TASC.

PROJECT INFORMATION

The programme will be summed up in a final International Symposium held in Tromsø from 24 to 27 August 1999, co-sponsored, amongst other, by the EU Commission and ICES. More detailed data and results are available in the 12 and 24 mo reports, or at the webside. For further information please contact Coodinator Prof. Kurt Tande, Norwegian College of Fishery Science - 9037 Tromsø, Norway. Email:kurtt@nfh.uit.no; web:http://calanus.nfh.uit.no/TASC.HTML

TITLE: **BIOCOLOR** - Ocean Colour for the determination of Water Column Biological Processes

CONTRACT NO: MAS3-CT97-0085

CO-ORDINATOR:

Dr. J.W. Patching
The Martin Ryan Marine Science Institute
National University of Ireland, Galway
Ireland

Tel. no. +353-91-750456
Fax no. +353-91-525005
Email: John.Patching@UCG.IE

PARTNERS:

Dr. Alison Weeks
Maritime Faculty
Southampton Institute
East Park Terrace
Southampton
SO14 0YN
Hampshire
England

Tel. no. +44-1703-319714
Fax no. + 44-1703-319739
Email: weeks_a@solent.ac.uk

Dr. Ian S Robinson
Dept. of Oceanography
Southampton Oceanography Centre
European Way
Southampton
SO14 3ZH
Hampshire
England

Tel no. +44-1703-593438
Fax no. +44-1703-593059
Email: i.s.robinson@soc.soton.ac.uk

Dr. Slawomir Sagan
Institute of Oceanology of Polish Academy ofSciences
PO Box 68
Postanców Warsawy 55
SOPOT
81-712
Poland

Tel no. +48-58-517281
Fax no. +48-58-512130
Email: sagan@iopan.gda.pl

PROJECT HOMEPAGE:

http://abyss.iopan.gda.pl/biocolor/

OCEAN COLOUR FOR THE DETERMINATION OF WATER COLUMN BIOLOGICAL PROCESSES

THE BIOCOLOR PROJECT

J.W. PATCHING
on behalf of the BIOCOLOR group
The Martin Ryan Marine Science Institute
National University of Ireland, Galway
Ireland

SUMMARY

The objective of this study is relate changes in the properties of the water column and associated successions in the phytoplankton with changes in optical properties and ocean colour. Models based on these relationships will be developed and validated. These models will facilitate the interpretation of measurements of ocean colour (remote or *in situ*) in terms of the temporal and spatial structures of phytoplankton communities. Biological, physical and optical data will be collected in two contrasting sea areas (the Baltic and western Irish shelf waters) by fieldwork employing conventional oceanographic techniques as well as the use of optical moorings and an underwater high-resolution spectrometer which will be developed as part of the project. Remote optical data from airborne (satellite) systems will also be processed and used. Data will be analysed and correlated to provide a description of the physical properties of the water column, their relationship to phytoplankton community structure and the overall effect of this on the optical properties of the water column and ocean colour. This data will then be used for the development and validation of models. Two types of optical model (semi-analytical and Monte Carlo) will be investigated Ultimately it is intended to provide a validated model which will improve the interpretation of ocean colour data and allow the monitoring of phytoplankton behaviour in greater detail than has been possible to date. This will result in an enhanced understanding of the interaction between physical processes and phytoplankton ecology within the oceans. The project has particular relevance to European coastal and shelf seas by facilitating remote monitoring of potentially harmful algal blooms.

INTRODUCTION

Ocean colour sensors mounted on satellites and aircraft have been used for the estimation of phytoplankton biomass using the ratios of water leaving radiance at different spectral bandwidths (e.g. Gordon et al., 1983). The recent introduction of sensors with higher resolution provides opportunities to gain more information derived from the light absorbing and backscattering properties of phytoplankton. If the major taxonomic groups can be identified by the variations which they cause in water leaving radiance, these new sensors will provide exciting new opportunities to differentiate between phytoplankton functional groups. This will be important not only for large scale studies such as the estimation of global phytoplankton biomass or (through links to models) primary production rates, but also in coastal regions where, for example, identification and prediction of potentially toxic phytoplankton blooms are crucial to the management of aquaculture industries.

The BIOCOLOR project commenced in September 1997. Its objective is to make hydrographic and optical field measurements over space and time-scales where the distribution and succession of major phytoplankton taxonomic groups are known to be diverse, and where there is an existing body of knowledge available. Study sites are located in the Baltic and to the west of Ireland. Relationships between the optical properties measured in bandwidths comparable to satellite based sensors, and the phytoplankton groups, as measured by taxonomy and pigment analysis, will be established. Models will then be developed to relate the ocean colour properties obtained *in situ* or remotely, to the water constituents present. These models will subsequently be validated using data derived from satellite mounted sensors and field expeditions. The tasks comprising the project have been grouped into six work packages:

Package A	Package B	Package C	Package D	Package E	Package F
Optical fieldwork instrumentation	Field surveys	Fieldwork analyses	Satellite and airborne imagery	Development of optical models	Data and model integration

OPTICAL FIELDWORK INSTRUMENTATION

The main spectrographic instrument to be used in the project is SUMOSS, an underwater high resolution spectrometer based on optical fibre technology (Robinson et al., 1995). It is designed to measure beam attenuation, scattering at different angles and up/downwelling irradiance throughout the visible spectrum at less than 10 nm intervals. The instrument will be used to measure both apparent and inherent optical properties of the water in full spectral detail, making it possible to investigate the optical 'closure' problem. The prototype instrument has been used to collect data in coastal waters and has undergone laboratory calibration tests. It is now being modified and prepared for deployment from vessels during BIOCOLOR cruises in the Baltic and to the west of Ireland. Results from the instrument will be compared to those obtained with standard spectroradiometers, both *in situ* and in the laboratory.

In order to obtain longer data series than could be obtained from instruments deployed from vessels, moorings carrying optical sensors are being prepared for both Irish and Baltic sites. The first of these, which will be deployed in Irish waters in Spring 1998 (see below for further fieldwork details) will be equipped with an *in situ* fluorometer , a system logging upwelling irradience at 4 wavelengths, TS and current meters.

FIELD SURVEYS AND FIELDWORK ANALYSES

Five major fieldwork surveys are proposed for BIOCOLOR:

1	Sept. 97	Shelf seas W of Ireland	Spatial survey
2	Feb./ March 98	Gulf of Gdansk, Baltic	Spatial survey
3	March/April 98	Galway Bay and shelf seas W of Ireland	Spatial survey and mooring (Galway Bay)
4	August 98	Shelf seas W of Ireland	Spatial survey and mooring
5	Spring 99	Gulf of Gdansk, Baltic	Spatial survey and mooring

The optical measurements carried out during spatial surveys using SUMOSS and other instruments will provide the absorption coefficient, the scattering coefficient, and beam attenuation at high spectral resolution. Information will be obtained about particulate size distribution from Coulter counting and phytoplankton species from microscopic analysis. Measurements will also be made of the light absorbing pigments using high performance liquid chromatography (HPLC). Laboratory -based spectrophotometric analyses of water samples will quantify the absorption and scatterance of particular components (e.g. phytoplankton, gelbstoff, and non-chlorophyllous particles). Measurements of horizontal and vertical variation in temperature, salinity and nutrients will provide descriptions of the physical and chemical oceanography of the study areas.

Optical measurements will also be carried out over a short spatial interval for an investigation into the problems of sub-pixel variability in remote sensing. One of the important differences between remotely sensed and *in situ* measurements is their sampling capabilities. Satellite sensors are capable of viewing large areas almost instantaneously, but their spatial resolution is limited to about 1 km. Consequently the quantities derived from such satellite data are averaged over areas of at least 1 km^2. This can present problems both for validating such measurements against point observations, and also for the applicability of calibration algorithms. In this study, by measuring the spatial variability of the optical properties of the water at resolutions finer than 100m, it will be possible to quantify the extent of consequent errors in the remotely sensed data product (e.g. chlorophyll concentration) in situations where the spatial variability of the water leaving radiance is high.

Cruise 1 was scheduled to take place during the period 27th August- 6th September with the objectives of confirming the oceanography of proposed study areas to the west of Ireland and allowing an initial testing of methodologies and processing strategies for samples and data. It was intended to use the Irish national research vessel "Celtic Voyager" to carry out a series of

offshore transects (between 52°N and 54°25'N) crossing the Irish Shelf Front, but operations were curtailed by adverse weather, which allowed for the completion of only one transect.

Cruise 2 is scheduled for the Gulf of Gdansk during the period 23rd February - 4th March. This cruise will use the research vessel "Oceania" and will be based on a grid of 30 stations at 5 Km intervals. It is expected that, at the time of the cruise, phytoplankton densities will be low and the water column will be mixed to a depth of approximately 60m. The constancy of water properties with depth will provide data suitable for testing light modelling.

The third fieldwork exercise will take place in Galway Bay and waters to the west of Ireland during the months of March and April 1998 and should encompass the period of the spring bloom with consequent changes in phytoplankton biomass and succession. A moored instrument assembly will be located in the centre of the bay throughout the period . The mooring will be serviced at fortnightly intervals by the RV "Connemara" which will carry out a spatial survey around the site on each occasion. Additionally the RV "Celtic Voyager" will be used for a major spatial survey within the Bay and over the Celtic Sea front to the west of Ireland during the period.

The fourth BIOCOLOR exercise will be a RV "Celtic Voyager" research cruise which is scheduled for 1-24th August 1998. During this cruise a moored instrument assembly will be sited off south-west Ireland and a spatial survey will be conducted in the area. It is predicted that the spatial survey will encounter both diatom blooms (arising from upwelling and headland mixing) and dinoflagellate blooms (arising from meteorological conditions).

The final BIOCOLOR exercise will take place in the Gulf of Gdansk during the spring of 1999. Preliminary planning calls for both a spatial survey and a moored instrument assembly. It is predicted that the period should encompass both dinoflagellate and *Mesodinium* blooms.

SATELLITE AND AIRBORNE IMAGERY

The acquisition, processing and analysis of satellite derived optical data will be carried out throughout the project, so as to provide an overview of the inter-annual, seasonal, regional and mesoscale variability context in which the field campaigns are taking place and as an aid to model formulation and validation.

Satellite data will be acquired from the NOAA AVHRR sensor, from the ATSR-2 on ERS-2 and from the NASA SeaWiFS sensor on Seastar. In each case data will be obtained at as high a level of processing as possible and quality assessed, including additional cloud screening and if necessary improving the atmospheric correction. Geolocation will also be quality controlled. Composite maps of the derived variables will be generated on a standard grid at regular intervals, for electronic distribution to the other partners along with a brief written interpretation. During the cruise periods, the AVHRR data will be acquired and processed rapidly, compressed into compact image files and transmitted electronically to the research vessels within as short a time as possible after the overpass. It is also planned to validate

chlorophyll pigment concentrations delivered by the standard SeaWiFS algorithms, by comparison with *in situ* data from the field campaigns.

The Modular Optoelectronic Scanner (MOS) flying on the Indian satellite IRS-1, is the first satellite-borne sensor which has a large number of narrow spectral bands in the visible wavelengths. MOS data will be acquired for both study sites during and on either side of the fieldwork periods. Data will be processed, atmospherically corrected, and comparison will be made with the *in-situ* measurements of both optical properties and phytoplankton concentration. These will form the bases for tests of the atmospheric correction, and the construction of chlorophyll algorithms based on multiple spectral channels. Attempts will also be made to distinguish the different pigments from the hyperspectral satellite data.

DEVELOPMENT OF OPTICAL MODELS

Development of underwater light models has reached the stage at which it is believed that the input of the inherent optical properties (absorption, scattering and beam attenuation) at high spectral resolution, can be used to determine upward and downward irradiance at many depths, as long as the incident skylight and sea surface properties are known. If the specific inherent optical properties (i.e. absorption etc. per unit mass) are determined for the various components in the water, and for particular phytoplankton populations, it should be possible to simulate water leaving radiance given the concentration of the components. Ultimately, by inverting the model using iterative or neural net methods, the objective is to determine the concentrations of the components of the water from remotely sensed hyperspectral water-leaving radiance. In this project we intend to critically examine the validity of this modelling approach using comprehensive measurements of optical properties and water constituents. This work-package will focus initially on the forward modelling process, in the context of the particular phytoplankton populations found in the study areas. It is very important to improve and validate such models before they are used in inversion methods for the analysis of remote sensing data.

A preliminary task is to derive inherent optical properties from laboratory measurements. Numerical analysis of the absorption spectra from both laboratory spectrophotometric measurements, *in situ* absorption and reflectance will be used to identify spectral absorption peaks. These peaks will be compared to the individual absorption by the pigments identified by HPLC. The information about the distribution and concentrations of the pigments will be used to model absorption and will be compared with measurements.

The central task of the work-package is to model hyperspectral water leaving radiance by two methods. Firstly a semi-analytical model will be used, inputting laboratory spectrophotometric measurements of the absorbance and scatterance of water, phytoplankton, gelbstoff and non-chlorophyllous particles (Gordon et al., 1988). The modelled light field will be compared to the hyperspectral *in situ* water leaving radiance (remote sensing reflectance). If necessary, improvements to the proposed semi-analytical models will be made to fit the observations.

Secondly, measurements of absorption and scattering coefficients, beam attenuation and incoming radiance at high spectral resolution will be used to predict upwelling and downwelling irradiance, reflectance, and water leaving radiance using Monte Carlo type models (Kirk, 1981). The model predictions will be compared with the measured apparent optical properties in order to evaluate the accuracy of the models.

The two different modelling approaches will be compared. Finally, the validated models will be used in an inversion procedure to recover the water constituent concentrations from the reflectance (or remotely sensed water leaving radiance). Measurements made during field studies, including independent data which have not been used to train the models or the inversion, will then be used to evaluate the success of the inversion process.

DATA AND MODEL INTEGRATION

Efficient validation, collation, archiving and distribution of fieldwork and optical data, whether obtained *in situ*, remotely or in the laboratory is essential for successful modelling. Validation and collation of fieldwork data will be co-ordinated by the Martin Ryan Marine Science Institute and optical data by the Department of Oceanography, Southampton Oceanographic Centre. Ultimate responsibility for data management lies with the co-ordinator. During the project, data sets will be available to partners through the secure area of the project web-pages. Data sets will also be archived on optical disks for use by project participants and, ultimately, other researchers.

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TITLE: Dissemination and exploitation of a Coupled Hydrodynamical-Ecological Model for Regional Shelf Seas
(COHERENS)

CONTRACT NO.: MAS3-CT97-0088

COORDINATOR:
Dr. Patrick Luyten
Management Unit of the Mathematical Models of the North Sea (MUMM)
Gulledelle 100, B-1200 Brussels
Belgium
Tel. no.: +32 2 773 21 38
Fax no.: + 32 2 770 69 72
E-mail: mastpl@camme.ac.be

PARTNERS:

Dr. Paul Tett
Napier University (NUE)
Department of Biological Sciences
10 Collinton Road
Edinburgh EH10 5DT
United Kingdom
Tel. no: +44 131 455 2633
Fax no.: +44 131 455 2291
E-mail: p.tett@napier.ac.uk

Dr. Roger Proctor
Proudman Oceanographic Laboratory
(POL), Bidston Observatory
Birkenhead, Merseyside L43 7RA
United Kingdom
Tel. no. : +44 151 653 8633
Fax no.: +44 151 653 6269
E-mail: rp@pol.ac.uk

Dr. Meirion Jones
British Oceanographic Data Centre
(BODC), Bidston Observatory
Birkenhead, Merseyside L43 7RA
United Kingdom
Tel. no: +44 151 653 8633
Fax no.: +44 151 652 3950
E-mail: bodcmail@pol.ac.uk

A COUPLED HYDRODYNAMICAL-ECOLOGICAL MODEL FOR REGIONAL SHELF SEAS COHERENS

Patrick J. Luyten

Management Unit of the Mathematical Models of the North Sea
Gulledelle 100, B-1200, Brussels, Belgium

SUMMARY

The main objective of COHERENS is the dissemination and exploitation of a three-dimensional integrated model for coastal and shelf seas developed within the two previous MAST-PROFILE projects. The FORTRAN program is composed of a physical part for currents, temperature and salinity, a biological module, a sediment module and both an Eulerian and a Lagrangian module to simulate the advective-diffusive transport of contaminants. A detailed manual with a description of the model and a user guide is in preparation. The program will be presented in a user-friendly format. Tests are available to check the portability of the code and to make a technical evaluation of model performance. A graphical routine adapted to the model's output is provided. The model will be scientifically validated by simulating a yearly cycle in the North Sea and comparing the results with observational data. The source code, model documentation and visualised model results will be made available on a CD-ROM. User support and information concerning further upgrades will be provided after termination of the project.

1. INTRODUCTION

Concern over water quality in European shelf seas has given rise to the development of coupled physical-biological numerical models as tools for understanding the relevant physical and biological processes and the influence of human activity on the ecological conditions. The aim is to predict the effect of the changing conditions on the biota and to simulate the input and dispersion of contaminants. During the last twenty years a series of three-dimensional hydrodynamic models for shelf seas have been developed at different research institutes. An overview can be found in e.g. Nihoul and Jamart (1987), Dyke and Davies (1992), Lynch and Davies (1995), including the Backhaus model (Backhaus, 1985) and the Princeton Ocean Model (Blumberg and Mellor, 1987). In recent years some of these models have been coupled with a biological module (e.g. Aksnes et al., 1995; van den Berg, 1996). The design of the computer code and the validation of a fully coupled model often requires several years of effort. Common features of most models are modules for solving the Navier-Stokes equations and advection-diffusion type equations for active and passive scalars. On the other hand the parameterisations of some processes (turbulence, surface waves, biological interactions) need improvement and further progress may be expected in forthcoming years. A variety of schemes are available from the literature for the parameterisation of turbulence and a proper selection often depends on "where" and "how" the program is applied. The implementation of a biological module can be limited by computer memory and CPU time if

the module involves a large number of state variables, and it is thus desirable to parameterise the biological processes in a way that simplifies the numerical integration.

A three-dimensional model framework has been developed within two previous MAST-projects (PROFILE I and II). This is a fine-resolution hydrodynamic model for coastal and shelf seas resolving mesoscale to seasonal scale processes and is coupled to biological and resuspension models. The program is written in FORTRAN 77 and has four major components:

1. a physical part with a general module for solving advection-diffusion type equations;
2. a biological module describing the cycling of carbon and nitrogen through microplankton and detrital components with corresponding changes in nitrate, ammonium and oxygen concentrations;
3. a sediment module describing the deposition and erosion of suspended organic and inorganic material through a "fluff" layer;
4. two modules for the transport of contaminants using either the Eulerian method where the concentrations are determined by solving advection-diffusion equations or the Lagrangian method where an ensemble of particles is advected by the current and dispersed by a random walk method.

The structure of the program consists of a "core" part and a series of modules. This modular design allows easy updating of any particular process, or the inclusion of an alternative solution method, or the addition of new processes. The core updates the current field by solving the Navier-Stokes equations and contains the advection-diffusion module. A series of switches is implemented permitting the user, for a particular simulation, to select whichever processes are required.

The model has been used to simulate conditions in the North Sea and stratified coastal areas. Although capable of improvement, the model and the associated code are now at the stage where they can be made available to the scientific and coastal management communities for further diagnostic use and for testing as a prognostic and management tool. The specific objectives of COHERENS are to:

1. write a detailed manual with the model's description and a user guide;
2. test the portability of the code and to evaluate model performance by running a series of test simulations on several machines at different institutes;
3. create and document a graphical interface for user output;
4. validate the model against the available data of the 1988-1989 UK Natural Environmental Research Council's North Sea Project;
5. establish the scientific content of the model by publications in the scientific literature;
6. produce a CD-ROM with the source code, model documentation and visualised model results;
7. set up a communication channel for user support and information about further updates of the program.

2. MODEL DESCRIPTION

The characteristics of each program component are summarised below. Different options, selected by a switch, are marked by a *. The interactions between the different modules are displayed schematically in Figures 1 to 4.

1. General aspects
    - The equations are solved either in Cartesian or in spherical coordinates (*) on an Arakawa C-grid. In the former case the f-plane approximation is used and the horizontal axes can be rotated arbitrarily in the horizontal plane.
    - Sigma-coordinates are introduced in the vertical with the possibility for non-uniform grid sizes.
    - A series of schemes (upwind, Lax-Wendroff, TVD) are available for the advection of currents and scalar quantities which may be updated in future versions (*).
    - Harmonic analysis on user-defined variables can optionally be performed by the program (*).
    - Three forms of output are available: time series, time-averaged output and harmonic output. Grid locations and output times are selected by the user.
    - Error traps are provided which stop execution of the program with an explaining message when a user-supplied model parameter has an incorrect value.

2. Physics
    - The mode-splitting technique is used to solve the 2-D and 3-D momentum and continuity equations as in the Princeton Ocean Model (Blumberg and Mellor, 1987).
    - It is possible to include temperature, salinity or both (*). The absorption of solar radiation in the upper part of the water column is implemented by an optical module (Sharples and Tett, 1994).
    - The program incorporates a variety of turbulence closure schemes ranging from simple algebraic expressions to one- or two-equation turbulence energy models, such as the Mellor-Yamada (Galperin et al., 1988) and k-ε (Luyten et al., 1996) schemes (*).
    - The open boundary conditions for the depth integrated equations are based upon the method of Riemann characteristics (e.g. Røed and Cooper, 1987). Various formulations can be selected permitting the user to apply different conditions at open sea and river boundaries.
    - The effect of wave-current interaction on the bottom stress can be included using the formulation described in Signell et al. (1990) and Davies and Lawrence (1994) (*).
    - Different formulations for the wind stress and surface heat fluxes are available as given in Geernaert (1990) (*).

3. Biology (*)

    Water-column biology and nutrient cycling are described by a microplankton-detritus module (Tett and Walne, 1995) with associated optical equations which take account of light attenuation by all organic and inorganic particulates. The module describes the cycling of carbon and nitrogen through microplankton and detrital compartments, with

corresponding changes in dissolved concentrations of nitrate, ammonium and oxygen. The microplankton compartment provides an efficient parameterisation of fast autotrophic and heterotrophic processes, effectively including most of the types of organisms that are specified separately in "microbiological loop" models (e.g. Baretta-Bekker, 1995). Microplankton dynamics are mainly those suggested by the "cell-quota, threshold-limitation" theory described in Droop (1983). The effects of mesozooplankton are imposed as a grazing pressure, which removes some microplankton, and converts the rest to detritus, with a slower rate of decay.

4. Sediments (*)

   All particulate compartments of the biological model have a sinking rate, and can deposit to the sea-bed. The sediment model also describes suspended inorganic particle concentrations as one or two state variables, which may carry contaminants (in future versions) and influence light attenuation. Deposition and resuspension of particulates involves a "fluff" layer of finite capacity (Jago et al., 1993). Resuspension increases as a power function of bed stress (Jones et al., 1996), and the absence of the usual threshold for the resuspension of cohesive sediments can be seen as a simple parameterisation for a heterogeneous population of particles and bed types.

5. Contaminants (*)

   Two types of transport models are available (*). The first one uses an Eulerian approach and solves advection-diffusion type equations for a number of user-defined dissolved substances. The second one is a Lagrangian type model using passive tracers. Vertical and horizontal diffusion of suspended particles is determined by a random walk method (Maier-Reimer, 1980). In both models new input of suspended material either by river discharge or at the open sea boundaries can be defined by the user.

3. TECHNICAL VERIFICATION

The program has been constructed and validated during the PROFILE projects by a few partners on a limited number of machines. Before the program can be released to a more extended user group a series of test simulations must be performed and intercompared by the partners using a broad range of computing platforms. At least one PC is included in the evaluation. The aim of this exercise is to:

- test the portability of the code;
- intercompare model performance using a number of predefined parameters (output parameters, CPU time);
- test which machine-independent code optimisations can be implemented without affecting the model results;
- define a minimum set of computer requirements for running the code.

A series of idealised test cases have been developed for this study. Their source code and input data will be made available to future users. The first intention is to compare the performance of the different numerical schemes for the advection of currents and scalars, and the different turbulence closure schemes, which are implemented in the program. Secondly, they show the ability of the model to simulate the strong density fronts in coastal areas, including river plume salinity fronts and thermal fronts, and seasonal thermal stratification in

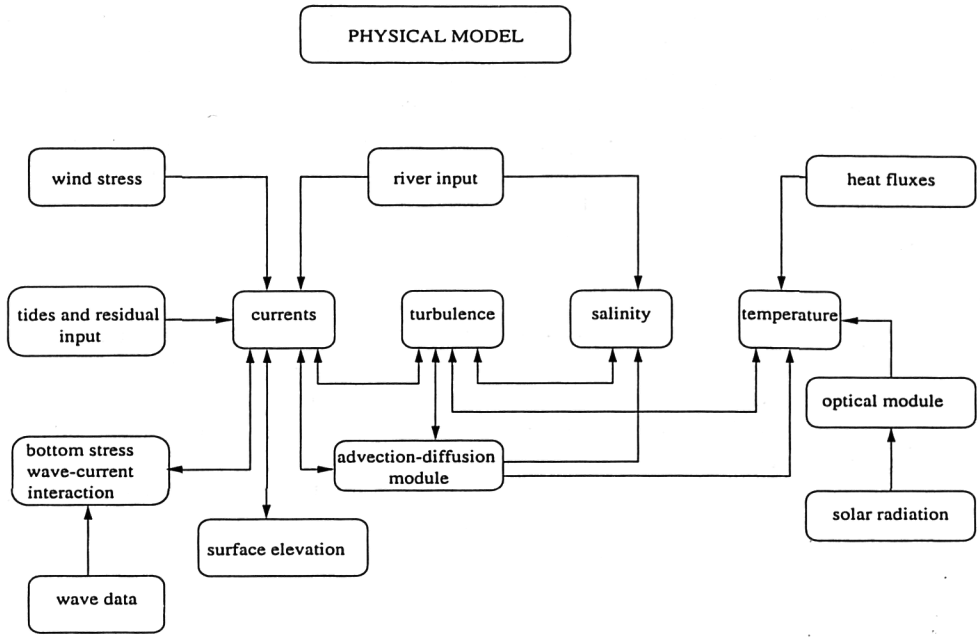


Figure 1: Schematic diagram of the physical model.

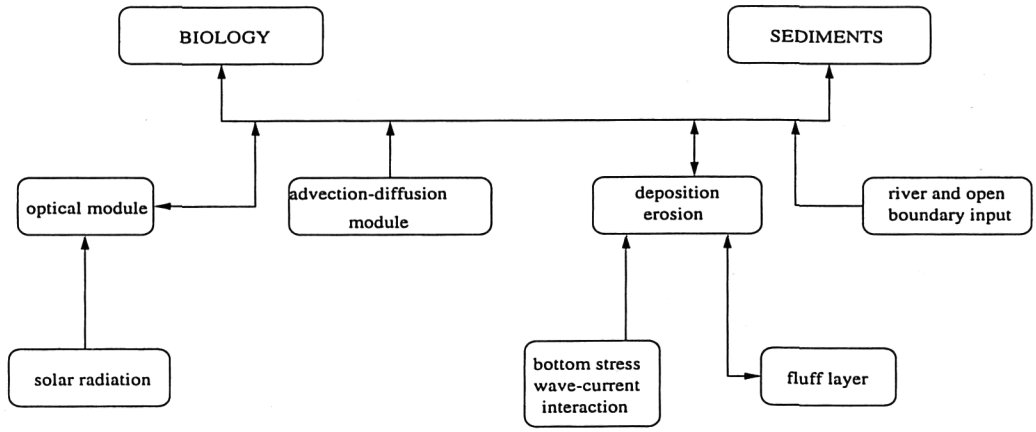


Figure 2: Schematic diagram of the biological model.

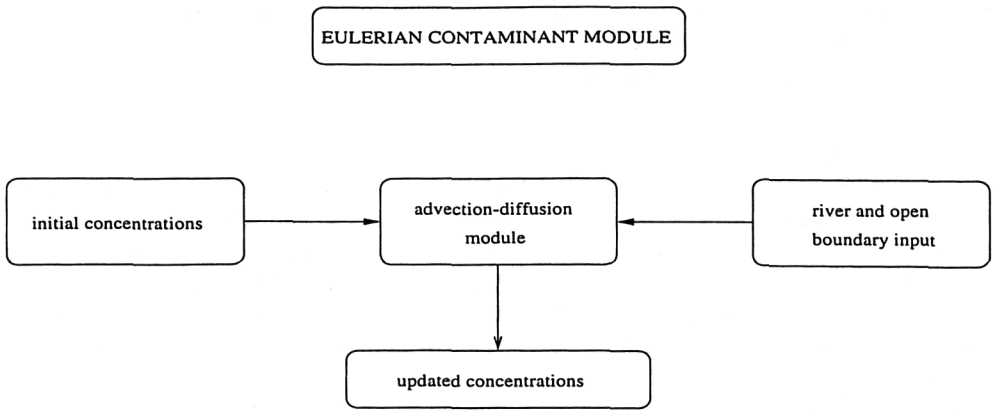


Figure 3: Schematic diagram of the Eulerian transport module for contaminants.

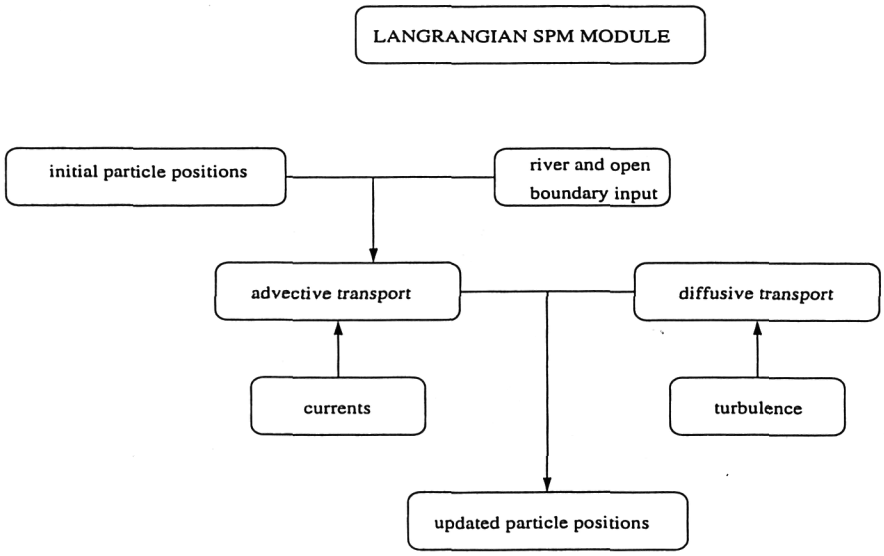


Figure 4: Schematic diagram of the Lagrangian transport module for suspended particles.

shelf seas. One test case illustrates the performance of the biological and sediment components of the program. Simplified initial and forcing conditions are considered in each test case allowing a clear interpretation of the results.

The following nine tests are available:

1. the evolution of an initially stratified surface layer forced by an imposed surface stress. This is a 1-D test intended to compare different turbulence closure schemes.
2. the advection of a lateral front by a prescribed oscillating current over a sloping bottom in an open channel. The problem serves to test the different advection schemes.
3. the rotating cone problem. A square-shaped closed basin is considered. The simulation shows the evolution of an initial "cone-shaped" distribution of a scalar field rotating around the centre of the basin.
4. the adjustment to equilibrium in a closed channel of an initial horizontal density jump. The numerical results are compared with an analytical solution.
5. the development of baroclinic eddies in a rotating basin after James (1996). This test case has been used in the intercomparison study of the NOMADS project (Tartinville et al., 1998) and serves to compare the advection schemes for momentum and scalars.
6. the seasonal evolution of thermal stratification at station CS of the North Sea Project (Luyten, 1996). This is a 1-D test using realistic forcing data.
7. the 1-D simulation of plankton blooms and sediment resuspension at a seasonally stratified location in the North Sea.
8. the evolution of an initially lateral density front in an open channel under the influence of tidal advection and diffusive forces.
9. the formation and evolution of a 3-D river plume front with tidal forcing using idealised forcing conditions and a simplified bathymetry.

Other test cases are being developed.

4. GRAPHICS INTERFACE

A graphical user interface is developed to allow the visualisation of datasets output from the model. The interface is a X-Windows/Motif application requiring X11R5 and Motif 1.2 libraries which must be available on the target machine.

The application, written using ANSI compliant "C" code to allow a greater portability across platforms, is a window based graphical user interface (GUI) that allows easy access to model results. The user builds up a "Query" which defines the required dataset attributes (date/time, current, elevation, ...) and display mode (filled or line contours, vectors). The query is built upon common windows tools such as sliders, radio box menus, ... such that only a minimal set of instructions is required to familiarise with the application.

The application can be used to view almost any dataset that conforms to the common output format of the model data, such that new data types can be added at a later stage without the requirement for recompilation of the program. A full description and a user guide will be provided to facilitate installation and use, and will be available on the final CD-ROM.

5. DOCUMENTATION

A full documentation of the program with a detailed user guide is being prepared. It is composed of the following parts:

- A "Quick Installation Guide" permitting the user to install the program, run a test case and check the portability of the source code before reading the remaining chapters of the manual.
- A scientific part with a detailed description and discussion of the model equations and the scientific background. The physical, biological, sediment and contaminant components are dealt with separately.
- A description of the numerical methods and model parameterisations.
- User instructions enabling the user to initialise the program for a particular application. A series of model parameters (e.g. switches, time step, spatial resolution, grid arrays, biological parameters, output specifiers, initial and open boundary conditions, meteorological and wave input data, ...) must or may be supplied to the program. For some parameters default values are adopted by the program making it easier for a less experienced user to run the model. All other input variables must be given in the form of a series of FORTRAN routines written by the user. Example files with a generic source code and a series of guidelines for an appropriate selection of model input variables are included in the manual.
- A schematic presentation of the program structure and instructions for advanced use, permitting an experienced user to adopt changes in the source code and to make further updates.
- A description of all test cases including visualised results.
- An overview of the results obtained with the model. This includes the plume simulations performed in PROFILE (Huthnance, 1997), the NOMADS North Sea experiments (Proctor, 1997) and the North Sea simulations described in the next section.
- A reference manual with a technical description of each module and a listing of program variables and constants.
- Plans for improvement foreseen in forthcoming years.

The documentation will be available on a CD-ROM at the end of the project together with the source code of the main program and the test cases. A written version will be maintained and further updated after termination of the project.

6. NORTH SEA CASE STUDY

The program has been applied to the study of physical and biological processes in coastal areas with an important river input (e.g. Ruddick et al., 1995) and for the simulation of the advection and dispersion of contaminants in the North Sea. An important objective of the project is to demonstrate its scientific usefulness by simulating a full annual cycle in a typical shelf sea and comparing the results with observational data sets.

The area, selected for the study is the part of the North Sea between 4°W and 57°N including the Channel, the Southern Bight and the central North Sea (see Figure 5). A fine resolution (~4 km) grid is adopted in the horizontal allowing a realistic simulation to be made and to

study the impact of frontal processes on the biological system. The simulation starts at 1 January 1989 when the water column is vertically mixed and ends at 31 December 1989 covering the formation and erosion of the thermocline and the spring and autumn blooms of plankton. The evolution of the salinity field is simulated including input of the most important river discharges and fluxes at the open boundaries. Tidal boundary data are obtained from a wider area model for the Continental Shelf. Meteorological data (wind components, atmospheric pressure, air temperature, relative humidity, cloud coverage derived from satellite images) are supplied from an atmospheric model. Initial conditions for temperature, salinity, biological state variables and sediment concentrations are derived from the NERC North Sea Project data set and a three-dimensional baroclinic model for the Continental Shelf.

The model results will be compared with the North Sea Project data collected at more than 120 stations in the southern and central North Sea (Figure 5). The data set consists of vertical profiles of temperature and salinity taken at approximatively monthly intervals. Concentrations of chlorophyll, nitrate and suspended sediment concentrations are available for three depths at most of the stations.

The outcome of this case study will be the subject of a thorough scientific evaluation of the model. A series of recommendations will be formulated for improvements which can be incorporated in future releases of the program.

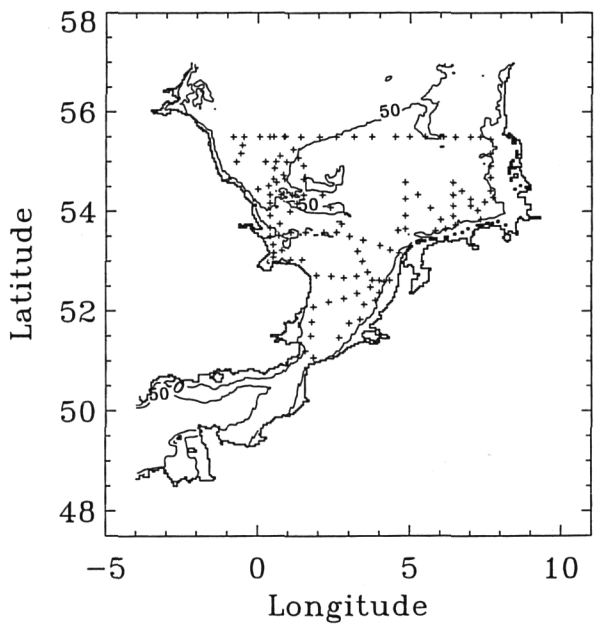


Figure 5: Area of the North Sea case study. The locations of the North Sea Project data stations are denoted by a "+".

7. DISSEMINATION AND EXPLOITATION

The results of the previous tasks will be synthesised to establish a set of criteria for future users indicating:

- level of experience (scientific, programming);
- machine requirements;
- type of applications for which the program gives the most efficient results..

A CD-ROM will be produced and distributed with:

- the complete source code, including the data needed for running the test case simulations;
- the documentation using hypertext which enables links to be made with other sections or separate figures;
- figures and model results in animated form;
- the graphics software;
- instructions for installing the source code and running the test cases;
- a license agreement and user specifications.

The following channels will be established for dissemination of the program and the setup of a user group:

- An information page is installed on the World Wide Web (http://www.mumm.ac.be/~patrick/mast) with the aims of the project, a brief model description, presentation of model results and contact addresses.
- Potentially interested users are contacted by the partners.

User support will be provided by two partners (MUMM and NUE) after termination of the project for a period of two years. The aims are to give further advice on how to initialise the model (e.g. specific values of model parameters) and to allow bug reporting. The user will bear full responsability for the simulations performed with the model and the output analysis. Users will be informed about further updates and are requested to give suggestions for improvement and information concerning their exploitation of the model (area, type of simulation, type of machine, publications). A user list will be created and continuously updated permitting a full evaluation of the model's exploitation to be made.

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TITLE: Effect of nutrient ratios on harmful phytoplankton and their toxin production **(NUTOX)**

CONTRACT NO: MAS3-CT97-0103

COORDINATOR: Prof. Edna Granéli
Institute of Natural Sciences
University of Kalmar
Box 905
S-391 29 Kalmar, Sweden
Tel.: +46-480-446224, fax: ++46-480-446262
E-mail: edna.graneli@ng.hik.se

PARTNERS:

Egil Sakshaug
Trondhjem Biological Station
University of Trondheim
Bynesveien 46
N-7018 Trondheim, Norway
Tel: +47 73 59 15 83
Fax: +47 73 59 15 97
E-mail: Egil.Sakshaug@vm.unit.no

Jan Pallon
Dept. of Applied Nuclear Physics
University of Lund
Box 118
S-221 00 Lund, Sweden
Tel: +46 46 222 76 37
Fax: +46 46 222 47 09
E-mail: Jan.Pallon@pixe.lth.se

Serge Y. Maestrini
Centre de Recherche Marine et Aquaculture
IFREMER-CNRS
BP 5
F-17137 L'Houmeau, France
Tel: +33 46 50 06 21
Fax: +33 46 50 06 00
E-mail: smaestri@ifremer.fr

Bernd Luckas
Inst. of Nutrition & Environment
University of Jena
Dornburger Str. 25
D-07743 Jena, Germany
Tel: + 49 3641 949650
Fax: +49 3641 949652
E-mail: B5belu@rz.uni-jena.de

Rosa Martinez
Dept. of Aquatic and Environmental Sciences
& Techniques
Avda. de los Castros s/n
E-39005 Santander, Spain
Tel: +34 42 20 18 49
Fax: +34 42 20 17 03
E-mail: martiner@ccaix3.unican.es

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

EDNA GRANÉLI[1], EGIL SAKSHAUG[2], JAN PALLON[3], BERND LUCKAS[5], ROSA MARTINEZ[5], SERGE Y. MAESTRINI[6]

[1]Institute of Natural Sciences, Kalmar, Sweden; [2]University of Trondheim, Norway; [3]University of Lund, Sweden; [4]University of Jena, Germany; [5]University of Santander, Spain; [6]CNRS-IFREMER, L'Houmeau, France

1. INTRODUCTION

The quantitative and qualitative compositions of inorganic nutrients are factors that have an impact on the taxonomic composition of the phytoplankton present in marine and fresh waters. Likewise, the toxin production by a given phytoplankton species may also be affected by the nutrient composition in the water. Most healthy marine phytoplankton cells posses nitrogen to phosphorus as ratio of 16:1 atoms (Redfield ratio) under nutrient balanced conditions. Under nutrient limiting conditions the cells present are more and less stressed, inducing a higher production of certain metabolites such as lipids, aminoacids, polysaccharides, toxins etc... In most European marine waters the ratios and concentrations of nitrogen (N) and phosphorus (P) in relation to silica (Si) have increased due to the high input of N and P from human activities. At the same time toxic algal blooms of non-silica requiring species, such as prymnesiophytes, dinoflagellates and blue-green algae have increased in these waters. Outbreaks of harmful algal blooms have resulted in serious losses regarding fish industry, human health, and recreational resources. The European Union has recognized the importance of harmful algal blooms studies in the Supplement to the MAST-III work programme and Corrigendum document (1996).

NUTOX investigates if the increase in nitrogen and phosphorus to silicon concentrations/ratios has promoted the dominance of harmful phytoplankton species in natural communities, and how nitrogen to phosphorus ratios/concentrations regulate toxin production in certain species. A combination of new standardized and advanced methods will be used in NUTOX to allow the simultaneous determination of the toxin content, the elemental composition, the genetic expression, and the bio-optical characteristics of a toxic phytoplankton cell at the species level in natural

communities. These techniques will help us to adress the following issues:
a) The nature of the connection between high N:P to Si-ratios and selection towards toxic species.
b) The effect of N/P ratios on the physiology (e.g. cellular chemical composition, toxin production, pigments characteristics) of different toxic species isolated from northern (Skagerrak and Baltic) and southern (Atlantic) European waters.
c) The differences and similarities in the gene expression of the PSP-toxin producer *A. tamarense* isolated from different sites in the Skagerrak and the southern Atlantic coast, and how genetical inheritance is influenced by the effect of different N/P ratios/concentrations.
d) The possibility of reversing from a high toxin production to a low one by manipulation of the N/P ratios.

The results obtained in NUTOX will allow identification of some key mechanisms leading to a toxic phytoplankton bloom and a high level of toxin production. On this basis a guideline for the use to the European Community management policy in order to minimize toxin production and toxic blooms in sensitive areas will be suggested.

2. OBJECTIVES

The overall aim of NUTOX is to obtain information on the importance of *unbalanced* versus *balanced* nutrient conditions concerning nitrogen, phosphorus and silicon for the selection and toxin production in certain European harmful phytoplankton species. NUTOX thus aims to suggest how to minimize the blooms of harmful phytoplankton and their toxin production in coastal waters.

The main objectives of NUTOX are:

1-To investigate if the harmful algal blooms of non-diatom species are a consequence of the high N:P/Si ratios/concentrations due to the increase in the discharge of nitrogen and phosphorus into European marine and brackish waters during the last 50 years.

2-To investigate the connection between intracellular nutrient status and toxin production for toxic or potentially toxic species of marine/brackish phytoplankton from some sites in Europe where toxic blooms are a nuisance. The objective is thus to establish if toxin production is regulated by external nutrient conditions (i.e. increase under nutrient stress).

This will be obtained through:

-Determining if the increase of N and P in relation to Si, in most European waters, has favoured the occurrence of blooms of non-siliceous harmful algal species such as prymnesiophytes, dinoflagellates and blue-green algae.

-Comparing the toxicity responses to various N/P ratios (i) for different algal clones (intraspecific differences) from Atlantic and Baltic coastal waters and (ii) for different toxic algal species (interspecific differences).

-Quantifying the effects of N and P manipulation on the toxicity of different toxic algal species.

-Producing general guidelines for minimizing or inhibiting phytoplankton toxin production by manipulating N/P ratios in the supply medium.

3. WORKPLAN

We have chosen to investigate phytoplankton from areas in Europe where harmful species have been reported to have increased during the last 3 decades, and/or are a threat for the aquaculture industry. The sites of interest are the Spanish and French Atlantic coast, the Skagerrak and the Baltic Sea (west coast), where outbreaks of harmful phytoplankton blooms have been numerous on this time span.

The overall strategy of NUTOX is to combine (i) field studies (mesocosms) with laboratory experiments, and (ii) natural phytoplankton communities with monoalgal cultures studies, thus allowing for the determination of some of the regulatory mechanisms behind toxic phytoplankton blooms. In NUTOX, several phytoplankton species will be isolated and manipulated in different experiments. These species belong to different algal groups: dinoflagellates, prymnesiophytes and blue-green algae (cyanobacteria). Because these algae produce different toxins (Paralytic Shellfish Poisoning, Diarrhetic Shellfish Poisoning, hepatotoxins, ichtyotoxins), and because they have different ecological strategies, new knowledge concerning the effects of N:P-ratios/concentrations on their toxin production will be achieved in NUTOX.

The scientific content of NUTOX is subdivided into 5 work packages:

Work package 1. Development, standardization, and simultaneous application of new advanced

techniques (nuclear microprobe, bio-optics, toxin analyses) adapted to yield information on the species-specific level in natural phytoplankton communities.

Work package 2. Effects of high N/P ratios in relation to Si on the structuration of phytoplankton communities - marine mesocosm studies.

Work package 3. Effects of different N/P -ratios on phytoplankton toxin production and on gene expression - laboratory experiments.

Work package 4. Decreasing toxin production by deliberate manipulation of the N/P ratios. Laboratory experiments and marine mesocosm experiments.

Work package 5: Application of the final results for producing general guidelines for minimizing or inhibiting phytoplankton toxin production through the manipulation of N/P ratios in the supply medium.

TITLE: Molecular Ecology of the Photosynthetic Procaryote *Prochlorococcus*, a Key Organism of Oceanic Ecosystems (project PROMOLEC)

PROJECT NO: MAS3- CT97- 0128

COORDINATOR:

Dr. F. Partensky
Station Biologique de Roscoff
CNRS UPR 9042 et Université Paris 6
BP 74, F-29682 Roscoff cedex
Tel.no. (Fax): +33 2 9829 2314 (2324)
E-mail : partensk@sb-roscoff.fr

PARTNERS:

Dr. W. Hess
Universität zu Berlin
Institüt für Biologie
Chausseestrasse 117
D-10115 Berlin, D
Tel.no. (Fax): +49 302 093 8144 (8141)
E-mail : Wolfgang=Hess@rz.hu-berlin.de

Dr. N. Tandeau de Marsac
Institut Pasteur
Unité de Physiologie Microbienne
28, rue du Dr Roux
F-75724 Paris cedex 15, F
Tel.no. (Fax): +33 1 4568 8415 (4061 3042)
E-mail : Ntmarsac@pasteur.fr

Dr. J.M. Garcia Fernandez
Facultad de Veterinaria
Universidad de Cordoba
Dept. Bioquimica y Biologia Molecular
Avda. Medina Azahara, s/n
E-14071-Cordoba, ES
Tel.no. (Fax): +34 5721 8686 (8688)
E-mail : bb1gafej@uco.es

Dr. D. Scanlan
University of Warwick
Dept of Biological Sciences
CV4 7 AL Coventry, UK
Tel.no. (Fax): +44 203 52 3523 (3701)
E-mail : dp@dna.bio.warwick.ac.uk

Dr. H. Claustre
Laboratoire de Physique & Chimie Marines
BP 8, La Darse
F-06230 Villefranche-sur-Mer, F
Tel.no. (Fax): +33 4 9376 3729 (3739)
E-mail : claustre@ccrv.obs-vlfr.fr

Dr. A. F. Post
Interuniversity Institute of Eilat
Steiniz Marine Biology Lab.
P.O. Box 469, Eilat, IL
Tel.no. (Fax): +972 7636 0122 (74329)
E-mail : Anton@vms.huji.ac.il

MOLECULAR ECOLOGY OF THE PHOTOSYNTHETIC PROCARYOTE *PROCHLOROCOCCUS*, A KEY ORGANISM OF OCEANIC ECOSYSTEMS

PROMOLEC

F. PARTENSKY

Station Biologique de Roscoff
CNRS UPR 9042 et Université Paris 6
BP 74, F-29682 Roscoff cedex

SUMMARY

The project PROMOLEC will focus on *Prochlorococcus*, the smallest and most abundant photosynthetic prokaryote of the oceans. It will essentially aim at studying 1) the diversity of natural populations of this ubiquitous microorganism and its control by environmental factors using a combination of classical and novel methods (biochemical, physiological and genetic) and 2) the nutrient and growth status of *Prochlorococcus* cells in the field using molecular tools. An extensive preliminary work of characterization of *Prochlorococcus* isolates will be necessary to find and design the relevant molecular probes and better understand some of its basic cellular processes (growth, photosynthesis, nutrition).

1. INTRODUCTION

The recent introduction of molecular techniques in biological oceanography has allowed scientists to study natural communities with a level of resolution never attained by previous approaches. Among the major breakthroughs permitted by this approach is the discovery of several novel taxa of microorganisms, which have never been brought into culture yet. These include the ubiquitous and abundant α-proteobacteria SAR 11 (Giovannoni et al. 1990, 1997), the green non-sulfur bacteria SAR 202 (Giovanonni et al., 1996) as well as Archeae (Delong, 1992, Fuhrman et al., 1993; Delong et al., 1994), which were previously thought to be restricted to environments displaying extreme conditions such as deep sea hydrothermal vents or hyperhaline habitats. These works have shown that 1) it is not necessary to isolate and culture organisms to demonstrate their presence and study their distribution, 2) the gene sequences obtained from the field can be directly compared to that of other natural communities or cultured organisms and 3) it is possible to obtain semi quantitative estimations of the relative abundance of uncultured organisms. Till now, most molecular studies have dealt with the genetic diversity of communities of microorganisms and (or) the distribution of unknown heterotrophic groups and have used the sole *rrn* gene, encoding the 16S rRNA molecule, as a molecular marker. Falkowski and LaRoche (1991) have however predicted that a number of other oceanographic questions may be resolved by this kind of approaches, including microbial metabolism, photosynthesis regulation and limitation of phytoplankton growth by nutrients. Among these questions, the study of the diversity, structure, function and dynamics of communities of *autotrophic* picoplankton is one of the fields where one can be expect to see the most significant advances in the forthcoming years. These communities not only play a very important role in the biogeochemical cycling of carbon, especially in

oligotrophic parts of the world oceans and seas, but also constitute an essential compartment of the microbial food webs.

Two major questions concerning these important components of the marine living community are of particular interest:

- What is the extent of the genetic diversity in a group of genetically related, marine photosynthetic microorganisms and which factors control this diversity in the field?
- What are the biochemical and genetic processes controlling photosynthesis, nutrient assimilation and growth in these organisms and how are they affected by environmental factors in the field?

The biological models used nowadays by molecular biologists and biochemists have most often little if any ecological relevance. To draw solid ecological conclusions from laboratory studies and check them on natural populations, it is necessary to deal with model organisms which are ubiquitous, ecologically important (i.e. represent a significant part of the phytoplankton biomass and production), and allow easy genetic work. The marine prokaryote *Prochlorococcus* (Chisholm et al. 1988, 1992) constitutes one of the best candidates for such studies. It proliferates in oligotrophic areas of the world oceans and seas between 45°N to 45°S (Olson et al., 1990; Partensky et al., 1996) including the Mediterranean and Red Seas (Vaulot et al., 1990; Veldhuis and Kraay, 1993; Lindell and Post, 1995). It is also the smallest (ca 0.6 µm diameter) and numerically the most abundant photosynthetic organism known to date in the oceans. Typical concentrations in the central Pacific or Atlantic are 2 to 3 10^5 *Prochlorococcus* cells per mL (Campbell and Vaulot, 1993; Partensky et al., 1996). Because of its abundance, this organism is an important contributor (20-50%) to the photosynthetic biomass and primary production in oligotrophic areas (Li et al., 1992; Goericke and Welschmeyer, 1993; Campbell et al., 1994). *Prochlorococcus* is particularly well suited for *in situ* studies since (1) natural populations are easily identifiable and can be precisely counted by flow cytometry (see e.g. Olson et al., 1990), (2) its specific pigmentation, including pigments unique to this organism (divinyl-chlorophylls *a* and *b)*, can be identified by HPLC pigment analyses (Goericke and Repeta, 1993) and (3) because of *Prochlorococcus* tiny size, pre-filtration of seawater through small-size pore filters allows to obtain natural samples almost devoid of all other autotrophic organisms. *Prochlorococcus* is able to sustain growth and photosynthesis under a very wide range of irradiance from the surface (100% incident sun light) to depths of ca. 100-200 m receiving less than 0.1% of the incident light irradiance (Olson et al., 1990; Campbell and Vaulot, 1993). This remarkable ability may be the result of highly efficient adaptation mechanisms of the photosynthetic apparatus and (or) of a large genetic diversity. Moreover, *Prochlorococcus* is most abundant in subsurface waters with low to undetectable levels (< 3 nM) of inorganic nutrients (nitrogen and phosphorus). This raises the question of which biochemical mechanisms or alternative modes of nutrition (chemo- or heterotrophy) this organism may have developed to both optimize its nutrient assimilation and reduce functional and (or) structural alterations of its photosynthetic and growth apparatus expected during nutrient depletion.

The isolation of different pigmentary types of *Prochlorococcus* with distinct irradiance optima for growth and photosynthesis (Moore et al., 1995), as well as the observation at certain depths of populations distinguishable by their chlorophyll fluorescence (Campbell and Vaulot, 1993), suggest that this genus is in fact constituted by several genetically distinct populations or species. The large genetic diversity of *Prochlorococcus* has also been confirmed by comparing restriction fragment length polymorphism (RFLP) patterns or by sequencing of the *rrn* gene from a variety of strains isolated from different locations (Scanlan et al., 1996;

Urbach et al., 1997). In the field, a similar genetic variability was demonstrated within a single water sample, by amplifying, cloning and sequencing the RNA polymerase (*rpoC1*) gene from natural populations of the Sargasso Sea (Palenik, 1994). This outlines another potential interest of *Prochlorococcus*, as a model to study the effects of abiotic factors on the genetic diversity within this genus.

For all these reasons, the project PROMOLEC will focus on *Prochlorococcus*. The interest of studying a single, but ecologically important, microorganism is that it allows very fine and elaborated measurements of its characteristics to be performed in natural environments. In contrast, a study on a community is generally limited to either global or average measurements on heterogeneous populations, which hardly reflects the dynamics and particularities of the individual components.

2. WORKPLAN

The first objective of PROMOLEC will be to characterize the diversity of natural populations of *Prochlorococcus* using a combination of approaches (genetic, biochemical and phenotypic) and the role of environmental parameters on the origin and maintenance of this diversity. The second objective will be to develop molecular tools to monitor the physiological status of natural populations of this prokaryote. To reach these objectives, it will first be necessary to make extensive studies on cultured strains to study their genetic and physiological diversity as well as the structure, function and regulation of their photosynthetic apparatus, nutrient acquisition systems and cell cycle machinery. One major novelty of this project will be to apply a range of molecular biology techniques to the study of cultured and natural populations and to relate the information provided by these tools to that obtained with traditional methods (e.g. HPLC pigment analyses, ^{14}C incubation, spectrophotometry). This original approach should allow to better understand the reasons of the ecological success of this outstanding organism. A (non-limitative) list of genes and functions that will be studied is shown in Table 1.

Table 1: Genes and functions studied or searched for within the different topics of PROMOLEC

Gene name	Molecule encoded	Topics
cpeA/B	Phycoerythrin	Photosynthesis/genetic diversity
dnaA	Enzyme controlling DNA replication	Growth and cell cycle
ftsZ	Enzyme controlling cell division	Growth and cell cycle
glnA	Glutamine synthetase	Nutrient assimilation
nifH	Nitrogenase reductase	Nutrient assimilation
nrtA	Nitrate transporter	Nutrient assimilation and limitation
ntcA	N-uptake regulatory protein	Nutrient assimilation and limitation
pcb	*Prochlorococcus* antenna	Photosynthesis/genetic diversity
psbA	D1 (PS II core)	Photosynthesis/genetic diversity
psbC	CP43 (internal antenna of PSII)	Photosynthesis/genetic diversity
pstS	Phosphate-binding protein	Nutrient assimilation and limitation
rrn	16S rRNA	Genetic diversity

The different topics will be studied within distinct work packages, each gathering activities in the laboratory and in the field. Two workshops gathering all participants have also been planned. The first one will consist at working on *Prochlorococcus* cultures and will aim at testing the specificity of molecular probes as well as studying the physiological responses of cells to light and nutrient stresses. The second workshop will focus on natural *Prochlorococcus* populations and will aim at determining the genetic and phenotypic diversity as well as the physiological status of cells collected during a natural bloom in the Red Sea. Beside these workshops, numerous natural samples will be collected during cruises conducted either in the Mediterranean or Red Sea or the Atlantic ocean, within the framework of different oceanographic programmes. Thus, we will gather information on *Prochlorococcus* populations (and as a side product: associated picoplankton) from a variety of marine ecosystems.

(A) GENETIC DIVERSITY OF STRAINS AND NATURAL POPULATIONS

The evolutionary relationships between *Prochlorococcus* and other photosynthetic organisms begin to be well known, in particular its close phylogenetic relatedness with marine *Synechococcus* cyanobacteria, despite their very different pigmentation (see e.g. Urbach et al., 1992; Hess et al., 1995, 1996; LaRoche et al., 1996). However, the intrageneric diversity of *Prochlorococcus* has been much less studied (Scanlan et al., 1996; Urbach et al., 1997). Moreover, it is still not clear whether cultured strains are representative of field populations, how diverse are the latter and how environmental parameters, such as light and nutrients, may influence this genetic diversity (Palenik, 1994).

To answer these questions, different *Prochlorococcus* clones available in culture as well as newly isolated strains will be genetically characterized by sequencing *rrn* and *psbA* genes (see Table 1). Gene sequences from the different strains and sequences from other organisms taken from data banks will then be aligned and gene regions conserved among *Prochlorococcus* strains but having one or several nucleotides difference with other organisms will be searched for. These regions will be used to design *Prochlorococcus*-specific probes and primers, necessary for the study of natural populations. Total DNA will be extracted from seawater collected in coastal waters of the Mediterranean and Red Seas or during cruises, then primers will be used to amplify partial gene sequences from the sole *Prochlorococcus* cells. Oligonucleotides, which can be designed to be specific of given *Prochlorococcus* genotypes, will be used as molecular probes to determine the relative proportion of these genotypes to the *Prochlorococcus* DNA or total DNA by *in situ* hybridization (see e.g. Amman et al., 1990). This approach will allow to study the effects of geographical location, depth, season and hydrological conditions on *Prochlorococcus* diversity even though some genotypes may not be culturable in the laboratory.

This work package also includes an extensive genetic characterization of *Prochlorococcus* genome, which should help future molecular studies dealing with this organism.

(B) PHOTOACCLIMATION VS. PHOTOADAPTATION

Photosynthesis is the central process in phytoplankton life. Using sun light energy, it allows the transformation of inorganic carbon into organic molecules, which are then incorporated into the structure of cells and, at a higher level, into the marine food chain. For a given organism, one of the major processes which determine the functional relationship between photosynthesis and irradiance is the "photo*acclimation*". This term refers to the capacity of a

cell to maximize light harvesting when photon densities are low and minimize photooxidative damage to the photosynthetic machinery at high irradiance levels (Falkowski and Laroche, 1991a). In the specific case of *Prochlorococcus*, the real extent of the physiological plasticity of cells in the field is hindered by the probable occurrence of several, genetically distinct populations characterized by different pigment contents, as well as by different irradiance optima for growth and photosynthesis (Campbell and Vaulot, 1993; Moore et al., 1995; Partensky et al., 1996). Strains more or less representative of these different physiological types of *Prochlorococcus* have been isolated in culture (Partensky et al., 1993, 1997; Moore et al., 1995). In the field, this *evolutionary* process, that can be termed "photo*adaptation*" is possibly driven by long-term or permanent exposure to particular light conditions. This superimposition of *physiological* and *evolutionary* processes leads to an *apparent* high adaptability of *Prochlorococcus* populations to light.

Within the PROMOLEC project, partners will try 1) to set the precise limits between photo*acclimation* and photo*adaptation* processes, 2) to determine in different ecosystems whether there are few *Prochlorococcus* genotypes with large photoacclimational capabilities or many different genotypes with limited photoacclimational capabilities and 3) to identify clear-cut genetic signatures for the different phenotypic types of *Prochlorococcus*. *Prochlorococcus* strains as well as natural populations collected from different depths and sites will be characterized using different approaches.

The genetic approach will consist in sequencing relevant photosynthetic genes using a similar method as for the *rrn* gene (see above). The *pcb* gene, which encodes the apoprotein of the major divinyl-chlorophyll *a/b* light harvesting complex, is specific of the sole *Prochlorococcus* genus among open ocean organisms and shows a large variability among the two most studied strains (LaRoche et al., 1996). Although functionally less important in *Prochlorococcus*, the *cpeA/B* genes, encoding the α and β subunits of the phycoerythrin are also interesting to distinguish strains or populations since they are present only in some *Prochlorococcus* isolates and possibly also in natural populations from the bottom of the euphotic zone (Hess et al., 1996). Other photosynthetic genes, for which there are no sequences available in *Prochlorococcus* yet, such as the *psbC* gene, which encodes an internal antenna of the photosystem II (CP43), may also be a good candidate to distinguish different *Prochlorococcus* pigment types (Partensky et al., 1997). Expression of these genes will also be studied after light shifts. This will help understand the dynamics of photoacclimation for the different *Prochlorococcus* pigment types.

The biochemical approach will consist in studying the structural and functional organization of *Prochlorococcus* light-harvesting complexes. Indeed, preliminary analyses showed that they differ between the different physiological types of *Prochlorococcus* (e.g. surface vs. deep isolates; Partensky et al., 1997). The effect of light on the structure and properties of these complexes will also be studied for each physiological type. Even if these kinds of experiments are only feasible with cultured organisms, the results will greatly help understand how natural populations photoacclimate *in situ*.

The phenotypic approach will consist in determining the growth rate, pigment composition by HPLC (Vidussi et al., 1996), the light absorption capabilities and the photosynthetic performances of different strains grown under a range of irradiances and of pre-screened natural *Prochlorococcus* populations.

(C) NUTRIENT UPTAKE AND LIMITATION

In the euphotic zone of oligotrophic oceans, one of the most important factors which control phytoplankton abundance beside light is nutrient availability. A large body of evidence suggests that the major limiting nutrients are N, P and trace metals, particularly Fe (Hecky and Kilham, 1988; Martin et al., 1990). By determining what nutrient is limiting growth of individual components within a community, one can expect to forecast which taxon will preferentially grow under given hydrological conditions and how the species composition of the community may be affected by short term changes in these conditions. To reach this objective, it is necessary to develop first a basic knowledge to be able to interpret molecular signals from organisms in the natural environment and infer from such signals how, and to what extent, the growth and functions of these organisms are limited by external factors. A number of key proteins are known to respond to limitation in photosynthetic organisms. Cyanobacteria, for instance, usually respond to nitrogen limitation by inducing proteases which degrade their N-rich phycobiliproteins (Collier and Grossman, 1994), by fixing atmospheric nitrogen (Mitsui et al., 1986) and (or) by inducing high affinity uptake systems for urea and nitrate (e.g. Omata, 1995). Under inorganic phosphate starvation, many microorganisms induce a high affinity phosphate transport system. In the marine cyanobacteria *Synechococcus* sp., for instance, a major polypeptide of 32 kDa is induced or de-repressed under P limitation (Scanlan et al., 1993). Several regulatory genes for both nitrogen and phosphorus assimilation have been identified and characterized in cyanobacteria (Vega-Palas et al., 1990; Luque et al., 1994; Scanlan et al., 1993, 1997).

The question of nutrient limitation is especially intriguing in the case of *Prochlorococcus* which is able to grow in environments where no mineral nutrients can be detected, such as the mixed layer of oceanic subtropical waters (Campbell and Vaulot, 1993; Lindell and Post, 1995; Partensky et al., 1996). To understand better this ability, the presence of protein components of uptake systems involved in N (*ntrA*, *ntcA*, *glnA*) and P (*pstS*) acquisition will be looked for in *Prochlorococcus* and the expression of the corresponding genes will be studied under nutrient stress conditions. Those proteins which are specifically induced during N or P starvation will then be used as markers of the limitation of cells in these nutrients in the field. Antibodies will be raised and immunofluorescence microscopy or immuno-blotting techniques will be used to recognize specifically cells expressing those proteins. Using this technique, the nutrient status of natural populations of *Prochlorococcus* will be studied at different timescales (e.g. seasons or stages of a bloom) and locations (e.g. at different depths and/or sites). The effects of this eventual nutrient depletion on photosynthesis will also studied both in culture and in the field.

(D) GROWTH AND CELL CYCLE

All cellular processes that concur to organic matter synthesis such as photosynthetic energy accumulation or nutrient uptake finally lead to the final processes of DNA replication and cell division. The latter is the key process that transforms cell growth into population growth. The cell cycle is loosely defined as the coordination of all cellular processes between cell birth and cell division. In eukaryotes, the cell cycle can be divided into 4 phases: G_1 , S, G_2 and M. S corresponds to the replication of DNA and M to mitosis, while G_1 and G_2 are intermediate phases dedicated to cell growth. The past 10 years have revealed that, for eukaryotes, all key proteins involved in the regulation of the cell cycle such as cyclins, are extremely well conserved across evolution from yeast to man. In prokaryotes, much less is known. Only a few organisms, such as *E. coli*, have been investigated (Donachie, 1993). Some fundamental

differences appear between prokaryotes and eukaryotes (Fig. 3). For example, in prokaryotes there is no M (i.e. mitosis) phase. There also appears to be less co-ordination between cell growth and DNA replication, so that some cells may have more than 2 copies of the genome and still not divide.

Recently it has been shown, by measuring the cell cycle of picophytoplankton in oceanic waters with flow cytometry, that the application of the cell cycle concepts can yield invaluable information on both the nutritional status and the net growth rate of natural populations. Flow cytometry has been used to obtain time series of cell cycle distributions of the marine photosynthetic prokaryote *Prochlorococcus* in oligotrophic areas (e.g. Vaulot et al., 1995, Liu et al., 1996). These data revealed that these prokaryotes are highly synchronized to the daily light cycle with division rates in the upper euphotic zone of the order of 1 doubling per day (0.69 day^{-1}).

While information on the cell cycle of natural populations of picophytoplankton, and especially of *Prochlorococcus*, is accumulating, still very little is known on how the cell cycle of these prokaryotes is regulated. At the genetic level, some key sequences such as oriC, the origin of replication, and some key genes such as *dnaA*, coding for a protein required for DNA replication, or *ftsZ*, essential for cell division, have been well characterized. However, the cell cycle is probably less conserved among prokaryotes than among eukaryotes.

The effects of light intensity, light duration (relevant to the natural photocycle) and light modulation (i.e. progressive variation from dark to maximum irradiance) on *Prochlorococcus* cell cycle will be investigated in detail in culture. This should allow to better interpret diel patterns observed in the field. Another aim of the project PROMOLEC will be to design molecular probes that could be used to assess the growth status of natural populations. For this purpose, key cell cycle genes (such as *dnaA* and *ftsZ*) will be cloned and sequenced in one axenic strain. The cloned genes will be used as homologous probes to study the regulation of cell cycle under laboratory and (if feasible) under field conditions directly at the RNA level.

At last, the eventual coupling between cell cycle and photosynthesis will be investigated to know whether variations in photosynthetic parameters might be either directly related with light rythmicity or controlled by the sequence of genetic and biochemical events entailed by the cell cycle.

CONCLUSION

The multi-disciplinary work planned within PROMOLEC should allow to have a very large and unprecedented picture of the genetics, ecophysiology and diversity of the smallest and the most abundant photosynthetic organism known to date on Earth: *Prochlorococcus*. This organism contributes 30-50% of the photosynthetic biomass and primary production in oligotrophic parts of the Pacific and Atlantic oceans (tropics and gyres). In addition, it also plays a significant role in some regional seas, such as the Mediterranean and Red seas. Since huge areas are concerned (about 55% of the world ocean), it is clear that *Prochlorococcus* constitutes one of the major contributors to the carbon cycle, a topic which is the main focus of major current oceanographic programs, like JGOFS.

This single organism has therefore an influence at a global scale and the information that will be drawn from the PROMOLEC project should therefore be useful for many members of the oceanographic community.

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TITLE: Process of Vertical Exchange in Shelf Seas (project **PROVESS**)

CONTRACT NO: MAS3-CT98-0159

CO-ORDINATOR:

Mr. John Howarth
Proudman Oceanographic Lab., Bidston Observatory
Birkenhead, Merseyside, L43 7RA, UK
Tel: 00 44 (0)151 653 8633
Fax: 00 44 (0)151 653 6269
E-mail : mjh@pol.ac.uk

PARTNERS:

Dr. Ken Jones
Dunstaffnage Marine Lab., PO Box 3,
Oban, Argyll, PA34 4AD, UK
Tel: 00 44 (0)1631 562244
Fax: 00 44 (0)1631 565518
E-mail : kjj@dml.ac.uk

Dr. Meirion Jones
British Oceanographic Data Centre,
Proudman Oceanographic Lab.,
Bidston Observatory,
Birkenhead, Merseyside, L43 7RA, UK
Tel: 00 44 (0)151 653 8633
Fax: 00 44 (0)151 653 6269
E-mail : bodcmail@pol.ac.uk

Prof. Gunther Krause
Alfred-Wegener Institut, Columbusstraße,
Postfach 120161, D-27515, Bremerhaven, D
Tel: 00 49 471 48 31 170
Fax: 00 49 471 48 31 724
E-Mail
gunther_krause@awi-bremerhaven.de

Dr. Andy Visser
Danish Institute for Fisheries Research
Dept. Of Marine and Coastal Ecology
Kavalergaarden 6,
DK-2920 Charlottenlund, DK
Tel: 00 45 33 96 34 25
Fax: 00 45 33 96 34 34
E-mail : awv@dfu.min.dk

Prof. Jürgen Sündermann
Institut für Meereskunde,
Universität Hamburg, Troplowitzstraße 7, D
22529, Hamburg, D
Tel: 00 49 (40) 4123 2606
Fax; 00 49 (40) 560 5926
E-mail : suendermann@ifm.uni-hamburg.de

Dr. Patrick Sauvaget
Laboratoire d'Hydraulique de France
6 rue de Lorraine, F-38130 Echirolles
(Grenoble), F
Tel: 00 33 (0)4 76 33 42 37
Fax: 00 33 (0)4 76 33 42 39
E-mail : patrick.sauvaget@lhf.fr

Dr. Georg Umgiesser
Dept. of Oceanography, ISDGM-CNR,
1364 San Polo, 30125 Venezia, I
Tel: 00 39 41 5216 875
Fax: 00 39 41 2602 340
E-mail : georg@lagoon.isdgm.ve.cnr.it

Dr. Adolf Stips
Space Applications Institute
Marine Environment TP272
7-8111 Joint Research Centre
I-21020, Ispra (Varese), I
Tel: 00 39 332 789 876
Fax: 00 39 332 789 304
E-mail : adolf.stips@jrc.it

Dr. Patrick Luyten
Management Unit of the Mathematical
Models of the North Sea,
Gulledelle 100, B-1200, Brussels, B
Tel: 00 32 2 773 2138
Fax: 00 32 2 770 6972
E-mail : mastpl@camme.ac.be

Dr. Hans van Haren
Nederlands Instituut voor Onderzoek der Zee
PO Box 59, 1790 AB den Burg, Texel, NL
Tel: 00 31 (0)222 369300
Fax: 00 31 (0)222 369451
E-mail : hansvh@nioz.nl

Dr. Paul Tett
Dept. of Biological Science
Napier University, 10 Collinton Rd,
Edinburgh, EH10 5DT, UK
Tel: 00 44 (0)131 455 2633
Fax: 00 44 (0)131 455 2291
E-mail : p.tett@central.napier.ac.uk

Dr. Anouschka van der Meulen
RWS/RIKZ, PO Box 20907,
2500 EX Den Haag, NL
Tel: 00 31 (70) 3114290
Fax: 00 31 (70) 3114321
E-mail : a.vdmeulen@rikz.rws.minvenw.nl

Dr. Christian Grenz
Station Marine d'Endoume
UMR 6535 - LOB, Rue de la Batterie des Lions,
F13007, Marseille, F
Tel: 00 33 (0)4 91 04 16 41
Fax: 00 33 (0)4 91 04 16 35
E-mail : grenz@com.univ-mrs.fr

Prof. J.H. Simpson,
School of Ocean Sciences, Menai Bridge,
Gwynedd, LL59 5EY, UK
Tel: 00 44 (0)1248 382844
Fax: 00 44 (0)1248 382612
E-mail : oss035@sos.bangor.ac.uk

Dr K.D. Pfeiffer
HYDROMOD, Banhofstraße 52
D-22880, Wedel, D
Tel: 00 49 (0)4103 13057
Fax: 00 49 (0)4103 3317
E-mail : pfeiffer@hydromod.de

Dr. David Hydes
Southampton Oceanographic Centre
Empress Dock, Southampton,
SO14 3ZH, UK
Tel: 00 44 (0)1703 596547
Fax: 00 44 (0)1703 596554
E-mail : d.hydes@soc.soton.ac.uk

Dr. Slawek Sagan
Institute of Oceanology, Polish Academy of Sciences, 81712 Sopot, PL
Tel: 00 48 58 5517 283 x211
Fax: 00 48 58 5512 130
E-mail : sagan@ocean.iopan.gda.pl

PROCESSES OF VERTICAL EXCHANGE IN SHELF SEAS PROVESS

M.J. Howarth

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

SUMMARY

PROVESS is a three year MAST III project due to start on 1 March 1998 studying vertical exchanges in shelf seas. The main aims of the project are described and the work plan outlined.

1. INTRODUCTION

Vertical exchanges are central to many shelf sea processes, for instance the development and erosion of the pycnocline (particularly the diurnal and seasonal thermoclines and the lutocline close to the sea bed); the onset and decline of phytoplankton blooms; particle sedimentation and the remineralisation of particulate matter in the benthic boundary layer. Vertical exchanges are controlled principally by the turbulence characteristics of the water column, with the surface mixed layer, the pycnocline and the benthic boundary layer especially significant. Turbulence is generated both at the surface, by wind stress and (breaking) waves, whitecapping and Langmuir circulations, and at the sea bed, through the action of bottom friction. At the pycnocline turbulence levels are reduced and vertical fluxes can be inhibited. Turbulence characteristics at any location therefore depend on the water depth, tidal current strength, nature and degree of stratification, composition and shape of the sea bed, strength of the winds and waves and on the presence of Langmuir circulation, inertial currents and internal waves. In turn the nature and strength of the turbulence affects the local dynamics and thermodynamics.

A considerable reliance is placed on turbulence closure schemes to quantify fluxes in shelf sea environmental models - a crucial example is the entrainment of nutrients into the photic zone. Studies have shown that accurate modelling of physical processes in the water column, especially of vertical advection and turbulent mixing, is critical for predicting plankton dynamics (Sharples & Tett, 1994). In present models the entrainment of nutrients across the thermocline appears to be incorrectly estimated, so that predictions of autumn blooms and midwater chlorophyll maxima are in error. The failure to estimate nutrient fluxes accurately stems from a lack of understanding in two areas - firstly the quantification of vertical fluxes in the vicinity of the thermocline and secondly which processes control nutrient recycling in the benthic boundary layer. PROVESS will study the physical-biological coupling involved in recycling by measuring and modelling both the agglomeration - sedimentation - deposition - resuspension of particulates, and the mineralisation of nutrients, in relation to bed stress and turbulence regimes in the bottom mixed layer at sites with contrasting physical forcing. A key aspect will be to distinguish processes occurring in the water column from those in the 'fluff layer' formed by freshly deposited particulates and those in the compacted sediment of the sea-bed.

Measurements of turbulence properties in continental shelf seas (dissipation rate throughout the water column and intensity over a wide frequency range) are the heart of the project. These, together with biological measurements concentrating on fluxes near the sea bed, will be made

at two contrasting sites in the North Sea. The data sets will be applied to test the robustness of parameterisations and to establish the domain of validity of the models. Since turbulence also directly affects the environment perceived by particles, including living biota, detritus and suspended sediment, studies will be made of aggregation, flocculation and sedimentation of particulate organic and inorganic matter and of trophic interactions. New hypotheses about turbulence effects on zooplankton grazing rates, diet selectivity, vertical distribution and patchiness will be tested against process oriented field and laboratory measurements. The project contributes to the long term goal of developing robust water column plankton models applicable in the full range of turbulence environments encountered in shelf seas.

2. OBJECTIVES

PROVESS is an interdisciplinary study of the vertical fluxes of properties through the water column and the surface and bottom boundaries based on the integrated application of new measuring techniques, new advances in turbulence theory and new models. Its objectives are to -

Improve understanding and quantification of vertical exchange processes in the water column, in the surface and benthic boundary layers and across the pycnocline.

Explore mechanisms of physical-biological coupling in which vertical exchanges and turbulence significantly affect the environmental conditions experienced by biota.

Apply innovative technologies to the measurement of physical microstructure features and phenomena, in particular turbulence properties in the water column.

Provide a new, comprehensive and synoptic data set for validation of vertical fluxes of energy and matter calculated by physical and biological models.

Develop 1-D physical models for the computation of statistical moments of microstructure phenomena and integrated biological-physical models of the water column, including fluxes from the surface and the sediment.

Test and validate the models against measurements of mean and fluctuating properties in the water column.

Provide modules for vertical exchanges which can be implemented in state-of-the-art 3-D water quality and ecological models.

3. WORKPLAN

The project is founded on the synthesis of experimental, theoretical and modelling studies aimed at improving understanding of small-scale features of coastal seas and their effects on vertical exchange processes. The measurement of vertical profiles of turbulence dissipation rate and intensity in shelf seas is central. These, and measurements of nutrient recycling in the benthic boundary layer will be made at two contrasting sites, Figure 1 - in a shallow, tidally dominated region (the southern North Sea) and in a lower energy region where the surface mixed layer and the benthic boundary layer are separated (the northern North Sea). Coupling between biology and turbulence will be investigated. The turbulent physics and integrated biological-physical water column models will incorporate the understanding gained from the process studies and be tested against the measurements.

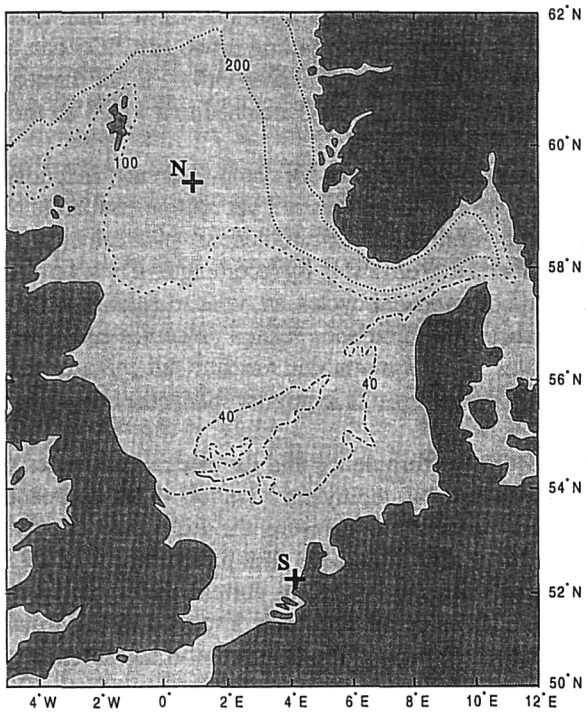


Figure 1 Map showing the positions of the northern (N) and southern (S) North Sea experiment sites. Depth contours are in metres.

Turbulence measurement innovations

The major aim is to make measurements of accessible turbulence parameters, with an ultimate goal of determining all the main terms in the turbulent kinetic energy (TKE) equation - (i) production, (ii) dissipation, (iii) work against buoyancy forces, (iv) time derivative of TKE and (v) its vertical diffusion - including correlators of higher than second order. Until recently it has not been possible to measure any of the parameters, except for restricted measurements in the bottom boundary layer. New techniques will be exploited to make measurements of turbulence parameters throughout the water column. Since vertical fluxes of particles are also of interest, new methods will be applied to provide improved profiles of particle size and concentration.

Turbulent dissipation measurements will be obtained with two different proven microstructure probe systems - FLY 4 and MICSOS. The FLY 4 profiler has recently been used successfully to make one of the first series of vertical profile measurements of dissipation in shelf seas, in the Irish Sea (Simpson *et al.*, 1996). Measurement of dissipation are made to within 0.15 m of the sea bed; near surface coverage is limited by the influence of the ship's wake and by the distance taken for the probe to achieve a uniform fall velocity - a few metres. Turbulent velocity fluctuations can be sensed on length scales down to 6 mm which allows direct determination of most of the dissipation spectrum, except in the most energetic shelf sea regions.

The MICSOS system is being developed within the EUREKA project EUROMAR -MICSOS (Prandke *et al.*, 1995). Data are acquired by a free-falling probe with an approximate sinking speed of 0.5 m s^{-1} and a sample rate of 1 kHz, down to a maximum depth of 100 m. Turbulence

velocity fluctuations can be sensed on length scales down to 3 mm; dissipation levels down to 4×10^{-8} W m^{-3}. As well as operating as a falling probe MICSOS can be deployed in a rising mode, making dissipation measurements to within O(0.01 m) of the sea surface. In this mode the instrument still records on the ship, but is attached to a winch on the sea bed.

Both systems will be deployed at both sites for comparison and redundancy, since high quality dissipation measurements are crucial and are not yet routine. Separate measurements will also enable estimation of spatial intermittence in turbulence, which can be large (Moum *et al.*, 1995). The instruments will be operated from a ship by recording five or six profiles in quick succession every half hour, over one or two tidal cycles, in order to acquire sufficient data for profound evaluation of microstructure and turbulence related processes and to achieve high confidence levels for derived quantities. Both systems can measure temperature and salinity fine structure in parallel with the velocity measurements to provide independent measures of vertical exchange.

Measuring the kinetic energy of turbulence and its spectral properties has until recently been possible only near the sea bed by deploying a lander. This approach will be followed by employing an instrument platform to measure the full range of mean and turbulent flow properties to a height of 2 m above the bed. The measurement of TKE further up the water column will be attempted with fast sampling current meters and / or pulse coherent high frequency doppler techniques using the approach described by (Lohrmann *et al.*, 1990). With a 300 kHz coherent system, these authors report successful measurements of turbulent intensity and Reynolds stress to a range of 10 m from the bottom boundary. Their approach has been applied by van Haren *et al.* (1994) using a bottom frame equipped with an upward looking 600 kHz ADCP (5 beams, 160 MB memory) and a downward looking standard 1200 kHz ADCP, accompanied by a "fast response" accurate thermistor string.

Most particles in marine environments are aggregates whose effective *in situ* size bears little relation to the absolute size of the primary constituents (Bale & Morris, 1987; Eisma, 1986). Since many aggregates are fragile and easily disrupted by conventional sampling, size measurement demands *in situ* techniques. Such techniques, of varying effectiveness and / or difficulty, exist - photography (Eisma, 1986), laser diffraction (Bale & Morris, 1987 & 1991) and sedimentation devices (McCave & Gross, 1991). Natural aggregation / disaggregation processes (for instance due to turbulence) are important over relatively small time and vertical space scales, demanding techniques capable of high resolution. *In situ* laser diffraction systems can provide this but operate via light transmission over fixed optical paths which are problematic in high, low and fluctuating SPM concentrations and at depths greater than 30 m (Bale & Morris, 1991).

These problems can be overcome using backscatter, rather than transmission, techniques. A new laser sizing instrument using a single window backscatter system has been adapted for *in situ* deployment, avoiding the need for a conventional optical path and thereby reducing the effects of turbulence generated between source and detector, over- and under-saturation of the signal in low and high SPM concentrations, and pressure distortion. The instrument is operated via an umbilical cable and has been successfully deployed in depths of up to 100 m over a wide range of particle concentrations. It is capable of high resolution sampling in space (as a vertical profiler) and time, and its capabilities have been systematically investigated using a variety of natural sediments and calibration standards. It has also been directly compared with standard techniques including microscopy, Coulter Counter and laser diffraction.

Southern and Northern North Sea Experiments

The experimental sites were chosen to satisfy specific turbulence regimes and to obtain simple boundary conditions for the different symmetries (1-D, 2-D, 3-D) and research foci under consideration. Site selection was based on previous studies and on numerical model sensitivity analyses. The northern North Sea site was chosen to minimize the significance of advection, horizontal gradients, topography and irrelevant processes, such as fronts. Whilst satisfying these criteria would have been beneficial at the southern site, this was not fully possible in the tidally dominated, shallow coastal waters. The sites' salient characteristics are listed in Table 1.

Table 1. Characteristics of the two experimental sites.

	Southern North Sea	Northern North Sea
Position	52° 15′ N 4° 17′ E	59° 20′ N 1° E
Time of year	April - May	September - November
Water Depth (m)	16	100
M_2 max amplitude (m s^{-1})	0.75	0.15
Max current (m s^{-1})	1.0	0.6
ΔT (°C)	-	7 - 1
Thermocline depth (m)	-	35 - 100
ΔS	1	small
Halocline depth (m)	5-10	cf thermocline depth
Max wind speed (m s^{-1})	20	25
Max significant wave height (m)	5	10
period (s)	8	10
Internal motion	No	Yes
Sediment	Muddy-sand	Muddy-sand
Biology	Eutrophic	Oligotrophic

The aim of the southern North Sea experiment is to study vertical processes related to turbulence in a high tidal energy environment: flocculation and sedimentation of (in)organic material, the development of high concentration near-bed (benthic fluff) layers, and remineralisation of nutrients in flocs and benthic layer. Of special interest is the near-bottom current structure, sediment concentration and the possible formation of high concentration benthic layers. The experiment will take place in spring, preferably coinciding with the decline of the phytoplankton bloom. Measurements will cover the tidal and neap-spring tidal cycle, to quantify the effect of variations in turbulence, salinity and suspended matter concentration. Mineralisation will be studied using benthic chambers placed on the sea bed by divers. Near-bed current structure and sediment concentration will be measured with instruments placed in a benthic frame.

The Dutch coastal zone in the southern North Sea is a shallow area (10-30 m) characterised by strong tidal action. Wind-induced waves can reach the bottom boundary layer and the sea bed. Buoyant spreading of outflowing Rhine and Meuse river water has a profound effect on water column characteristics: rapid switching from vertically homogeneous to strongly stratified can occur within a tidal cycle due to tidal straining (Simpson & Souza, 1995). High freshwater and nutrient inputs from the rivers cause strong phytoplankton blooms in spring and late summer (Fransz, 1986), and meteorological events related to stratification are important as well for phytoplankton and sediment dynamics (Jones & Gowen, 1990).

The objectives of the northern North Sea experiment are to study turbulence regimes during the autumnal breakdown of stratification, from September to November, including the mixing of nutrient rich near bed water into the photic zone leading to an autumn bloom. Of major importance are exchanges across the thermocline and the processes leading to the deepening of the thermocline, including surface mixing and cooling and overturning in the surface mixed layer. It will be based on experiences gained during FLEX'76 when physical and biological measurements were made during the onset of stratification in the northern North Sea (Burchard & Baumert, 1995). Optical properties and photosynthetic characteristics of the phytoplankton community will be studied. Benthic fluxes will studied using a multicorer. Initially the water column will be stratified and inertial and internal motion will be present. For this phase the dynamics of the surface layer is largely unaffected by the effects of tidal friction near the sea bed, which in any case is small. At all times exchanges across the thermocline will be of interest. During the experiment there will be periods of intense surface mixing caused by the large storms, which are accompanied by strong winds and large waves, the largest are capable of resuspending sea-bed sediment (Howarth & Glorioso, 1995).

Away from the coasts in the northern North Sea tidal currents are weak and water depths are 100 m or greater, so that the surface mixed layer and the benthic boundary layer are well separated. In summer the water column stratifies (thermocline depth 35 m, surface to bottom temperature difference 7 - 8 °C). The breakdown of stratification occurs between September and December, through surface heat loss in conjunction with mixing caused by a series of large storms which usually cross the Atlantic and the northern North Sea from west to east. A site not affected by Atlantic inflows, the Fair Isle / Dooley current and the Norwegian Coastal Current has been selected. The sea bed is flat over large areas.

At both sites measurements will be concentrated at a central position, with additional measurements made to estimate horizontal gradients and transports, essential for interpretation of the vertical exchange observations. There is some redundancy in the measurement strategy to minimise the effects of instrument loss or failure, and to establish data quality by cross-referencing. Moorings will be deployed for a 2-3 month period to determine the tides and to sample in different conditions - spring / neaps; windy / calm. There will be intensive ship-based operations - dissipation measurements for several 24 hour sessions, benthic measurements, repeated water column sampling, determination of spatial gradients. At some time during each experiment two ships are planned to be on site, one occupying a central station and the other conducting surveys in the region up to 50 km away to estimate gradients and advective fluxes of key physical, chemical and biological parameters.

Observations of turbulence, dissolved inorganic nitrogen, silicate, phytoplankton and micro-heterotrophs (amount and dominant species) and organic detritus in the surface mixed layer and upper thermocline are needed to test predictions of the dynamics of plankton blooms that follow the entrainment of nutrients into the surface mixed layer. The key measurements for developing parameterisation and testing of the benthic-pelagic model include: near-bed current shear; oxygen demand and nitrate+nitrite, ammonium and silicate fluxes at the sediment-water interface (including the fluff layer, Overnell *et al.*, 1995), and of oxygen demand of water samples from the bottom mixed layer; sediment and fluff layer organic content; concentrations of dissolved nutrients, oxygen, and particulate organics in the bottom mixed layer. Sedimentation fluxes will be measured at the northern site only, since high turbulence at the southern site would render trap data of doubtful value. Denitrification rates will be estimated from the model once this has been validated against other measurements of nitrogen flux

Plankton-turbulence coupling

Variations in zooplankton feeding rates and diet preferences will be investigated with respect to quantified levels of prey and turbulent dissipation. Two hypotheses will be tested:
a) the composition of zooplankton diets will vary with turbulent dissipation rates and feeding strategy (ambush predator v. filter-feeder).
b) estimates of plankton feeding rates can be improved if turbulence effects on diet composition, encounter rate, and capture success and prey patchiness are considered.

Field component:
Feeding rates of zooplankton will be compared with food abundance and distribution, and turbulent dissipation rates. Egg production rates and gut contents (biochemical analyses of gut pigment contents, Kleppel, 1993) of copepods collected in different environments will be measured and compared with turbulent dissipation rates and food abundance. Comparisons of turbulence effects on biotic responses will be compared between the study sites, and over time.

Laboratory component:
Turbulence effects on feeding rates, behaviour and diet composition will be investigated in controlled laboratory experiments. Existing experimental setups for turbulence studies of biological problems will be improved and calibrated. Zooplankton food consumption rates will be measured in experiments using controlled prey densities, sizes and species combinations. These are intended to extend the results of findings based on a few species (Kiorboe & Saiz, 1995) to more zooplankton species and sizes, and to provide behavioral data (e. g. perceptive distances, handling times, activity patterns) required by turbulence-based feeding rate models.

Variations in zooplankton vertical distributions and patchiness will be evaluated with respect to vertical profiles of turbulent dissipation, food, light and water column structure. For an effective comparison of vertical profiles of turbulence and zooplankton distributions, the zooplankton sampling (pumped zooplankton samples and optically-derived particle counts) will be conducted on the same vessel as that being used to collect turbulence data.

Two hypotheses will be tested:
a) zooplankton occupy depths which minimize turbulence-induced stress, even though such behaviour could result in exposure to less food.
b) zooplankton and phytoplankton patch size (m - 10 m scale) depends on dissipation rate and on body size, which via swimming ability, is a likely to correlate with ability to resist turbulent dispersion.

Modelling, physics

To achieve credible biological simulations with a water column model it is essential to apply the best possible physical model. The following physical processes will be addressed:-
Interaction between turbulence and tidal and wind-driven currents.
Diurnal and seasonal cycles of heating and cooling, including the formation and evolution of the thermocline.
Interaction between waves and currents at the sea surface (wave breaking as a source of turbulence energy) and at the bottom (enhancement of the bottom stress due to non-linear waves / current interaction).
Sediment damping of turbulence.

Influence of internal wave activity on turbulence in the thermocline.
Role of horizontal and vertical advection.

Various turbulence schemes are envisaged, with most effort being put into the last two listed:-
- simple models with a flow and/or Richardson number dependent viscosity and diffusivity
- TKE models with a simple mixing length parameterisation
- Mellor-Yamada level 2
- k-ϵ type formulations

The existing models will be extended by including appropriate source terms for energy production due to internal waves (including the internal tide) and wind forced motions such as inertial oscillations which can produce large shears at the pycnocline. An explicit input of TKE at the surface from the breaking of surface waves will be incorporated following the approach of Craig & Banner (1994). The influence of internal waves on stratified turbulence will be investigated using recent developments by Kantha & Clayson (1994) and Large *et al.* (1994). Different formulations for the wave-current interaction at the sea bed will be tested.

As has been shown recently by comparative theoretical analysis of Mellor-Yamada and k-ϵ models, the Mellor-Yamada model is principally not capable of simulating the Thorpe scale in stably stratified flows. The k-ϵ model is able to do that if the parameter c3 is chosen according to Burchard & Baumert (1995). Therefore, although both models will be used, since both are widespread in the oceanographic community, the k-ϵ model will be preferred. This new finding underlines the crucial and leading role of theoretical thinking and analysis for successful numerical modelling and measurements.

Since horizontal and vertical advection can be assumed to be small in most of the physical problems, a series of 1-D simulations will be made with realistic forcing parameters. Wind stress and heat fluxes will be derived from observed meteorological data using existing formulations. The sea surface slope for the tide and mean barotropic flow will be obtained from existing large scale 2-D models. Models result will be compared with existing publicly available data sets.

A more profound comparison will be made when the turbulence measurements are available:
- turbulence dissipation rate
- turbulence kinetic energy
- fluxes of momentum, temperature, salinity
- bottom stress (essential to study the wave-current interaction)

and a validated unified 1-D physical model will be constructed, containing options for the selection of different turbulence schemes, formulations of wave/current interaction, surface fluxes, ... which can be applied to the study of different physical processes.

Three-dimensional hydrodynamical models are required to describe some of the physical processes, e.g. convective processes, wave-current interaction on a mobilised bed, generation and propagation of internal waves. The unified 1-D model, above, will be integrated into an existing 3-D model. This will then be applied to the northern North Sea site to evaluate the role of advection there and estimate the accuracy that may be expected with 1-D turbulence modelling.

Integrated biological-physical modelling

The development of the physical and the integrated biological-physical water column process models will be performed in close interrelation, with the aim of the continued development of

a 1-D model of the water column with dynamic coupling between physical and microbiological processes, as a platform for testing hypotheses about the relationship between production and mineralisation processes and the turbulence regime.

Benthic-pelagic coupling

To improve understanding of the effects of turbulent flows on the sedimentation and remineralisation of organic particulates.

To provide (for the 3D model) a submodel for the simulation of mineralisation in the bottom mixed layer and sea-bed.

To test the hypothesis that the bottom mixed layer is the dominant site of mineralisation at sites where deposited material is regularly resuspended by tidal stirring.

Pelagic biology

To develop a pelagic submodel able to simulate the seasonal shift from diatoms to other algae and the effect of this on the amount, sinking rate, and carbon : nitrogen : silicon ratio of sedimenting particles.

To improve the modelling of (i) the surface mixed layer turbulence distribution and thickness in relation to phytoplankton photosynthesis, and of (ii) turbulent diffusion of nutrients across the thermocline, and entrainment by the surface mixed layer.

To test the improved model against observations of blooms in the surface mixed layer, prior to use in the 3-D model.

The starting point will be an existing 1-D model, which has four components:-

a turbulence closure model for computing seasonal cycles of turbulent diffusivities from tidal and meteorological forcing at defined sites on the continental shelf (Sharples & Tett, 1994).

a model for the resuspension and deposition of particulate material from a 'fluff' layer overlying the sea-bed (Jones *et al.*, 1995).

a model for autotrophic and heterotrophic microbial processes in the water column, involving microplankton and detrital compartments, and the elements carbon, nitrogen and oxygen, where the key principle is the parameterisation as a single compartment of all processes with similar time-scales: thus the microplankton compartment includes phytoplankton and the bacteria and pelagic protozoa that exploit primary production and which can reproduce at the same rate as the autotrophs (Tett & Walne, 1995).

a diagenetic model for the mineralisation of carbon and nitrogen (with consequent oxygen demand) in sediments (Soetaert *et al.* 1996).

The main tasks are (i) to study the influence of the improved turbulence schemes on biological fluxes; (ii) to include the effects of lateral gradients of stability and nutrients; (iii) to improve the coupling between the benthic 'fluff' and diagenetic models; (iv) to include descriptions of turbulence-related processes influencing particle size and sinking rate; (v) to include cycling of biogenic silicon; and (vi) to represent seasonal changes in the properties of the plankton that are related to sedimentation. Although the last task could be done by increasing the complexity of the microbial ecosystem representation, given the complexity of the interactions amongst the main components of the complete model, simple and robust submodels will be sought. The extent to which submodel complexity is necessary will be examined and a solution sought which involves minimum additions to the existing micro-plankton-detritus model.

The 1-D model will be forced by meteorological data and information on tidal and residual flows taken from observations or the 3-D physical model. The remaining problem is how to supply the

grazing pressure exerted by mesozooplankton on the microplankton. Although this could be done with an explicit mesozooplankton model our initial preference is to impose the pressure on the basis of observations at the experimental sites. The 1-D model will be integrated into the limited area 3-D model and preliminary calculations will indicate the role of spatial variability in the biological response of the 1-D model.

4. CONCLUSIONS

The project is founded on the integration of experimental, theoretical and modelling studies of vertical exchanges in shelf seas, including the joint analysis and interpretation of measurements and model calculations. Innovative measurements of turbulence properties in continental shelf seas (dissipation rate throughout the water column and intensity over a wide frequency range) are the heart of the proposal. These, together with biological measurements concentrating on fluxes near the sea bed, will be made at two contrasting sites in the North Sea - one shallow, high energy, the other deeper, low energy. Since turbulence directly affects the environment perceived by particles, including living biota, detritus and suspended sediment, studies will be made of aggregation, flocculation and sedimentation, and of trophic interactions. New hypotheses about turbulence effects on zooplankton grazing rates, diet selectivity, vertical distribution and patchiness will be tested against process oriented field and laboratory measurements. Water column numerical models describing turbulent physics and integrated biology / physics will incorporate the understanding gained from the process studies and be rigorously tested against these fundamental measurements, to establish the robustness of parameterisations and the domain of validity of the models. The improved understanding will be applied to the exchange of nutrients across the thermocline and to nutrient recycling in the benthic boundary layer. This fundamental research will contribute towards the long term goal of developing robust water column plankton models applicable in the full range of turbulence environments encountered in shelf seas.

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TITLE: The Impact of Appendicularians in European Marine Ecosystems (project **EURAPP**)

CONTRACT NO: MAS3-CT98-0161

COORDINATOR: Dr. G. Gorsky
UPMC/CNRS-INSU
Observatoire Océanologique de Villefranche
B. P. 28
06230 Villefranche sur mer, France
Tel. no. +33493763816, Fax. +33493763834
e-mail : gorsky@obs-vlfr.fr

PARTNERS:

Dr. Gabriel Gorsky, Coordinator
Laboratoire d'Océanographie Biologique
et d'Ecologie du Plancton Marin
Université Pierre et Marie Curie
Observatoire Océanologique
06230 Villefranche sur mer
France
Tel.+33493763816 ; Fax.+33493763834
e-mail : gorsky@obs-vlfr.fr

Dr. Roger Harris
Plymouth Marine Laboratory
Prospect Place
West Hoe
Plymouth PL1 3DH
Great Britain
Tel. +441752633400 Fax.+441752633101
e-mail : RPH@WPO.NERC.AC.UK

Dr. Per Flood
Bathybiologica S.A.
Gerhard Gransvei 58
N-5030 Landas,
Bergen
Norway
Tel.+4755271954 ; Fax.+4755271954
e-mail : Per.Flood@zoo.uib.no

Dr. Paolo Burighel
Universita Degli Studi di Padova
Via VIII Febbraio 2
35122 Padova
Italy
Tel. +39498276175 ; Fax.+39498276199
e-mail : burighel@civ.bio.unipd.it

Dr. Jose-Louis Acuna
Universidad de Oviedo
Departamento de Biologia
de Organismos y Systemas
San Francisco 7
33071 Oviedo
Spain
Tel. +3485104794 Fax.+3485104866
e-mail : acuna@sci.cpd.uniovi.es

Professor Hans Jorgen Fyhn
University of Bergen
Zoologisk Institut
Allégaten 41
N-5007 Bergen
Norway
Tel.+4755583588 ; Fax.+4755589673
e-mail :hans.fyhn@zoo.uib.no

IMPACT OF APPENDICULARIANS IN EUROPEAN MARINE ECOSYSTEMS

G. GORSKY
UPMC/CNRS-INSU, Observatoire Océanologique
B.P. 28, 06230 Villefranche sur mer, France

SUMMARY

The EURAPP project described below represents a multidisciplinary effort aiming to improve the knowledge on the ecological role of distinct Appendicularian species in the marginal seas of Europe. The main objectives of the EURAPP project will be described and the work plan presented.

1. INTRODUCTION

The distribution of grazing pressure among the different protozoan or metazoan primary consumers has important implication for the cycling of nutrients and energy within pelagic food webs. Most of the studies concerns the rates and feeding behaviour of copepods as the most numerous component in the plankton samples. It becomes, however, clear that the importance of other groups and notably that of Tunicate filter feeders had been systematically overlooked. Among the Tunicates the class of the delicate pelagic Appendicularia was particularly neglected, mostly because of the sampling difficulties, inadequate conservation and the difficulty to work with living specimens.

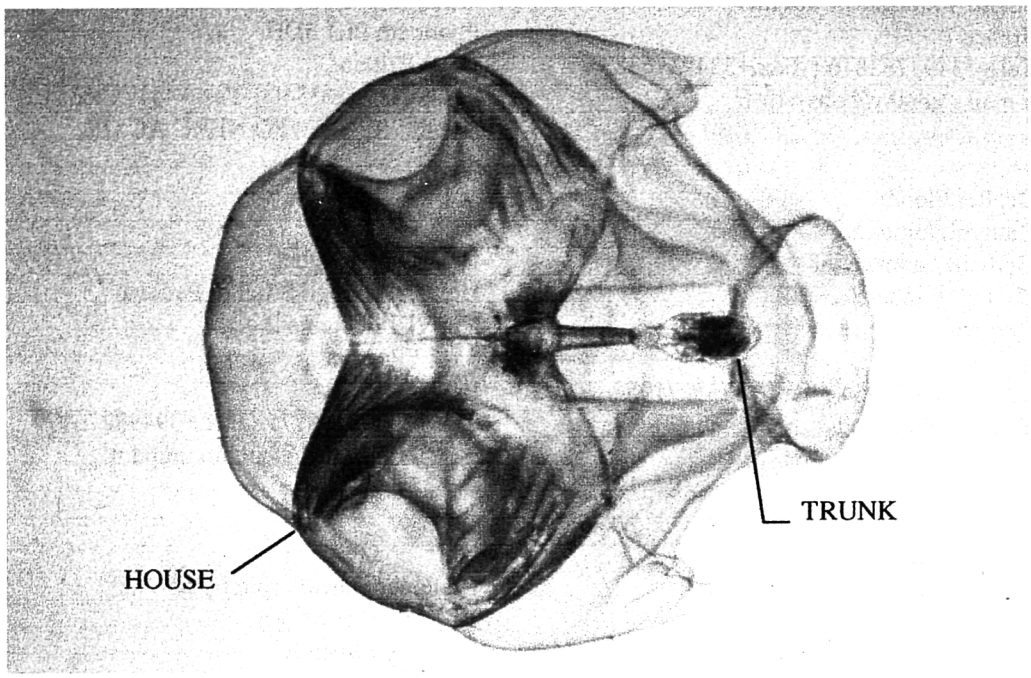


Figure 1. *Oikopleura dioica* Fol, 1872, in its house. The trunk of the presented individual measures 0,8 mm and the diameter of the house is about 1 cm. (Photo R. Fenaux)

Appendicularia (Fig. 1) are present in all oceans and seas, except Dead -, Aral -, Azov - and Caspian Seas. They are found in temperatures from -20°C to +30°C, in salinities from 4 to 41‰ and from surface to the depth of more than 2000 m. Few species are adapted for cold

waters, but these may occur in large numbers. The biodiversity is much larger for warm waters and a total of some 70 species has so far been identified world-wide (Fenaux 1993). Their capacity to form blooms is known from the last century (Quoy and Gaimard 1836), and the major part of data concerning their distribution originate from oceanographic cruises from the last century and the first half of the present one.

The repeated sampling of Appendicularia in the same region, with standardised techniques over several years, is a rare event. Only few studies deal with species succession and time series. Fenaux (1963) demonstrated a succession of populations of distinct Appendicularian species throughout the year in the Bay of Villefranche sur mer (NW Mediterranean).

Appendicularians are suspension filter feeders. An external system of filtration (the house) is continuously secreted by specialised cells of the animal's trunk. There are previous suggestions in the literature that appendicularians are specially suited to capture and ingest small particles, based on the small pore size of the food concentrating filters of their houses (Flood 1978, 1981, 1991, Deibel et al. 1985, Deibel and Powell 1987). But only recently has it been shown that oikopleurid appendicularians can efficiently capture sub-micrometer sized particles (Flood et al., 1992, Deibel and Lee, 1992; Bedo et al., 1993). The role of small (10nm to 0,2 mm) particles in the dynamics of pelagic ecosystems is considered with great interest in contemporal marine research. Particles in this size range make up the so-called "microbial loop" through which a large fraction of oceanic production is recycled. Also, materials fitting into the operational category of DOC, are now recognised to be composed to a great extent by colloidal. However, these small particles seem to be out of reach for the majority of mesozooplankton organisms, including copepods. Therefore, in current conceptual pictures of the pelagic food web, most production by the "microbial loop" is thought to be lost in respiration, due to the number of trophic links involved in this pelagic compartment.

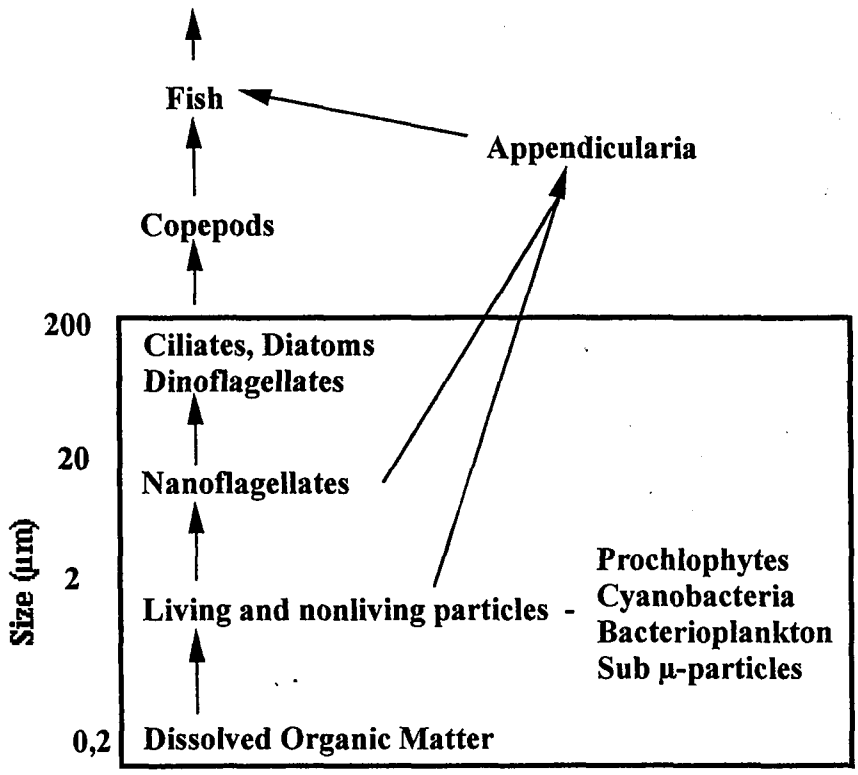


Figure 2. The simplified marine food web with the microbial loop (outlined) and the appendicularian short-circuit. Modified from Fenchel (1988).

The existence of a metazoan capable of short-cutting the size-related trophic chain (Fig. 2) and directly consume the microbial and colloidal pelagic compartments, and capable of compacting that biomass into body tissue, rapidly sinking faecal pellets and marine snow, is of great relevance to the dynamics of pelagic ecosystems and to the vertical flux of particulate matter.

Whereas ingestion rates of Appendicularia were studied in some details, there exist no information at all on digestive capacity and assimilation in Appendicularia. All studies referring to assimilation and enzymatic hydrolysis of particulate organic matter by planktonic organisms refer to copepods (as reviewed by Mayzaud 1986). There is an urgent need for such studies, especially since it has recently been reported that *Oikopleura dioica* in Kingston Harbor, Jamaica (at 29°C) on average showed a 10.7 fold increase in biomass over 24h (Hopcroft and Roff 1995)!. The generation time is approximately 1,5 days at this temperature. This increase in biomass is 1 order of magnitude higher than for the most representative copepod species and much in excess of most multicellular organisms. This extraordinary production potential of appendicularians combined with their abundance, which is second only to that of copepods, emphasises their understated importance in marine planktonic research.

The capacity of appendicularians to use suspended organic matter as food may explain their successful adaptation to both superficial phytoplankton rich layers and more "hostile environments" in the aphotic depth. Karl and Knauer (1984) found in sediment traps a peak of freshly discarded larvacean houses between 900 and 1400 m. Their data indicated the existence of several layers of intense biological activity. These layers were situated in the oxygen minimum zone (between 700 and 900 m) and in the sub-oxygen minimum zone (1000-1400 m deep). The authors concluded that the deep maximums in RNA and DNA synthesis of micro-organisms associated with particles are the result of "in situ" biological activity. The above observations corresponds to those made during the French Gyrocean oceanographic cruise using the CYANA submersible in south-west Mediterranean, where a deep layer of appendicularians was discovered between 900 and 1500 m. The *M. gyroceanis* holotype was collected at the depth of 1200 m.

Several giant Bathochordeus houses m^{-3} were reported by Barham (1979) from the mesopelagic waters in the Pacific Ocean off Mexico and by Hamner & Robison (1993) in Monterey Bay (California). Youngbluth (1984) noted near Bermuda a density of 10 mesopelagic appendicularians m^{-3}. The same value, as a maximum concentration, was reported by Gorsky et al. (1991) in Mediterranean between 350 and 800 m for a new species *O. villafrancae*. It is likely that the midwater filter feeding communities of Appendicularia, by their rapidly sinking faecal pellets and production of large mucus aggregates, contribute significantly to a "cascade"-transfer of organic carbon to deep layers.

O. dioica has higher respiration and excretion rates than copepods of similar weight (Gorsky et al. 1987). This high metabolic activity is maintained in low food concentrations as well. The short generation time (temperature related, from 2 days to weeks) and high fecundity (up to 1000 eggs per individual) can explain the massive appendicularian blooms as rapid reaction to favourable environmental changes.

The aim of the EURAPP project is to improve our understanding of the role of Appendicularia in representative marginal seas of Europe, by studying them at several organisational levels; from their seasonal, geographical and vertical distribution, abundance, biodiversity and population dynamics, through their ecophysiology and role in vertical particle fluxes, to their individual capacities as represented by structural, functional and chemical parameters and behaviour. The results of this research will be implemented in population dynamics and individual based models in order to predict the ecological impact of Appendicularia in European waters.

2. OBJECTIVES AND METHODOLOGY

The general objective of the EURAPP project is to improve our knowledge about the ecological role of distinct appendicularian species in representative marginal seas of Europe, in relation to the flux of colloidal and particulate organic matter, and in relation to the structure, dynamics and resilience of important components in the marine plankton community as a whole.

Specific objectives are :

- To determine the spatial and temporal distribution, the biodiversity and the population dynamics of appendicularians related to the environmental changes in the marginal seas of Europe.
- To study the role of appendicularians in transformation of organic matter and cycling of elements in the sea.
- To describe the functioning of appendicularians at organism level in controlled conditions.
- To determine the importance of appendicularians as predator and as prey in regard to their particular nutritional behaviour and adaptive capacity.
- To model the population dynamics and the ecophysiology of appendicularians.

The following methodologies will be used :

- Net collections associated to CTD data acquisition, water sampling for chemical and biological analyses and meteorological data acquisition.
- Underwater Video Profiler and ROV prospection.
- Appendicularian, phytoplankton, and copepod laboratory culture.
- HPLC, AFC, Perkin Elmer 2400 CHN elemental analyser, TOC 5000 Shimadzu, HPLC-620 LC system, Iatroscan TLC/FID analyser Coulter Counter, light and electron microscopy, advanced video equipment, image analysis.
- Models : Ecophysiological model, Individual based model, Population dynamics model.

3. WORKPLAN

The scientific work within the EURAPP Project is structured in Workpackages (WP), Tasks and Subtasks :

WP 1. Population density and dynamics
- Task 1.1. Field survey in NW Mediterranean
- Task 1.2. Field survey in Norwegian fjords
  - Subtask 1.2.1. Net, CTD and water sampling in Norwegian fjords
  - Subtask 1.2.2. 'In situ' survey of Appendicularia by new underwater techniques
- Task 1.3. Field survey off Plymouth
- Task 1.4. Field survey in Cantabarian sea

WP 2. Biodiversity
- Task 2.1. Species description by morphological descriptors
- Task 2.2. Species description by imaging technologies
- Task 2.3. Genome size of appendicularians

WP 3. Function of individuals and Interaction at organism level

WP 3a. Function of individuals

Task 3.1. Growth rate, generation time and fecundity

Task 3.2. Digestive capacity, gut passage and assimilation

Task 3.3. Appendicularians chemical composition and nutritive value

Task 3.4. The contribution of appendicularians to the cycling of carbon

WP 3b. Interaction at organism level

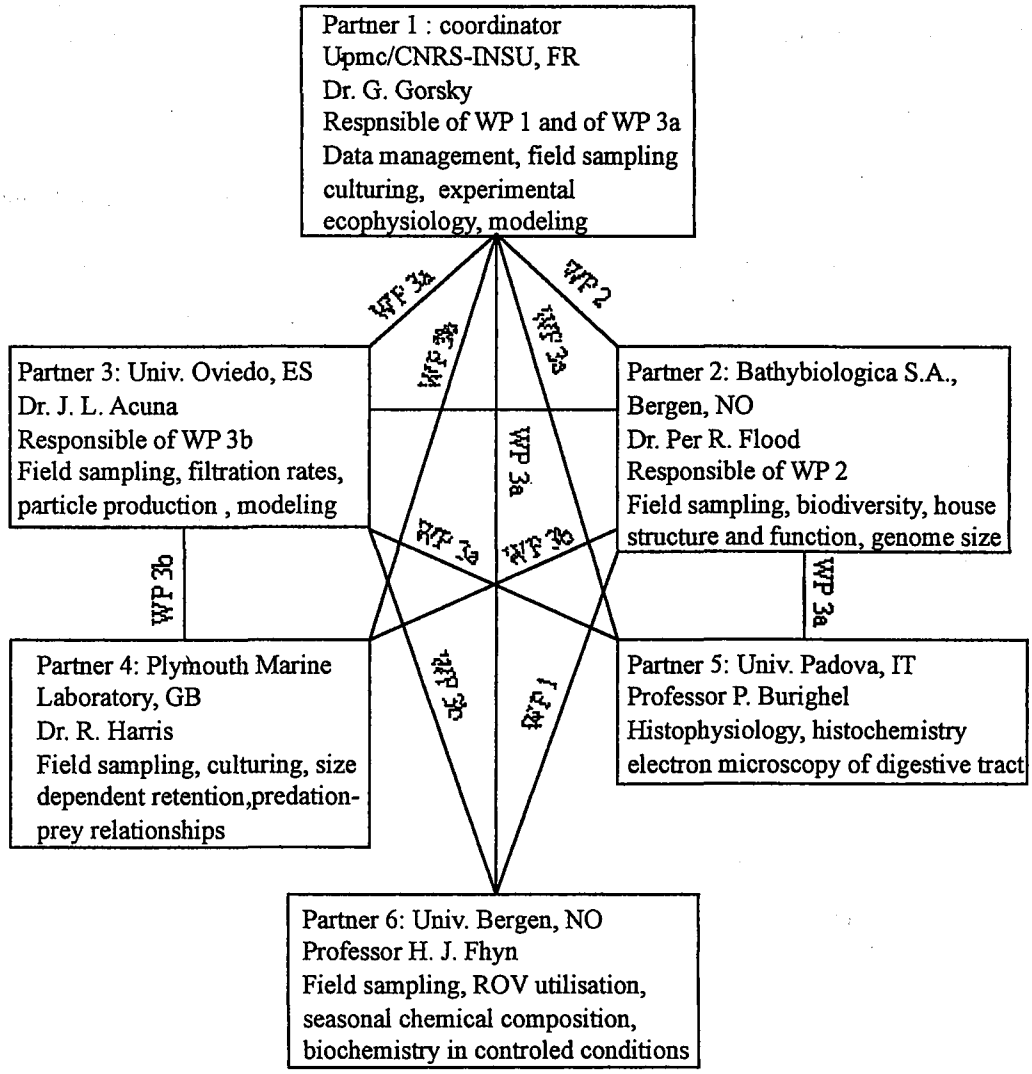
Task 3.5. In situ techniques to measure filtration and ingestion rates of appendicularians

Task 3.6. Size dependent efficiency in the retention and ingestion of particles by appendicularians

Task 3.7. Determination of the production rates of large particles by appendicularians

Task 3.8. Competitive interactions and predation on Appendicularia.

COLLABORATIVE LINKS BETWEEN PARTNERS.



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TITLE: **Ecological effects of protection in Mediterranean marine reserves (ECOMARE)**

CONTRACT NO: MAS3-CT97-0155

COORDINATOR:

R. Goñi
Centro Oceanográfico de Baleares
Muelle de Poniente, s/n
Apartado 291
07080 Palma de Mallorca - España
Tel. No. 34-(9)71-401877.
Fax No. 34-(9)71-404945
E-mail: goni@ctv.es

ASSOCIATED PARTNERS:

Dr. A. Ramos-Esplá
Departamento de Ciencias Ambientales
y Recursos Naturales
Laboratorio de Biología Marina
Universidad de Alicante
Campus de San Vicente
03080 Alicante - España
Tel. No. 34-(9)6-5903668
Fax. No. 34-(9)6-5903464

Dr. A. Pérez Ruzafa
Departamento de Ecología e Hidrología
Facultad de Biología
Universidad de Murcia
Campus Espinardo
30100 Murcia - España
Tel. No. 34-(9)68-307100
Fax. No. 34-(9)68-363963

Dr. M. Zabala
Facultad de Biología
Universidad de Barcelona
Avda. Diagonal, 645
08028 Barcelona - España
Tel. No. 34-(9)3-4021417
Fax. No. 34-(9)3-4111438

Dr. P. Francour
GIS MARSEILLE
Parc Scientifique et Technique de Luminy
13288 Marseille - Cedex 9 - France
Tel. No. 33-4-91-829135
Fax. No. 33-4-91-411265

Dr. S. Planes
Laboratoire d'Ichtyécologie Tropicale
et Mediterranéenne
Ecole Practique des Hautes Etudes
URA CNRS 1453
Université de Perpignan
66860 Perpignan - France
Tel. No. 33-4-68-662055
Fax No. 33-4-68-503686

Dr. F. Badalamenti
CNR-ITPP
Laboratorio di Biologia Marina
Via G. da Verrazano, 17
91014 - Castellammare del Golfo (TP)
Italia
Tel. No. 39-924-35013
Fax. No. 39-924-35084

Dr. R. Chemello
Istituto di Zoologia
Departamenti di Biologia Animale
Università di Palermo
Via Archirafi, 18
90123 Palermo - Italia
Tel. No. 39-91-6177158/9
Fax. No. 39-91-6172009

Dr. E. Voultsiadou
Depart. Zoology
School of Biology
Univ. of Thessaloniki
54006 Thessaloniki - Greece
Tel. No. 30-31-998321
Fax. No. 30-31-998269

Dr. N.V.C. Polunin
Center for Tropical Coastal Manag. Studies
Dept. of Marine Sciences
University of Newcastle Upon Tyne
Ridellery Building
Newcastle Upon Tyne NE17RU - U.K.
Tel. No. 44-191-2226675
Fax. No. 44-191-2227891

ECOLOGICAL EFFECTS OF PROTECTION IN MEDITERRANEAN MARINE RESERVES - ECOMARE

Raquel GOÑI
Instituto Español de Oceanografía
Centro Oceanográfico de Baleares
Palma de Mallorca, Spain

SUMMARY

Marine protected areas are being established around the world at a rapid rate. Some offer protection to pristine natural communities while others attempt to halt further deterioration of sensitive habitats or serve as fishery management tools for long term sustainability of coastal fisheries. The Mediterranean Sea supports the biggest population and the highest human pressure of all the European seas. Because most of the production occurs in the narrow limits of the continental shelves and the human impacts take place there, marine reserves are one of the few available tools to manage this area for sustainable use and for protection of biological diversity of unique ecosystems. At present there are 17 operational marine reserves in the EU Mediterranean littoral where researchers from Spain, France, Italy and Greece study the effects of protection in the ecosystems. Most of the research carried out in Mediterranean reserves has focused on populations of exploited species. However, reserve protection can lead to an intricate array of changes to community structure at all trophic levels, starting with direct effects on the populations of exploited species and impacting other populations through biological interactions between them. Also, the work carried out so far by the various EU Mediterranean teams involved in assessing the effects of protection in littoral communities has lacked integration and coordination. In order to move forward in this line of work, the ECOMARE project will unite and coordinate efforts of a broad group of EU research teams involved in assessing the effects of protection in Mediterranean littoral ecosystems. Work will be carried out by thematic working groups working in parallel which will focus on the following five aspects of the "reserve effect": 1) human activities affected by protection; 2) recruitment; 3) changes in demographic structure and reproductive biology; 4) "cascade effect" and trophic interactions; and 5) relations with the habitat and spatio-temporal distribution. A simple conceptual model of the reserve effect will provide the initial framework for this activities.

The objectives of ECOMARE are:

1. To establish the state of knowledge of the responses of marine communities to protective measures in Mediterranean littoral ecosystems;
2. To identify main research needs and steps forward to progress from the assessment of effects on exploited species to the assessment of the effects of protection at the community level;
3. To standardize working methodologies and data analysis and management procedures for research in priority areas so that future investigations can be carried out in a coordinated and comparable manner.

INTRODUCTION

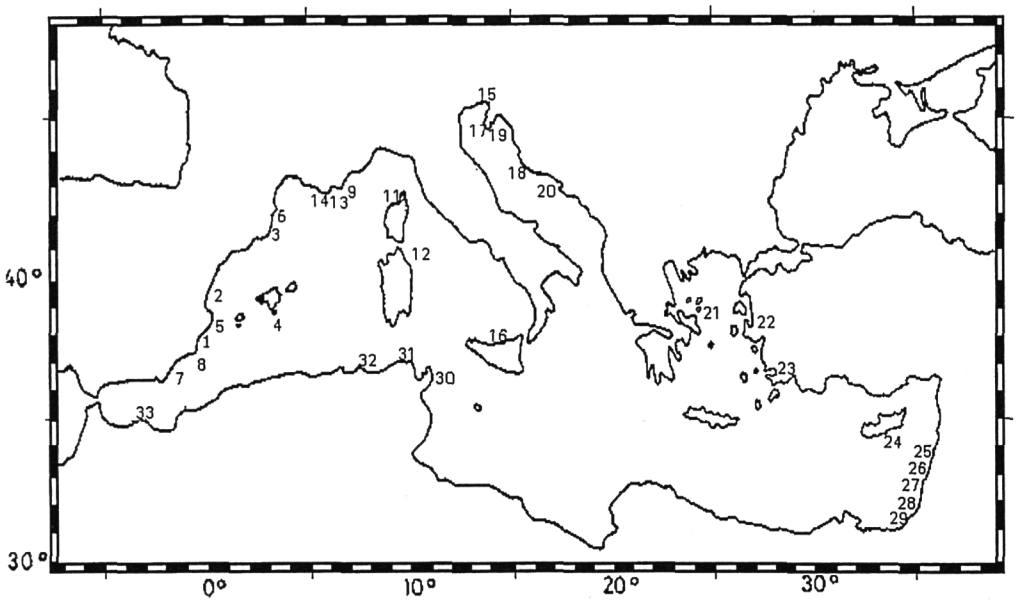
Of all the EU seas, the Mediterranean holds the largest number of marine reserves (17 in number by 1995): Spain, 8; France, 6; Italy, 2; and Greece 1. The rest of the Mediterranean holds 16 marine reserves (1995 figures), 1 in Slovene, 3 in Croatia, 2 in Turkey, 1 in Cyprus, 4 in Israel, 2 in Tunisia, 1 in Algeria, and 1 in Morocco (Figure 1) (Boudouresque & Ribera, 1995; A. Ramos, pers.comm.). Mediterranean marine ecosystems are characterized by high species diversity relative to North Atlantic ecosystems (e.g., Peres, 1967; Fredj *et al.*, 1992); with only 0.8% of the world ocean surface, the Mediterranean holds 7.5% of the marine species (Boudouresque & Ribera, 1995). Marine reserves in the Mediterranean have been established with the aims of providing refuge to threatened species (e.g. *Monachus monachus*, *Pinna nobilis*, *Patella ferruginea*, *Caretta caretta*, *Epinephelus* spp.), protecting ecosystems or habitats with particularly high biodiversity (e.g., seagrass beds, coralligenous communities) (Boudouresque & Ribera, 1995; Ramos & McNeill, 1994), facilitating recovery of already damaged areas, protecting breeding stocks, improving recruitment to neighbouring areas, or restocking marine species of commercial interest. In the Mediterranean, conservation of the cultural heritage and the promotion of traditional, sustainable uses may also be objectives of the creation of marine reserves.

One important reason for the special attention afforded to the protection of the Mediterranean littoral is the enormous human pressure exerted from the highly populated Mediterranean coastline, from overexploitation of living resources to urban development, tourism and dumping. The Mediterranean sea supports the biggest population and the highest human pressure of all EU seas (Anon, 1995b). Because most of the production occurs in the narrow limits of the continental shelf and the human impacts take place in that area, marine protected areas are one of the few available tools to manage this area for sustainable use and for protection of unique ecosystems.

STATE OF KNOWLEDGE: THE "RESERVE EFFECT"

In spite of the obvious interest in this form of coastal management, there is limited knowledge of the ecological effects of protection- or "reserve effect". By "reserve effect" (RE) it is understood the set of changes undergone by the living components of a protected area when one or several human impacts are removed (Boudouresque & Ribera, 1995). Several elements of the RE have been reported by different authors, notably the "refuge effect" (e.g., Garcia-Rubies & Zabala, 1990; Harmelin & Cachet, 1992; Bayle & Ramos, 1993; Francour, 1994), the "cascade effect" (e.g., Moreno *et al.*, 1986; Boudouresque *et al.*, 1992; Sala & Boudouresque, in press), and the "buffer effect" (Francour, 1994). The overall assessment of the RE is difficult because knowledge of the dynamics of marine ecosystems and of the interactions between their different components is limited. Moreover, the effects of protection may be overridden by long-term changes in oceanographic features or may be reduced by poaching, confounded by behavioural changes of the organisms due to protection, or non existent due to, e.g., the small size of the reserve (Jones *et al.*, 1992). This is particularly so given the small area of many of the sites which have been protected.

This problem has interested a large number of researchers working in tropical and temperate reefs around the world, in response to the need of managers to know whether these costly protective measures are having the intended effects. The problem has also interested Mediterranean research teams, first in France and more recently in Spain and Italy.



1. M.R.	Tabarca	18. N.P.	Kornati Islands
2. M.R.	Columbretes	19. N.P.	Brioni Islands
3. M.R.	Medas	20. N.P.	Mljet Islands
4. N.P.	Cabrera	21. N.P.	Northern Sporades
5. M.R.	Cabo de San Antonio	22. N.P.	Foça
6. M.R.	Ses Negres	23. N.P.	Köycegiz
7. N.P.	Cabo de Gata	24. M.R.	Lara
8. M.R.	Cabo de Palos	25. M.R.	Les Palmiers
9. N.P.	Port-Cros	26. N.P.	Rosh Hanikra
10. M.R.	Banyuls-Cerbère	27. M.R.	Dor-Habonim
11. M.R.	Scandola	28. M.R.	Tanimin
12. M.R.	Lavezzi	29. M.R.	Maagan Michael Isl.
13. M.P.	Carry-le-Rouet	30. M.R.	Galiton d l'Ouest
14. M.R.	Larvotto	31. M.R.	Zembra-Zembretta
15. M.R.	Miramare	32. N.P.	El-Kala
16. M.R.	Ustica	33. N.P.	Alhozima Islands
17. M.R.	Strunjan		

Figure 1: Map showing locations of Mediterranean marine reserves. Sources: Anon, 1995; A. Ramos, pers.comm. 1996. Hunting refuges and fishery reserves are excluded.

The majority of studies directed to evaluating the effects of marine reserves in the Mediterranean littoral have centered in the assessment of changes in fish populations. Results of these studies corroborate that protection leads to increases in abundance, size and biomass of the most vulnerable species (Bell, 1983; Garcia & Zabala, 1990; Bayle & Ramos, 1993; Francour, 1991a,b; Binche, 1992; Harmelin & Bachet, 1992; Harmelin *et al.*, 1995) in rocky substrates but not so in *Posidonia* meadows (Francour, 1994). Somewhat inconclusive evidence is provided by Dufour *et al.* (1995) who report impoverishment and maintenance of fish abundance in the reserve and non reserve areas respectively relative to an earlier assessment. Only mean or modal size of vulnerable species is found to be significantly correlated with protection by all authors.

A few studies also address the effects of protection on invertebrate and algae communities in the Mediterranean. Boudouresque *et al.* (1992) report results of an analysis of the RE on macrozoobenthos species of the Scandola reserve where macrozoobenthos was found poorer in both number of species and abundance in the protected area. The difference was attributed to the increased amount and average size of predatory fish in the reserve. Sala & Zabala (1996) and San Martin (1995) report changes in the structure of sea-urchin populations as a result of predation by fish in the reserves of Medes Islands and Carry-le-Rouet respectively.

Finally, while in the Mediterranean littoral some authors found that species diversity was not a good predictor of the effect of protection (Bayle & Ramos, 1993; Harmelin *et al.*, 1995), other researchers report a positive association between species diversity (Shannon's) and protection for both fish and macrozoobenthos (Francour, 1992; Boudouresque *et al.*, 1992). However, the significance of the response of this variable is conditioned by the fact that it is sample-size dependent and influenced by the structure and complexity of the sites (Garcia-Charton, 1995), as well as by the occurrence of erratic species (Bayle & Ramos, 1993).

Despite the agreement on some of the findings of these studies, the conclusions that can be drawn about the effects of protection on Mediterranean littoral fish assemblages are limited. In addition to differences in size, age and location among Mediterranean reserves, the studies carried out there differ in a number of important aspects, in particular the species or communities studied, the type of bottom (seagrass beds *vs* rocky bottoms), the duration of the study (pluriannual or instantaneous), and the methodological approach (in particular, choice of sampling units and level of replication, survey design), among others.

Figure 2 presents a simple model which illustrates the complexity of the processes that contribute to the "reserve effect". Reserve status can lead to an intricate array of changes to community structure at all trophic levels, starting with direct effects on the populations of exploited species and impacting other populations through ecological interactions between them. These changes may also affect the structure of the habitat in which species live conditioning further their behaviour and distribution. Protection status not only affects living communities but also results in a different range of human uses and impacts in the reserve itself or surrounding areas (e.g. increase of underwater tourism; Harmelin & Marinopoulos, 1994; Sala *et al.*, 1996). This differential pattern of human use or of activities affected by protection is another variable to be accounted for by the "reserve effect" model. Thus, while the study of fish assemblages provides a good tool for assessing effects of protection when the primary objective of reserve creation is to protect and restock exploited fish species, more comprehensive ecological studies, where all functional compartments of the ecosystems are considered, are needed to obtain a complete understanding of the RE.

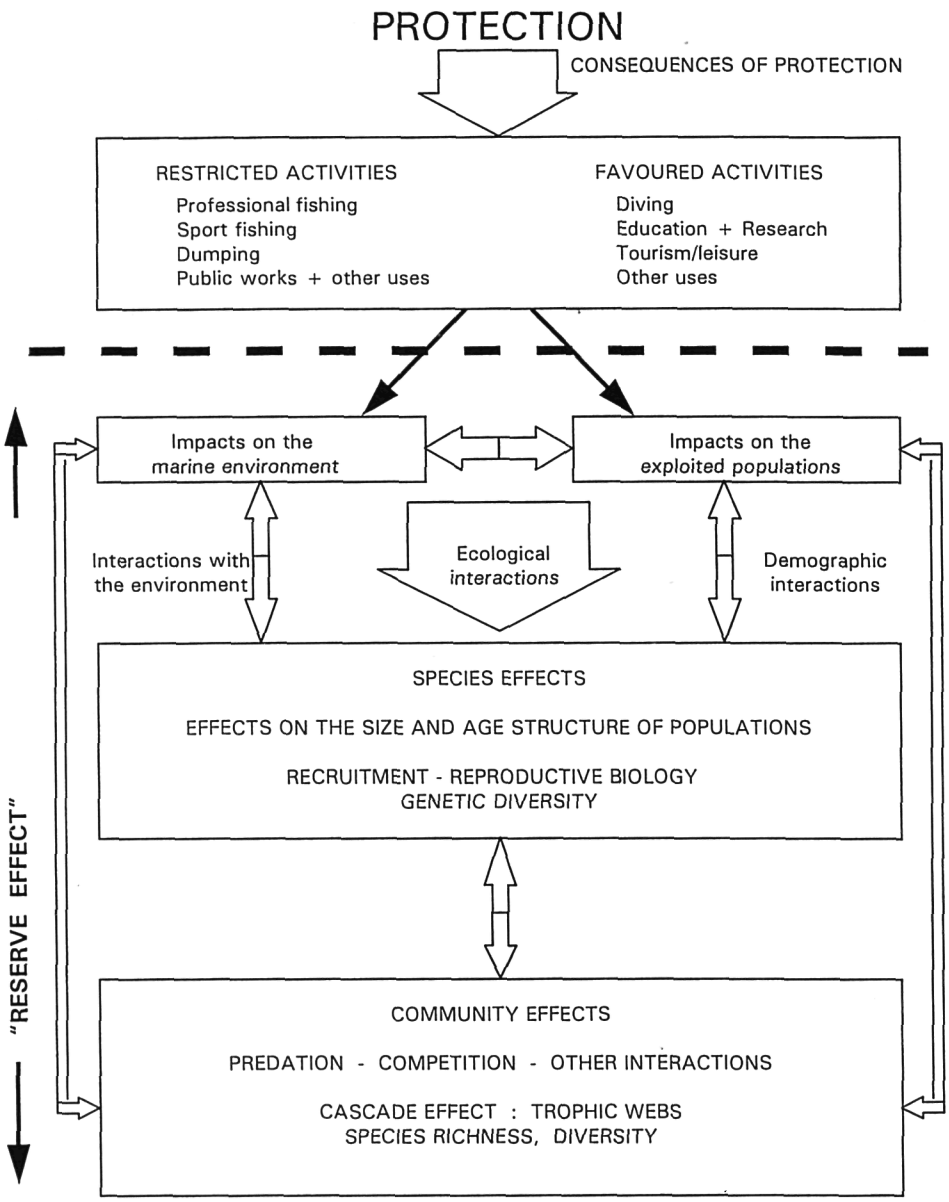


Figure 2 : Diagrame of simple model of the "reserve effect".

The work carried out so far by the various research teams involved in assessing the effects of protection in Mediterranean littoral communities has lacked integration and coordination. In order to move forward in this line of work, there is a need to, first, collate and further analyze what has been done and achieved so far by each team individually, and second, to consider appropriate ways to increase the complexity and realism of future studies of the ecological

TASK STRUTURE OF THE PROJECT

The work of ECOMARE is organized in three tasks:

TASK I. Design of a conceptual model of the reserve effect in Mediterranean littoral ecosystems

TASK II. Critical analysis of available knowledge on variables and processes identified in conceptual model for Mediterranean marine reserves.

SUBTASK IIa: Review available information on variables and processes identified in conceptual model of the reserve effect in the Mediterranean.

SUBTASK IIb: To carry out a critical analysis of available information on the main variables and processes identified in the conceptual model.

SUBTASK IIc: Preparation of publication "*Critical analysis of available knowledge of the effects of marine reserve protection in Mediterranean littoral ecosystems*".

TASK III. Standardization of working methodologies and data management.

SUBTASK IIIa: Examine working methods employed, identify weaknesses and propose improvements for topics identified in TASK II.

SUBTASK IIIb: Discuss, review and agree on recommended methodologies and working practices to be used in future research.

SUBTASK IIIc: Preparation for publication of a booklet on recommended protocols for future research.

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effects of protection. Because assessment of the RE requires carefully designed sampling programmes, most studies rarely fulfil the requirements of rigorous statistical testing (due to lack of true controls, point-zero data or to problems of pseudoreplication, most commonly). Finding solutions to these problems, studying methodologies used elsewhere and agreeing on common working protocols is considered a third important axis of fruitful cooperation between these teams.

OBJECTIVES

The overall aim of ECOMARE is to unite and coordinate the efforts of a broad group of research teams involved in assessing the effects of protection in Mediterranean littoral ecosystems. Within EU waters, Mediterranean reserves are singled out for this study, not only because of their geographical proximity, but also because they share important oceanographic and ecological features.

The specific objectives proposed in this action are:

1. To establish the state of knowledge of the responses of marine communities to protective measures in Mediterranean littoral ecosystems.

2. To identify the main research needs and steps forward to progress from the assessment of effects on exploited populations to the assessment of the RE at the ecosystem level.

3. To standardize the working methodologies and data analysis and management procedures for research in the areas identified in 2 so that in the future, investigations can to be carried out in a coordinated and comparable manner.

APPROACH

To attain the stated objectives, the concerted action will first build a conceptual model of the reserve using as starting point the simple model (Figure 2). The simple model will be upgraded with contributions prepared by the participating teams around thematic components. The conceptual model will provide the reference framework for the second phase of the project. In this phase, the participants will conduct a review of the available information for Mediterranean marine reserves on the relevant themes identified in the conceptual model. This information will be used to carry out a critical analysis of the status of knowledge on the effects of protection in Mediterranean littoral ecosystems. In turn, this analysis will lead to the identification of research priorities and pertinent questions that need to be addressed in the future. In the third phase of the project, the participants will study, recommend and standardize methodologies for survey, monitoring and experimental designs needed to address the set of chosen research priorities and questions. Data quality, exchange and storage in the context of the design of a common data base will also be addressed at this stage.

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I.1.3. Marine biodiversity

TITLE: BIOdiversity and Genetics of Algal Populations (BIOGAP)

CONTRACT NO: MAS3-CT95-0019

COORDINATOR:

Myriam Valero
Laboratoire de Génétique et Evolution des Populations Végétales
URA CNRS 1185, GDR CNRS 1002
Bâtiment SN2, Université de Lille 1
F-59655 VILLENEUVE D'ASCQ CEDEX
FRANCE
tel: Int + 33 20 43 40 24
fax: Int + 33 20 43 69 79
E-mail: Valero@univ-lille1.fr

PARTNERS:

Chris Gliddon
Brambell Building
School of Biological Sciences
University College of NorthWales
BANGOR, GWYNEDD LL57 2UW,
UNITED KINGDOM
tel: Int + 44 1248 382 533
fax: Int + 44 1248 371 644
E-mail: chrisg@bangor.ac.uk

Per Åberg
Department of Marine Botany
University of Göteborg, Box 461
405 30 GÖTEBORG, SWEDEN
tel. Int.+ 46 31 773 27 07
fax Int.+ 46 31 773 27 27
E-mail: per.aberg@marbot.gu.se

Bernard Kloareg
Laboratoire de Biologie Cellulaire et
Moleculaire des Algues Marines
UPR CNRS 4601, GDR CNRS 1002
Station Biologique de Roscoff
29680 ROSCOFF, FRANCE
tel: Int + 33 98 29 23 23
fax: Int + 33 98 29 23 24
E-mail: kloareg@sb-roscoff.fr

Pedro A. Sosa
Departamento de Biologia
Universidad de Las Palmas
Campus Universitario de Tafira
35017 LAS PALMAS
CANARY ISLANDS, SPAIN
tel.: Int + 34 28 45 44 67
fax: Int + 34 28 45 29 22
E-mail: Pedro.Sosa@biologia.ulpgc.es

Jeanine L. Olsen
Department of Marine Biology
Biological Centre, RUG, P.O. Box 14
NL-9750 AA HAREN
THE NETHERLANDS
tel.: Int + 31 50 63 22 52
fax: Int + 31 50 63 52 05
E-mail: olsenjl@biol.rug.nl

BIODIVERSITY AND GENETICS OF ALGAL POPULATIONS

(BIOGAP)

Myriam Valero, Edwin Abeln, Per Åberg, Claire Billot, Nieves Bouza, Hector Cabrera, Christophe Destombe, Carolyn Engel, Oscar Gaggiotti, Chris Gliddon, Luo Hong, Bernard Kloareg, Annelie Lindgren, Monika Morchen, Per Nilsson, Jeanine L. Olsen, Henrik Pavia, Sylvie Rousvoal, Pedro A. Sosa, Wytze T Stam, Gunilla Toth, Rémi Wattier

1. INTRODUCTION

The extent, cause and maintenance of biodiversity are among the most important biological issues of our time (*Diversitas*, Systematics Agenda 2000), yet our knowledge of marine biodiversity remains seriously under-described and is not well understood (BioMar 1995, Grassle 1991, Hedgecock 1994, Lasserre 1992). Culotta (1994), for example, has estimated that less than seven percent of the world's oceans has been sampled. Even if we acknowledge that the coastal zones are far better studied, it remains a fact that most of the knowledge about benthic organisms remains in the discovery-descriptive stage. In this context, the integration of systematics, biogeography, demography and population genetics presents a new challenge for ecologists and evolutionary biologists to elucidate the key factors that affect speciation and extinction of populations (Lande 1988).

Spatial structure of genetic diversity plays an important role in estimating biodiversity below the species level and in examining the interaction of a species with environmental parameters

that structure the ecosystem. Since population structure and genetic divergence are tightly coupled, species with very different life history strategies are expected to speciate in different ways and at different rates (Avise 1994, Brown et al. 1990). Benthic seaweeds offer an important opportunity to investigate the genetic and demographic divergence with respect to the very different life histories strategies that seaweeds have.

The overall objective of BIOGAP is to develop specific testable models for gene flow and demography. The coupling of matrix modelling and gene flow is new and will contribute to both theoretical and empirical models from which meaningful projections about ecosystem stability/resilience and the maintenance of biodiversity can be made. Spatial genetic structure and gene flow will be modelled using data from a suite of single-locus DNA markers, microsatellites developed for each target species. Evolutionary demography will be investigated using a matrix modelling approach that accommodates particular life-history graphs, standard vital rate measurements and microsatellite data. The algal species that have been chosen represent the principal range of seaweed life histories and are of significant ecological importance along the European coastlines. The different partners have expertise in population genetics, demography, molecular biology of algae, evolutionary biology, biogeography, phycology, and modelling and all have played and continue to play pioneering roles in the above areas with respect to marine algae.

2. OBJECTIVES AND ORGANISATION OF BIOGAP

The principal aims of BIOGAP may be summarised as follows:

1) to establish population genetic models for benthic marine macrophytes that do not fit standard textbook models-- in particular for ecologically important seaweeds that exhibit different life history types;

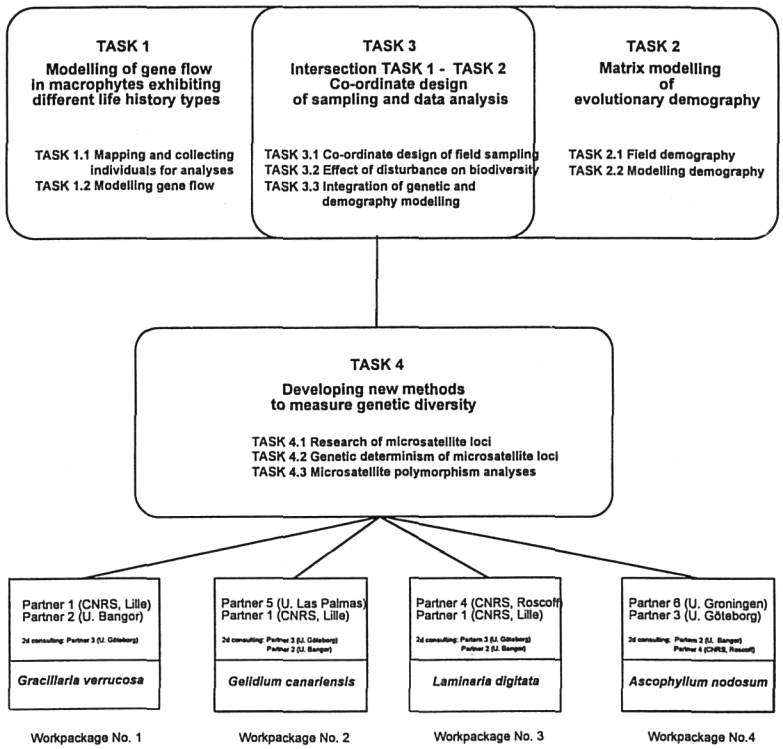
2) to develop an understanding of the role of benthic coastal population dynamics from a genetic perspective;

3) to build more comprehensive models in which genetically diverse populations that behave in ecologically different ways contribute differentially to stability and resilience;

4) to explore genetic diversity in benthic seaweeds in order to examine how different levels of genetic diversity affect or actually drive changes in biodiversity.

The organisation of BIOGAP is schematically represented in Figure 1.

Figure 1. Interrelationships between the tasks and the partners in BIOGAP



3. METHODS

Field sampling

Each target species were sampled according to a hierarchical, stratified sampling (Table 1).

Table 1. Spatial scales used in field sampling.

Description	Distance between entities
Region	>100 km
Location	0.5 -15 km
Site	20 - 500 m
Plot	1- 50 m
Square	0.1 - 2 m

Field sampling was made along the European coastlines along a latitudinal gradient. The field work is focusing (1) on mapping the exact location of individuals (with sex and ploidy level identification) which is being used for spatial genetic analyses and (2) on measuring vital rates (i.e., recruitment from propagules, vegetative regeneration, development through stage-classes, and mortality) which are among the basic parameters of demography.

Molecular analyses

Microsatellite loci are being developed for each target species. Finding microsatellites is involving establishment of a genomic library for each target species, screening that library with oligonucleotide probes corresponding to consensus sequences of known microsatellites, sequencing the candidate clones, testing the new microsatellite locus for polymorphism and finally checking for Mendelian inheritance.

Microsatellite polymorphism is being analysed within and among populations for each species. This is involving DNA isolation for PCR analysis, PCR amplification, and electrophoresis.

Genetic data analyses

Data from microsatellite loci presented in this paper were analysed using unbiased estimators of Wright's F-Statistics (Weir and Cockerham, 1984). The methods of genetic data analysis have been designed and tested for use in haploid and diploid organisms. Computer simulation models are being developed to investigate the consequences of both isomorphic and heteromorphic haplo-diploid life cycles on these methods of analysis, and to validate the models by comparing their predictions with the results obtained from the genetic analysis of each species.

Demography data analyses

Data from regular field sampling of basic vital rates presented in this paper were analysed using a matrix modelling approach (see for review Caswell, 1989) which provides a way to integrate population dynamics and population structure. Algal life histories were modelled and converted to a projection matrix, from which the asymptotic population growth rate λ, the reproductive values for each stage class, the sensitivity and elasticity of λ are being calculated. This approach will allow the estimation of fitness variation in space and time and moreover to give information about where a population is potentially most vulnerable.

Comparison and integration of demography and genetics

The integration of demography and genetics is being achieved using the coalescent approach introduced by Orive (1993) which allows the determination of the effective population size for species with complex life-histories. This approach was extended to include the case of haplo-diploid species inhabiting patchy habitats. The genetic data obtained in the field studies is being used to predict the effective population size and degree of genetic variability for each algal species studied in the project. This approach will allow us to assess how variation in life

history traits and range distribution affects biodiversity at the infra-species level.

4. RESULTS AND DISCUSSION

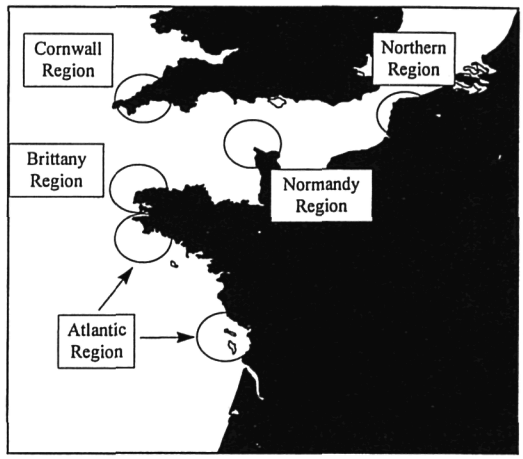
Genetic diversity

The species studied in the BIOGAP program exhibit different life-history and distribution patterns. Red algae such as *G. gracilis* and *G. canariensis* have macroscopic haploid and diploid phases and are patchily distributed while brown algae such as *L. digitata* have a microscopic haploid phase and a macroscopic diploid phase and have a continuous spatial distribution. The results obtained so far for *G. gracilis* and *L. digitata* allowed us to shed some light on the effect of these differences on the genetic structure of marine macroalgae.

Three regions (Northern France, Brittany, and Atlantic) were studied in order to analyse genetic structuring in *G. gracilis* at four microsatellite loci. The sampling design consisted of 8 locations including 13 populations. In *L. digitata*, we studied four regions (Cornwall, Brittany, Normandy and Northern France) using three microsatellite loci. The sampling design consisted of 15 locations including 19 populations (Figure 2).

As expected when working with microsatellite loci, genetic diversity in terms of number of alleles was quite high for both species. In *G. gracilis*, when all loci were considered together, each of the three regions had at least one allele that was specific to that region. In *L. digitata*, on the other hand, with the exception of a single population in Cornwall, all alleles were present in all regions. The high variability was also reflected in the high values observed for the genetic diversity indices (Tables 2 and 3 respectively for *G. gracilis* and *L. digitata*).

Figure.2: Sampling scheme for the genetic analyses in *G. gracilis* and *L. digitata*



However, the variability seemed to be unequally distributed among regions for both species but there was no specific region effect on diversity, since results depended on the species considered. In *G. gracilis*, genetic diversity was lowest in the Brittany populations while the Atlantic populations had the highest diversity. In *L. digitata*, however, genetic diversity was lowest in Cornwall and highest in Brittany.

Table 2. Standard genetic diversity indices and genetic structuring (F_{is}) for each studied population in *Gracilaria gracilis*.

Regions	Locations	Populations	Nb of genes	Hexp.	Hobs.	Mean nb of alleles / locus	Mean F_{is} over 4 loci	P
Northern France	Audresselles	audreselles1	48	0.506	0.464	5.000	0.104	*
	Wimereux	wimereux1	36	0.733	0.428	6.000	0.389	***
		wimereux2	16	0.701	0.492	4.750	0.206	*
	Gris Nez	grisnez1	62	0.717	0.608	7.250	0.175	**
		grisnez2	46	0.747	0.760	7.000	0.009	ns
Brittany	Batz	batz1	42	0.480	0.195	4.250	0.587	***
		batz2	48	0.683	0.556	5.250	0.216	**
	Mazou	mazou	48	0.429	0.416	4.333	0.516 [a]	***
Atlantic	Lodonnec	lodonnec1	36	0.581	0.465	7.333	0.172 [a]	*
		lodonnec2	20	0.557	0.674	3.667	0.056 [a]	ns
	Chaucre	chaucre1	48	0.774	0.572	9.250	0.281	***
		chaucre2	48	0.655	0.564	8.250	0.162	***
	Sable Vignier	sableVignier	62	0.761	0.604	10.000	0.224	***
Mean				0.640	0.523	6.333		

[a]- F_{is} were estimated from 3 locus

Table 3. Standard genetic diversity indices and genetic structuring (F_{is})for each studied population in *Laminaria digitata*

Regions	Locations	Populations	Nb of genes	Hexp	Hobs	Mean nb of alleles / locus	Mean F_{is} over 3 loci	P
Cornwall	Looe	Hannafore B.	104	0.027	0.028	2.000	-0.006	ns
		Plaidy Beach	168	0.252	0.155	4.333	0.394	***
	Veryan Bay	Porthluney Co	166	0.340	0.388	4.000	-0.131	*
		Hemmick B	152	0.369	0.343	4.000	0.078	ns
	Saint Yves	Carbis Bay	38	0.478	0.486	3.000	0.034	ns
	Saint Agnes	Trevellas Port	38	0.228	0.253	3.000	-0.079	ns
Brittany	Sieck	Goldehec	186	0.410	0.464	3.667	-0.114	ns
		Buzoc	184	0.599	0.621	6.333	-0.031	ns
	St Efflam	Porz Mellec	168	0.634	0.617	7.333	0.033	ns
		Beg Douar	156	0.548	0.563	6.000	-0.022	ns
	Enez Eock	Enez Eock	184	0.542	0.511	6.000	0.064	*
	Men Houarn	Men Houarn	178	0.550	0.533	6.000	0.038	ns
	Penmach	P. d'Eckmühl	98	0.472	0.441	4.333	0.075	ns
	Sillon Talber	Sillon Talber	54	0.547	0.452	5.000	0.192	**
Normandy	La Hague	Clos Conin	54	0.574	0.647	4.333	-0.106	ns
	Barfleur	Pte Landemer	62	0.458	0.470	4.333	-0.008	ns
Northern France	Gris Nez	Gris Nez	62	0.417	0.378	3.000	0.099	ns
	Nid de Corbet	Nid de Corbet	192	0.489	0.477	3.000	0.029	ns
	Pointe Creche	Pointe Creche	184	0.389	0.467	2.667	-0.143	ns
Mean				0.438	0.436	4.333		

Genetic structuring within populations

The genetic structure within populations varied significantly among populations for both species (F_{is} values, Table 2 and 3 respectively for *G. gracilis* and *L. digitata*). However, the two species are very different in their within population structure. For *G. gracilis*, most of the populations exhibited deviations from random mating and in all cases they were due to heterozygote deficiency while in *L. digitata* only a few populations showed structuring and most of these were confined to the Cornwall region.

To elucidate the origin of the observed heterozygote deficiencies (spatial sub-structuring or inbreeding), populations with large sample sizes were subdivided into two or more sub-populations. In general, no spatial sub-structuring could be detected suggesting an inbred mating system. However, in one *G. gracilis* population (GrisNez1, Table 2) the significant heterozygote deficiency could be explained by the occurrence of spatial sub-structuring. This

last result suggests that genetic differentiation may occur at a scale lower than 10 metres in this species.

Spatial genetic structuring among populations

Table 4 gives the three F-statistic values obtained accross all populations studied in the two above mentioned species and in *Gelidium canariensis*. Note that despite the fact that different markers were used for the red algae (microsatellites for *Gracilaria* and allozymes for *Gelidium*), the F-statistic values obtained for the two red algae are quite similar. The overall level of genetic structuring (F_{it}) was higher for the two species of red algae species (G.g and G.c) than for the brown algae (L.d.). Moreover, the within population structure (F_{is}) was four times higher in the unevenly distributed species (G.g and G.c) than in the uniformly distributed one (L.d.). F_{st} values were showing higher genetic differentiation among populations in *Laminaria* but this is due to the fact that in this latter case, one of the region (Cornwall) is separated from the others by the privailing current pattern in the English Channel. If the populations of Cornwall are excluded from the analysis, then the F_{st} values drop below the ones observed in the red algae species.

Table 4: F-statistic values obtained across all populations studied in each species

Species	F_{is}	F_{st}	F_{it}	number of loci
Gracilaria gracilis	0.256***	0.136***	0.357***	4
Gelidium canariensis	0.230***	0.130***	0.330***	5[a]
Laminaria digitata	0.061***	0.240***	0.285***	3

[a]: these data were obtained with allozymes

The differences in the pattern of genetic structure among species are in agreement with the differences in dispersal capabilities and the distribution of individuals and populations across the landscape

Demography

For three of the studied species (*Gracilaria gracilis, Gelidium canariensis and Ascophyllum nodosum*) field data on survival, size distribution, recruitment etc. have been gathered, and the variation of these traits compared on several spatial scales. Although the three species are very different in several aspects (e.g., spatial distribution, preferred habitat characteristics, life cycle) they also share some characteristics, e.g., high survival rates and long life span.

For all three species , one of the most challenging tasks is to estimate reproductive success, and here the combination of genetics and demography is essential.

Field demography of *Gelidium canariensis* was studied in two locations in Gran Canaria. The results show that there was a significant difference between the two locations in the size of individuals, but not on smaller spatial scales or between years. The survival rates were similar in the two locations, but there was a significant difference in recruitment. The results also indicate that the population structure is stable in both locations.

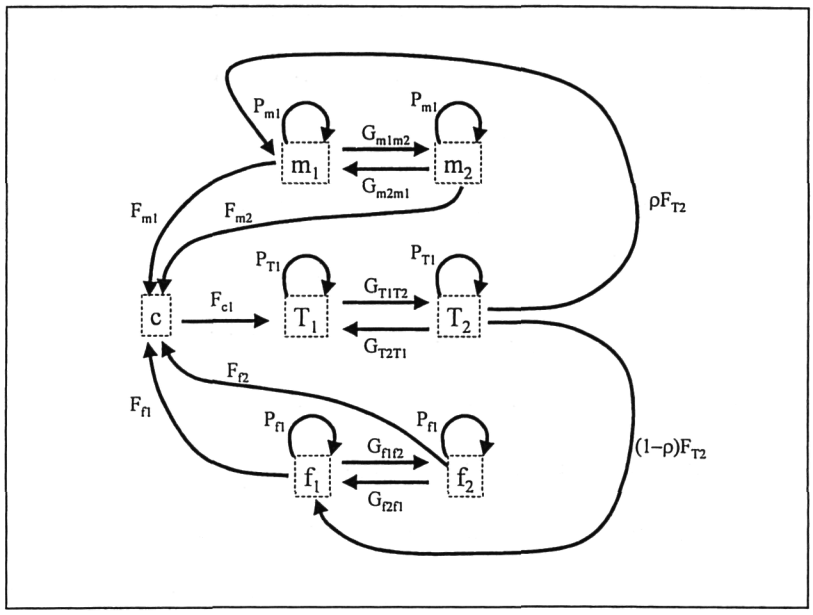
Field demography of *Ascophyllum nodosum* was studied in three regions: Roscoff (France), Isle of Man (UK), and Tjärnö (Sweden). Swedish populations differed significantly from the populations in the other regions in several traits (e.g, number of plants per area, size of individuals). A possible explanation for these differences is the larger environmental variability (spatial and temporal) in Sweden compared to Roscoff and Isle of Man. These patterns will be further analysed both in the field and through stochastic modelling of the demography.

Demographic modelling

In order to model the demography of a complex haplo-diploid life cycle, we adapted the framework proposed by Ang and De Wreede (1990). The model we will use for analyzing the

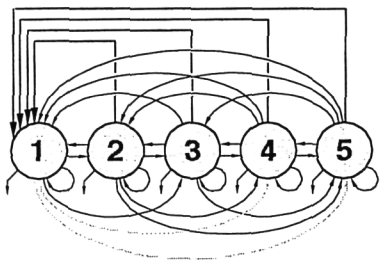
demography of *Gracilaria gracilaria* and *Gelidium canariensis* is shown in Fig. 3.

Figure 3: Life-cycle graph for the demographic model for the haplo diploid model. c = cystocarp, T = tetrasporophyte, f = female gametophyte, m = male gametophyte



For the diploid species *Ascophyllum nodosum*,a matrix model has also been developed, and it's corresponding life cycle graph is shown in Fig 4. Population projection matrices with 5 size classes and a projection interval of one year were constructed for each plot within sites, locations and regions giving a total of 24 survival matrices. Recruits within a plot were assumed to be offspring of individuals within the plot and used to estimate the size-specific fertility. In the calculation of fertility, it was also assumed that fertility was proportional to individual size. Adding the fertility to the survival matrices gave the projection matrices. Common transition probabilities were those for staying in the same class or growth to next larger size class. There was no ice during the winter and thus the survival pattern in Tjärnö was similar to that in the Isle of Man and Roscoff. Mortality was clearly size dependent with highest mortality in class 1 with the smallest individuals. However, mortality figures were in general low and in some plots all individuals survived.

Figure 4: Life-cycle graph for the demographic model for the diploid model. Number 1 to 5 denotes stage classes of increasing individual size.



The asymptotic population growth rate λ showed a significant small scale variation among Sites within Locations and Regions (Table 5). The mean values for Sites ranged from 0.94 to 1.25. The mean values for different Regions were 1.09 in Tjärnö, 0.98 in Isle of Man and 0.99 in Roscoff but they were not significantly different (Table 5).

Table 5. ANOVA of number of juveniles per unit area. The factor Location (Region) was not significant ($p>0.25$) and has been eliminated and pooled.

Effect	*df*	*SS*	*MS*	*F*	*P*
Region	2	8154	4077	1.68	0.240
Site (Region)	9	21849	2427	43.5	0.000001
Residual	12	669	56		

The analyses of the demography of *Ascophyllum* for the first year revealed few differences among regions. However, so far we have only data for one year and it was analysed with deterministic models. During the third year of the project we will obtain field data for a second year, which will increase the statistical power of our tests, and we will then analyse both the spatial and temporal variation in demography. Ongoing manipulative field experiments of effects of changes in density on individual growth and survival will also aid the development of density dependent demography models.

5. PERSPECTIVES

There are two aspects of biodiversity that we aim to model during the next year: (1) biodiversity in terms of establishment, survival and growth of local populations (2) biodiversity in terms of genetic diversity of local populations or sets of populations.

The first aspect (population viability) can be modeled with demographic models where stochasticity is introduced. Stochasticity can be introduced either according to a theoretical model, or by using actual temporal and spatial variability measured from the field. Data for this type of modelling is available, or will be available for three of the four study organisms: *Gracilaria*, *Gelidium* and *Ascophyllum*.

The second aspect (genetic biodiversity) can partly be investigated with the genetic model. An important type of environmental variation is that natural populations become more fragmented leading to decreased genetic exchange among populations. The effects of this can be investigated in the genetic model by changing the elements of the migration matrix. Another type of environmental variation is introduced when conditions such as growth or survival change leading to variations in population size. The genetic model is not presently capable of modelling such variation (nor are we aware of any such model published). If this can be accomplished in 1998 is uncertain. However, input data for this type of genetic modelling is already available for *Gracilaria*, and will be available for *Ascophyllum* and *Gelidium* when the genetic markers have been developed.

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TITLE: BIOMAERL: maerl biodiversity, functional structure and anthropogenic impacts.
(project **BIOMAERL**)

CONTRACT NO.: MAS3-CT95-0020

COORDINATOR: Professor P.G.Moore,
University Marine Biological Station Millport,
Isle of Cumbrae,
Scotland, KA28 0EG, UK
Tel.no (Fax).: +44 1475 530581 (530601)
E-mail: pmoore@udcf.gla.ac.uk

PARTNERS:

Professor. M.Glémarec,
Université de Bretagne Occidentale, Institut Universitaire Européen de la Mer, UMR CNRS 6539 Ecologie benthique Place Copernic, 29280 Plouzane, France. Tel. no.: +33 2 98498677 (8645)

Professor J Mora Bermúdez,
Departamento de Bioloxía Animal, Facultad de Bioloxía, Universidade de Santiago de Compostela, 15706 Santiago de Compostela, Galicia, Spain.
Tel. no. (Fax): +34 81 563100 (596904)

Dr A.A.Ramos Esplá
Ciencias Ambientales (Biologia marina), Universidad de Alicante,
03080 Alicante,
Spain.
Tel. no. (Fax): +34 6 5903668 (3464)

Professor P.J.Schembri,
Department of Biology,
University of Malta, Msida,
Malta.
Tel. no.(Fax):+356 342488 (312110)

MAERL GROUNDS: HABITATS OF HIGH BIODIVERSITY IN EUROPEAN SEAS

By
BIOMAERL team[1]

[1](comprising in alphabetical order: E. Abella[4], C.Barbera[5], J.A.Borg[6], M.Glémarec[3], J.Grall[3], J.Hall-Spencer[2], E.Lanfranco[6], M.Lastra[7], P.G.Moore[2] [Co-ordinator], J.Mora[4], A.A.Ramos-Esplá[3], M.Rizzo[6], A.Sánchez-Mata[4], A.Seva[5], P.J.Schembri[6], C.Valle[5])

[2]University Marine Biological Station Millport, Isle of Cumbrae, Scotland, UK, KA28 0EG
[3]Université de Bretagne Occidentale, UMR CNRS 6539 Ecologie benthique, Institut Universitaire Européen de la Mer, Place Copernic, 29280 Plouzane, France.
[4]Departamento de Bioloxía Animal, Facultad de Bioloxía, Universidade de Santiago de Compostela, 15706 Santiago de Compostela, Galicia, Spain.
[5]Ciencias Ambientales (Biologia marina), Universidad de Alicante, 03080 Alicante, Spain.
[6]Department of Biology, University of Malta, Msida, Malta.
[7]Departamento de Ecologia y Biologia Animal, Facultad de Ciencias, Universidad de Vigo, Apdo.874, 36200 Vigo, Spain.

SUMMARY

The BIOMAERL programme is a 3-year collaborative programme between laboratories in UK, Spain, France and Malta which began in February 1996. Its main aims are described in the Workplan. A full inventory of the biological composition (biodiversity) of maerl bed assemblages in these regions therefore has yet to be completed, but progress is outlined below.

1. INTRODUCTION

Maerl beds are characterized by accumulations of unattached thalli of calcareous rhodophytes. They occur worldwide (Bosence, 1983; Carannante *et al.*, 1988; Steller and Foster, 1995), yet few have been studied ecologically in any detail Many such beds are under immediate threat from human impacts: most notably, in Europe, from
direct exploitation (Cabioch *et al.*, 1997), towed demersal fishing gear (Hall-Spencer, 1995, 1998) and eutrophication effects (Grall and Glémarec, 1997, in press).

The EC-funded BIOMAERL project, linking laboratories in the United Kingdom, France, Spain and Malta, has set out: a) to examine W.European maerl-bed biodiversity, b) to establish the functional roles played by key elements of the biota, c) to assess the impacts of a variety of anthropogenic assaults on representative grounds, and d) to compile an inventory of NE Atlantic and Mediterranean maerl-bed biota.

In many ways maerl beds are analogous to sea-grass beds or kelp forests. All are structurally complex, perennial habitats formed by marine plants that support a high associated biodiversity. Maerl beds especially form isolated, fragile habitats supporting many rare, unusual or endemic species and, as such, they are of particular international conservation interest (Bosence, 1976, 1979; Blunden *et al.*, 1981; Nunn, 1993; Bellan-Santini *et al.*, 1994; Hall-Spencer, 1998). They may also be of significance as nursery grounds for commercial species of fish and shellfish, e.g. scallops (Thouzeau, 1991; G.A.Fisher, unpubl.).

Large maerl thalli are among the oldest marine plants in the N. Atlantic and contribute deposits that take hundreds, perhaps thousands, of years to accumulate, since even optimal growth rates are extremely slow (Potin *et al.*, 1990; Littler *et al.*, 1991). For this reason, management of the exploitation of maerl-forming *Lithothamnion corallioides* (P. & H.Crouan) P. & H.Crouan and *Phymatolithon calcareum* (Pallas) Adey & McKibben is obligatory under the EC Directive on the Conservation of Natural Habitats and Wild Fauna and Flora (1992).

2. WORKPLAN

Pairs of maerl grounds have been identified for study by participants in the Clyde Sea area (Scotland), Galicia (Spain), Brittany (France), Alicante (Spain) and Malta (Fig. 1). pairs of maerl grounds have been identified for study. Each pair represents a ground that has been impacted anthropogenically and a relatively pristine control ground. In Scotland, Alicante and Malta impacts to maerl habitats derive mainly from the use of towed demersal fishing gears. In the Ria de Vigo (Galicia), the major impacts derive from organic matter falling from moored rafts used in the culture of the edible mussel (*Mytilus edulis* L.). Mussel faeces and pseudofaeces from the extensive culture rafts moored above maerl beds rain down onto the maerl surface, altering sediment structure and compromising the ability of maerl thalli to photosynthesize and grow. In the Bay of Brest (Brittany), maerl beds are also affected by high nutrient and sediment loadings due to eutrophication, with nutrient inputs there deriving both from the industrialized estuary and run-off from surrounding agricultural land. Another major way in which European maerl habitats are impacted by Man is through direct extraction. Maerl is valued commercially as a soil conditioner. So, another pair of sites in Brittany (in the Glenan archipelago) are being compared to assess the impact of maerl extraction practices.

Comprehensive samples have been taken not only of the benthic environment of each maerl ground (including bathymetry, macro- and micro-architecture of the maerl surface, granulometry, calcimetry, organic matter content, pH and Eh profile), but also of the water column overlying the BIOMAERL study sites (including measurements of seawater temperature, salinity, Secchi disc transparency, seston content, current speed as well as chlorophyll and photosynthetically active radiation on occasion). Edaphic measurements have been collected seasonally over one to two years.

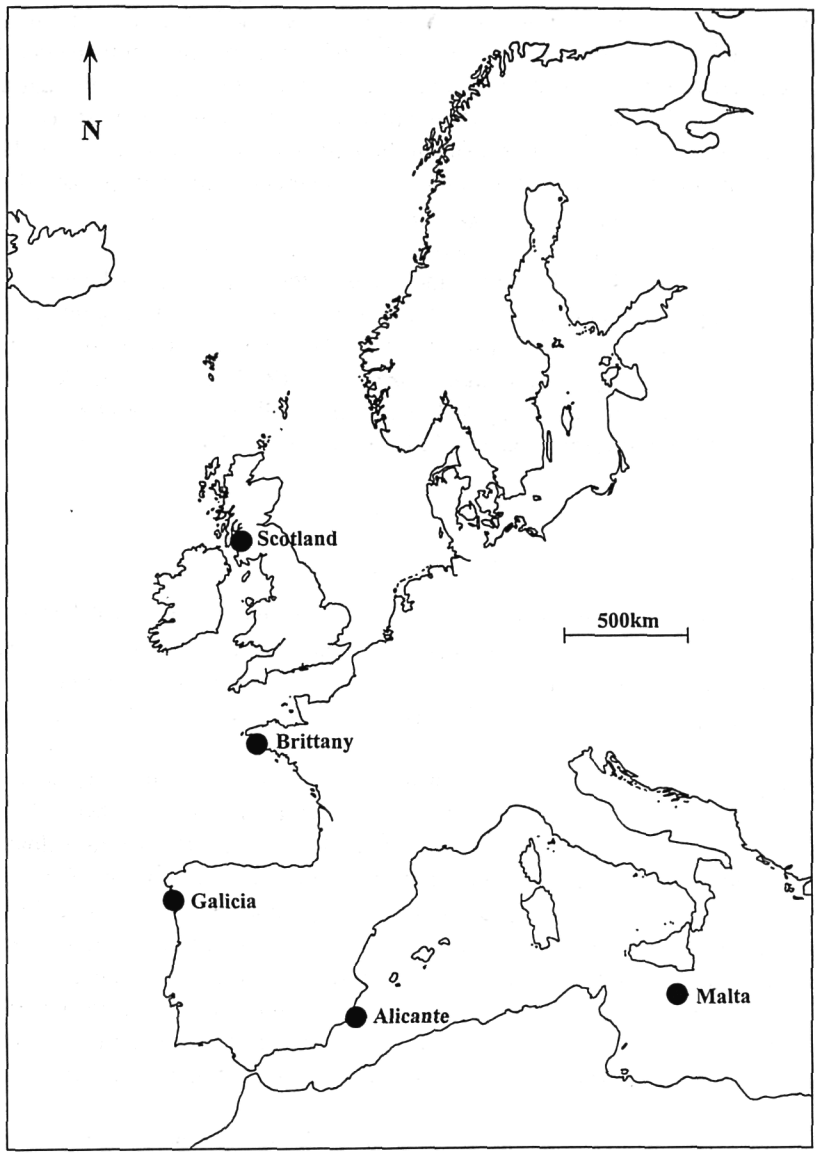


Fig.1. Map of BIOMAERL study sites.

Biological samples of the maerl biota have been taken quantitatively over a two year period, either directly by divers using quadrats and/or cores *in situ*, or by deployment of a variety of indirect sampling gears from ships (grabs, box corers). Megafauna and macrofauna have been compared; infaunal samples being sieved through a 1mm screen as standard. Detailed data on population structure, biomass and population density are being generated for the commonest and/or structurally most important key species from each ground . In addition, semi-quantitative and qualitative faunistic/ floristic data have been gathered using towed dredges and trawls and by direct diver observation. In these ways we are gradually accumulating a comprehensive inventory of the biota at the study sites.

3. RESULTS

1) Sampling

In order to achieve as comprehensive coverage of the biota as possible, it has been necessary: a) to utilize as many methods of sampling as possible; and b) for sampling to take place over all seasons of the year. This was because not every organism present on the ground was captured in any one type of gear, and there were strong seasonal influences at work both in terms of species occurrences (migrations), and/or population fluctuations (both real and apparent). To illustrate this latter point, Fig. 2 shows the seasonal pattern of population densities recorded by divers for a species of infaunal holothurian (*Neopentadactyla mixta* (Ostergren)) from site UKI (Stravanan Bay, Bute, Scotland) .

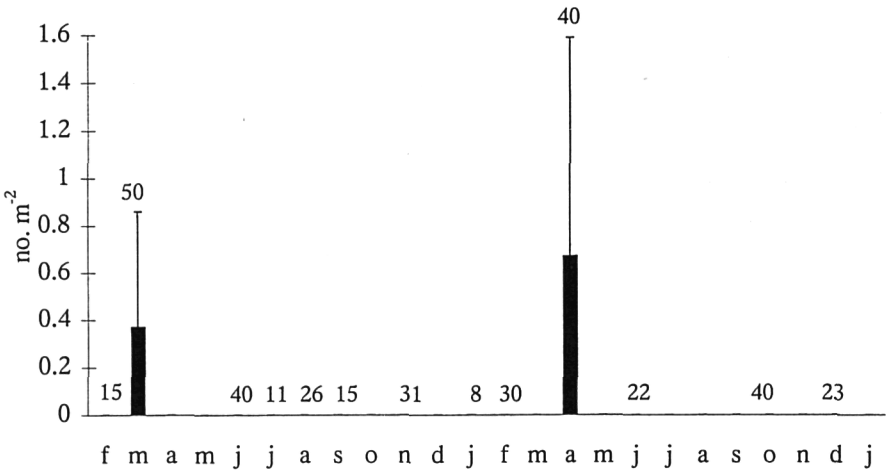


Fig. 2. Mean numbers of the holothurian *Neopentadactyla mixta* counted by divers in replicate $1m^2$ quadrats at UKI from February 1996 - January 1998. Error bars are + one standard deviation, *n* values are indicated above each month sampled.

It would be easy to misinterpret such data as showing this species to be absent for most of the year. Use of an airlift to excavate sediment to a depth of 1m (following methods in Keegan and Könnecker, 1973), however, showed that this sea cucumber was present year-round, but was only seen by divers (by virtue of its feeding crown being extended into the water column) at the time of year that planktonic food was available in abundance, i.e. during the spring phytoplankton bloom. The rest of the time it was invisible to divers, at any rate during the day (no night-time observations available). Contemporaneously with these diving observations, routine Van Veen grab sampling (10 replicates on each sampling occasion) failed to reveal this organism, as it retracts into the sediment beyond the penetration depth of the grab (*ca* 20cm).

So, despite its large size and abundance (>4 m^{-2}), it could easily be overlooked, even by intensive sampling with an inappropriate gear.

It is important for the sampling of rare or highly dispersed biota also that maerl grounds are investigated using towed sampling gears. These gears have therefore been used (*inter alia*), but with care to minimize damage to the ground. Thus in the Bay of Brest, species like the sponge *Tethya aurantium* (Pallas), the cnidarian *Aureliania heterocera* (Thompson), the polychaetes *Hermonia hystrix* (Savigny in Lamarck) and *Psammolyce arenosa* (Chiaje), the decapod crustaceans *Thia scutellata* (Fabricius), *Pirimela denticulata* (Montagu), *Maja squinado* (Herbst), *Pisa armata* (Latreille) (to name but a few) have been captured only using an AQUAREVE dredge. Highly mobile species, like mysid crustaceans and most epibenthic fish are capable of avoiding grab samplers. They have been sampled using towed sledges, dredges and trawls and, in Malta, using bottom-set gillnets.

2) Components of maerl-bed biodiversity

European maerl-bed biodiversity has components on widely different scales. The overarching consideration, in such an Atlantic-Mediterranean comparison as ours, is biogeographical. The BIOMAERL partnership covers the whole temperate province from Galicia to Scotland, and encompasses a latitudinal cline from the western Mediterranean to Malta. A few species, e.g. the sea urchin *Echinocyamus pusillus* (O.F.Müller, the amphipods *Leptocheirus hirsutimanus* (Bate) and the crab *Liocarcinus corrugatus* (Pennant), occurred in all (or nearly all) of the BIOMAERL study sites, but the majority of species have geographical limits between different regions considered. The polychaete *Hesione pantherina* (Risso), for instance, reaches its northern limits of distribution in the Bay of Brest area. Some species are Mediterranean endemics, like the amphipod *Urothoe hesperiae* Conradi, Lòpez-Gonzàlez and Bellan-Santini (our record of which off Alicante represents only the second since its description in 1995), others like the anemone *Bolocera tuediae* (Johnston) are northern species, not occurring in BIOMAERL sites further south than Scotland.

The maerl beds investigated have proved to be remarkably heterogeneous in terms of their sediment composition. Some contain deep unstratified maerl, others are made up of a shallow veneer of maerl over mud, sandy mud or coarse sand. Some grounds have a complete cover of living maerl, some are made up of patches (or strips) of maerl and rhodoliths between shelly sands, while others again may be composed exclusively of dead maerl. Some grounds, notably those from open-water sites, have a megarippled surface that is reorientated periodically by storm activity. Some grounds have the maerl thalli bound together by other organisms (e.g. holdfasts of the kelp *Laminaria saccharina* (L.) Lam., and the nests of the bivalve *Limaria hians* (Gmelin) in Scotland; rhizoids of the chlorophyte *Flabellia petiolata* (Turra) Nizamuddin and the rhodophyte *Polysiphonia setacea* Hollenberg off Malta), stabilizing the surface. The activities of deep-burrowing bioturbatory invertebrates (e.g. *Upogebia, Cerianthus, Chaetopterus*) will also modify the properties of maerl sediments.

An understanding of the role and dynamics of habitat structural complexity and three-dimensional heterogeneity will clearly be central to any explanation of maerl bed biodiversity. The high biodiversity of European maerl grounds can be judged from the fact that, to date, over

460 spp of animals and 63 spp. of algae have been recorded from our most northerly (Scottish) sites.

A functional analysis of the maerl bed biota is currently being undertaken, in which the trophic composition of the biota at all BIOMAERL sites will be related to natural hydrodynamism and, subsequently, to the various anthropogenic impacts described in the Workplan. Fig. 3 shows the seasonal variability in population density of one polychaete species in the Bay of Brest maerl grounds investigated, and reveals significant differences in density between the control and impacted sites. This species would seem to be especially sensitive to eutrophication, its density being considerably reduced on the impacted ground. It is often the case that species at their geographical limits prove to be especially sensitive to environmental perturbation.

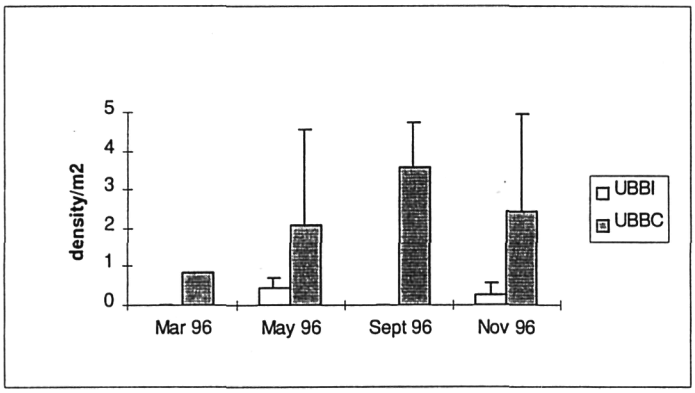


Fig.3. Seasonal variation in the population density of the polychaete *Hesione pantherina* at two sites (UBBI = impacted ground, UBBC = control ground) in the Bay of Brest, Brittany as derived from grab samples. Error bars are +1SD.

DISCUSSION

Maerl beds are unusual benthic habitats, not only because they are derived from living calcareous rhodophytes, but also because they exhibit structural properties that are intermediate between solid and soft sedimentary environments. In some respects (like high permeability, high carbonate content) their structure has resonances with shell-gravel or coral-rubble grounds. In both maerl and shell-gravel habitats, a comparatively open calcareous matrix will facilitate irrigation of interstices (cf. Riedl and Machan, 1972; Webb and Theodor, 1972), promoting a characteristic and diverse infauna. Previous ecological studies on European maerl beds are scant (Cabioch, 1968; Keegan, 1974), most workers have tended to focus on particular elements of the biota, such as the flora (Maggs, 1987) or particular faunal taxa, like the Mollusca (Nunn, 1993; Hall-Spencer, 1998). The present programme is probably unique in attempting to cover such a wide range of sites and inventory the majority of the macrobiota encountered.

Evolutionary and ecological factors determine the origin and maintenance of biodiversity. While the biodiversity of maerl beds cannot compare with tropical calcareous (coral reef)

ecosystems (Reaka-Kudla, 1996), nevertheless, in comparison with other continental shelf habitats in temperate waters, maerl bed biodiversity is impressive. The longevity of maerl thalli, coupled with their complex, open-lattice architecture and need for clean water areas in the euphotic zone with high water exchange rates provides a perennial heterogeneous habitat provide the explanation. Interestingly, that other ecosystem of high biodiversity in European seas, the kelp holdfast, especially that of *Laminaria hyperborea* (Moore, 1973, 1974), is also a long-lived, plant-based habitat in the photic zone. Were data available on the meiofauna of maerl beds (not included in the BIOMAERL programme), then the biodiversity of maerl beds would be even more impressive.

Fortunately, the high fragility and vulnerability of this unique living sediment to human influences (which include direct exploitation for agricultural fertilizer and indirect impacts derived from eutrophication or demersal fishing gear which smashes and erodes maerl beds and increases turbidity) has now been recognized (as witnessed by inclusion of the main maerl-forming algae in the EC Habitats Directive).

Conservation measures need to be established that take cognizance of the role of these grounds: a) as foci for biodiversity (often of specific assemblages of organisms not found elsewhere); and b) as nursery grounds for commercial fish, like juvenile gadoids and shellfish (scallop) species. Maerl grounds are effectively a non-renewable resource, and should be treated as such. The BIOMAERL programme, when complete, will provide the first biogeographical inventory of macrofaunal and floral species in European seas, including identification of key species, their population structure and an analysis of their functional significance in this ecosystem. Assessment of the different anthropogenic threats to this biodiversity experienced over the range of sites considered, will generate recommendations as to the most effective management strategies for this sensitive habitat necessitated by the status of maerl-forming species under the EC Habitats Directive (1992).

We see one way forward as being the establishment of an Environmental Quality Standard for European maerl grounds which is capable of containing, and integrating, all the pertinent structural and functional aspects of the habitat revealed by our studies. Perhaps this might be achievable by allocating a point score to each of the following indicators: edaphic complexity (sediment stratification), basic energy resources (% organic matter, % epifauna / infauna, % macrodetritivores), complex trophic interactions (% predators, % microdetritivores). A summated score would then represent the overall biodiversity status of a particular maerl bed. Such an index would be capable of being monitored over time to provide a check on environmental change, especially any deterioration. It would also supply a mappable, objectively-derived descriptor that, by virtue of being independent of species composition, would be capable of direct comparison at a panEuropean scale. Further funding would be needed, however, to test the validity of these ideas.

ACKNOWLEDGEMENTS

This study was made within the framework of the BIOMAERL project with financial support from the European Commission's Marine Science and Technology Programme (MAST III) under contract MAS3-CT95-0020.

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TITLE: Integrating Environmental and Population Variation: A Model for Biodiversity Studies (project **AMBIOS**)

CONTRACT NO: MAS3-CT95-0042

COORDINATOR:

Dr P. J. Mill
School of Biology
University of Leeds
Leeds, LS2 9JT
UK
Tel.no. (Fax) +44 113 233 2846 (2835)
E-mail: p.j.mill@leeds.ac.uk

PARTNERS:

Prof. T. Backeljau
Department of Invertebrates
Royal Belgian Institute of Natural Sciences
Vautierstraat 29
B-1000 Brussels
Belgium
Tel.no (Fax) +32 2 627 4339 (4141)
E-mail: tbackeljau@kbinirsnb.be

Prof. A. Frias Martins
Universidade dos Açores
Apartado 1422
Rua da Mãe de Deus 58
P-9502 Ponta Delgada
São Miguel
Azores, Portugal
Tel.no (Fax) +351 96 65 3044 (3455)
E-mail: frias@uac.pt

Dr E. Gosling
School of Science
Regional Technical College
Galway
Ireland
Tel.no (Fax) +353 91 75 3161 (1107)
E-mail: egosling@aran.rtc-galway.ie

Dr J. Grahame
School of Biology
University of Leeds
Leeds, LS2 9JT
UK
Tel.no. (Fax) +44 113 233 2852 (2835)
E-mail: j.w.grahame@leeds.ac.uk

INTEGRATING ENVIRONMENTAL AND POPULATION VARIATION: A MODEL FOR BIODIVERSITY STUDIES (AMBIOS)

***P.J. MILL, •T. BACKELJAU, ~A.M. FRIAS MARTINS, °E. GOSLING, *J. GRAHAME, ~C. BRITO, *A. CLARKE, ~R. MEDEIROS, *C. WILDING, °I. WILSON, •B. WINNEPENNINCX, *R. CLARKE, •H. DE WOLF.**

*School of Biology, University of Leeds, Leeds, LS2 9JT, UK, °School of Science, Regional Technical College, Galway, Ireland, •Department of Invertebrates, Royal Belgian Institute of Natural Sciences, Vautierstraat 29, B-1000 Brussels, Belgium, ~Departamento Biologia, Universidade dos Açores, Apartado 1422, Rua da Mãe de Deus 58, P-9502 Ponta Delgada, São Miguel, Azores, Portugal.

SUMMARY

The AMBIOS project started on 1 February 1996 and runs for three years. Its primary aims are to address the problems inherent in defining biodiversity and to develop appropriate operational concepts. To this end a detailed study is being made of biodiversity in a group of littoral snails with contrasting life histories, reproductive modes and degrees of intraspecific pheno- and genotypic variation. Since some of these species appear to be in the process of differentiation and radiation the project also aims at studying the history and dynamics of speciation (phylogeny and phylogeography). Morphometric, molecular, ecological and physiological techniques are being employed. In this context, a wide range of molecular techniques are being assessed for their usefulness in analysing biodiversity.

1. INTRODUCTION

Biodiversity can be defined as "The variability among living organisms from all sources, including *inter alia* terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (Rio, 1992). Considerable effort has been put into the conservation of biodiversity including, at the level of the European Community, the establishment of Special Protection Areas (SPAs) and Special Areas of Conservation (SACs) through the Birds and Habitats Directives respectively. However, we still understand little of what is meant by biodiversity at either the habitat or the organism level. With regard to habitat, either broad zones can be considered or these may be subdivided into ever more precisely defined categories; indeed the EC categorises 168 natural habitat types in need of conservation within the confines of Europe alone. Similarly, at the level of the organism a range of degrees of diversity exist. Almost certainly the level of diversity of the habitat will affect diversity at the organism level. However, it is by no means clear why some environments or groups of organisms should be more biologically diverse than others. From a conservation point of view a number of questions need to be answered. Thus we need to know what diversity exists within a species, how this diversity is generated, maintained or lost, and at what level

this diversity should be conserved. These questions entail a search for Evolutionarily Significant Units (ESUs) (e.g. Moritz, 1994a, b; 1996); but also involve other operational concepts such as what is the minimum population size and what degree of biodiversity is required for evolutionary processes to proceed? It is only by understanding the nature of biodiversity at both the habitat and species level that we can begin to answer such questions.

To generate biodiversity at the organism level it is necessary that genetic polymorphisms are established in populations. Some polymorphisms may be neutral (Kimura, 1983) and hence unrelated to the environment while others may be maintained by selection (Gillespie, 1991) and directly correlated with environmental factors. Some variation may represent environmentally induced phenotypic responses. Variation is inherent in populations and new variation may be protected, and thus contribute to future evolutionary change, by the formation of reproductive barriers; the stronger the barrier the greater the impediment to gene flow between such separated populations.

If we are to understand biodiversity it is important to understand how reproductive barriers are formed and hence how independent genetic entities arise within populations. It is also necessary to understand in what way habitat heterogeneity contributes to providing a framework within which variation is facilitated. The most useful way of achieving such an understanding is by working on a group of organisms which has considerable, recognisable diversity at the intra-species level, which is clearly in the process of interspecific diversification, and which lives in a spatio-temporally variable environment. The periwinkles (Mollusca, Gastropoda: Littorinidae) of the European marine intertidal are such a group of organisms and were therefore chosen as the model for the AMBIOS project. To investigate littorinid diversity, morphometric, molecular, ecological and physiological methods are being applied in an attempt (1) to determine those techniques which maximise our understanding of diversity at different taxonomic levels and (2) to provide a comprehensive, integrated picture of the patterns and dynamics of biodiversity in a variable, yet spatially constrained environment.

2. MATERIALS AND METHODS

Littorinid snails are important grazers, and hence structuring agents, in the rocky intertidal on European shores. About nine Atlantic species are currently recognised. *Littorina striata* and *L. littorea* are species with planktonic eggs and larvae and consequently show considerable gene flow between even very distant populations, so that genetic differentiation is comparatively low. These are in contrast with the group of so-called 'rough' periwinkles, the *L. 'saxatilis'* group, within which between three and, possibly, five species are currently recognised by different authors (e.g. Barnes, 1993; Reid, 1996). *L. arcana* and *L. compressa* are both egg-layers and their specific status is non-contentious. However, *L. saxatilis*, a live-bearer, is extremely variable; indeed it may comprise more than one species as is illustrated by the controversial status of for example *L. neglecta* and *L. tenebrosa*. In any event, there are clearly recognisable forms within this taxon and it occupies a very wide range of habitats from extremely exposed shores to salt marshes and isolated, brackish lagoons.

In order to try and understand the nature of the variation within these species and the interaction with habitat, a wide range of techniques is being employed, and if necessary developed, by the different laboratories in the consortium. These include analysis of shell morphometrics using both traditional measurements and computer-aided image analysis, supplemented by transplantation experiments in the field. Starch and polyacrylamide gel

electrophoresis (SGE and PAGE) are applied to screen allozyme variation, while PAGE and isoelectric focusing (IEF) are used to investigate esterases, radular myoglobins (Mb) and structural proteins (SP). Both techniques are also combined to obtain two-dimensional electrophoretic patterns of Mb and SP. Genetic variation is further assessed at the DNA level by random amplified polymorphic DNA (RAPD), microsatellite markers, single strand conformation polymorphisms (SSCPs), and sequence analysis of calmodulin introns, nuclear rDNAs (18S, 28S, ITS) and mitochondrial DNA genes. At the physiological level thermal tolerance is being studied.

3. RESULTS

GEOGRAPHIC AREA OF THE PROJECT

The core of the work is carried out at a number of key sites in the British Isles (e.g. St. Ann's Head), Ireland (e.g. Aran Islands) and the Azores (e.g. Ilheu de Vila Franca do Campo), but surveys of genetic and morphological variation are extended to all relevant areas, including Macaronesia (Azores, Madeira, Canary Islands, Cape Verde Islands), the Mediterranean, and the whole of the European Atlantic coasts from southern Portugal to the Arctic. Non-European material is sometimes included, where appropriate, to test specific hypotheses or to provide phylogenetic outgroups.

MORPHOMETRIC ANALYSIS OF SHELL CHARACTERISTICS

In addition to broad geographical morphometric surveys of different species, two detailed local studies have been carried out: one on *L. striata* and one on *L. saxatilis*.

Microgeographic and temporal morphological variation have been explored in *L. striata* at Ilheu de Vila Franca do Campo (São Miguel, Azores). This species shows a temporally stable spatial heterogeneity of shell features in relation to wave-exposure and/or thermal regimes. Nodulose shells, which predominate at sheltered sites, remain smaller, have a smaller aperture and weigh less than smooth shells which dominate wave-exposed sites (De Wolf *et al.*, 1997). Furthermore, specimens transplanted from sheltered to wave-exposed sites show a significant increase in aperture size, thereby allowing a large foot surface to provide a better holdfast against wave dislodgement (De Wolf *et al.*, 1997). A recent, devastating hurricane allowed this hypothesis to be tested further. If aperture size indeed provides a better protection against wave dislodgement, then the mean aperture size of a population would be expected to be larger after such a hurricane. Early results indicate that this was indeed the case.

Correlation between morphological and molecular diversity on a local (few m) scale has been investigated in *L. saxatilis* on two shores in south Wales. One of these is a gently sloping muddy shore (The Gann), the other comprises a steep rock slope facing landwards (St Ann's Head). There is congruence between the morphometric and RAPD data, particularly at St Ann's Head. (Mantel test significance of matrix correlation between morphology based Mahalanobis distances and genetic RAPD Prevosti distances is $p=0.0305$). However, genetic variation has no significant correlation with embryo morphology. These results suggest that the pattern of genetic variation covaries with the pattern of morphological variation but that, since this is not the case for pre-emergence embryos, the morphological variation may be a consequence of environmental moulding which happens to mirror the pattern of genetic variation. The pattern of genetic

variation at St Ann's Head also shows a striking pattern in that animals from the lowest shore (*Pelvetia* zone) are more similar to each other than animals higher up the shore.

ENZYME ELECTROPHORESIS

SGE and PAGE were used to investigate 37 enzymes in populations of the rough periwinkle complex (*L. saxatilis, L. arcana, L. compressa* and *L. neglecta*) and in *L. striata* and *L. littorea*. For the *L. saxatilis* complex, 15 enzymes encoded by 19 putative loci (including one esterase locus), were well resolved, 13 of which were polymorphic. Ten loci were well resolved and scorable in *L. striata*, yet only five of these were polymorphic (esterases not included).

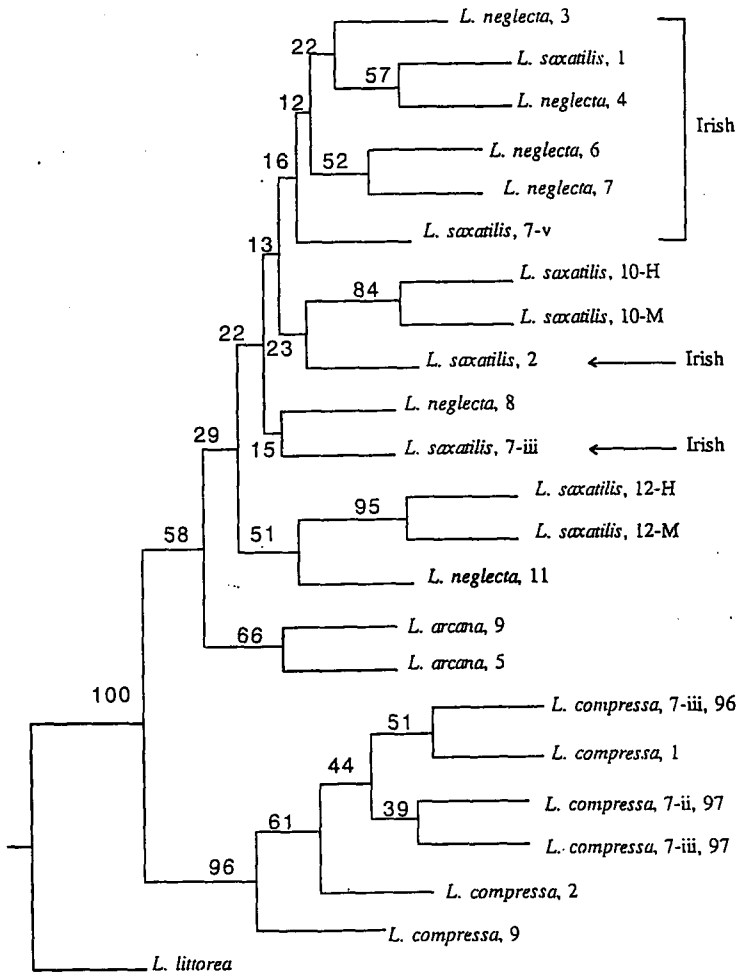


Fig. 3.1 Neighbour-joining tree based on nine loci (excluding AAT-1). Shore stations are given for *L. compressa* to enable comparison between different years. Samples were bootstrapped 100 times, the input order jumbled twice, and the consensus tree globally rearranged and generated from the 100 bootstrapped data set.

In *L. saxatilis*, there was evidence for natural selection shaping the spatial distribution of allele frequencies at one locus (AAT-1) as has been found previously (Johannesson *et al.*, 1995; Wilson & Gosling, 1998a). All other allozyme loci in this species and all loci in *L. striata* revealed no linkage disequilibria and had genotype proportions in agreement with Hardy-Weinberg equilibrium expectations.

High levels of genetic variability were shown by *L. arcana*, *L. neglecta* and, in particular, *L. saxatilis*, whereas *L. compressa* had greatly reduced levels. Neighbour-joining showed that *L. compressa* clustered separately from *L. saxatilis* and *L. arcana*. *L. neglecta* populations also formed a monophyletic group, but this broke down after AAT-1 was removed from the analysis, and *L. saxatilis* and *L. neglecta* samples clustered mostly by region (Fig. 3.1) (Wilson & Gosling, 1998b). No species-specific alleles were found at high enough frequencies to separate all species of rough periwinkle. However, *L. compressa* was identified by the high frequencies of some alleles which were rare in the other species. It seems as if *L. neglecta* and *L. saxatilis* may not have diverged sufficiently to be distinguished from each other by allozyme markers. Preliminary analysis suggests that *L. tenebrosa* is genetically differentiated from *L. saxatilis*, despite the ample opportunity for gene flow between the two taxa at the locality studied on the west coast of Ireland (Gosling *et al.*, 1998).

In contrast, PAGE surveys of polymorphic enzyme loci in *L. striata* at micro- and macrogeographic scales suggest that, despite the conspicuous morphological heterogeneity of this species, there is little allozyme differentiation. Consequently gene flow estimates (based on F_{ST}) are very high (Nm>10). There are no indications of significant genetic differentiation between morphotypes (nodulose vs. smooth) or different wave-exposure regimes (De Wolf *et al.*, 1998a). Nevertheless, the macrogeographic analysis covering the whole distributional range of *L. striata* suggests that the Cape Verde and Azores populations display, respectively, eight and two unique alleles that are not present elsewhere. These observations are indicative of some degree of macrogeographic differentiation between the Cape Verde Islands and the other Macaronesian archipelagos. However, there is no clear evidence for an isolation by distance model, since there was no significant correlation between geographic and genetic distances between populations (Mantel test). This may be the result of historical factors and the pattern of sea currents. Interestingly, there is a significant negative correlation between the mean number of alleles per locus and increasing latitude (northern islands show less allelic diversity).

IEF of esterases in *L. striata* confirmed the PAGE results (De Wolf *et al.*, 1998b). Thus *L. striata* shows a high degree of genetic homogeneity, even among very distant populations, and the morphological patterning in this species persists in the presence of considerable gene flow.

TWO-DIMENSIONAL ELECTROPHORESIS OF PROTEINS

The power of this technique is being investigated and a protocol has been established for the two-dimensional electrophoresis of proteins. In order to evaluate the resolving power of the 2D electrophoresis, Mb/SP of *L. striata* have been analyzed with PAGE, IEF and 2D electrophoresis. Both PAGE and IEF show nearly no variation, while 2D gels yield highly complex patterns with more than 40 well resolved spots, representing several polymorphisms. However, a number of technical and practical caveats limit the wide application of this technique.

SCREENING RADULAR MYOGLOBIN POLYMORPHISMS

With native PAGE, *L. striata* showed a Mb pattern that is indistinguishable from the corresponding profiles of *Littoraria* spp., *Nodilittorina* spp. and *Melarhaphe neritoides*. Similarly *L. littorea*, *L. saxatilis* and *L. compressa* shared a similar profile, as did *L. obtusata* and *L. fabalis*. *L. arcana*, however, revealed a quite different Mb profile, although subsequent surveys showed that this different Mb profile also occurs in *L. saxatilis*. Using IEF at pH 4-6.5, species differentiation became more obvious. Once again *L. striata*, *Littoraria* spp. and *Nodilittorina* spp. shared an identical Mb profile, yet *M. neritoides* was now clearly differentiated. For the other species, the IEF and PAGE patterns were largely congruent. *L. saxatilis* from Norway and Spain yielded exactly the same Mb patterns and the species was only weakly polymorphic. In contrast, *L. littorea* showed a considerable degree of intraspecific variation, particularly in France where a high number of 'unusual' Mb profiles was found, suggesting some degree of genetic differentiation (Medeiros *et al.*, 1998). However, the population genetic analysis of these patterns was difficult, if not impossible, because there is no unequivocal genetic framework in which the Mb profiles can be interpreted (e.g. how many loci are involved? What is the quaternary structure of littorinid Mb?) (Olabarria *et al.*, 1998).

The Mb profiles of the Atlantic *Littorina* species were further compared with those of *L. scutulata*, *L. plena* and *L. keenae*, three species from the Pacific coasts of North America which are supposed to be close relatives of *L. striata*. The IEF comparison showed that *L. keenae* has a unique Mb profile (though reminiscent of that of *L. striata*), while *L. scutulata* and *L. plena* have Mb profiles that are similar to that of *L. saxatilis* and *L. littorea*. These observations are highly congruent with current phylogenetic data on these animals.

SCREENING DNA POLYMORPHISMS

Random Amplified Polymorphic DNA (RAPD)

RAPD data of *L. striata* were interpreted assuming that each RAPD band represents a di-allelic locus in Hardy-Weinberg equilibrium. Two primers yielded six polymorphic and consistently scorable RAPD bands of 220 bp to 1640 bp. None of these bands discriminated between smooth and nodulose *L. striata*. In general, the RAPD data for this species were highly congruent with the corresponding allozyme data, even to the point that RAPD heterozygosity estimates (0.244-0.306) and *Fst* values (0.002-0.076) were numerically very similar to the equivalent values obtained from the allozymes (De Wolf *et al.*, 1998c). Hence gene flow estimates calculated from *Fst* values were also very high and indicated limited or no macrogeographic differentiation. However, there was a tendency for a north-south pattern in heterozygosity estimates since the lowest values were found in the Azores (north), while the highest values were observed in the Cape Verde Islands (south). The same tendency was noted for allozyme data and non-specific esterases.

A preliminary RAPD analysis revealed a band that distinguished between two forms of *L. saxatilis*, 'H' and 'M', which show a partial reproductive barrier (Grahame *et al.*, 1997; Wilding *et al.*, 1998). Subsequent cloning and sequencing of this RAPD band showed that at least seven different sequences are involved. Clone 1 exhibited a GTT repeat motif and primers have been designed to amplify this repeat region. There is evidence that, when these primers are applied to *L. saxatilis* H and M, a larger fragment is occurring solely in (5-25% of) the H animals and never in M specimens (Fig. 3.2). Band stabbing and direct sequencing of other bands has also

confirmed their identity as alleles of the targeted region. Although it seems unlikely that we will have a marker for H and M, the frequency of the repeat may be useful for examining reproductive isolation.

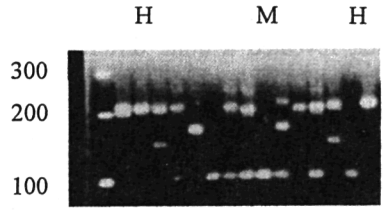
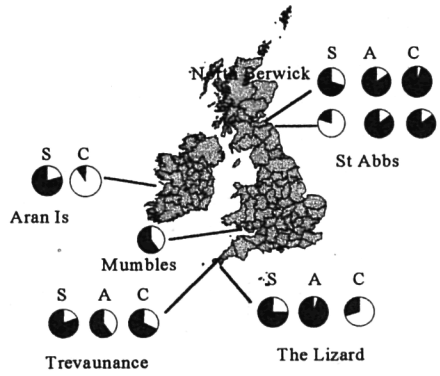


Fig. 3.2 Variation seen in the size of the GTT repeat motifs between *L. saxatilis* H and M forms.

Calmodulin Intron Sequences

Calmodulin introns (non-coding, presumably selectively neutral sequences between coding stretches of DNA) have been amplified using universal primers, cloned and sequenced. Two loci (separate introns - CAD1 and CAD2) have been identified, suggestive that calmodulin is not single copy in *Littorina*, and primers have been designed for these. The calmodulin introns seem to be present throughout the genus *Littorina* and it is possible that *L. littorea* and *L. aleutica* possess a third intron. Sequence information for both introns has been gathered for a number of species but it appears to have limited usefulness for separating species in the *L. saxatilis* complex. The frequencies of the two alleles in CAD1 in *L. saxatilis*, *L. arcana* and *L. compressa* differ on a macrogeographic scale, but on a given shore they do tend to separate populations of these species (Fig. 3.3).



S, *L. saxatilis*; A, *L. arcana*; C, *L. compressa*

Fig. 3.3 Allele frequency patterns of the calmodulin intron CAD1 in *L. saxatilis* at various locations in Britain and Ireland.

Mitochondrial DNA

Mitochondrial DNA sequencing is concentrating on cytochrome *b* (Cyt *b*) and cytochrome oxidase I (COI). In order to design COI primers, fragments of *L. saxatilis* mitochondrial DNA have been cloned and over 8kb of cloned material have been sequenced. The resulting gene

order (Fig. 3.4) differs from both that of the polyplacophoran *Katharina* (Boore & Brown, 1994) and that of the pulmonate gastropods (Yamazaki *et al.*, 1997).

From the samples analysed so far it is evident that the two datasets are reasonably congruent but that neither has enough fixed variation to adequately separate species with high support. Part of the mtDNA COI region has been amplified for samples from a range of sites in the UK. Variation in this region has been shown to be considerable and there are a number of haplotypes. However, paraphyly is exhibited, with some *L. compressa* sequences clustering with *L. arcana*, and *L. arcana* with *L. saxatilis*. The haplotype of the last species separates into two groups. Athough the groups do not appear to pertain to specific geographic regions or morphotypes, one of them does seem to be more common in south east England.

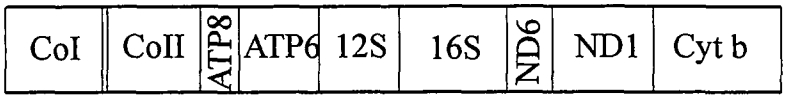


Fig. 3.4 The gene order of the mtDNA sequenced.

Nuclear rDNA sequences

Complete 18S rDNA sequences of *Littorina littorea*, *L. obtusata*, *L. saxatilis* (s.s.), *L. compressa*, *L. striata*, *Nodilittorina punctata*, *Littoraria undulata* and *Melarhaphe neritoides* were determined, as well as of the 'mesogastropod' prosobranchs *Pomatias elegans* and *Bursa rana* (both serving as outgroups). Sequence lengths varied between 1823 bp in *L. obtusata* and 1831 bp in *L. striata*. The secondary structure of the corresponding 18S rRNA molecules were inferred to improve sequence alignment and to assess possible structural elements of phylogenetic relevance.

Initial Neighbor-Joining (NJ) trees of Jukes-Cantor distances revealed, with *B. rana* as outgroup (and excluding *P. elegans*), two clades: (1) (*L. littorea* (*L. obtusata* (*L. saxatilis*, *L. compressa*))) with all branches supported by bootstrap values of 95-100%, and (2) (*L. striata* (*Littoraria undulata* (*Nodilitorina punctata* [Atlantic], *Nodilittorina punctata* [Mediterranean]))). Maximum parsimony (MP) with successive weighting and Maximum likelihood (ML) analyses supported the NJ results, but in addition provided strong bootstrap support for the placement of *L. striata* at the base of the *Littorina* clade (Fig. 3.5). The sequence divergence between Mediterranean and Atlantic *Nodilittorina punctata* was of the same magnitude as that between *L. saxatilis* and *L. compressa*, thus suggesting either a taxonomic differentiation or a geographic divergence between the Atlantic and the Mediterranean populations as is observed in a number of other marine organisms.

Clearly, the 18S rDNA sequences successfully resolved the littorinid divergences included here, even among very closely related species (e.g. *Neritrema* spp. or *Nodilittorina punctata*). Compared to previous molecular analyses, the 18S rDNA data performed in this respect as well as mitochondrial Cyt *b*, and even better than mitochondrial 12S and 16S rDNA sequences. However, with respect to the basal radiation between *Littorina*, *Nodilittorina* and *Littoraria*, the 18S rDNA results were less stable. These findings suggest that, contrary to current ideas, 18S rDNA sequences may be well suited to resolve rapid radiations that took place relatively recently and in certainly less than 40 myr. Indeed, the older radiations studied here are close to 40 myr and it is precisely these cladogenetic events that are less well resolved. This is perhaps not surprising

since, during rapid radiations, only fast evolving sites will accumulate substitutions that mark the branching order. If such radiations occurred recently, this information will still be present in the molecule. However, if a long period has elapsed since the splitting, these fast evolving sites will proceed with accumulating mutations, and these new substitutions will eventually obliterate the original ones that marked the cladogenetic event.

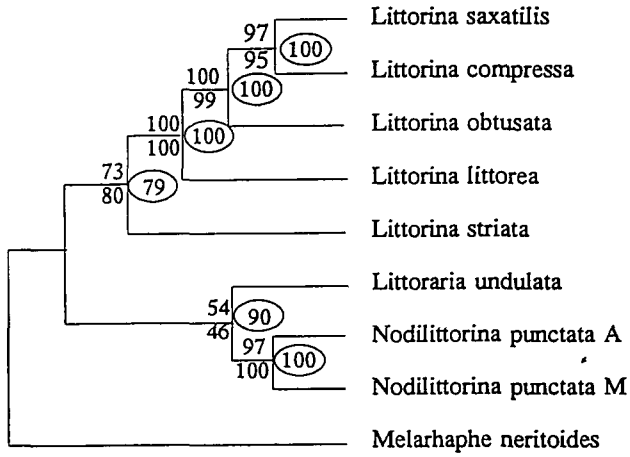


Fig. 3.5 MP and ML tree of littorinid relationships based on 18S rDNA sequences. Values at the branching points are bootstrap or support values for ML with FastDNAML (below), for ML with the PUZZLE algorithm (encircled) and for MP (above). A, Atlantic; M, Meditteranean.

The 18S rDNA data are further being supplemented by a parallel sequence analysis of a less conservative 750-800 bp stretch of the 28S rDNA gene. Preliminary phylogenetic analyses suggest that the 28S and 18S rDNA data yield highly congruent results.

SINGLE STRAND CONFORMATION POLYMORPHISMS (SSCPs)

In close collaboration with the University of Guelph (Canada), a SSCP protocol has been developed for a mitochondrial Cyt *b* stretch. Four fragments have been isolated; their sizes in bases are: i, 276; ii, 254; iii, 212; iv, 225. An example of variation in fragment i i . Data have been obtained for *L. saxatilis*, *L. arcana*, *L. neglecta*, *L. tenebrosa* and *L. compressa*.

Twenty one SSCP products (combining fragments i and ii) have been sequenced. From the most parsimonious tree using the DNAPARS program in PHYLIP, *L. littorea* and *L. arcana* cluster separately from each other and from a single cluster comprising samples of *L. neglecta*, *L. saxatilis*, *L. tenebrosa* and *L. compressa*.

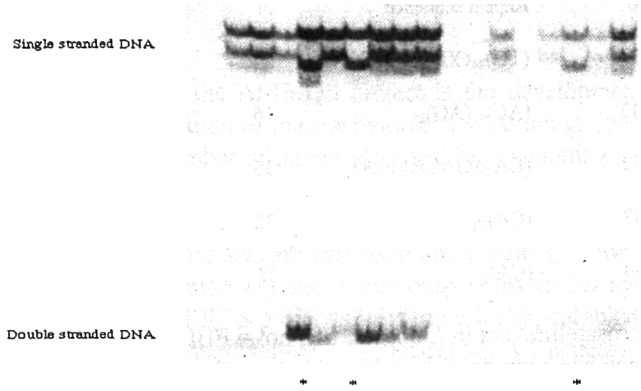


Fig. 3.6. Photograph of single stranded DNA conformational polymorphism (SSCP). Variant haplotypes in the mtDNA cytochrome *b* gene are asterisked.

MICROSATELLITE MARKERS

A protocol has been developed to screen *L. striata* for the presence of possible repeat motifs. 38 repeat sequences appeared to be good microsatellite candidates and were retained for primer development. Primer sets have been developed for 10 of these repeat sequences and PCR-amplification conditions have been optimized for six of them. The relative performance of different *Taq* polymerases and two different radioactive labelling methods (^{35}S versus ^{32}P) was tested. This showed the ^{32}P labelling produced fewer artificial bands and is thus to be preferred (Winnepenninckx & Backeljau, 1998).

A first analysis of the six microsatellite loci in *L. striata* from the Azores and the Cape Verde Islands showed that one locus produced fragments of less than 70 bp, making it very difficult to interpret gels. Therefore this locus was not further considered. The five other loci (Table 3.1) were remarkably polymorphic with a minimum average number of alleles per locus of 19.2. (Winnepenninckx & Backeljau, 1998). However, this figure must be an underestimation of the real numbers of alleles, because the sample size of specimens screened are still too limited and the geographic population sampling is certainly not comprehensive enough. For all loci, except 2.3, there were considerable discrepancies between observed and expected heterozygosity levels (homozygote excess), which are probably due to the prevalence of null alleles.

The five microsatellite loci were also tested for cross-species amplification in *L. obtusata*, *L. saxatilis*, *L. arcana* and *Nodilittorina punctata*. Unfortunately, no positive results were obtained. This means that the current primers seem highly specific for *L. striata*.

Locus	EBI no.	Repeat sequence	N	NA
1.4	Y14839	$(TG)_{24}CG(TG)_2CG(TG)_{13}$	24	19
1.131	Y14840	$(AC)_{19}(AG)_{25}$	16	15
1.151	Y14842	$(CA)_3(GACA)_4(CA)_{21}$	35	27
1.152	Y14843	$(CA)_{22}$	32	17
2.3	Y14844	$(CA)_{25}$	16	18

Table 3.1. Analysis of five microsatellite loci in *L. striata*. EBI no. = EBI accession number under which the repeat sequence has been deposited; N = number of specimens screened; NA = minimum number of alleles observed.

THERMAL TOLERANCE STUDIES

The upper thermal tolerance, using heat coma measurements, of selected littorinid populations have been measured to provide a phenotypic estimate of biodiversity at a physiological level. All species examined form a very characteristic distribution over a relatively small temperature range (usually around 6°C) and all of the species of rough littorinid examined have heat coma temperatures of around 30°C. Thermal tolerance does not change with shore height. Thus, *L. obtusata*, which occupies the lower regions of the shore possesses similar thermal tolerances to those at the top of the shore (*L. arcana* and *L. saxatilis* "H") (Table 3.2).

Heat coma has been shown to be a very "plastic" phenomenon. Values vary on a geographical scale, with littorinids on the west coast of the U.K. generally showing significantly higher heat coma temperatures compared to those on the east coast (Table 3.2).

	South Wales		**Northeast England**	
Species	**Mean HCT (°C) ± s.e.**	**N**	**Mean HCT (°C) ± s.e.**	**N**
L. saxatilis "H"	31.64 ± 0.34	27	31.96 ± 0.36	28
L. saxatilis "M"	33.00 ± 0.31	30	31.97 ± 0.20	29
L. arcana	33.13 ± 0.18	91	32.70 ± 0.44	28
L. compressa	34.16 ± 0.43	30	does not occur	-
L. littorea	33.43 ± 0.33	21	31.48 ± 0.30	31
L. obtusata	35.93 ± 0.57	21	32.06 ± 0.68	30

Table 3.2 Heat coma temperatures in littorinids of the subgenus, *Neritrema*.

Values have also been shown to vary on a very local scale where extremes in environment occur, and with season. The effect of duration of acclimation in the laboratory has been studied in *L. arcana*, *L. saxatilis* and *L. littorea*, and appears to have no effect on heat coma temperature.

4. DISCUSSION

The primary aim of the AMBIOS project is the development of operational concepts in the analysis and conservation of marine biodiversity. Although most AMBIOS subprograms are still in full progress, a number of interesting points are beginning to emerge as the different data sets are integrated.

Classical morphometric data are very useful in describing some aspects of shell shape but may be less effective in assessing detailed shape components. In this respect the image analysis approach developed in the AMBIOS project seems to be highly complementary. Of the methods used for screening molecular biodiversity, 2D electrophoresis appears to be a less efficient technique, despite providing a considerably higher resolution than PAGE or IEF. Indeed, the large scale application of 2D electrophoresis is very time consuming because the method does not allow the screening of many individuals simultaneously. Moreover, it appears that, from the population genetic point of view, there remain problems in scoring and interpreting polymorphisms. Similarly, littorinid Mb profiles are not unambiguously interpretable as Mendelian traits and their genetic interpretation therefore remains highly speculative. Nevertheless, littorinid Mb may be useful for phenetic analyses of variation, as well as for taxonomic and phylogenetic purposes. In this context it is evident that IEF provides a higher resolution than PAGE, since this latter method does not resolve a number of hidden variants that are uncovered by IEF. Similarly, the calmodulin intron may provide useful information for producing a littorinid phylogeny but not for separating the variation within *L. saxatilis*. In contrast, classical allozyme electrophoresis and RAPD yielded highly congruent population genetic results and are allowing large scale surveys of many individuals. However, the information yield per locus is higher with allozymes than with RAPD. The microsatellite analyses are highly successful in detecting variation, but require intensive laboratory work and still present a number of technical and interpretative problems (e.g. null-alleles). Finally, it appears that combining SSCP with sequencing may be a very promising approach for population genetic analysis because it combines both 'classical' genotyping and allele frequency determination with sequence information on the alleles involved.

For the development of operational concepts, the AMBIOS data clearly demonstrate that studying and conserving biodiversity requires a multidisciplinary approach that must be applied at different spatial scales. The genetic differentiation between the H and M forms in *L. saxatilis*, shows that even very small distances must be considered, at least in species with non-planktonic development. This point is further supported by *L. neglecta* and *L. tenebrosa*, two *L. saxatilis* like forms whose taxonomic status is still debated. On the other hand, our molecular data for the planktonic developing *L. striata* suggest some degree of macrogeographic differentiation (scale of thousands of km). In contrast to the molecular data, morphological and physiological diversity is a result of genetic and phenotypic components in both the planktonic and non-planktonic species. This is well-illustrated by the heat tolerance work and the transplantation experiments. Thus, it is obvious that classical taxonomic 'species' boundaries only describe a limited part of biodiversity, so that conservation efforts which are restricted to this level of differentiation may provoke an important loss of evolutionary relevant variation present at the intraspecific level. This problem can be circumvented by applying the 'Evolutionarily Significant Unit' (ESU) and the somewhat less comprehensive 'Management Unit' (MU) concepts (see Moritz, 1994a, b, 1996). These concepts can, for example, be applied to the macrogeographic differentiation in *L. striata* (Cape Verde Islands versus the other Macaronesian islands) or to some of the microgeographic genetically differentiated forms of *L. saxatilis*. The use of the ESU and MU concepts has, furthermore, the advantage that even if the taxonomic status of certain populations

or forms (e.g. *L. tenebrosa* and *L. neglecta*) is still debated or confused, these populations can nevertheless be considered for conservation issues. This may also apply to the suggested Atlantic-Mediterranean differentiation in *Nodilittorina punctata*. Finally, this approach will be less subject to the confounding effects of phenotypic variation than the classical taxonomic inferences. These latter have indeed produced a large number of putative species (particularly in the *L. saxatilis* group), which subsequently appear to be nothing but phenotypes of the very same gene pool. A case in point are the nodulose and smooth forms of *L. striata*.

As an extension of the ESU and MU concepts, the AMBIOS project is also endeavouring to identify 'Evolutionarily Significant Areas' (ESAs) (e.g. Moritz, 1996), by focusing on particular habitats, or on isolated and peripheral populations. Examples are a number of unique lagoons where *L. tenebrosa* occurs parapatrically with *L. saxatilis*, the Cape Verde Islands where *L. striata* reaches its highest degree of diversity and the *L. saxatilis* population in São Miguel (Azores), which is truly peripheral and isolated compared to other *L. saxatilis* populations. The application of the ESA concept provides direct guidelines for conservation actions and represents therefore a potentially very useful and practical tool for protecting biodiversity.

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TITLE: MIcrobial Diversity in Aquatic Ecosystems (**MIDAS**)

CONTRACT NO: MAS3-CT97-0154

COORDINATOR:

Dr. Carlos Pedrós-Alió
Institut de Ciències del Mar, CSIC
Passeig Joan de Borbó s/n
E-08039 Barcelona, Spain
Tel.: +343 221-6416, fax: +343 221-7340
E-mail: cpedros@icm.csic.es

PARTNERS:

Ian Joint
Plymouth Marine Laboratory
Prospect Place, The Hoe
Plymouth PL1 3DH, United Kingdom.
Tel +44 1752-66-3476
Fax +44 1752-66-3101
E-mail i.joint@pml.ac.uk

Bo Riemann
National Environmental Research
Institute, P.O.Box 358
Frederiksborgvej 399, P.O.Box 358
DK-4000, Roskilde, Denmark.
Tel +45 46-301-200
Fax +45 46-301-114
E-mail hmbri@wpgate.dmu.dk
BRi@dmu.dk

Francisco Rodríguez-Valera
Universidad Miguel Hernández,
Campus de San Juan, Apdo. 374
E-03080 Alicante, Spain
Tel +34 96-591-9451
Fax +34 96-591-9457
E-mail frvalera@aitana.cpd.ua.es

Frede Thingstad
University of Bergen
Jahnebakken 5
N-5020 Bergen, Norway.
Tel +47 55-212-662
Fax +47 55-323-962
E-mail Frede.Thingstad@im.uib.no

Kim Gustavson
Water Quality Institute
Agern Allé 11
2970 Hørsholm, Denmark
Tel +45 42-865-211
Fax +45 42-867-273
E-mail kig@vki.dk

MICROBIAL DIVERSITY IN AQUATIC ECOSYSTEMS MIDAS

CARLOS PEDRÓS-ALIÓ[1], IAN JOINT[2], BO RIEMANN[3], FRANCISCO RODRÍGUEZ-VALERA[5], FREDE THINGSTAD[5], KIM GUSTAVSON[6]

[1]Institut de Ciències del Mar, CSIC, Barcelona, Spain; [2]Plymouth Marine Laboratory, Plymouth, United Kingdom; [3]National Environmental Research Institute, Roskilde, Denmark; [4]Universidad Miguel Hernández, Alicante, Spain; [5]University of Bergen, Norway; [6]Water Quality Institute, Hørsholm, Denmark

1. INTRODUCTION

The disappearance of species from our planet is perceived as a menace for our future and as a loss of genetic resources for potential useful applications. This loss of diversity is most dramatic and obvious in the case of tropical rain forests. Spectacular epiphytes, colorful birds and bizarre insects are disappearing at alarming rates through human action. Thus, an increasing amount of resources is being put into the study of biodiversity. Several international organizations have sponsored workshops to analyze the problem of shrinking biodiversity and to propose solutions. The European Union has recognized the importance of diversity studies in the Supplement to the MAST-III work programme and Corrigendum document (April 15, 1996).

Microorganisms are the most abundant and most genetically diverse living beings and yet, their diversity is essentially known. Recently, several molecular techniques have been adapted to yield information on the diversity of microorganisms *in situ*. It is vital that studies are begun with a clear ecological question in mind, so that the appropriate method is chosen and the right community is sampled. In MIDAS we have chosen techniques from different approaches because each one opens a different window into bacterial diversity. To our knowledge nobody has tested several of these techniques simultaneously in the same environment to compare the information they provide. We have chosen to use these techniques in environments with special characteristics that make them excellent as test environments. After comparing the techniques, we will use them to study several questions about microbial diversity:

a) Seasonal changes in the abundance of given species in coastal ecosystems.

b) Similarities and differences among contrasting European marine systems.

c) Short-time scale changes and response of bacterial diversity to different nutrient regimes in mesocosms.

d) Effects of viruses and predation by protozoa on bacterial diversity.

We will also isolate bacteria to demonstrate the usefulness of the techniques to retrieve microorganisms of potential commercial application.

2. OBJECTIVES

The overall aim of MIDAS is to establish a framework (including development and testing of concepts, techniques and strategies) designed to measure diversity and to retrieve microorganisms of potential importance to the biotechnology industry from marine ecosystems. This framework is necessary both to monitor the response of marine ecosystems to human activities and environmental change, and to provide an improved basis, through coordinated European research effort, for exploiting the potential of microorganism diversity in the sea.

The specific objectives of MIDAS are:

1. Develop techniques (specially molecular techniques) to examine diversity of marine microbial ecosystems.
2. Test the developed methods by analyzing patterns of diversity in experimental model ecosystems and in natural environments.
3. Examine the mechanisms responsible for maintaining diversity in natural microbial communities.
4. Develop strategies to isolate microorganisms of potential commercial significance from marine environments. This involves knowing where to look for them and how to isolate them.
5. Analysis of natural microbial assemblages using molecular biology techniques to describe diversity in different marine provinces.

MIDAS will contain the following interacting elements:

- Isolation of microbes of industrial potential and laboratory experiments using cultures of microorganisms.
- Testing of hypotheses of diversity using marine mesocosm experiments containing natural mixed plankton communities.
- Field studies from contrasting locations and modeling results of diversity.

3. WORKPLAN

The scientific content of MIDAS is subdivided into 6 work packages, each one described in Section 4 of the present annex with the following parts: summary information (title, responsible partner, duration and specific objectives), tasks, deliverables, and interdependence.

The rationale behind the construction of the 6 work packages includes methodological development for bacterioplankton in work package 1, and for phytoplankton in work package 2. Work package 3 will examine some mechanisms which may be responsible for maintaining prokaryotic diversity in marine environments. Work package 4 will develop strategies to isolate microorganisms of potential interest from marine environments. The last two work packages include testing of the methods in natural environments: Work package 5 includes a variety of natural environments and work package 6 comprises work in marine mesocosms. In both work packages we will also try to answer a few questions about diversity. The questions asked are those we thought could be answered with the methods developed during MIDAS.

Work package 1. Bacterioplankton diversity.
Work package 2. Phytoplankton diversity.
Work package 3. Effects of viruses (side-in) and protist grazers (top-down) on bacterioplankton diversity.
Work package 4. Retrieval of significant prokaryotes from marine environments
Work package 5: Field studies.
Work package 6. Application of techniques to measure and modelling the diversity of natural microbial communities in marine mesocosm experiments.

TITLE: **A REGISTER OF MARINE SPECIES IN EUROPE TO FACILITATE MARINE BIODIVERSITY RESEARCH AND MANAGEMENT**

Contractno.: MAS3-CT97-0146

CO-ORDINATOR Dr Mark J. Costello,
Ecological Consultancy Services Limited (EcoServe),
7 Glenmalure Park, Rialto, Dublin 8; Ireland.
Tel. +353-1-490 3237; 453 3195; Fax -492 5694;
E-mail mcostello@ecoserve.ie; World Wide Web site www.ecoserve.ie

PARTNERS

Dr Frank Bisby
Department of Botany, University of Reading
PO Box 221, Whiteknights, Berkshire RG6 2AS
United Kingdom

Dr Phillippe Bouchet and colleagues
Laboratoire de Biologie des Invertébrés Marins & Malacologie
Muséum National d'Histoire Naturelle
55 rue Buffon, 75005 Paris, Cedex 05
France

Prof. Michael D. Guiry
Department of Botany
Martin Ryan Institute
University College, Galway
Ireland

Dr Maria Ramos, J. Templado
Dept. biodiversidad y biologia evolutiva
Museo Nacional de Ciencas Naturales
José Gutierrez Abascal 2, E-28006 Madrid
Spain

Dr Ioannis Karakassis
Institute of Marine Biology
PO Box 2214, 71003 Heraklion, Crete
Greece

Dr Richard J. White
School of Biological Sciences
Bassett Crescent East
University of Southampton, Southampton SO16 7PX,
UK

Dr Jacob van der Land
National Museum of Natural History
Darwinweg, P.O. Box 9517, 2300 RA Leiden,
Netherlands

Dr Richard Warwick
Plymouth Marine Laboratory
Prospect Place, West Hoe, Plymouth PL1 3DH,
UK

Prof Allesandro Minelli
Dept. of Biology
University of Padova
Viale Gisueppe Colombo 3, I-35121 PADOVA,
Italy

Dr Denise Bellan-Santini
UMR DIMAR
Centre d'Océanologie
Rue Batterie des Lions, 13007 Marseille
France

Dr Torleiv Brattegard
Department of Fisheries and Marine Biology
Bergen High Technology Centre
University of Bergen, N-5020 Bergen
Norway

Dr Anastasios Legakis
Zoological Museum, University of Athens
Panepistimioupolis, 15784 Athens
Greece

Dr Jon-Arne Sneli
NTNU, Vitenskapsmuseet
Trondhjem Biologiske Stasjon
Bynesveien 46, N-7018 Trondheim
Norway

Dr Carlo Heip, J. Craeymeersch
Netherlands Institute of Ecology
Centrum voor estuariene en mariene oecologie
Korringaweg 7, 4401EA Yerseke
Netherlands

Dr Günther Radach
Institut für Meereskunde
Universität Hamburg
Troplowitzstr. 7, 22529 Hamburg
Germany

Mr Aricò Salvatori
Intergovernmental Oceanographic Commission
1 rue Miollis, 75732 Paris, Cedex 15
France

Dr Pierre Lasserre
DIVERSITAS -UNESCO
1 rue Miollis, 75732 Paris, Cedex 15
France

Dr Keith Hiscock Mr David Connor
Marine Nature Conservation Review
Joint Nature Conservation Committee
Monkstone House
City Road, Peterborough PE1 1JY
UK

A REGISTER OF MARINE SPECIES IN EUROPE TO FACILITATE MARINE BIODIVERSITY RESEARCH AND MANAGEMENT

Dr Mark J. Costello,
Ecological Consultancy Services Limited (EcoServe),
7 Glenmalure Park, Rialto, Dublin 8; Ireland

SUMMARY

The foundation of biodiversity research and management is correctly identifying and naming species. This Concerted Action proposal will in 24 months produce a register of marine species in Europe, linked with a bibliography of identification guides, register of taxonomic experts, and locations of collections of reference specimens, and an Information Pack on European marine biodiversity (based on this project's results). The species register is novel in its geographic extent, range of taxa covered, and that it will use the state-of-the-art World Wide Web software for publication and networking. It will be drafted by experts from published literature and existing (but more limited) species lists, circulated to a wider range of experts for comments, revised and finally verified before publication as a book. The quality of the finished product, and its wide availability to end-users, are key elements of the project. Both the draft and final versions will be in the public domain and accessible through the World Wide Web. It is anticipated that the register will become a standard reference (and technological tool) for marine biodiversity training, research and management in Europe.

INTRODUCTION

The marine environment is less visible, less documented, less constrained (more open and dispersive), and less understood than terrestrial ecosystems. The rate of discovery of marine species shows no sign of decreasing and continues at a high rate. This is even the situation in North European waters and particularly evident for the most species rich taxonomic groups (Costello *et al.* 1996). There compelling economic (commercial resources), ecological (protect ecosystem function and health), legal, and moral (stewardship of heritage), reasons for protecting marine biodiversity. The need for research and management of marine biodiversity has been recognised both by the European Union through its MAST and LIFE programmes, and throughout the world by the Convention on Biological Diversity (Rio de Janeiro 1992). Indeed, the second session of the Conference of the Parties of the Convention on Biological Diversity (Jakarta, Indonesia, November 1995) recommended that special attention was necessary for coastal and marine biodiversity.

A major global research programme on biological diversity has been launched called "DIVERSITAS", by the United Nations Education and Science Organisation (UNESCO), the Scientific Committee on Problems in the Environment (SCOPE), and the International Union of Biological Sciences (IUBS) (Anon. 1994). Within DIVERSITAS, marine biodiversity is one of the four special target areas of research (STAR) in recognition of the neglect of this subject. As yet, there are no European marine contributions to DIVERSITAS.

IUBS has also been involved in launching (in co-operation with others) the "Species 2000: indexing the world's known species" programme in 1994 (Bisby and Smith 1996). This initiative formally began in March 1996 and is linking together (a federation of) existing databases through the Internet. A European marine species register would readily form part of this network.

Another global organisation, the Intergovernmental Oceanographic Commission (IOC), has produced a draft "register" of the families of marine organisms of the world, the UNESCO Register of Marine Organisms (URMO). This is now accessible via the Internet. It is anticipated that this register will link with more specialist lists, be they taxonomic (e.g. world list of marine Isopoda) or geographic (e.g. proposed European marine species register).

Both the DIVERSITAS and IOC initiatives depend to a significant extent on the generous volunteering of time by organisations and individuals. Both organisations and others (notably IUBS and European Science Foundation) identify the need for networking, species inventories, training in taxonomy and other tools or measures to facilitate research in marine biodiversity. A clearly focused and funded European network of marine biodiversity experts could make rapid progress towards achieving these aims.

A MAST sponsored workshop reviewed marine biodiversity research in Europe in 1996 (Warwick *et al.* 1997). It found most national effort concerned describing marine biodiversity, involving inventorying, systematics, monitoring and field surveys. However, there was very little co-ordination of this work at a national level and none at a European level. Because of this it was not clear where geographic and taxonomic gaps lay. There was less effort in the areas of relating biodiversity to ecosystem function, such as would lead to a better understanding of patterns and processes to support marine environmental management (including nature conservation and resource use). The latter requires special research projects of which there have been disappointingly few at national and EU level. However, a common standard for the identification and naming of species is the foundation for the description of such patterns and processes. Therefore, it should be put in place as soon as possible to facilitate the other aspects of marine biodiversity research. At a European scale this would require easy access to a standard inventory of species names, list of identification guides and papers, reference collections for training and comparative studies, and contact details of taxonomic experts. Improved networking would

(a) enable the production of the first register of marine fauna and flora at a European scale,
(b) aid co-ordination and prevent duplication of existing work,
(c) identify gaps in expertise, publications, and taxonomic knowledge,
(d) facilitate the development of consortia to prepare new research proposals, and
(e) provide for European contributions to global marine biodiversity research activities.

This Concerted Action aims to publish (in electronic and book form) a register of marine species in Europe, linked with a bibliography of identification guides, register of taxonomic experts, and locations of collections of reference specimens, and an information pack on European marine biodiversity (based on the project's results).

METHODOLOGY

The Concerted Action will form a network of European researchers (marine taxonomists, biogeographers, and database managers), within which a series of Working Groups (Figure 1) would conduct:

- External liaison with other organisations (including DIVERSITAS, IOC, Species 2000, EEA, etc.) to avoid duplication and ensure a synergy of effort in biodiversity research;
- Design the content, structure, and dissemination of a European marine fauna and flora Species Register;
- Compile a bibliography of identification guides, register of taxonomic experts, and sources of reference collections;
- Collate and verify the Species Register data;

- Analyse the database for gaps in knowledge and tools (e.g. identification guides, taxonomic expertise) for marine biodiversity research;
- Produce an information pack on European marine biodiversity to disseminate the project results to students and public;
- Publish the Species Register and other project results on the World Wide Web and paper.

Communication between the Working Groups will be conducted by a central Secretariat and facilitated by a Steering Committee (Figure 1) and overlap between Working Group membership.

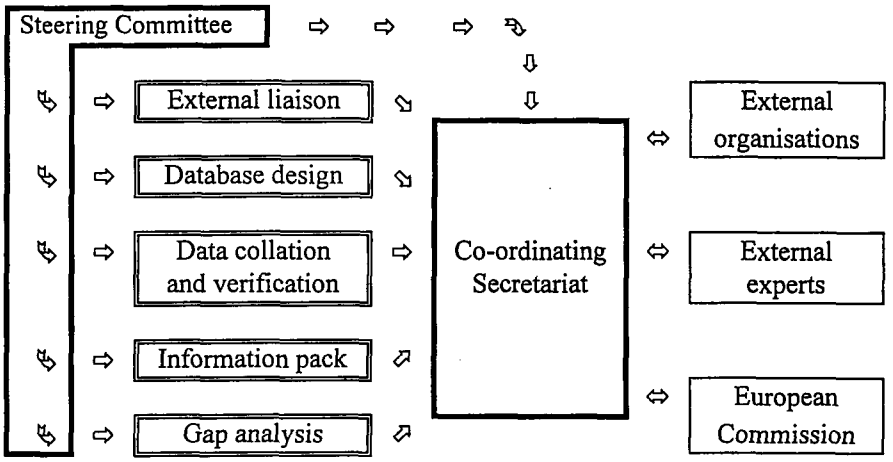


Figure 1. A flow diagram indicating the relationships between the Steering Committee, Co-ordinating Secretariat, Working Groups (boxes with double lined borders), and external organisations and persons.

A External Liaison Working Group will liaise with external organisations active in biodiversity research and management, including Species 2000 (IUBS), DIVERSITAS, IOC, and the European marine research stations (MARS) network. The Species Register will thus contribute to both European and global initiatives, avoid duplicating other activities, and aid national and European contributions to these organisations, to the Convention on Biological Diversity, to OSPARCOM, and to general marine environmental management. The project will provide a model of how Species 2000 can link with a regional project.

The linking and future development of this Species Register with other databases, acknowledgement of individuals contributing to the Register, and long term availability and revise-ability of the Register will be key issues addressed at an early stage in the project.

The participants will combine their data and knowledge to produce a Species Register of wider geographic and taxonomic scope, and greater accuracy and authority, than possible by individual efforts within the same time period. Working Groups will (a) analyse the data collected to identify gaps in taxonomic expertise, knowledge of certain taxa, and weaknesses of certain identification guides (including languages, quality), and (b) produce an Information Pack from the project results to aid university and public education in European marine biodiversity.

It is envisaged that the geographic scope of the register will cover all the continental shelf seas of Europe, from the Canaries and Azores to Iceland and northern Norway. It will

include the Mediterranean shelf and Baltic Seas. The taxonomic scope will not include non-macrophytes, fungi, bacteria, viruses, fossil or deep sea species. However, the potential for including such taxa in future revisions will be considered in the register design.

Participants 1 to 7 are those leading various working groups such that they have a major time contribution (≥ 30 days for the organisation) to the project. These partners also form the Steering Committee. The project will actively widen participation through seeking the involvement of taxonomic experts in ensuring quality control in the Species Register. It will not exclude other researchers who wish to participate (e.g. by attending meetings and correspondence) and recognises that valuable contributions may be made by people not yet contacted. Communication within and beyond the project network would include the use of the World Wide Web (WWW), newsletter, and Internet e-mail listserver discussion group.

The relationships between the activities of the Working Groups, the sources of information and outputs of this project are illustrated in Figure 2.

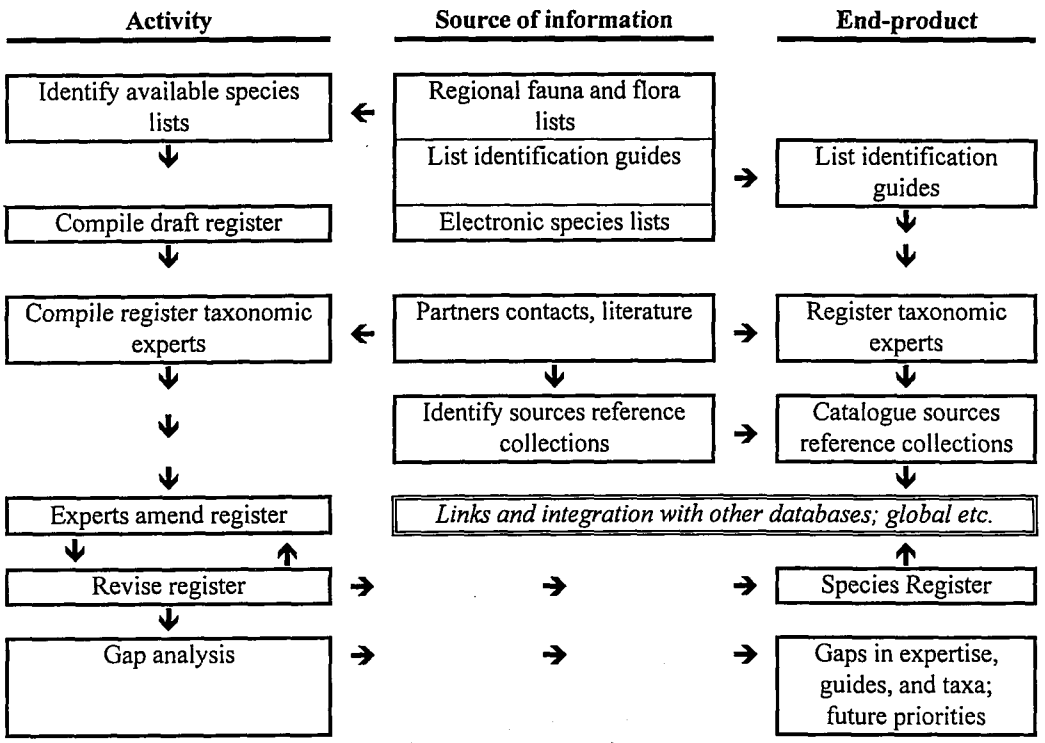


Figure 2. A diagrammatic representation of how the Species Register will be developed. Another end-product will be an Information Pack for students which will draw on the above end-products.

There are 11 project deliverables:

1. World Wide Web site
2. Newsletter on project aims, methods and progress
3. Report on *Rationale for design and long term dissemination of the Species Register*
4. Bibliography of identification guides
5. Register of marine taxonomists
6. Locations of reference collections
7. Report on *Priorities for future research*
8. *Species Register* published electronically
9. *Species Register* published as a book
10. Information pack for educational use
11. Final report to EC.

It is anticipated that the project will start in May 1998. Persons interested in contributing to the project are invited to contact EcoServe or any of the projects participants.

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

TITLE: Marine ecosystems regulation: trace metals and carbon dioxide limitations
(MERLIM)

CONTRACT NO: MAS3-CT95-0005

COORDINATOR:
Hein J.W. De Baar
Netherlands Institute for Sea Research
PO Box 59
NL - 1790 AB Den Burg, Texel
Tel.: +31 2223 69465, fax: +31 2223 19674
E-mail: debaar@nioz.nl

PARTNERS:

U. Riebesell/D. Wolf-Gladrow
Alfred-Wegener-Institut für Polar- und Meeresforschung
DE - Bremerhaven

M. Whitfield/R. Geider
Marine Biological Association of the United Kingdom
UK - Plymouth

C.M.G. Van Den Berg
University of Liverpool
Department of Earth Sciences
UK - Liverpool

(no manuscript submitted)

TITLE: **ASGAMAGE/the ASGASEX MAGE experiment**
ASGASEX - Air Sea Gas Exchange programme
MAGE: Marine Aerosol and Gas Exchange, an IGAC project

CONTRACT NO: MAS3-CT95-0044

COORDINATOR:
Dr.Wiebe A.Oost
Royal Netherlands Meteorological Institute (KNMI)
Wilhelminalaan 10
P.O.Box 201
3730 AE De Bilt, The Netherlands
Tel. + 31 30 220 66 70; Fax: + 31 30 221 04 07
E-mail: oost@knmi.nl

PARTNERS:

Dr.Søren Larsen
Risø National Laboratory,
Postboks 49,
DK 4000 Roskilde, Danmark
TEL: 00 45 4237 1212
FAX: 00 45 4675 5619
E-MAIL: metsol@risoe.dk

dr. Gerrit de Leeuw
FEL-TNO
P.O. Box 96864
2509 JG Den Haag, The Netherlands
TEL: 070 3740462
FAX: 070 3740654
E-MAIL: deLeeuw@fel.tno.nl

Prof.Peter S.Liss
School of Environmental Sciences
University of East Anglia
Norwich NR4 7TJ, United Kingdom
TEL: 00 44 1603 592563 (direct) of 56161
FAX: 00 44 1603 507719
E-MAIL: p.liss@uea.ac.uk

Dr. Peter Bowyer
Department of Oceanography
University College Galway
Galway, Ireland
TEL: 00 353 91 524411 ext.3202
FAX: 00 353 91 525005
E-MAIL: Peter.Bowyer@ucg.ie

Dr. David K.Woolf
Department of Oceanography,
the University,
Highfield,
Southampton SO9 5NH, United Kingdom
TEL: 00 44 1703 593038
FAX: 00 44 1703 593059
E-MAIL: David.K.Woolf@soc.soton.ac.uk

Prof. Meinrat .O.Andreae
Max Planck Institut für Chemie,
Abt.Biochemie,
Postfach 3060,
55020 Mainz, Germany
TEL: 00 49 6131 305420
FAX: 00 49 6131 305487
E-MAIL: moa@diane.mpch-mainz.mpg.de

Mr. Alan Hall
George Deacon Division
Southampton Oceanographic Centre
Empress Dock,
Southampton SO14 3ZH, United Kingdom
TEL: 00 44 1703 596463 or 596377
FAX: 00 44 1703 596149
E-MAIL: ah@soc.soton.ac.uk

Dr.Rob Upstill-Goddard
Department of Marine Sciences and
Coastal Management,
University of Newcastle Upon Tyne,
Ridley Building,
Newcastle Upon Tyne, NE1 7RU,
United Kingdom
TEL: 00 44 191 222 5065
FAX: 00 44 191 222 7891
E-MAIL: Rob.Goddard@newcastle.ac.uk

Dr.Phil D.Nightingale
Plymouth Marine Laboratory
Prospect Place
West Hoe
Plymouth PL1 3DH
UK
TEL: + 44 1752 633439
FAX: + 44 1752 633101
E-MAIL: P.Nightingale@pml.ac.uk

Contributors from outside the EU:

Mr.R.J. Anderson and Dr.S.D.Smith
Ocean Circulation Section,
Ocean Sciences Division,
Bedford Institute of Oceanography,
P.O. Box 1006, DARTMOUTH, N.S.
Canada B2Y 4A2
TEL: 1 902 426 3584
FAX: 1 902 426 7827 or 2256
E-MAIL: AndersonR@mar.dfo-mpo.gc.ca

Dr.Chris.W.Fairall
NOAA/ETL
325 Broadway,
Boulder CO 80303, USA
TEL: 00 1 303 497 3253
FAX: 00 1 303 497 6978
E-MAIL: cfairall@etl.noaa.gov

ASGAMAGE: Resolving riddles in air-sea gas exchange.

Wiebe A. Oost, Royal Netherlands Meteorological Institute

1. INTRODUCTION

Two of the biggest deficiencies in our knowledge of the radiative forcing of climate involve our inability to precisely indicate and predict air-sea gas exchange rates. First, how much anthropogenic CO_2 goes into the oceans? In societal terms: is there any chance the oceans will save us from greenhouse warming by soaking up more CO_2? Second, to what extent might the climate be altered if we inadvertently changed the viability of phytoplankton, since they produce the DMS that forms the aerosols that control cloud reflectivity? Since we don't even know how much DMS the oceans emit today to better than a factor of two, how could we predict the impact of a 20% change?

The gas streams, or fluxes, F, are commonly described with the use of a transfer velocity, K, defined by (Liss, 1983; Liss and Merlivat, 1986):

$$F = K\Delta C$$

where ΔC is the concentration difference that drives the flux. The transfer velocity consists of

an atmospheric part, k_a, and a water phase part, k_w. For many gases, for example CO_2, K is almost exclusively controlled by the speed of transport in the water phase (Liss, 1983), so $k_w << k_a$, and $K \approx k_w$. (k_w is a kind of reverse resistance).The flux of such gases can then be given as:

$$F = k_w (c_w - c_{eq})$$

where c_w is the actual concentration in the bulk of the water, and c_{eq} is the equilibrium concentration in the water. c_w and c_{eq} can - in principle, at least - be measured, but k_w is not known with sufficient precision to allow us to calculate F with the accuracy needed to answer the questions stated above.

Traditional parameterizations of air-sea exchange, such as the two-layer approaches of Liss and Merlivat (1986) or Wanninkhof (1992), rely on measuring the concentration gradient across the air-sea interface and using windspeeds and temperatures to estimate a transfer coefficient (or exchange velocity). Although most of the uncertainty is usually ascribed to the transfer velocity, the possibility of differences between concentrations at about 5 meters depth (where many ships have their research-water intakes) and the surface microlayer (whose concentration should drive the flux) is another area of concern.

The persistence of these uncertainties is the main reason to promote the development of new technologies to measure gas fluxes between air and sea. Two of the most promising ones are eddy correlation and eddy accumulation (also called conditional sampling). Each of these methods relies on fast (>1 Hz) measurements of vertical windspeed to identify updrafts and downdrafts and accompanying chemical measurements to determine the concentrations in them, from which the flux can then be computed directly.

Both these techniques measure fluxes over periods of 20-30 minutes, which is the same time scale on which changes in windspeed, temperature, and other factors occur. This allows to address questions such as: How long after a windspeed increases do the accompanying higher fluxes last? Is there a depletion of the surface mixed layer, causing fluxes to decrease after an initial pulse? It may be that the fraction of DMS which evades to the atmosphere is higher when the winds come up, but that most of it is consumed in the water when the winds are low. One often finds high particle concentrations after frontal passages: is this in part because frontal squalls drive out extra DMS? How realistic are our current parameterizations, which are based on the evasion of natural and deliberate tracers from natural waters?

Eddy correlation (*ec*) has been used for decades to measure surface fluxes over land, and it is recognized as the most defendable technique because it relies on direct measurements of concentrations in updrafts and downdrafts. One directly measures the amount of material moving toward a surface and away from it, and the difference is the flux. Since the eddies can be quite small, however, sensors must provide precise measurements 1 to 10 times per second, which only few chemical sensors can achieve. *ec* has also been used over the oceans for measuring fluxes of heat, moisture, and momentum, even though the smaller marine turbulence levels make the measurements more challenging.

Attempts to measure marine CO_2 fluxes have been frustrated by several factors. The first is the small concentration variations over the oceans. An instrumental precision considerably greater than 0.1% is required to see these tiny fluctuations. Water vapor is also a problem. It

changes the density of the air, effectively diluting the volumetric concentration of CO_2 in wet updrafts relative to drier downdrafts. The Webb correction for this effect is often very large, leaving a substantial uncertainty in fluxes. Water vapor also causes a small interference in the nondispersive infrared analyzers frequently used for the CO_2 measurement. Although these problems are being gradually resolved with further instrumental development, the considerable difference that so far has been found between transport velocities derived from *ec* observations (all done at or near the coast) and the more generally used values, has generated considerable skepticism of *ec* in the ocean carbon community.

A related technique, eddy accumulation (*ea*), makes it possible to use slower sensors to measure fluxes. Fast valving directs air from updrafts and downdrafts into separate chambers, from which it can be measured by gas chromatographs and other slow sensors. While *ea* is less direct than *ec*, it reduces the demands on analytical systems and plumbing considerably, making drying, for instance, a simple alternative to the Webb correction.

2. OBJECTIVES

The primary method by which these new techniques can be validated is to make simultaneous measurements alongside established methods under field conditions. That is precisely the aim of ASGAMAGE, a MAST project involving an intercomparison experiment on and near the Dutch platform Meetpost Noordwijk (MPN; see Figure 1). The experimental phase took place in 1996 and at the time of writing (February 1998) the participants are interpreting the data.

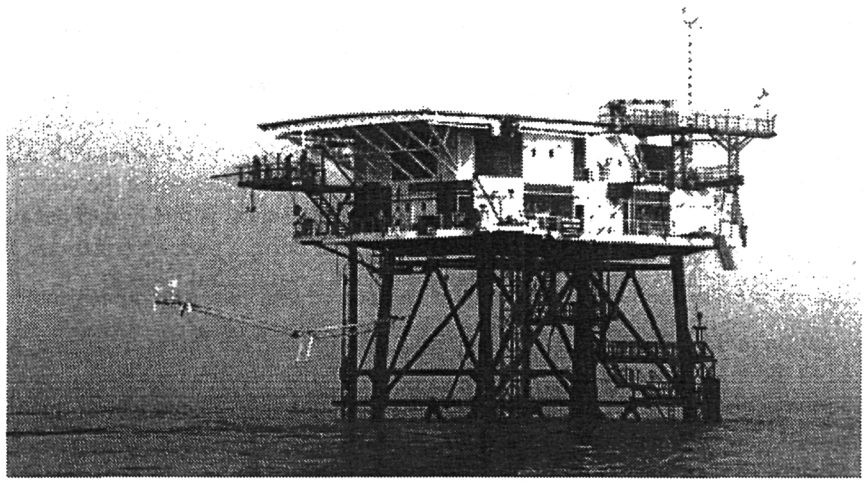


Figure 1. The Meetpost Noordwijk platform with the Westerly outrigger partially extended

The name of the project is a combination of two acronyms, ASGASEX and MAGE. ASGASEX, for Air Sea Gas Exchange, is a series of experiments on this subject at the MPN platform, the first of which took place in 1993. The present project is the second one in this series and it derives its name from the fact that it takes place under the aegis of MAGE (for

Marine Aerosol and Gas Exchange) an activity of IGAC, the International Global Atmospheric Chemistry programme of IGBP.

ASGAMAGE builds on micrometeorological experience gained in a number of international experiments such as HEXMAX (1986), the HEXOS Main Experiment, during which the impact of MPN on airflow and turbulence was well-characterized, and the 1993 ASGASEX project. In ASGASEX the CO_2 *ec* method was considerably improved, but the difference between it and the two-layer approach still remained. It may be related, however, to the presence of CO_2 gradients in the upper few meters of the sea, one of many factors that are being addressed in ASGAMAGE.

The project has four primary objectives:

1: To test new methods for the measurement of air-sea gas fluxes, particularly CO_2 and DMS,
2: To intercompare these with established methods for estimating the transfer velocities of trace gases over the sea,
3: To find relationships between the transport coefficients for the gas fluxes and relevant geophysical parameters, and
4: To find out whether there can be significant vertical gradients in carbon dioxide concentration in the upper meters of the water column.

3. PARTICIPANTS

ASGAMAGE involves 14 institutes from 7 countries as well as the owner of Meetpost Noordwijk, the Dutch government organization of Rijkswaterstaat.
The European participants (contractors and subcontractors) are from the following institutes:

Royal Netherlands Meteorological Institute (KNMI, the organizer of the project)
Max Planck Institut für Chemie (MPIC), Germany
Netherlands Institute for Sea Research (NIOZ)
Plymouth Marine Laboratories (PML, UK)
Risø National Laboratories (Risø, Denmark)
Southampton University Department of Oceanography (SUDO, UK)
Southampton Oceanography Center (SOC, UK)
Physics and Electronics Laboratory of the Netherlands Organization. for Applied Research (TNO-FEL),
University of Newcastle-Upon-Tyne (NUT, UK),
University College Galway (UCG, Ireland),
University of East Anglia (UEA, United Kingdom).

Participants from outside the EU are

Bedford Institute of Oceanography (Canada)
NOAA Climate Monitoring and Diagnositcs Laboratory (NOAA/CMDL, USA)
NOAA Environmental Technology Laboratory (NOAA/ETL, USA).

The European institutes are supported by the MAST-3 programme.

4. EXPERIMENTAL PHASES

The two experimental phases of ASGAMAGE were succesfully performed in 1996, the first

one (the A-phase) in May, when the maximum DMS concentrations occurred, and the second one (the B-phase) in October, when the winds were higher and more westerly.

A wide variety of techniques was used and intercompared:

1. Four independent *ec* systems for CO_2 fluxes were deployed simultaneously, offering an opportunity to test the methods' reproducibility and identify the causes of differences. These were accompanied by *ec* measurements of momentum, heat, and water vapor.
2. The first attempts were made to measure fluxes of DMS over the sea with *ec*, using new high-speed sensors.
3. Two *ea* systems were deployed in parallel with the *ec* measurements.
4. A method that allows for shipboard application is the inertial dissipation (ID) technique, which uses the inertial subrange (high frequencies) of power spectra to determine fluxes. (Ship motions can be neglected because they occur in a different frequency range.) The ASGAMAGE *ec* data allow interpretation in terms of the ID method as well.
5. Concentration measurements in the air and at several depths in water were used to estimate fluxes using the traditional two-layer approach.
6. The evasion of multiple deliberate tracers was used to estimate transfer coefficients.
7. The reliability of passive radiometry and thermometry (measurement of the thermal skin effect) as a means of deducing the transfer velocity of gases (excluding bubble-mediated transfer) was tested. The use of thermal imagery offers the most direct method of studying transfer mechanisms in the sea surface laver.

During the fall period measurements were also made from the UK ship "Challenger", operating near MPN. The vessel performed a multiple tracer experiment, a sophisticated and well established method to determine the transfer velocity. A new development in this respect was the use of conservative tracers (Rhodamines WT and sulpho-G and bacterial spores) to create an overdetermined system that should provide a higher accuracy. Simultaneously shipboard measurements of marine biogenic gases (DMS, CO_2, CO, CH_4, N_2O, low molecular weight hydrocarbons, and halocarbons) in seawater and air were made, in order to be used for two-layer flux calculations.

Since waves and bubbles are clearly central to understanding air-sea exchange, special efforts were made to characterize them. Waves were measured with a wave wire and a directional wave buoy, while whitecap coverage was measured with video cameras and a directional microphone. Below the surface, breaking waves were studied with a high frequency sector-scanning sonar and a very fine beam sonar that measures the large bubbles (high void fractions) near the surface. The vertical penetration of bubble clouds was measured with upward-looking sonars of four frequencies, giving a parametric description of the size distribution of the bubbles vs. depth and time. The bubble size distribution at a single depth was furthermore measured with laser-optical instruments. Large bubbles were measured by a video system and ultrasound.

Gradients of physical and chemical properties in the water column can affect the comparison of the two-layer method with other techniques, so these too were carefully measured. Current profiles near the platform were measured during parts of the experiment with an Acoustic Doppler Current Profiler and an electromagnetic current meter. Sea water temperature, salinity, fluorescence and dissolved gases were measured at different depths. In addition,

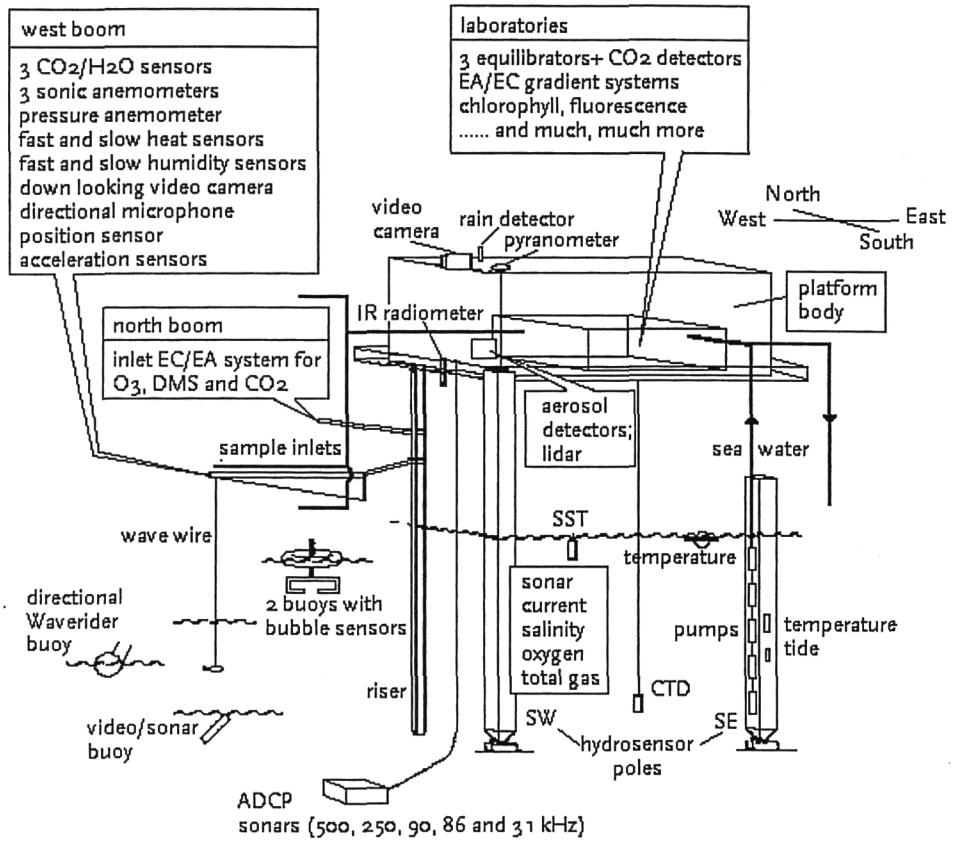


Figure 2. A schematic overview of the sensors used at Meetpost Noordwijk during ASGAMAGE.

dissolved oxygen and total gas partial pressure were measured with *in situ* instruments at several depths.

A schematic overview of most of the sensors used at MPN is given in Figure 2

5. HOW ARE WE PROGRESSING TOWARD OUR OBJECTIVES?

The first ASGAMAGE workshop has taken place on September 22-25, 1997 and a large number of results could be presented, be it that many of them still have a preliminary character. The present status of our four objectives can be summarized as follows:

Objective 1: To find relationships between the transport coefficients for the gas fluxes and any relevant geophysical parameters.

Most data have been converted now into physical quantities and have been corrected and screened for their quality. The data analysis is at a stage that the question contained in this

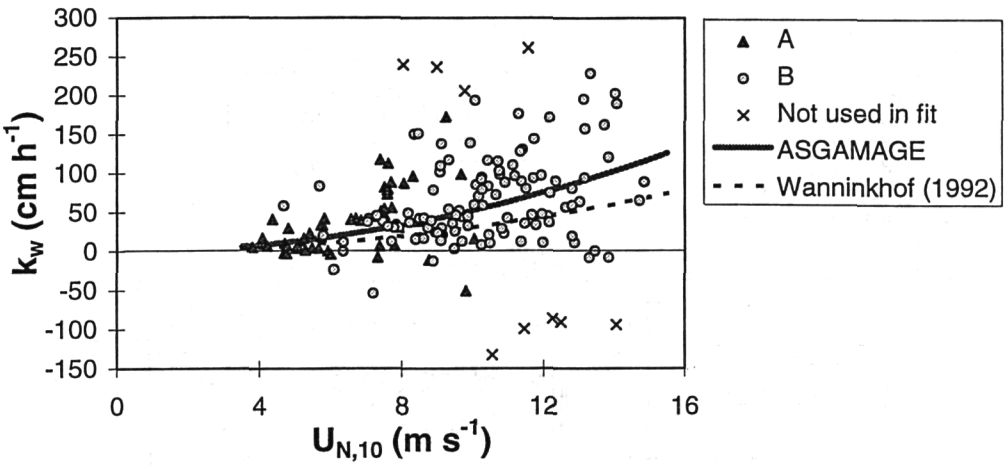


Figure 3. Computed k_w normalised to 20 °C versus the neutral wind speed at a height of 10 m, $U_{N,10}$, for the ASGAMAGE data set. Triangles: ASGAMAGE-A; Circles: ASGAMAGE-B; Crosses: outliers, removed from the fit. (not shown: four outliers with k_w < -150 cm h^{-1} and one with k_w > 300 cm h^{-1}). A quadratic fit through the data, $k_w = 0.53\ U^2_{N,10}$ is also shown (solid line), along with the Wanninkhof (1992) fit, $k_w = 0.31 U^2_{N,10}$ (dashed line). The ASGAMAGE fit optimises for CO_2 flux.

objective can be adequately addressed. A number of participants already studied the relationship between the transport coefficients and the main parameter, the wind speed. A preliminary result for this relationship found from KNMI flux data and averaged CO_2 concentrations (from data measured by KNMI, NIOZ and TNO-FEL) is given in Figure 3.

Further analysis requires combining data from several institutes, an activity that is presently in progress.

Objective 2: To intercompare different methods and systems to measure the transfer velocity of trace gases over the sea.

Figure 4 shows the results found by NUT and PMT, using the differential tracer (*dt*) technique.

The values found for the transfer coefficient for CO_2 with the *ec* technique are still something like a factor of two higher than those found with the *dt* technique, even though both types of measurements have been done in the most careful way, applying all techniques, precautions and corrections presently known. Both techniques are furthermore to be considered as in principle sound with only minor uncertainties, at least compared to the ratio of the resultant values.

A factor that so far has been neglected in the comparison of the values resulting from both techniques is the difference in the times needed: whereas the *ec* technique needs 20 to 45 minutes, *dt* measurements require a time span of 24hrs or longer. From a first order analysis of the effect of fluctuations in the flux and in the concentration difference across the surface, the

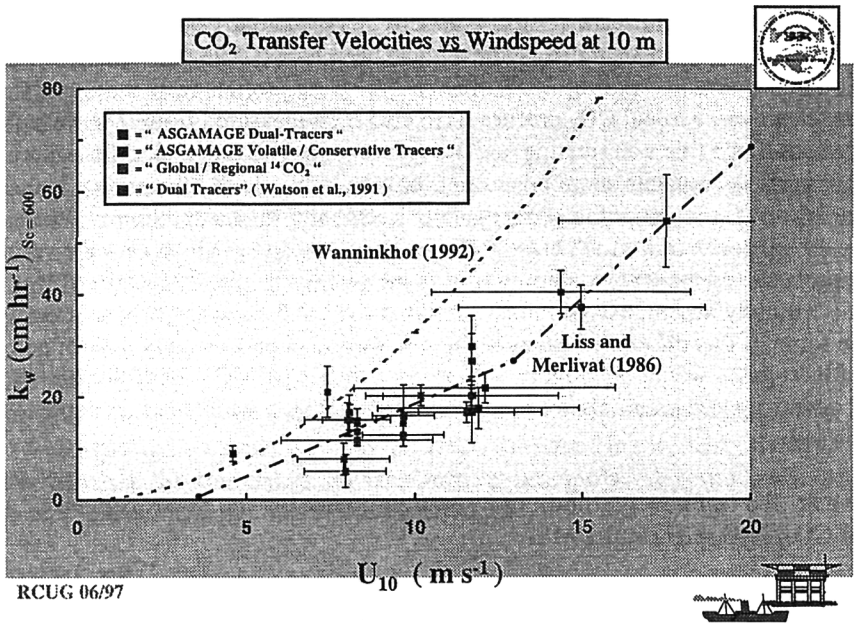


Figure 4 Transfer velocity versus 10m wind speed found by the Challenger crew, using the differential (multiple) tracer technique

conclusion can be drawn that for time scales long compared with the time in which e.g. the wind changes, a correction factor applies that is proportional to the average value of the correlation of the fluctuations in the flux and in the concentration difference. The measured data show that both the flux and the concentration difference are correlated with the wind, so they are of necessity also correlated to each other. Based on this conclusion an attempt was made to estimate the correction factor, which turned out to be of the order of 0.06 and so could not explain the difference in the measured values for k. This value must, however, be considered as little more than a guess: the formalism for the correction was developed only after the experiments were finished and the correlation values, needed for a better founded value, were not available.

Other factors that may be important for the intercomparison of the techniques are the effects of processes in the water right at the surface, surfactants and the horizontal homogeneity at the measurement site. More information in these respects will become available as the modeling work progresses.

Objective 3: To find out whether and, if at all, under what conditions there can be a significant vertical change in the carbon dioxide concentration in the upper meters of the water column.

From information obtained later it turned out that the extremely strong CO_2 concentration fluctuations, measured at a depth of 5m below MSL during the 1993 ASGASEX experiment, which were the basis for this research objective, must be considered as incidental. They have to all probability been caused by an episode of extremely high CO_2 concentrations in the waters of the river Scheldt. These concentrations have been measured by Frankignoulle et al (1996). The vertical CO_2 profiles, measured at the platform during the A as well as during the

B phase, do not show significant vertical gradients, except in one case at the very end of the B-phase, when the flux measurements already had been halted. Even this gradient was only a fraction of those measured during ASGASEX. All of these profiles were measured during slack tide. However, vertical CO_2 profiles have also been measured from RRS "Challenger" during periods that a tide was running and these data suggested that under those circumstances significant vertical gradients could be present. Another factor in this discussion is the modelling effort that at present is being made at KNMI and Risø. A preliminary version indicates the existence of a small, but significant concentration gradient near the surface, i.e. in the upper meter of the water column for inert gases. For chemically reactive CO_2 this gradient is virtually absent, except in the skin layer right at the surface, whereas the flux is about the same. If this difference exists in the real world, experimentally determined k_w values of inert gases would be roughly 10% smaller than k_w of CO_2. Thus, further efforts to find and quantify these gradients are required and should be concentrated on depths very close to the surface.

Objective 4: To test new methods and new equipment for the measurement of air-sea fluxes of CO_2, N_2O, CH_4 and DMS.

New methods that have been applied during ASGAMAGE are

- The differential tracer method using non-volatile tracers and a large overdetermination of the system through the use of five different tracers;
- The eddy correlation technique for DMS and O_3
- The relaxed eddy accumulation technique for DMS
- The inertial dissipation method
- The simultaneous use of two CO_2 fluctuation sensors to reduce experimental noise.

New equipment:

- The closed NOAA/CMDL ultrasensitive CO_2 detection system, used for eddy correlation, relaxed eddy accumulation and gradient measurements of the CO_2 flux.
- The latest version KNMI Infrared Fluctuation Meter (for eddy correlation measurements)
- The equipment needed for the new techniques described above.

The large majority of these new methods and equipment have yielded useful results. Only the eddy correlation and relaxed eddy accumulation measurements with the NOAA/CMDL instrument have only yielded upper limits, due to the long inlet tube, an insufficient flow speed in that tube and an unexpected difference in the effective flow speeds of water vapor and CO_2 in the tube.

6. CONCLUSIONS AND OUTLOOK

The preliminary results already indicate that ASGAMAGE, despite a few setbacks, can in general be considered as a successful experiment. The difference of something like a factor two between the *ec* and *dt* data is a large improvement compared with earlier results. The high quality of the data, resulting from the careful way in which data were treated and interpreted, was at the bottom of this result. That there nevertheless still is a difference suggests that we should no longer attribute it to the way the measurements are performed, but look for more fundamental differences.

Eddy-flux methods provide us with the most direct measurements of air-sea fluxes. The comparison with the differential tracer results can, however, only be made by converting the *ec* flux values into values of k, which involves concentrations right at the surface, which are very difficult to measure.

Their time resolution will permit more accurate parameterizations of fluxes than existing techniques. We cannot afford not to develop these methods because our climate models are so sensitive to air-sea exchanges that we must have accurate ways of measuring the fluxes. Experiments like ASGAMAGE are essential both to develop new techniques and to earn the confidence of a justifiably critical scientific community.

ACKNOWLEDGEMENTS

The first part of this paper draws heavily on an article the author wrote together with Prof. Barry J. Huebert, of the University of Hawaii, USA, for Issue No.6 of IGACtivities, the IGAC Newsletter. Much of the material for the later sections was provided by other ASGAMAGE participants, listed at the beginning of this contribution.

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I.1.5. Fluxes across the water/sediment interface

TITLE: Hydrothermal fluxes and biological production in the Aegean

CONTRACT NO: MAS3-CT95-0021

COORDINATOR: Paul R. Dando
University College of North Wales Bangor
School of Ocean Sciences
Menai Bridge
UK - Gwynedd LL59 5EY
Tel.: +44 1248 351151, fax: +44 1248 382620
E-mail: oss109@sos.bangor.ac.uk

PARTNERS:

Roberto Meloni
Consiglio Nazionale delle Ricerche
Istituto per lo Studio della Dinamica delle Grandi Masse
I - La Spezia

Kostas Makropolous
National and Kapodistrian University of Athens
Department of Geophysics and Geothermy
GR - Athens

Bo Barker Jørgensen
Max-Planck Institut for Marine Microbiology
D - Bremen

Peter Linke
Christian-Albrechts Universität Kiel
Forschungszentrum für Marine Geowissenschaften
D - Kiel

Jens Kristian Gundersen
Århus Universitet
Institute of Biological Sciences
DK - Århus

Carlos Nike Bianchi
ENEA - Ente per le Nuove Tecnologie, l'Energia e l'Ambiente
Marine Environment Research Center
I - La Spezia

Michael Thomm
Christian-Albrechts Universität Kiel
Institut für Allgemeine Microbiologie
D - Kiel

Doris Stüben
Universität Karlsruhe (Technische Hochschule)
Institute für petrographie und Geochemie
Fakultät für Bio- und Geowissenschaften
D - Karlsruhe

Soterios Varnavas
University of Patras
Department of Geology
School of Natural Sciences
GR - Patras

(no manuscript submitted)

I.1.6. Sedimentary processes

TITLE: European North Atlantic Margin: Quantification and Modelling of Large-scale Sedimentary Processes and Fluxes (project **ENAM II**)

CONTRACT NO: MAS3-CT95-0003

COORDINATOR:
Dr. Jürgen Mienert
GEOMAR Forschungszentrum für marine Geowissenschaften der Christian-Albrechts-Universität zu Kiel
Wischhofstr. 1-3
D-24148 Kiel
phone: +49-431-600 2319
fax: +49-431-600 2930
e-mail: jmienert@geomar.de

PARTNERS:

Prof. Dr. Julian A. Dowdeswell
Centre for Glaciology
Institute of Earth Studies
The University of Wales, Aberystwyth
UK-Dyfed, SY23 3DB
phone: +441-970-62 2782
fax: +441-970-62 2780
e-mail: jud@aber.ac.uk

Prof. Dr. Hans-Petter Sejrup
University of Bergen
Department of Geology, Sec. B
Allegaten 41
N-5007 Bergen
phone: +47-555-83505
fax: +47-555-89416
e-mail: sejrup@geol.uib.no

Prof. Dr. Björn Malmgren
University of Göteborg
Department of Marine Geology
Box 7064
S-40232 Göteborg
phone: +46-31-773 4900
fax: +46-31-773 4903
e-mail: bjorn.malmgren@marine-geology.gu.se

Dr. Gerard A. Auffret
IFREMER
Centre de Brest
B.P. 70
F-29280 Plouzane
phone: +33-98-22 40 40
fax: +33-98-224570
e-mail: gauffret@ifremer.fr

Dr. Dan Evans
British Geological Survey
Marine Geology
Murchinson House, West Mains Road
UK - Edinburgh, EH9 3LA
phone: +441-31-440320
fax: +441-31-668 4140
e-mail: DEV@wpo.nerc.ac.uk

Dr. Antoon Kuijpers
Geological Survey of Denmark
Thoravej 8
DK-2400 Copenhagen, NV31106600
phone: +45-381-42367
fax: +45-381-42050
email: aku@geus.dk

Dr. Tjeerd C.E. van Weering
Netherlands Institute for Sea Research
P.O. Box 59
NL - Den Burg, 1790 AB
phone: +31-2223-69395
fax: +31-2223-19674
e-mail: haas@nioz.nl

Prof. Dr. Jean-Pierre Henriet
Renard Centre of Marine Geology
University of Gent
Krijgslaan 281
B-9000 Gent
phone: +32-9-2644585
fax: +32-9-2644967
e-mail: jeanpierre.henriet@rug.ac.be

Dr. Robert Devoy
Coastal Resources Centre
University College
Lea Maltings Prospect Row
IRE - Cork
phone: +35-321-276871
fax: +35-321-271980
e-mail: r.devoy@ucc.ie

Prof. Dr. Anders Elverhøi
University of Oslo
Department of Geology
Blindern
N-0316 Oslo
phone: +47-22-959617
fax: +47-22-854215
e-mail: anders.elverhoi@geologi.uio.no

Dr. Neil Kenyon
Southampton Oceanography Centre
Seafloor Processes Division
Empress Dock
UK - Southampton, SO14 3ZN
phone: 44-1703-596570
fax: 44-1703-683066
e-mail: Neil.H.Kenyon@soc.soton.ac.uk

Prof. Dr. Tore O. Vorren
University of Tromsø
Institute of Biology and Geology
P.O. Box 3085
N-9037 Tromsø
phone: +47-776-44394
fax: +47-776-45600
e-mail: torev@ibg.uit.no

SUBCONTRACTOR:

Irish Marine Data Centre
80 Harcourt Street
IRE - Dublin 2
phone: +353-1-4757100
fax: +353-1-4757104
e-mail: bronwyn.cahill@marine.ie

EUROPEAN NORTH ATLANTIC MARGIN: QUANTIFICATION AND MODELLING OF LARGE-SCALE SEDIMENTARY PROCESSES AND FLUXES

J. MIENERT

GEOMAR Forschungszentrum für marine Geowissenschaften
der Christian-Albrechts-Universität zu Kiel
Wischhofstr. 1-3
D-24148 Kiel

SUMMARY

The European North Atlantic Margin (ENAM) project aims towards a better understanding of the processes influencing sediment stability, gas hydrates and mass wasting events. The changes in hydrographic conditions over geological time scales, for example during the last 18,000 kyr from glacial to interglacial times, influence the stability of gas hydrates at high latitudes, which play a key role in sediment stability. The frequency, causes and flow behaviour of mass wasting events related to gas hydrate stability indicate a spatial and temporal variability of marine systems from the formerly glaciated to the nonglaciated margin and from the shelf edge to the continental slope.

INTRODUCTION

Submarine gas hydrates appear to be common in northern European continental margin sediments because seismic reflection data and sampling have documented their existence (Eicken & Hinz, 1993; Andreassen *et al.*, 1995; Mienert & Posewang, 1997; Vogt et al., 1997, Mienert & Bryn, 1997; Posewang & Mienert, in press). Quantitative information about the distribution and concentration of gas hydrates in Norwegian margin sediments, however, is still poorly constrained. They are mainly inferred from seismic reflection surveys (e.g. Andreassen & Hansen, 1995; Posewang & Mienert, in press). Even though large research efforts have been devoted to deciphering the sedimentary processes moulding the margins (e.g. Dowdeswell et al., 1996), the timing, causes and flow behaviour of these large-scale events in relationship to gas hydrates are still largely unknown (Mienert et al., in press, Henriet & Mienert, in press). Physical properties of sediments prone to sliding and slumping are also poorly known as are the timing and amplitudes of the destabilisation of gas hydrates. These changes must be understood in order to generate reliable models for large-scale sedimentary processes, in particular, mass wasting events. In the future this will require major research programmes and efforts to develop new technologies in close cooperation with industry.

PRELIMINARY RESULTS

At the mid-Norwegian margin, the Trænadjupet slide has affected an area of about 15,700 km^2, of which the slide scar area comprises 8,170 km^2 (Figure 1 and 2) (Laberg & Vorren, in prep). The Trænadjupet slide involves sediments of late Cenozoic age and has a total volume of 760 km^3. The slope gradient within the slide scar is approx. 1.2° and sediments have moved up to 200 km from the present shelf break into the Lofoten Basin. The headwall of the slide scar is 150 m high and 120 km long (Figure 3). An up to 100 m high escarpment has been found further downslope. This may imply that sediments at different stratigraphic levels were affected by the failure or that several episodes of sediment failure have occurred within this area. Relatively little sediments have been deposited within the slide scar after the failure(s) occurred. The area where slide sediments accumulated is characterised by a hummocky

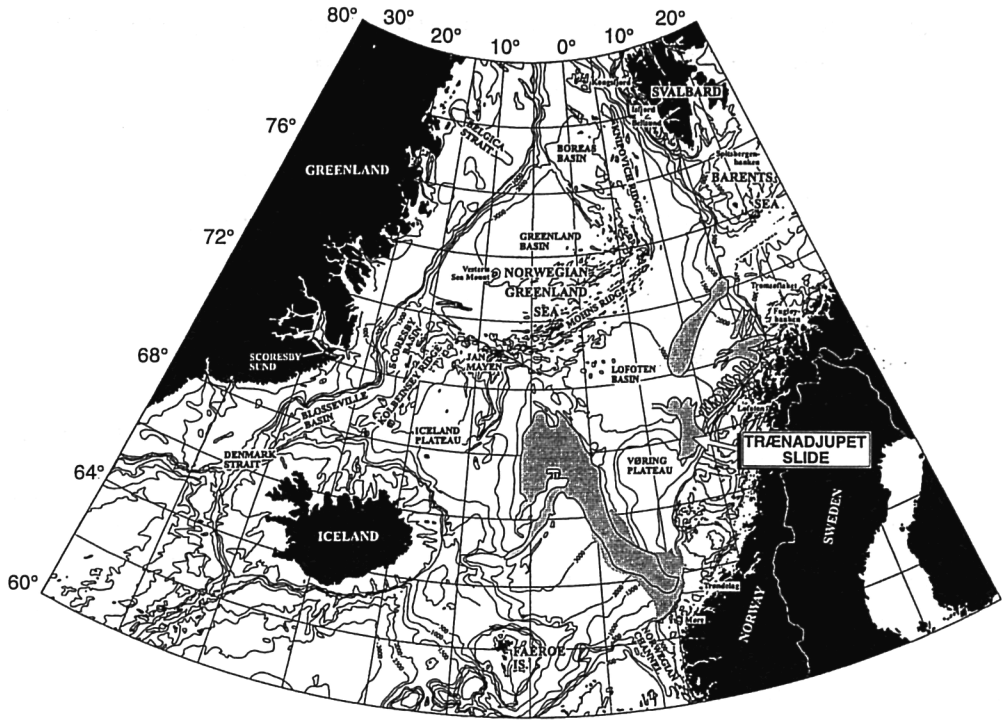


Figure 1: The Norwegian-Greenland Sea continental margins showing the major slides on the Norwegian margin icluding the Trænadjupet slide (Vorren et al., in press).

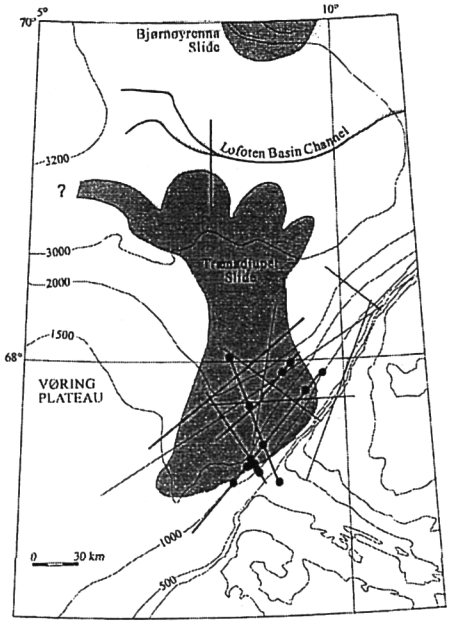


Figure 2: Area on the Mid-Norwegian margin continental slope where the Trænadjupet slide events eroded the sea floor. The seimic profiles are indicated by solid lines and the core stations by solid circles.

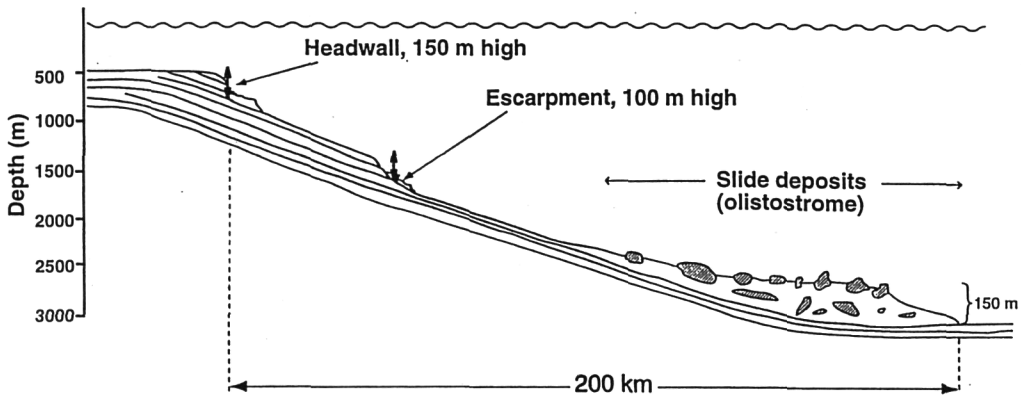


Figure 3: Cross transect of the Trænadjupet slide showing the headwall.

topography indicating that the sediment failure(s) has affected both unconsolidated and more consolidated sediments, i.e. smaller and larger blocks floating in an unconsolidated matrix. The distal slide accumulation is draped by 1 - 2 m of hemipelagic sediments (Figure 4). The Trænadjupet slide is probably relatively young (late Pleistocene - Holocene ?) because: i) the slide scar forms a prominent relief within the present sea floor , and ii) the slide-affected area is draped by a relatively thin layer of hemipelagic sediments. The existence of gas hydrates has been suggested on the base of bottom simulating reflectors observed in reflection seismic profiles and in (HF-OBH) high-frequency ocean bottom seismic data. The decomposition of these gas hydrates and the emergence of mud diapirs at the headwall of the slide may have triggered the slide event.

At the Storegga slide region, geophysical studies of gas hydrates at a drill site location (Bryn & Mienert, 1997) show a double BSR at about 0.35 s TWT and the deeper one at about 0.41 s TWT. ENAM seismic data, which are from the area NW of the drill site, show also two BSRs, but one at 0.1 s TWT and the deeper one at 0.35 s TWT (Posewang & Mienert, in prep.). Using average compressional wave velocities the deeper BSR is placed at approx. 285 mbsf which corresponds well to the theoretical base of the hydrate stability zone (HSZ). The calculated geothermal gradient using the phase diagram is approx. 50°C/km which is in agreement with the measured temperature gradient of 50°C/km in the bore hole (pers. comm. Norsk Hydro) where the strong BSR occurs at about 270 mbsf. The double BSRs show a patchy distribution and lateral consistency and moreover are not continously traceable such as internal lithological reflections, bubble pulses, multiples, peg-leg multiples or common BSRs. Therefore it is very unlikely that these are acoustic artefacts. Thus presently research is concentrating on the environmental conditions - which are not yet identified - that the causes unusual observed seismic pattern related to gas hydrates.

Modelling of the HSZ development for the time period from the Last Glacial Maximum (LGM) to the present indicates that the HSZ decreased between 120 and 40 metres depending on water depth. At about 1000 m water depth the HSZ decreased by about 80 metres. Since changes in the HSZ are apparantly long-term processes, we still are far away from understanding the sea floor reactions and developments involved in such a scenario. However, the identification of pockmarks and mud volcanoes on the continental slope (Vogt et al., 1997,

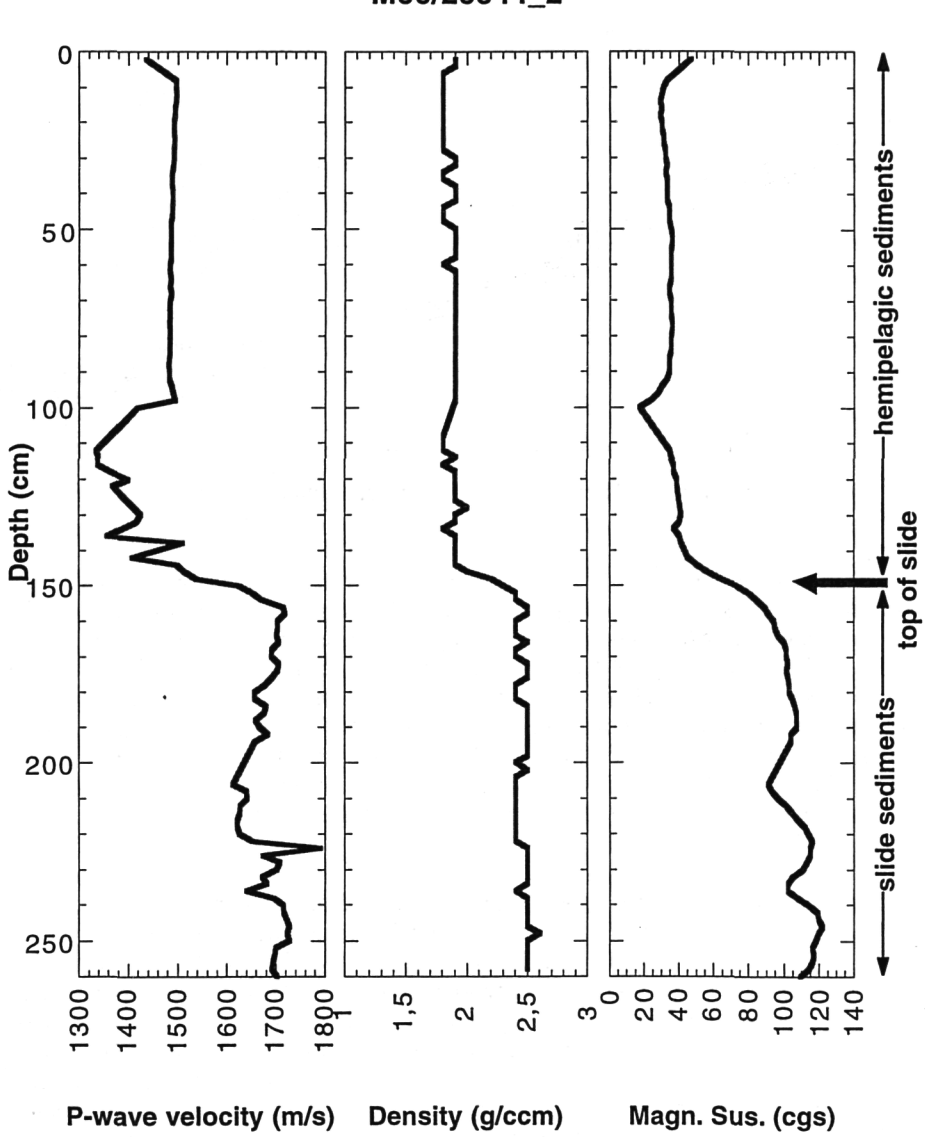


Figure 4: Sediment core physical property data showing the top of the last slide event and the thin draping of deposits after the slide event.

Mienert et al., in press) and craters on the shelf (Solheim and Elverhoi, 1993) point towards ongoing or past gas/fluid escape processes (Mienert and Posewang, in press) (Figure 5).

At the transition zone from the formerly glaciated to the non-glaciated margin region, the acquisition of high-resolution seismics and side-scan sonar data showed a major deep-sea fan off the Celtic Sea margin and long seismic lines allowed to tie into the canyons upslope. Quantification of sedimentary processes deduced from sonograph and seismic interpretations for the glaciated and nonglaciated north-eastern Atlantic margin has been started. Long-range side-scan sonar images of the "glaciated" Barents Sea margin have been analysed in

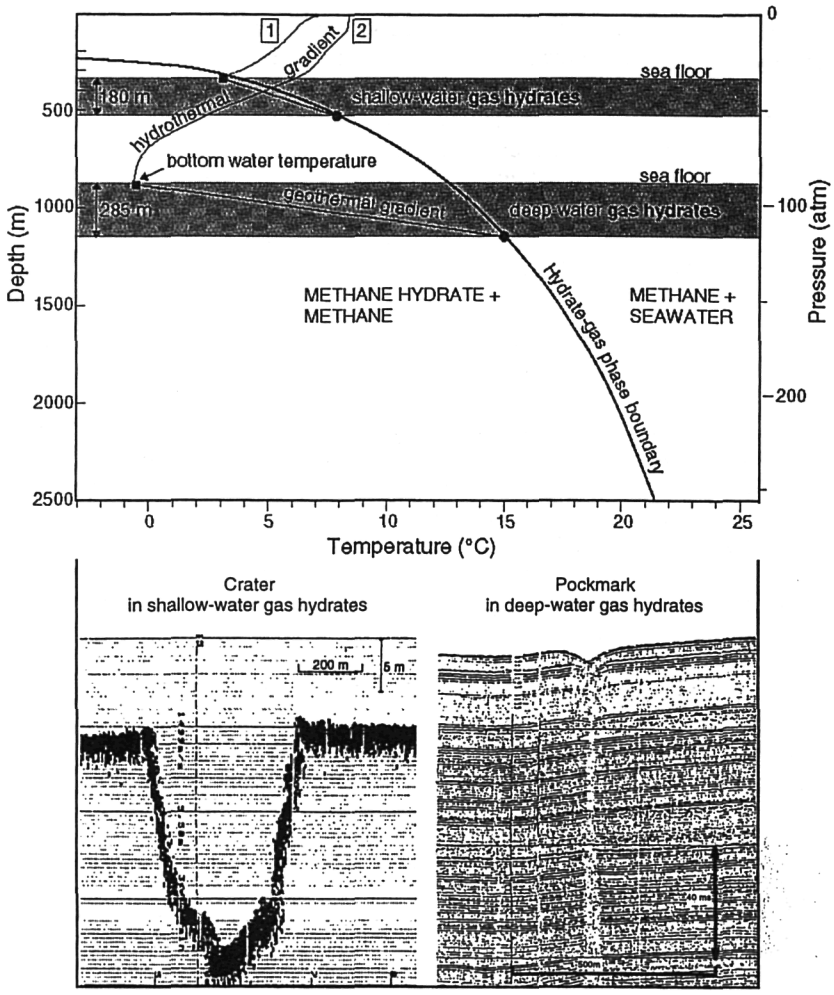


Figure 5: Stability curve for a mixture of pure methane and pure water. The geothermal gradient is 3°C/100 m for shallow-water gas hydrates and 5.5°C/ 100 m for deep-water gas hydrates. Under these conditions and the given bottom water temperatures, the HSZ in the shallow-water area of the Barents Sea has a thickness of 180 m and, in the deep-water area of the Storegga Slide, a thickness of 280 m. An increase in temperature or a decrease of pressure would lead to a dissolving of the gas hydrates and an escape of methane in the oceanosphere. Indicators of eruptive releases of gas exist in the shallow-water area through up to 30 m deep craters and, in the deep-water area, through 5 m deep pockmarks.

conjunction with results from previous geophysical investigations to test a qualitative model for sedimentation over the Bear Island trough mouth fans. Modelled sediment volume is in good agreement with the volumes inferred from seismic records. For the "nonglaciated" Celtic margin, interpretation of a few high-resolution slope sequences is in progress. From the data of the Celtic fan, a number of preliminary observations can be made. From the bathymetric survey, one can recognise the main area typical of a modern fan. The upper fan is characterised by the area where the main channel is bounded by high levees. The middle fan is characterised by a channel less pronounced in the topography. Finally, in the lower fan, the the channels lose

their surface expression. If we include the Austell Ridge and the Meriadzek Basin, the total area of the fan is about 17,000 km^2. Indications of channelisation appear in the upper Oligocene, but it is postulated that the modern fan reaching up to 500 m in thickness is mainly a Plio-Quaternary construction. Evidence of activity during the deglaciation and in the Holocene is recorded in the cores. The acoustic facies are suggestive of sand layers. Fan activity during a period of rising sea level, or even high stand, is likely when the head of feeding canyons intercept the shelf in areas of relict sand accumulations. The Celtic Banks, recently recognised as possible remnants of a deltaic system and submitted to a high-energy hydrodynamic regime are likely sources for the present-day fan sands.

Studies of several types of slope instability features west of Ireland using side-scan sonar showed that contour currents are one of the main ways that slopes in the region are fashioned. Sandy contourites are rarely recognised in studies of either ancient or modern sediments but are shown to be very significant in this part of the Atlantic. Side-scan sonar proved to be the most effective way to map the pathways of strong currents. Through this method, a hitherto unknown, strong northward-directed current was discovered in the Porcupine Seabight. Strong currents were also sweeping sands along the upper slope east of Rockall Bank and along the slope west of Porcupine Bank. Complex channels shaped by the cold, salty overflow water from the Norwegian Sea were mapped in the Iceland Basin. The deep sea turbidite channel system in the Porcupine Seabight was shown to be inactive during the Holocene. (This is in contrast to the situation in nearby submarine canyons which, during the same period, appear to have been the pathways for sands that have been brought to the shelf edge by tidal currents.) Terraces had developed along the channel, probably due to a slumping process.

MODELLING SEA FLOOR STABILITIES AND ICE FLOW BEHAVIOUR

Preliminary incorporation of the field data for numerical modelling of the time-dependent rate of sediment delivery from the former ice sheet intermittently bounding the north-eastern Atlantic to the continental shelf edge and upper slope has been accomplished for the Barents Sea area and is now extended to the south towards the transition from a formerly glaciated to a nonglaciated margin area. The numerical ice sheet modelling of sediment fluxes from the Eurasian ice sheet to the European continental margin is proceeding well. We have produced preliminary predictions of sediment flux from the ice sheet for the last 30,000 years, which is linked to the time-dependent numerical ice sheet model we currently use.

Laboratory experiments have displayed that hydroplaning/lubrication is critical for the mobility of subaqueous gravity driven mass transport. The presence of a basal layer of water severely reduces the bed friction and offers an additional explanation for the long travel distances and high velocities of many submarine flows on very gentle slopes. Hydroplaning also affects the rate of erosion and channelisation. The conditions for and consequences of a hydroplaning/lubricating layer have been demonstrated in terms of analytical calculations. A critical velocity for hydroplaning to occur is established with representative parameter values from the Bear Island fan. Equilibrium solutions for the stress reduction by lubrication/hydroplaning on a debris flow overriding a deforming mud layer is deduced from an analysis in cooperation with G. Parker (St. Anthony Falls Laboratory, University of Minnesota, USA). If the shear forces are present mainly in the underlying mud and a basal layer of water, the overriding debris flow moves more or less as a rigid block independent of rheology. Hence, an expression for the terminal velocity is found by a block consideration of the flowing masses, anticipation of a dynamic drag, constant coefficients and no wave resistance. With the equilibrium solutions for stress reduction, including parameter values representative for the North Atlantic margin, the hydroplaning rigid block is found to exceed

the critical velocity for hydroplaning to occur. Besides there are orders of magnitude difference in run-out length with and without hydroplaning. Hence the analytical calculations support the experimental results of sediment rheology independence and long run-out distance.

It is importnat to note that preliminary tests of existing numerical models based on either Bingham or Bagnoldian considerations of the flowing mass reveal that neither of the two models are applicable for huge subaqueous debris flows in their present versions. It seems to be necessary to adjust the code to the large quantities and long duration of large-scale subaqueous slides, combine the two concepts and include the effects of hydroplaning/lubricating layer and mass entrainment, and finally, allow different mechanisms for mass transport in various regions along the travel path.

ACKNOWLEDGEMENT

The paper is a result of the 2nd ENAM workshop in Keele (Irland). The contributions from ENAM partners are greatly acknowledged. This work is funded by the European Commission under contract MAS3-CT95-0003.

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TITLE : Coring Stable And Instable Realms in European Seas (project **CORSAIRES**)

CONTRACT NO: MAS3-CT950045 Concerted Action

COORDINATOR : Dr. J.P. Henriet
Renard Centre of Marine Geology (RCMG)
University of Gent
Krijgslaan 281, S8, B-9000 Gent, B
Tel. n° (Fax) : +32 9 264 4585 (4967)
E-mail : jeanpierre.henriet@rug.ac.be

PARTNERS :

Dr. H. Amann
Technical Universität Berlin - MAT
Müller-Breslau-Str. (Schleuseninsel)
D-10623 Berlin, D
Tel. n° (Fax) : +49 30 311 84 220 (200)
E-mail : amann@resy.vws.tu-berlin.de

Dr. G. Auffret
IFREMER, Géosciences Marines
Centre de Brest, BP 70
F-29280 Plouzané, F
Tel. n°(Fax) : + 33 298 224259 (4570)
E-mail : gauffret@ifremer.fr

Dr. Y. Lancelot
Centre d'Oceanologie de Marseille
Case 901 - Luminy
13288 Marseille Cdx 09 - F
Tel. n°(Fax) : + 33 4 91 82 96 11 (65 48)
E-mail : lancelot@com.univ-mrs.fr

Mr. A. Skinner
British Geological Survey
Murchison House, West Mains Road
Edinburgh EH9 3LA, UK
Tel. n°(Fax) : + 44 131 667 1000 (4140)
E-mail : ACSK@WPO.NERC.AC.UK

CORING STABLE AND INSTABLE REALMS IN EUROPEAN SEAS CORSAIRES

J.P. HENRIET and the CORSAIRES Team

c/o CORSAIRES Office
Renard Centre of Marine Geology (RCMG)
Universiteit Gent
Krijgslaan 281, 9000 Gent, B

SUMMARY The Concerted Action CORSAIRES promotes a sustainable European drilling action along Europe's margins and organizes for such purpose various scientific prospective and technology development workshops, stimulates technological project proposals, organizes site preparation actions and fosters educational initiatives.

1. INTRODUCTION : A Grand Challenge in the Deep-Sea

The author was twelve when, in 1957, the preparations for the *International Geophysical Year* were seeping to the public. An exceptional mobilization for the study of the Earth's oceans, polar areas, atmosphere and outer space. A global international commitment, which for the exploration of the oceans revived the spirit of the late 19th' cruise of the *Challenger*. A momentum which forged in the forthcoming decade a unique cooperation under the Antarctic Treaty, in the exploration of space, the race to the abyss, the onset of ocean drilling, the unveiling of the dynamics of the lithosphere. Discoveries would embrace the Earth's magnetosphere and radiation belts, mid-ocean ridges morphology and ocean current patterns, polar frontiers and atmospheric dynamics. A colourful artwork series in *Life* in the early sixties, vividly illustrating such thrilling discovery of our planet, ruined a boy's pocket-money, and determined his career.

He was twelve again an October day of 1994 in Bremen, when he witnessed the *défilé* of national delegates of all European states, stepping to the floor to endorse Europe's *Grand Challenges in Ocean and Polar Sciences*.

Ocean forecasting, ice coring, marine biodiversity, polar oceans, coastal dynamics and the deep-sea as a changing environment were formally identified as priority fields in which Europe - through its leading structures - decided to spend a major effort in the forthcoming decade. A decision which built upon two corner stones.

The first one was the careful intoduction of the Bremen conference by thematic Euroconferences, prepared through an exemplary cooperation between ESF and EC over a period of nearly five years.

The second one was the fact that the European Union - through a pioneer programme called MAST - had transformed in less than a decade a landscape of scattered laboratories and institutes into a genuine European marine community, in which transnational cooperation became the rule. Through MAST I, MAST II, European scientists and teams had matured towards a tight scientific community which has gained scientific leadership in many fields and which had laid the foundations for focalized grand ventures, challenges for the next decade : EuroGOOSE, EPICA, European ocean margin drilling.

The scientific programme drafted as outcome of the Euroconference *"The Deep-Sea as a Changing Environment"* (Suess & Le Pichon, Eds., 1994) could have been drafted today, close to five years later. It hasn't lost an iota of its visionary strength. High-resolution 4-D benthic exchange and transformation mechanisms, margin stability and high-resolution sedimentary records of changing environments, material and energy fluxes through fluid flow at the seabed are today - more than ever - major challenges in particular on those European margins which will face industrial development in the 21st century.

The conceptual division into the respective HiBETS, MASTER and GEOFLOW programmes proposed in the latter Euroconference was and is a sound approach for practical implementation, as it may help in structuring in a natural way teams and tools, but we identify today objectives on Europe's margins which - in one and the same marginal basin of Europe - call for an *integrated* action.

The term *action* is also befitting. There is a time for concertation, for the draft of a scientific programme, for its endorsement, and for its *implementation.* Throughout the Bremen meeting, the "MASTER" (Margin Stability and Environmental Record) community emphasized the need for ground-truthing key sites of Europe's margins, where high sedimentation rates offer unique perspectives for assessing the natural variability of climate in recent geological times, but where - through the same fluxes - large-scale slope instabilities are looming large.

Ground-truthing implies the acquisition of cores, long records, down to 200 to 300 m below the seabed, beyond the depth range of classical gravity coring, and beyond the specificity and capacity which a global drilling programme like ODP can or should offer. But gathering such cores is only one facet of the challenge. Developing new technology for addressing new scientific objectives is an inherent part of the challenge. And focusing on topics which can build bridges between different disciplines may herald a new level of reinforcement of the cohesion of European marine science.

Such were the terms of reference given to the CORSAIRES team at the issue of the Bremen conference. CORSAIRES drew its acronym from the MASTER subprogrammes STAR (STAble Regions) and INSTAR (INSTAble Regions), in full respect of their etymological particularity : "CORing Stable And Instable Realms in European Seas". A project aiming to support European projects and teams which individually could hardly get access to drilling. A concerted and integrated initiative, to optimize ship time and mobilization costs, potentially drawing upon the opportunities of

both an international programme like ODP for true deep-sea targets and e.g. European geotechnical vessels for shallower slope and shelf sites.

CORSAIRES started in 1996 as a MAST III Concerted Action, with objectives :

(1) to develop a scheme which should contribute to offer to a wide spectrum of scientific teams, projects and programmes a coordinated access to an appropriate drilling vessel, at a sustainable pace both in terms of resources and scientific valorization,

(2) by its nature of a "horizontal", concerted action, it aims to contribute to strengthen the cohesion of pan-European research projects and programmes targeted on the study of the sedimentary record of environmental changes and on seabed processes, with a strong educational and training sensitivity to make young European scientists and students aware of the potential of ocean drilling,

(3) to identify new technological needs and to stimulate European proposals for forging these tools.

These objectives are in full coherence with the 1997 Position Paper of the ESF Boards for European Marine and Polar Science (EMaPS) : "European initiatives in science and technology for deep-sea coring and drilling" (d'Ozouville & Jacobs, Eds., 1997) .

Ocean coring and drilling are identified in this paper as key technologies not only for Europe's geoscientists as they try to understand more fully the evolution of the planet, but also for the oil and gas industries in the exploration and exploitation of natural resources. Ocean margin drilling opens a true opportunity for European Science and Industry to advance in pace, on topics of both prime fundamental and applied interest. It is an opportunity for real synergy, which has to be exploited now, because industry cannot wait, and because environmental safety cannot be allowed to lag behind.

2. Margin Stability and Environmental Record themes : the CORE GROUPS

In January 1995 an open call for interest to initiate the CORSAIRES project resulted in 98 core site proposals from 47 European institutes and laboratories. They cover the entire European continental margin, yet can be grouped in 5 clusters : the Norway - Faeroer - Rockall region, the Porcupine - Celtic Sea - English Channel region, an area off the coast of Southern Portugal, the French - Italian Mediterranean Sea and the Greek Mediterranean. The scientific objectives of the proposals within each Core Group formulate coherent research topics and frame within EC projects. Most of them reflect present-day "hot topics" in the "Margin Stability and Environmental Record" (MASTER) themes of the Deep-Sea Grand Challenge.

The Norway - Faeroer - Rockall Core Group

The sites - most of which had been proposed within the framework of the EC MAST "ENAM" project (European North Atlantic Margins) and some national projects - are situated along the northern North Atlantic shelf margin and slope, from Norway to west of Scotland and to Rockall, as well as around the Faeroer and the submerged Bill Bailey and Lousy volcanic banks. This region is characterized by :

(a) the voluminous sediment supply during Quaternary glaciations, when glacial debris was transported to the shelf break by ice streams and dumped on the upper continental slope. Debris flows built large sediment cones prograding into the basin : North Sea Fan, Sula Sgeir Fan, Barra Fan. Large-scale instabilities affected the margins (Storegga slide).

(b) bottom currents associated to the Norwegian Deep Sea Water and Norwegian Sea Overflow Water control a pattern of contourite deposition and sea floor erosion around the Faeroer and the submerged volcanic banks. They display a strong variability between glacial and interglacial periods.

The definition of the general stratigraphy of this margin, the timing of major events of slope failure, the subsidence history of the volcanic banks and the history of the Norwegian Sea Overflow Water and the Norwegian Deep Sea Water currents are major drilling objectives.

The Porcupine Basin - Celtic Sea - English Channel Core Group

The Porcupine Basin is located Southwest of Ireland. It is the subject of extensive industrial exploration, in particular in view of the forthcoming South Porcupine Petroleum Licensing Round (1998), but it has only recently attracted the attention of the international scientific community. Most of this scientific attention is focused on the occurence of large mud mounds and cold water coral reefs, possibly related to gas seeps. Drilling proposals aim to elucidate the internal structure, biogeochemical messages, environmental setting and paleoclimatic controls on the genesis and development of such giant mounds.

The English Channel proposals focuses on the Hurd Deep, a 150 km long depression deeply incised in Cretaceous and Jurassic sediments and partially filled by younger sediments. Its origin is a matter of intense debate. The proposed drilling aims to resolve the problem by studying the nature and age of the infilling sediments.

The Celtic Sea shelf edge and slope are characterized by a post-Miocene prograding prism, cut by active canyons that feed a deep submarine fan, the Celtic Sea Fan. A large field of polygenic sand banks fringes the shelf edge. Despite many high-resolution seismic studies, neither age nor origin or development of these units is fully understood.

The South Portugal Core Group

The coring proposals in this area aim to study the changing fluxes of sediments through time related respectively to the Mediterranean outflow and the glacial/interglacial migration of the polar front. The history and palaeoceanography of the Mediterranean outflow can be studied by coring contourite deposits at the southern Portuguese margin.

The southward migration of the polar front has caused changes in the productivity of the surface waters and hence in the supply of organic matter to the slope sediments, which can reflect upon the stability of the slopes through the generation of gas. The detection of Heinrich events and the mapping of fluxes of ice rafted debris may help to analyse the variations in circulation in response to polar front migration.

The French - Italian Mediterranean Core Group

Three subclusters have been identified in this Core Area : the Gulf of Lions with the Rhône Fan, the Nice Slope with the Var Canyon and the Adriatic shelf.

Two legs have been proposed over the Rhône delta which spreads over a relatively wide muddy shelf and feeds a major deep-sea fan, and which is considered to be an excellent target to analyse the validity of sequence stratigraphic models for passive margins.

The Nice slope is a steep slope with major sediments instabilities, feeding the Var canyon and fan. A coring leg is proposed through the fan system to establish a comparison with ancient turbidite systems and to better understand the turbidite current dynamics and their record over the past 300.000 years. Another leg focuses on the geotechnical calibration of seismic data near sediment failure zones at the shelf break and upper slope.

The Adriatic basin sedimentary sequences consist of a continuous marine muddy section which is thought to be ideal to record and date high-frequency climate and sea level fluctuations.

The Greek Mediterranean Core Group

This Core Group covers the area from the western Adriatic Sea to the Aegean Sea. Sites have also been proposed on the Nile delta. It is a very large area with a complex structure. As a consequence the Core Group gathers a large number of core sites proposals with as many research topics. In general the core site proposals and their objectives can be grouped into five main topics :

(a) general stratigraphy and sediment characterization of basin sediments to calibrate seismic data and study tectonic and depositional processes in some of the main sedimentary basins,

(b) dating of marker horizons for quantifying subsidence rates and sediment supply,

(c) palaeoseismicity studies,

(d) hydrothermal processes and volcaniclastic deposition in the Hellenic arc to elucidate the evolution of the arc and its influence on the geochemical, sedimentological and climate history of the region as recorded in the marine sediments,

(e) the role of fluvial input in Neogene palaeoceanography to test productivity versus anoxia models with regard to Neogene sapropel formation.

3. SCIENTIFIC PROSPECTIVE: Gas Hydrates, Carbonate Mud Mounds and Cold Water Reefs along Europe's margins

Beyond the objectives of most of the proposals recorded early 1995 from the European scientific community, a special theme has moved towards the foreground, which offers challenging issues for future research along Europe's margins. Topics of a prime fundamental importance and with far-streching implications in areas of offshore exploration and exploitation, and topics which are at the cross-roads of geological, biogeochemical, geophysical, biological, palaeoceanographic and palaeoclimatic research. Topics which had been identified under the Deep-Sea Grand Challenges themes GEOFLOW ("GEOlogically induced FLOW through the seabed and material transport") and HiBETS ("High-resolution 4-D Benthic Exchange and Transformation Studies "), but which gain now an unsuspected momentum and actuality in view of recent discoveries along Europe's margins and their possible relevance in Europe's western frontier in offshore exploration.

A first theme focuses on gas hydrate research and its importance both at the global level and for European margin research. The *CORSAIRES Workshop "Gas Hydrates : Relevance to World Margin Stability and Climatic Change"* organized in Gent in September 1996 (J. Mienert & J.P. Henriet, convenors), opened challenging research perspectives.

On the introductory "Tutorial Day", leading experts in oceanic hydrate research conveyed the state of the art in the booming research on oceanic gas hydrates to a captivated audience of some hundred delegates and often very young scientists. This Tutorial was followed by a two-day Workshop dedicated to the exchange of information and discussions about the most recent data and evolving theories. The preliminary results of ODP Leg 164 on Blake Ridge, off the eastern US coast, were a highlight, but many European results of gas hydrate research in the North Atlantic, Arctic, the Eastern Mediterranean, the Black Sea or other hydrate provinces of the world gave evidence of a still small yet actively developing European research potential.

Four "Round Tables" offered a platform for animated prospective thinking and debates about the way to go for meeting the grand scientific, technological and strategic challenges offered by oceanic gas hydrates (Henriet & Mienert, 1998). A most stimulating confrontation was no doubt the one between marine geoscientists and climate modellers, who certainly did not straigthforwardly share views on the potential

climatic impact of gas releases from the seabed, but both parties frankly admitted the discovery of new perspectives. The proceedings of this CORSAIRES conference are published as the Geological Society Special Publication 137 (Henriet & Mienert 1998bis).

A *second theme* resulted straigthforwardly from discoveries made in 1997 by CORSAIRES-stimulated site surveys in Porcupine Basin, off southwest Ireland, where an intriguing drilling target had been proposed for CORSAIRES drilling by British and Irish scientists, in the heart of one of Europe's most promising deep hydrocarbon frontier provinces : a large carbonate mud mound with abundant *Lophelia* cold water coral communities, which might be related to thermogenic gas seeps. Quite a few of these mounds had been reported from industrial seismic data by Hovland et al. (1994), some with a height of more than 200 m and a cross section of several km. This target has been deemed quite attractive for a joint European effort, not the least for its potential for federating truly pluridisciplinary studies around a topic of both fundamental and applied relevance. The eventuality of the presence of shallow gas however requests the highest level of preparation and safety assessment through high-resolution reflection seismic surveys.

Site survey cruises stimulated by CORSAIRES have been embedded in an international educational effort : the IOC/UNESCO "Training Through Research" programme. A first cruise with a multinational team was organized in May 1997 with *R/V Belgica.* It soon revealed that the large mounds described by Hovland *et al.* are only one of several reef types and provinces in Porcupine Basin (Henriet *et al.* 1998). Two extensive and hitherto largely unsuspected deep-water reef provinces were discovered and mapped : a 1200 km^2 large province of buried mounds, many of them intriguingly ring-shaped, and a large barrier-type reef setting on the eastern margin of Porcupine basin. A follow-up survey was carried out in July 1997 with *R/V Prof. Logachev* with a mix of European and Russian students. A large number of shallow gravity cores, grab samples, video and photo material was gathered, while acoustic and seismic imaging further precised the morphology and extension of the "Hovland" and "Belgica-Logachev" mound ranges. These data are presently being exploited in a large number of laboratories in various European countries and Russia.

The post-cruise meeting of this UNESCO/IOC- and Flemish Government-supported "Training Through Research" (TTR) programme was organized in Gent in February 1998 as the second CORSAIRES thematic conference, with - co-sponsorship of STATOIL. It was largely a student-driven organization, in the spirit of the Floating University (PhD student B. De Mol, chairman of the organizing committee).

This *CORSAIRES / TTR7 "Carbonate Mud Mounds and Cold Water Reefs" Conference* drew a captivated audience from universities, industry and scientific institutes. Both senior experts and research students conveyed the state of the art in cold water carbonate and deep-water coral habitats research, from actual settings and fossil analogs. This blend of geologists, biologists, geophysicists, palaeontologists, environmental experts, hydrocarbon experts, policy makers, biogeochemists, etc. shaped a fascinating melting pot for brand new ideas, to be exploited soon.

Some highlights from the presentations and debates :

(a) Europe is unveiling along its Atlantic margins what might turn out to be one of the world's most extensive and diversified deep-water carbonate mud mound and cold-water coral belts. *Porcupine Basin may in deep-water carbonate research prove as prominent as Blake Ridge in gas hydrate research*, provided shallow drilling soon unlocks its numerous messages for science. Unlike Blake Ridge, Porcupine is on Europe's margins, and hence calls for a European initiative.

(b) Quantitatively, these extensive recent carbonate belts along the oceanic margins represent a hitherto unquantified CO_2 sink, which might solve maybe part of the modellers' enigma of the "missing CO_2 sink" in the carbon cycle (Dr. André Freiwald, *pers. comm.*). This urges for verification of the age and carbonate content of these mud mounds and even of the enigmatic thick and stratified carbonate-like deposits on the eastern margin of Porcupine Basin (the "sole" of the *Belgica* mounds), which call for drilling.

(c) Qualitatively, the phenomenon of large mud mound build-up on the deep-sea bed along Europe's margins requests a pluridisciplinary effort, federating geosciences, biosciences, physical oceanography and global change research, in a domain where industrial perspectives, environmental issues and scientific excitement meet. Gas seeps might be the initial control of some large mound settings, in particular of the ring-shaped reefs in the deep-sea, but environmental agents like currents and nutrient fluxes no doubt control their growth, in space and time: this topic clearly straddles the HiBETS and GEOFLOW themes.

(d) Europe has a large scientific community which has prepared itself for such challenge, both by extensive land studies on fossil equivalents in Ireland, Belgium, Italy and North Africa, and by the study of various habitats along the Norwegian and Faeroer margins. The new IGCP project 380 "Biosedimentology of microbial buildups (UNESCO-IUGS, 1995-1999) can prove an efficient gateway for the scientific exploitation of some significant drilling effort.

(e) The coincidence of such large coral habitats with Europe's western frontier in offshore hydrocarbon resources offers opportunities for improving Europe's expertise for the assessment of the sustainable use of the seabed, with due regard to the deep-sea ecosystems.

CORSAIRES and the Irish Petroleum Affairs Division are co-operating in the draft of a first *Catalogue and map of deep-water carbonate mud mounds and cold water coral reefs along Europe's continental margins* . A first draft of the catalogue and map from industrial data in the Irish EEZ has been presented at the Gent Carbonate Mud Mounds Workshop (Croker & O'Loughlin, 1998). This map could form the pilot map of a series, to be drafted in cooperation with various Geological Surveys and research institutes.

4. TECHNOLOGICAL PROSPECTIVE: HYACE, core logging, downhole measurements

A regular access to drilling vessels around Europe's margins should not only promote significant breakthroughs in fundamental science and environmental issues, but also provide a platform for the development of new tools.

Regarding coring technology, CORSAIRES has been able to build upon the recommendations of the 1995 "Coring for Global Change" Conference organized in Kiel (Mienert and Wefer 1996).

A first direct spin-off of the CORSAIRES Concerted Action is the MAST III HYACE project (Amann *et al.* 1998), involving research institutes and companies in Germany, France, Great Britain, Greece, The Netherlands, Norway and Spain. The HYACE (HYdrate Autoclave Coring Equipment System) is an innovative downhole controlled autoclave system to sample sediments of the deep-sea at *in situ* pressure and temperature. The particular target would be sediments containing gas hydrates on the continental slopes of Europe and worldwide, but it would serve any objective where e.g. the uncontaminated preservation of pore fluids and deep biosphere samples (bacteria) is of utmost importance. The international scientific community which gathered at the Gent CORSAIRES meeting on Gas Hydrates had unanimously supported such technological development, to be used on geotechnical vessels in Europe and worldwide, in particular also for the ODP programme.

A second topic actively promoted by CORSAIRES is the non-destructive logging of geophysical properties of cores. The first technological *CORSAIRES Workshop on "Core Logging"* was organized late July 1997 by IFREMER in Brest (convener G. Auffret). It was attended by 82 participants and provided a core logging intercalibration opportunity as well as demonstrations of core logging equipment for the workshop delegates. The port call of the *R/V Prof. Logachev* in Brest had been synchronized with the Core Logging Workshop for allowing the participation of the embarked students and researchers.

An outcome of the Brest Workshop, well prepared by a preliminary survey, is the submission of a concerted action proposal for *networking core measurement laboratories* and SME's in Europe.

Some identified objectives for such a network are :

(1) to evaluate the existing techniques,

(2) to design, manufacture and distribute a set of core standards dedicated to the intercalibration of core loggers,

(3) to compile, diffuse and update a bibliography about techniques and case studies,

(4) to organize training courses and to publish manuals,

(5) to express prospective views for the development of new technology.

The potential of *downhole measurements* in CORSAIRES-type boreholes has been evaluated and developments are stimulated by the Aix-en-Provence - Marseille pole of CORSAIRES. A new programme called "ARLES" (Automatic Recognition of Lithological Events) can improve the multi-scalar integration of downhole measurements and images by sorting, counting and measuring rock heterogeneities from Formation MicroScanner (FMS) downhole electrical images. Preliminary tests of the analysis of FMS borehole wall images have been performed on one of the ODP drill holes in carbonate rocks, as a testing ground in the process of adapting the logging techniques to efficient and relatively cheap operations on geotechnical vessels.

The greatest potential of using geotechnical vessels for scientific drilling may however result from the convergence of scientific and geotechnical downhole measurements, in particular in the emerging new field of "measurements while coring".

The second *CORSAIRES Technological Workshop "Measurement while Coring"* will be organized in Lisbon in May 1998. Invited experts from many parts of the world will convey their views on such new development. Particular emphasis may be laid upon the measurement of geotechnical parameters ahead of the bit, in first instance the undrained shear strength. Not only for its geotechnical relevance for the analysis of the stability of slopes, but also for its relevance in high-resolution lithological studies, for the study of early diagenesis in carbonte-rich sediments (cementation), for the evaluation of pore water pressure ahead of the bit, etc.

5. TRAINING AT SEA AND EDUCATION : CORSAIRES - TTR synergy

The co-operation between CORSAIRES and the *IOC/UNESCO "Training Through Research* " programme has demonstrated the power of such EC Concerted Action to project its outcomes to education at sea, around the theme of ocean coring. At the same time, a large research student community contributed to the preparation of drilling sites along Europe's margins. The joint embarcation of students on various research vessels, the joint analysis of cores in a post-cruise workshop and in various laboratories in the EU and Russia and the joint presentation of results on an international conference contribute to strengthen the *future* cohesion of European research, even beyond the EU dimension as it contributes to meet a major challenge for a 21st century Europe : the co-operation between western and eastern teams on the Eurasian continent.

This effort will certainly be continued. It forms a European component of the worldwide awareness of the need for education about the role of the oceans. Contacts could be further developed not only with Russia but also across the Atlantic with e.g. the US Consortium for Oceanographic Research & Education (CORE), striving for

similar goals (Mitchell & Schoedinger 1998). A striking feature of the latter programme is that it addresses not only university students, but also high school students.

CORE President Watkins urges "... to use the beauty and wonder of the oceans to excite and challenge our young people to learn more about the world they will soon be inheriting. The next generation of national leadership should be educated in the incredibly important role played by oceans of the world in supporting its rapidly expanding populations. If this can be done, then additional investment in ocean sciences and technology, badly needed, can be expected as a logical outcome" ... words which could straightforwardly have come out of a manifest for the UN's *"International Year of the Ocean 1998"*, and which can have for today's students an impact matching the one which some of us experienced at the dawn of the International Geophysical Year .

Ocean coring, which can open a horizon not only on the fascinating ocean dynamics but also on their *4th dimension* - namely the record of the development of oceanic margins through time and their response to varying environmental stresses and past climates - is an outstanding tool for realizing such objectives.

6. PILOT OPERATION PREPARATION

In addition to the Concerted Action tasks reported above, the first phase of the CORSAIRES programme has established numerous contacts for preparing a pilot operation. The main challenge again is not the gathering of the expertise, which is present in Europe, but the design of a sustainable funding line.

The core and baseline of such a sustainable funding has logically to be provided by EU support, because of its value for European science and technology, economical development , education and political cohesion, while added value should come from industry, geological surveys and national research foundations, whenever action focuses within their specific realm of interest.

Getting such a sustainable oceanic drilling scheme around Europe's margins sailing should become a major achievement of the *EU 5th Framework Programme.*

ACKNOWLEDGEMENT

The CORSAIRES programme has been started under theEC Concerted Action contract MAS3-CT950045. Initial support at the preparation stage had been granted by ESF. CORSAIRES acknowledges the co-operation of the numerous European and national scientific programmes, universities, institutes and governmental agencies contributing to this momentum towards sustainable drilling on Europe's continental margins.

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TITLE:	SIlicoN Cycling in the World Ocean: The Controls for Opal Preservation in the Sediment as Derived From Observations and Modelling **(SINOPS)**
CONTRACT NO:	MAS3-CT97-0141
COORDINATOR:	Dr. Ernst Maier-Reimer Max-Planck-Institut für Meteorologie Bundesstraße 55 D-20146 Hamburg, Germany Tel.: +49 40 41173-233, fax: +49 40 41173-298 E-mail: maier-reimer@dkrz.de

PARTNERS:

Dr. Ernst Maier-Reimer
Max-Planck-Institut für Meteorologie
Bundesstraße 55
D-20146 Hamburg, Germany
Tel.: +49 40 41173-233, fax: +49 40 41173-298
E-mail: maier-reimer@dkrz.de

Prof. Dr. Paul Tréguer
UMR CNRS 6539
Institut Universitaire Européen de la Mer
Université de Bretagne Occidentale
Site du Technopole Brest-Iroise
Place Nicolas Copernic
29280 Plouzane, France
Tel.: +33 2 98 49 86 64, fax: +33 2 98 49 86 45
E-mail: treguer@univ-brest.fr

Dr. Aude Leynaert
UMR CNRS 6539
Institut Universitaire Européen de la Mer
Université de Bretagne Occidentale
Site du Technopole Brest-Iroise
Place Nicolas Copernic
29280 Plouzane, France
Tel.: +33 2 98 49 86 57, fax: +33 2 98 49 86 45
E-mail: leynaert@univ-brest.fr

Dr. Olivier Ragueneau
UMR CNRS 6539
Institut Universitaire Européen de la Mer
Université de Bretagne Occidentale
Site du Technopole Brest-Iroise
Place Nicolas Copernic
29280 Plouzane, France
Tel.: +33 2 98 49 86 56, fax: +33 2 98 49 86 45

E-mail: Olivier.Ragueneau@univ-brest.fr

Dr. Christoph Heinze
Max-Planck-Institut für Meteorologie
Bundesstraße 55
D-20146 Hamburg, Germany
Tel.: +49 40 41173-245, fax: +49 40 41173-298
E-mail: heinze@dkrz.de

Dr. Thomas J. Crowley
Dept. of Oceanography
Texas A&M University
College Station, TX 77843-3146
Tel.: +1 409 845-0795, fax: +1 409 847-8879
E-mail: tom@ocean.tamu.edu

SILICON CYCLING IN THE WORLD OCEAN: THE CONTROLS FOR OPAL PRESERVATION IN THE SEDIMENT AS DERIVED FROM OBSERVATIONS AND MODELLING "SINOPS"

CHRISTOPH HEINZE[1], AUDE LEYNAERT[2], ERNST MAIER-REIMER[1], OLIVIER RAGUENEAU[2], PAUL TRÉGUER[2], THOMAS J. CROWLEY[3]

[1]Max-Planck-Institut für Meteorologie, Hamburg, Germany; [2]Institut Universitaire Européen de la Mer, Université de Bretagne Occidentale, Plouzane, France; [3]Texas A&M University, College Station, USA

1. INTRODUCTION

For future climate scenarios, coupled ocean-atmosphere climate models are used. These models are optimized with respect to the present climate. In order to assure that these models do not only reproduce the present climate but also changes to other climatic states, it is necessary to use these models for reconstructions of past climates. The model results of such attempts have to be compared and validated with sediment record findings.

For such comparisons up to now mainly the foramiferal isotopic record ($\delta^{18}O$, $\delta^{13}C$) and calcium carbonate dissolution indices (lysocline depth changes, $CaCO_3$ compensation depth changes, weight percentages of $CaCO_3$) have been used. Besides $CaCO_3$ and chemically almost inert clay, the third major marine sediment component is opal (biogenic silica). Opal is produced preferentially in upwelling areas by diatoms (phytoplankton) and radiolarians (zooplankton). Sediment core analysis has shown that also opal content in marine pelagic sediments carries a climate signal (e.g., Keller and Barron, 1983; Kumar et al., 1995). Estimates of the gross budget of the present marine silicon cycle are summarized in Tréguer et al. (1995) and Nelson et al. (1995). Up to now, however, the potential of biogenic silica as a paleo climate tracer is limited due to a lack of qualitative and quantitative understanding of processes which govern the marine silicon cycle.

The use of opal as a proxy for paleo-productivity reconstructions has been discussed during "OPALEO" (Ragueneau et al., 1996, meeting report in EOS), an international workshop held in Brest in June 1996, partly supported by the EC (MAS3 CT96 6332). Major result of this workshop was that opal provides a considerable potential as a paleoproductivity tracer (along with other productivity proxies in a multi-tracer approach), given a complete knowledge of the processes which govern the fate of opal from the silicification in the surface ocean down to the redissolution and accumulation in the sediment would be available (a detailed review about this issue will be published in Ragueneau et al., in preparation). Furthermore, in view of the growing data bases and available model concenpts it became obvious that observing and modelling scientists should combine their efforts in order to make a deciphering of the biogenic silica signal possible. Our project "SINOPS" within MAST-III is a first attempt to realize such an effort on the global scale.

2. OBJECTIVES

The basic goal of "SINOPS" is to collate existing observations about all aspects of opal available and to test and improve an existing geochemical OGCM (Ocean General Circulation Model) - the Hamburg Carbon Cycle Model (Maier-Reimer, 1993) – with these data. The four main objectives of the project are:

- (I) To provide a data base of observations and a general circulation model which allow comprehensive studies of the silicon cycling in the oceans.
- (II) To reproduce the first principles of silicon cycling in today's world ocean by use of an ocean general circulation model (OGCM).
- (III) To offer an explanation for the present opaline sedimentary distribution.
- (IV) To test our improved understanding of opal by a paleoceanographic application of the model and compare the simulations with the observed sediment record.

3. METHODOLOGY AND STRATEGY

In order to achieve the four major objectives described above we plan to persue the following procedure.

First of all, a comprehensive data base about biogenic silica will be set up. No particular field studies are planned within the project. Rather a most complete collation of already existing data on opal will be compiled. These data include all aspects of biogenic silica from the production in the euphotic zone (productivity measurements, rain ratios Si:C($CaCO_3$):C(POC)), the particulate flux through the water column (sediment trap data), down to the sediment (opal weight percentages in the sediment, deposition and accumulation rates). Of course, dissolved silica data from the water column and the sediment pore waters will also be included in the data set. Special emphasis will be placed on factors controlling opal dissolution and preservation since a profound knowledge of the associated processes plays a key role for a correct interpretation of the opal signal in the sediment. The data base to be compiled will be made available to the scientific community on a readily readable CD-ROM.

The basic modelling tool for the project will be the global Hamburg Carbon Cycle Model (Maier-Reimer, 1993) coupled to a chemically interactive sediment module (Archer et al., 1997; Bareille et al., in press; Heinze et al., submitted). This model is based on the grid and velocity field of a dynamical circulation model (the LSG-OGCM, Maier-Reimer et al., 1993) with 3.5°x3.5° horizontal resolution. The model includes parametrizations of basic processes governing the marine carbon and silica cycles such as air sea gas exchange, biogenic particle production, particle flux through the water column, redissolution and remineralization of biogenic particulate matter, sediment pore water reactions and diffusion, sediment accumulation and bioturbation. For the version which resolves the seasonal cycle (time step 1 month) as well as the annually averaged version (time step 1 year) control runs exist which serve as a starting point for improvements and development of more quantitatively correct parametrizations of natural processes. A seasonal model version is available which includes a refined trophic model including also zooplankton dynamics (Six and Maier-Reimer, 1996). In the initial phase of the project, emphasis will be placed on accelerating the model code in order to facilitate multiple integrations of sensitivity experiments during the optimization phase.

The combination of models and observations will start from a comparison of the existing model control runs with the data base. Deviations between model and measurements will have to be analysed in a systematic manner in order to identify weaknesses and strengths of the simulation. Results of this comparison will find the most

focussed way of improving the simulation within the next step of the project.

For an optimization of the agreement between simulated and observed marine silicon cycling experimentalists and modellers will work closely together. New parametrizations will be developed as soon as they can be derived from observational evidence. A one dimensional version of the geochemical model will be used for process oriented studies, and to test the code quickly for new approaches. Again, the focus will be on factors which influence the dissolution and preservation of biogenic silica within the water column and the bioturbated sediment. The result of this part of the project will be a - within the time frame of the project - optimal simulation of the marine silicic acid and opal distribution.

In a concluding step of the project, the improved model will be applied to two time slices of the paleocean: the Last Glacial Maximum (21 kyr BP) and the Miocene ocean (open Panamanian gateway). Both paleoceanographic situations are well documented by sediment core data for comparison and show considerable differences to the present ocean. Velocity fields from dynamical ocean model experiments as input for the geochemical model already exist for both time slices (Maier-Reimer et al., 1990; Mikolajewicz et al., 1993; Mikolajewicz and Crowley, 1997; Winguth et al., 1996) and are being refined at present. Existing simulations of past ocean sediment distributions show the potential of the model-observation combination for elucidating past climate changes (Heinze and Crowley, 1997; Heinze et al., submitted). From these studies, however, it became obvious, that a quantitative improvement of the simulations is needed for a better interpretation of the model results especially in view of the climate relevant role of the atmospheric CO_2.

4. AN EXAMPLE

In order to illustrate the sort of experiments which will be carried out during "SINOPS" we present here results from three different experiments with the annually averaged version of the Hamburg Carbon Cycle Model (see also Heinze et al., submitted). Relative to a control run, in two sensitivity experiments, the silicic acid pore water saturation value with respect to opal was doubled and halved. In the control experiment, a constant value of 1000 μmol/l was assumed. Observed silicic acid pore water profiles often level off at lower concentrations than this, indicating a local reduction in opal solubility (e.g., Archer et al., 1993). The extreme (and unrealistic)

(a)

(b)

(c)

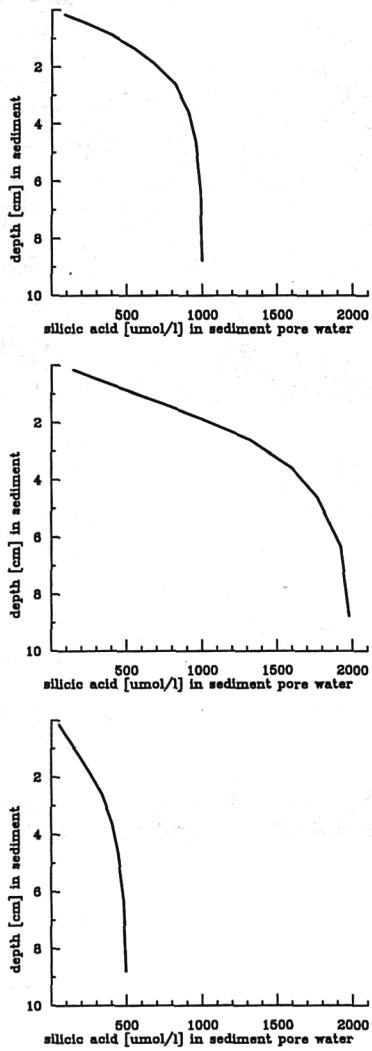


Figure 1: Simulated silicic acid sediment pore water concentrations at a grid point in the Ross Sea (Southern Ocean) for the (a) standard run and for two sensitivity experiments: (b) with the extreme assumption of a doubling, and (c) with a halving of the silicic acid saturation value with respect to opal. The unrealistically high value in (b) was chosen in order to test how linear the model response is for a change in the saturation value.

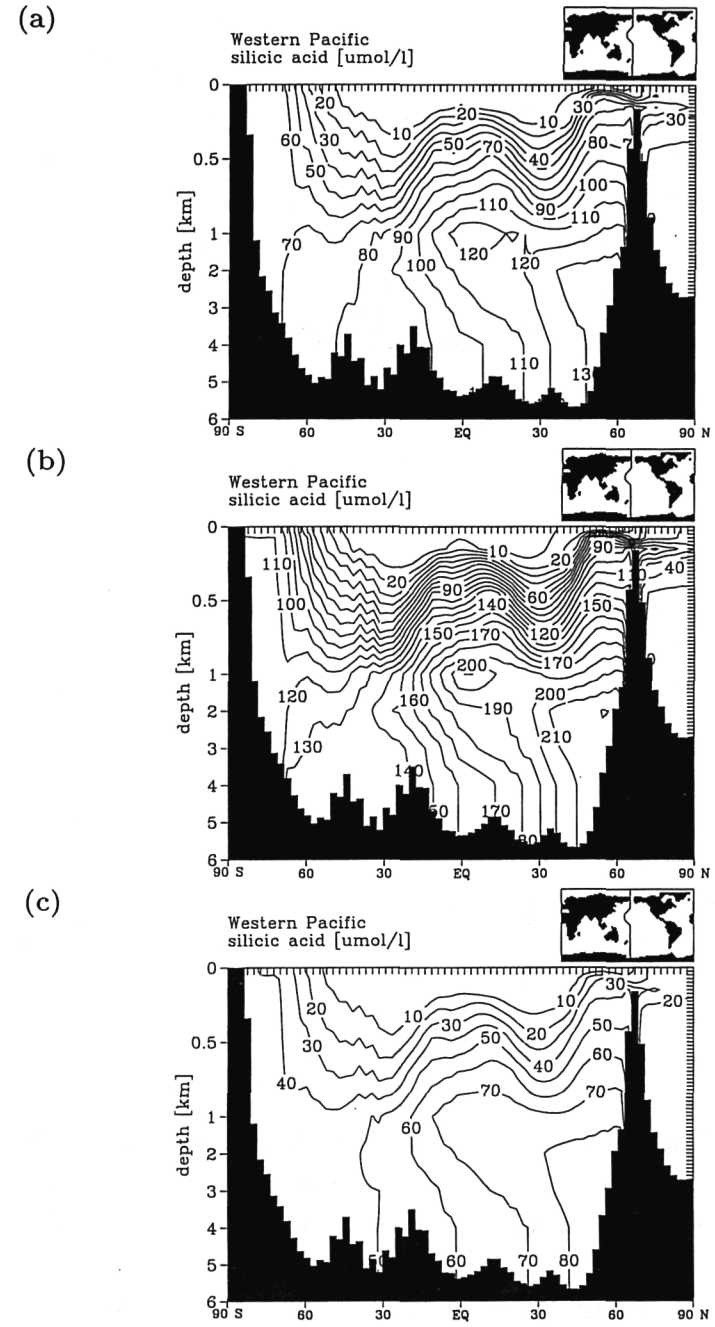
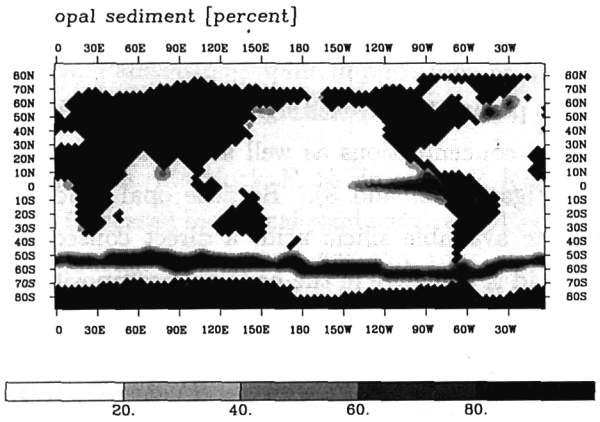
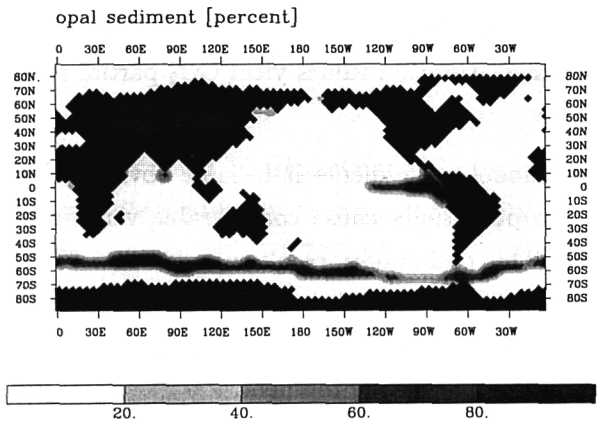


Figure 2: Simulated silicic acid concentrations along a cross section in the western Pacific Ocean for the (a) standard run , (b) a doubling, and (c) a halving of the pore water silicic acid saturation value with respect to opal.

(a)



(b)



(c)

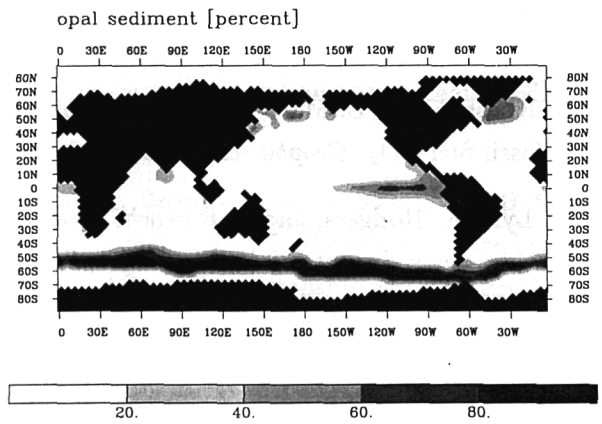


Figure 3: Simulated opal sediment distribution (average over the entire bioturbated zone) for the (a) standard run , (b) a doubling, and (c) a halving of the pore water silicic acid saturation value with respect to opal.

assumption of a doubling of the saturation value was tested additionally in order to investigate how linear the model response is.

A change in this parameter invokes significant changes in the water column and pore water silicic acid concentrations as well as the opal content within the bioturbated sediment (see Figs. 1, 2, and 3). Because opal production in the surface ocean is limited by the available silicic acid, a direct consequence of a change in water column silicic acid is a change in the hard part composition of marine biota. If silicic acid concentration increases, also opal production increases while $CaCO_3$ frustrule production declines. This has direct consequences for the atmospheric CO_2 partial pressure which decreases in parallel to the decrease of $CaCO_3$ production. While in the control run the resulting atmospheric pCO_2 is 278 ppm, the runs with a doubling and halving of the saturation values yield CO_2 partial pressures of 177 ppm and 414 ppm respectively.

Through these model experiments it became obvious, that changes in the biogenic opal budget can potentially cause considerable variations of the atmospheric CO_2 concentrations. This preliminary result suggests that "SINOPS" potentially will not only contribute to a better understanding of the sedimentary opal signal and the global silicon cycling but may also offer new perspectives for the climatically active role of silicon in the marine environment.

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TITLE: Making seismic reflection profiles available to the wider scientific community: SEISCAN – Capturing a European Legacy

CONTRACT NO: MAS3-CT97-0101

COORDINATOR:

Mr Peter R. Miles
Southampton Oceanography Centre
European Way,
Southampton, SO14 3ZH
United Kingdom
Tel.: +44 (0)1703 596560, fax: +44 (0)1703 596560
E-mail: P.Miles@soc.soton.ac.uk

PARTNERS:

Marc Schaming
Ecole et Observatoire des Sciences de la Terre,
5 rue René Descartes,
F-67084 Strasbourg Cedex, France
Phone +33 3 88416491
Fax +33 3 88616747
mschaming@eost.u-strasbg.fr

Dr Albert Casas
Dept. GPPG,
Facultat de Geología,
Universidad de Barcelona,
08071 Barcelona, Spain
Phone +34 3 4021418
Fax +34 3 4021340
albert@natura.geo.ub.es

Dr Maria Sachpazi,
Geodynamic Institute,
National Observatory of Athens,
Lofos Nymfon,
Athens 11810, Greece
Phone +30 1 3462710
Fax +30 1 3426005
m.scachp@egelados.gein.noa.gr

Dr Alessandro Marchetti,
OGS di Trieste,
Dept. Geofisica della Litosfera,
P.O. Box 2011,
34016 Opicina,
Trieste, Italy
Phone +39 40 2140230
Fax +39 40 327521
marchetti@ogs.trieste.it

MAKING SEISMIC REFLECTION PROFILES AVAILABLE TO THE WIDER SCIENTIFIC COMMUNITY: SEISCAN – CAPTURING A EUROPEAN LEGACY

PETER MILES[1], MARC SCHAMING[2], ALBERT CASAS[3], MARIA SACHPAZI[4], ALESSANDRO MARCHETTI[5]

[1] Southampton Oceanography Centre, Southampton SO14 3ZH, UK;
[2]EOST, Université Louis Pastuer, Strasbourg, France; [3]University of Barcelona, Spain;
[4]National Observatory of Athens, Greece; [5]OGS, Trieste, Italy

1. INTRODUCTION

Marine seismic reflection profiles have been collected in most European waters during scientific surveys by European academic institutions since the 1960s. Today, many of these data remain only as paper record sections - familiar to those who have participated in marine surveys. This is mainly due to the deterioration of recording media (magnetic tape), or the fact that appropriate instrumentation no longer exists, preventing re-play. The records often remain boxed and unreferenced; those of greater interest suffering more by handling and cutting, often to produce photographic prints for publication. Generally these data cannot be re-created and, with few exceptions, have not been archived in any photographic or reproducible form. Many centres did make photographic archives prior to the technological revolution but these are often small scale and not readily exchangeable. Photographic archives also became expensive to maintain.

2. OBJECTIVES

SEISCAN is a new 3 year MAST-III Supporting Initiative to rescue early seismic reflection profiles. The project will identify and locate seismic records, establish a metadata information base and enable large format digital scanning. Image archive will be to CD-ROM. This will create a seismic profile image database resource accessible to the wider scientific community. In addition to avoiding unnecessary re-acquisition of seismic data, a complete archival of existing data will help guide the location of new survey lines. For the geoscientific communities *SEISCAN* will make more data available for academic research in general and hopefully encourage further international collaboration. The project will additionally provide

data for monitoring the marine environment with direct relevance to the environmental impact of mass wasting, slope stability and the existence of gas hydrates.

3. THE DATA

The data in question are the electro-sensitive monochrome linescan paper records generally used to monitor seismic reflection data. These may have already been analyzed, possibly published and now lie un-referenced, inaccessible to many marine science workers for new regional analyses. The target data area covers European Exclusive Economic Zone waters beyond the shelf break in the NE Atlantic, Norwegian-Greenland Sea and Mediterranean Sea. These data represent 30 years of research funding throughout the EC. Data that can be re-played from magnetic tape will not be included in the archive but the reconstruction of trace information on paper back to digital form (wiggly trace) is planned as a secondary objective. This enables further processing of selected record sections.

4. PROJECT MANAGEMENT

SEISCAN is being co-ordinated from Southampton Oceanography Centre, UK (SOC) in collaboration with four partner European research centres:-

Ecole et Observatoire des Sciences de la Terre, Université Louis Pasteur, Strasbourg,
Facultat de Geologia, University of Barcelona,
Geodynamic Institute, National Observatory of Athens,
Osservatorio Geofisico Sperimentale di Trieste.

Each partner is responsible for liaison with research centres in separate European areas to collate metadata on seismic records qualifying for scanning. Scanning centres will be established in Barcelona and Strasbourg. These facilities may subsequently re-locate not only to Southampton, Trieste and Athens but elsewhere to meet demand. SOC and Strasbourg will share the database management and data processing responsibilities of the scanned seismic images. Data management and processing will be carried out to specific quality control criteria with each partner participating in monitoring the progress and security of data from their region. In addition, the implementation of common procedures across the project will enable partner institutions to pool processing and database management expertise.

Images created by the project will be stored on CD-ROMs for immediate retention by contributing institutions and a Web site (*http://www.soc.soton.ac.uk/CHD/Research/Seiscan*) will catalogue progress with links to partners. On completion of the project the images, their navigational information and metadata (conforming to the FGDC, 1994 standard) will be disseminated in a PC accessible format. Distribution of copies of the data sets with the major marine data centres and libraries will complete the data dissemination programme.

The project partners will first scan their own data, then their respective national data that exists outside their own institution. The scanning phase will then extend to data from all other European centres. To achieve this the project partners will each co-ordinate the data from separate European areas. The actual amount of data that qualifies for *SEISCAN* in Europe has been difficult to assess from the outset. However the scale of the problem has been recognised by the EC as sufficiently large to provide the funding. This was in response to wide agreement that national research funding has found increasing difficulties in meeting the costs of seismic archaeology. It is hoped that further international collaboration can extend this initiative to other waters.

5. CONCLUSION

SEISCAN began in October 1997. A project-wide hardware and software policy has been implemented with the installation of common systems. This has the major advantages of built-in exchangable platforms and familiar computing environments for partners at each centre. The image processing software of CALDERA is installed at each centre for integrated scanning, processing and annotation. National marine research centres and university departments throughout Europe are being invited to participate through requests for information. Institutions will be encouraged to place staff at partner or processing centres to aid data compilation. It is planned that skills and training will be shared throughout the participating institutions.

ACKNOWLEDGEMENTS

This contribution is adapted from Miles et al. 1997, Eos Volume 78 No 50:3.

I.2. Extreme marine environments

I.2.1. The deep sea floor

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

CONTRACT NO: MAS3 - CT950018

COORDINATOR: Dr A.L.Rice
Southampton Oceanography Centre, Empress Dock, Southampton
SO14 3ZH, U.K.
Tel: +44 (0)1703 596357
Fax: +44 (0)1703 596247
e-mail pht@soc.soton.ac.uk

PARTNERS:

Dr J.D. Gage,
Dunstaffnage Marine Laboratory,
PO Box 3, Oban,
Argyll, Scotland, PA34 4AD
Tel +44 (0)1631 562244, (direct 567821)
Fax +44 (0)1631 565518
e-mail JDG@dml.ac.uk

Dr Magda Vincx,
State University of Gent,
Institute of Zoology, Marine Biology Section,
K.L. Ledeganckstraat 35,
B-9000 Gent, Belgium
Tel +32 92 64 5210
Fax +32 92 64 5344;
e-mail Magda.Vincx@RUG.AC.BE

Dr H Weikert,
University of Hamburg,
Institut fur Hydrobiol. u. Fischereiwissenschaft,
Zeiseweg 9, 22765 Hamburg,
Germany,
Tel +49 40 4123 6680
Fax +49 40 4123 6696
e-mail weikert@rrz.uni-hamburg.de

Prof P Treguer,
Institut Universitaire Europeen de la Mer, URA CNRS - 1513,
6 Av le Gorgeu.,
29285 Brest Cedex, France
Tel +33 2 98 01 61 52
Fax +33 2 98 01 66 36
e-mail treguer@univ-brest.fr

Dr G. Wolff,
University of Liverpool,
Department of Earth Sciences,
PO Box 147,
Liverpool, L69 3BX
Tel +44 (0)151 794 4094
Fax +44 (0)151 794 4099
e-mail wolff@liverpool.ac.uk

Dr. L. Laubier,
Institut Océanographique,
Lab. de Physiologie des Etres Marins
195 rue Saint Jacques,
75005 Paris France
Tel +33 1 43 25 61 10
Fax +33 1 40 51 73 16
e-mail laubier@com.univ-mrs.fr

Dr Per Hall,
Dept of Analytical and
Marine Chemistry,
Univ. Goteborg,
S 41296 Goteborg, Sweden
Tel: +46 31 77 23623
Fax: +46 31 77 22785
e-mail per@amc.chalmers.se

Dr J. Patching
Marine Microbiology,
Ryan Institute,
University College,
Galway, Ireland
Tel +353 91 524411 ext 2398
Fax +353 91 525005 or 750456
e-mail John.Patching@ucg.ie

Dr. M. Sibuet,
IFREMER,
Centre de Brest,
BP 70, 29280 Plouzané,
France
Tel: +33 2 98 22 43 03
Fax: + 33 2 98 22 47 57
e-mail msibuet@fr.ifremer

Dr Tom Brey,
Alfred Wegener Institut
fur Polar und Meersforschung
Postfach 120161,
27515 Bremerhaven
Germany
Tel: +49 471 4831 316
Fax: +49 471 4831 149
e-mail tbrey@awi-bremerhaven.de

Dr Roberto Danovaro,
Marine Biology Section,
Facolta di Scienze,
Universita di Ancona,
Via Brecce Bianche, 60131 Ancona
Italy
Tel: +39 71 2204514,
Fax: +39 71 2204513
e-mail Danovaro@anvax1.unian.it

Dr G Duineveld,
Netherlands Institute for Sea Research,
PO Box 59, 1790 AB Den Burg,
Texel,The Netherlands
Tel: +31 2223 69533
Fax: +31 2223 19674
e-mail duin@nl.nioz

Dr. D. Roberts,
School of Biology and Biochemistry,
Queens University, Medical Biology
Building, 97 Lisburn Road,
Belfast, BT9 7BL,
Tel +44 (0)1232 272249
Fax 44 (0)1232 236505
e-mail D.Roberts@Queens.ac.uk

Dr Christophe Rabouille,
Centre des Faibles Radioactivités,
Domaine de CNRS,
91198 Gif-sur-Yvette,
France
Tel: +33 1 69 82 35 30
Fax: +33 1 69 82 35 68
e-mail rabouille@cfr.cnrs-gif.fr

Dr O. Pfannkuche,
Geomar,
Research Centre for Marine
Geosciences,
Wischhofstrasse 1-3,
24148 Kiel, Germany
Tel: +49 431 600 2113/2282
Fax: +49 431 600 2928
e-mail opfannkuche@de.geomar

Prof S P Varnavas,
University of Patras,
Dept of Geology,
26110 Patras, Greece
Tel: +30 61 991 972
Fax: +30 61 997 700
e-mail S.P.Varnavas@upatras.gr

BENGAL: HIGH RESOLUTION TEMPORAL AND SPATIAL STUDY OF THE BENTHIC BIOLOGY AND GEOCHEMISTRY OF A NORTH-EASTERN ATLANTIC ABYSSAL LOCALITY

A.L. RICE[1], J.D. GAGE[2], R.S. LAMPITT[1], O. PFANNKÜCHE[3] & M.SIBUET[4]
[1]Southampton Oceanography Centre, Southampton, U.K.;[2]SAMS, Oban, Scotland;
[3]GEOMAR, Kiel, Germany; [4]IFREMER, Brest, France.

SUMMARY

BENGAL runs for three years from 1 February 1996, with 17 partners from 9 European countries. It involves an intensive study of a single abyssal locality in the north-eastern Atlantic which will be visited and sampled several times over a period of about two years. The overall objective is to understand how the physics, chemistry and biology of the abyssal boundary layer respond to, and modify, the incoming chemical signal from the overlying water column and thus affect the palaeoceanographic record in the underlying sediment. Although good progress has been made, with several successful cruises gathering data for most of the projects specific tasks, a range of problems will preclude all of the objectives being achieved. Moreover, the early results suggest that 1997, the main field study year within the programme, was an unusually poor year for phytodetritus, precisely what we did not want! Nevertheless, BENGAL is one of the most intensive and successful studies ever undertaken at a single locality on the floor of the deep ocean and has already produced significant data, including an indication of a recent, and natural, major change in the structure of the benthic community.

INTRODUCTION

Background and current state of the art

The sediment drape of the deep ocean bed represents the largest store of organic carbon on the planet, and transport to the deep sea below the pycnocline has the potential for removing carbon from the surface waters and the atmosphere for a very long time if not permanently. Hence the deep-sea sediment can be regarded as a vast sink for carbon from natural and anthropogenic sources and also a record of past biogeochemical and climatic conditions. The deep-sea bed also provides a habitat for a structurally complex and taxonomically diverse community of predominantly small-sized animals depending on the amount of organic material available (Sibuet *et al*, 1989).

In the past, the small fraction of euphotic zone productivity exported to the seafloor as a sediment rain was assumed to take so long to reach the bottom that the levels of particulate organic matter reaching the seabed would be both low and refractory, so that the resulting sparsely dispersed benthic communities were thought to play only a minor role in oceanic processes and biogeochemical equilibria. Data from a variety of sources, including ^{228}Ra chronology of the shells of a benthic mollusc (Turekian, *et al*, 1975), sediment tray recolonisation experiments (reviewed in C.R. Smith & Hessler, 1987), low rates of organic degradation (Jannasch *et al*, 1970), 'snapshot' measurements of oxygen consumption of the sediment and of individual animals (e.g. K.L. Smith, 1978; Childress & Thuesen, 1982), and finally bioturbation measured as diffusive mixing from particle-associated radio tracers (Guinasso & Schink, 1975; Aller, 1982) and from time-lapse photographs of the long persistence of holothurian trails (Gardner *et al*, 1984), all supported the idea of a "low activity ecosystem" at the sea bed buffered from surface-driven exports of energy and material by the attenuating effect of the deep water column.

This encouraged a geochemical perspective of the recycling of particulate and dissolved material at the deep ocean floor that treated the biota as a 'black box' with simple

steady state input functions (measured by downward particle flux) and outputs (measured as oxidant flux)(e.g. Berner, 1980). The biologist's view on the other hand has been to map the passage of organic carbon or energy through the benthic food web in a box model quantifying energy flow in relation to community structure using boxes categorising faunal size classes and/or functional groups (Mahaut, 1991; Sibuet *et al*, 1993). In considering these divergent approaches it is necessary to recognise that the biological and physical processes mentioned below can impact the terms of the classical diffusion/advection model of diagenesis in several ways that render the assumption of a simple relationship between organic carbon degradation and concentration highly misleading (C.R. Smith 1992).

Time-series and other observations over the past decade now indicate much closer coupling of surface production to the deep-sea benthic ecosystem. The discovery of seasonal reproductive periodicities in benthic macro- and megafaunal species in the Rockall Trough was linked to a possible seasonally pulsed flux to the seabed (Lightfoot *et al*, 1979; Tyler & Gage, 1980). Seasonal variation in the 'drizzle' of relatively refractory particles was initially detected from sediment trap time-series (e.g. Deuser & Ross, 1980; Honjo, 1982; Wefer, 1989), with rapid transfer of particle flux being tracked into the deep ocean (Asper *et al*, 1992. Furthermore, that this rain of particles can be punctuated by dramatic 'downpours' of phytodetritus carpeting the bottom with labile food is now known from several sites in the Atlantic (Billett, *et al*, 1983; Rice *et al*, 1986; Thiel *et al* 1988/89; Hecker, 1990; Pfannkuche, 1993; K.L. Smith *et al*, 1994; Rice *et al*, 1994). The dynamic response of the benthic community in terms of *in situ* measurements of sediment community oxygen consumption (SCOC), microbial and meiofaunal biomass and growth rates, and the enriched gut contents of larger animals has been demonstrated in several studies (Aller & Aller, 1986; Lochte & Turley, 1988; Billett *et al*, 1988; Cahet & Sibuet, 1986; Cahet *et al*, 1990; Gooday, 1988; Graf, 1989; Gooday & Turley, 1990, Pfannkuche, 1992, 1993; Sibuet *et al*, 1982; Tyler *et al*, 1992; Pfannkuche & Lochte, 1993; Campos-Creasey *et al*, 1994; K.L. Smith *et al*, 1994). A similar response has been inferred in the timing of accelerated growth detected in skeletal markers and seasonally enhanced recruitment (Gage & Tyler, 1985; Gage, 1990, 1991) as well as in reproduction in macro- and megafauna (Tyler, 1988; Tyler *et al*, 1992). While as yet less clear, qualitative differences in pulsed detrital flux may also cause changes in behavioural activity of large deposit feeders, such as burrow stockpiling, coprophagy and selective grazing (Jumars *et al*, 1990; C.R. Smith, 1994), and in foraging patterns of scavenging abyssal fish (Priede *et al*, 1994; Mahaut *et al*, 1990).

Furthermore, a changed perception of the transmission of kinetic energy to great depths has altered significantly our view of the physical environment of the deep-sea benthic boundary. Although perhaps still to be regarded as characterised by low-energy bed flow, studies from the High Energy Benthic Boundary Layer Experiment (HEBBLE) indicate that pulses of erosion and deposition driven by surface-derived eddy motions transmitted to great depths may occur over large areas of the abyss, and be frequent in some (Gross *et al*, 1988; Hollister & McCave, 1984; Hollister, Nowell & Jumars, 1984; Klein, 1987; Richardson *et al*, 1993; Kontar *et al*, 1994; Auffret *et al*, 1994).

As in coastal waters, the deep-sea BBL ecosystem seems to be a complex web of energy and material flows involving huge diversity in form and activity fuelled by a variety of metabolic pathways and chemical reactions. Such functional diversity appears to allow organisms to extract energy from reduced organic matter over a wide range of oxic (and anoxic) conditions. While even knowledge of the standing crop, let alone dynamics of certain categories, such as the near-bottom bacterio- micro- and macrozooplankton, is particularly sparse, there are severe deficiencies in knowledge of the biology of the sediment dwellers at the level of the individual biota or functional group (defined by considering the size categories

and trophic behaviour at the species level). For example, the total oxygen demand of the sediment does not determine the oxygen respiration of such important groups as the bacteria, meiofauna and macrofauna, much less that of individual species, while the dissolved organic pool may provide an important trophic input to groups such as the pogonophora (Southward *et al*, 1986), and possibly the foraminifera and large agglutinated protozoans (Levin & Gooday, 1992). Even specific rates of carbon and nitrogen transfer between functional groups or compartments are quite often based on mass-specific respiration or feeding rates covering broad ranges. Indications (see above) are that the responses of these groups to episodically increased organic input or bed flow regime may be dramatically different from 'normal' levels. It is therefore risky to apply an arbitrary value from this range to bulk measurements obtained from benthic surveys for estimating material flows within the benthic ecosystem. While it is now known that animal guts are sites of elevated microbial biomass and probably activity, the implications in terms of the overall fate of sedimented particles is unknown, and as yet not taken into account in incubation experiments attempting to model early detrital degradation.

Deposit feeding has now been recognised as the activity responsible for nearly all biogenic movement of sediment in the deep sea. As in shallow water, bioturbation mixes and irrigates the sediment layer, and in doing so will profoundly modify sediment chemistry and material fluxes by creating a complex structure of microenvironments reflecting widely varying chemical conditions and patterns of solute and particle transports into and out of the sediment (Sibuet, 1984). Such activity and structure will compromise the overall significance of mass flux rates measured at the sediment surface. Yet empirical assessment of the significance of pattern and intensity of bioturbation seems to have little predictive value with regard to sediment fluxes elsewhere (Jumars & Wheatcroft, 1989). The significance of deep burrowing, spatially rare megafauna extending far below the oxic/anoxic chemocline, and hence profoundly modifying the sedimentary record, remain particularly enigmatic. Some, such as pogonophores, appear to feed independently of the deposit surface on reduced material 'mined' at depth in the sediment. Predictive models need therefore to be developed of deposit feeder body size allometry and energetics as functions of *a)* varying food quality over broad temporal scales and *b)* bioturbation style. At the same time, the role of deposit feeder digestion in the geochemical kinetics of organic matter remains underexplored.

The implications of these developments regarding global-scale biogeochemical processes are only just being addressed, and large uncertainties remain. In particular, better temporal and spatial definition of the various mechanisms (both physical and biological) controlling transformations of organic matter at the abyssal benthic boundary is required. These data need to be related to the origin, amount and quality of material buried, particularly in terms of the proxies in the sediment (isotopic composition of biogenic material and lipid and other biomarkers) utilised in palaeoceanography to decode past climate changes from the sediment record. They also need to relate to other studies on the continental slope, where both sediment biomass and metabolism are disproportionately high in relation to the restricted area.

An example of problems in interpreting proxies of past conditions is provided by biogenic silica (opal). The opal content of sediments has been used to reconstruct the past productivity of siliceous phytoplankton (mainly diatoms) in several regions of the world ocean (Lyle et al, 1988; Rea *et al*, 1991; Herguera, 1992; Bareille *et al*, 1991). However, Tréguer *et al* (1995) have recently shown that areas where opal is accumulating do not necessarily correspond to those where primary productivity is high, but only to regions where conditions lead to regionally enhanced preservation of silica. Consequently, it is important to understand how the opal profiles in sediments are likely to be affected by Non Steady State processes,

such as seasonality, which are not taken into account by present-day models of biogenic silica diagenesis.

Similarly, the preservation in the sediments of calcium carbonate debris from the skeletal remains of foraminiferans or coccolithophores has been a matter of considerable debate during the last ten years. This preservation is important because the pCO_2 in the atmosphere is influenced over long (>1000 year) time scales by changes in the dissolution/preservation ratio in the sediment (Sundquist, 1993). Calcite dissolution occurs when the water becomes undersaturated with respect to this particular phase, and is therefore driven by the water chemistry and pressure. Mineralisation of organic matter and the resulting pH decrease in sediment pore waters may promote undersaturation. The saturation horizon (the depth at which calcite becomes undersaturated) in the north Atlantic is situated between 4500 and 5000m depth. The BENGAL study site, at a depth of c4850m and with a significant seasonality in the supply of organic matter (see below), is therefore of particular interest to test the influence of the mineralisation, and its intra-annual variability, on the dissolution of carbonate.

Furthermore, for adequate budgeting of all inputs it is also necessary to take into account the variety of physically and biologically mediated transports to the benthic boundary layer besides passive sediment rain. These include: *a)* sediment movements driven by turbulent lateral advection caused by internal tides up to mass sediment resuspension and redeposition driven by abyssal "benthic storms", *b)* the significance of large organic packages from corpses of larger nekton and terrestrial plants, *c)* material fluxes and refluxes associated with active, biogenic transports by migrating abyssopelagic animals, and that caused by reproduction and larval dispersal.

Specific objectives of BENGAL

The main questions flowing from the above are: How important is the BBL community in the process of transferring sedimented material into the geological record? What feedback processes operate between the input and eventual burial of organic matter? Do high kinetic energy events have an important effect on the fate of sedimented material? Although all of these questions could not be answered within the project, three testable hypotheses were established:

- that there is a rapid and measurable response among all components of the BBL community to pulsed export flux from the euphotic zone
- that extreme, as much as normal, hydrodynamic conditions determine the fate of sedimented material flux to the deep-sea floor
- that the response of the benthic community, through physical and trophic feedback processes, is a major determinant of material flow and burial at the benthic boundary layer

To address these hypotheses, BENGAL has the following specific objectives:

a) To monitor, at a relatively simple but highly seasonal abyssal locality, the quantitative and qualitative temporal and spatial variations in the particulate flux to the benthic boundary layer over a full seasonal cycle and hopefully over the full lifetime of the project.

b) To monitor the hydrodynamic regime within the benthic boundary layer over a heavily instrumented field covering the station area.

c) To obtain *in situ* measurements of mass solute fluxes across the sediment/water interface, covering at least four seasonal intervals during a single year, and opportunistically over the remaining contract period.

d) To undertake a quantitative, analytical description of the composition and activities, including bioturbation styles, of all size classes of the BBL food web, over a full year.

e) To describe the temporal kinetics of organic matter both within the sediment and within the guts of benthic deposit feeders through observation and experiment. To relate these data to the abundance and distribution of micro- and meiofaunal organisms.

f) To improve our understanding of the complex relationship between the activity of the benthic fauna and its imprint on the sedimentary record using a combination of radio-isotope distributions within the sediment and biological studies.

g) To establish the relationship of all of the above to burial using a variety of proxies, including opal and lipid biomarkers and a mix of radio tracers covering a range of half lives.

h) To reconcile the divergent geochemical and biological approaches to models of seafloor-related cycling by developing a three-dimensional diagenetic model for the BBL system, incorporating the critical components identified from bioturbation modelling and flow network modelling of the BBL community.

To address these objectives, the specific activities within the project are organised into four Work Packages. Work Package 1, lead by S.O.C. (R.S. Lampitt), is concerned with the flux of material to the sea floor. Work Package 2, lead by GEOMAR (O. Pfannkuche), deals with interactions between the flux and the benthic community. Work Package 3, lead by SAMS (J.D. Gage), concerns the study of intra-annual changes in the composition and activities of the benthic communities. Finally, Work Package 4, lead by IFREMER (M. Sibuet) covers modelling and data management.

The BENGAL study site

The study site selected is on the Porcupine Abyssal Plain centred on 48°50'N: 16°30'W at a depth of about 4850m, some 270nm to the southwest of Ireland. This locality was one of a number of northeast Atlantic sites studied under MAST I and II contracts (see Rice *et al*, 1993, 1995) and has been visited several times since 1989. These earlier studies had demonstrated, *inter alia*, significant differences in the sediment chemistry and in the abundance, size structure, taxonomic make-up and behaviour of the benthos at these contrasting sites (Gooday, 1993; Rice, Thurston and Bett, 1994; Thurston, Bett, Rice and Jackson, 1994; Rice and Lambshead, 1994; Vincx *et al*, 1994; Santos *et al*, 1994; Gooday, Carstens and Thiel, 1995; Vanreusel, Vincx, Bett and Rice, 1995; Wolff *et al*, 1992). They had also begun to reveal the complexities of the benthic ecosystem at the Porcupine Abyssal Plain site, the most seasonal one studied and where major inter- and intra-annual variations in biogenic fluxes had been demonstrated (Rice, Thurston & Bett, 1994; Rice *et al*, 1994) as at the nearby BIOTRANS/JGOFS site (Newton *et al*, 1994).

But the previous MAST projects did not attempt to quantify or characterise the vertical flux within the water column, nor did they measure directly geochemical fluxes within the sediment column or across the sediment-water interface. Consequently, quantitative variations in the vertical flux could not be related directly to changes in the benthic communities. In any case, all previous studies of the effects of the seasonal deposition of phytodetritus on the abyssal benthos in the Atlantic have been based on samples collected in different years and have had to discount inter-annual variations. BENGAL attempts to overcome many of these problems by visiting the site several times over a relatively short period, to take "spot" samples with a variety of gears including corers, trawls and photographic techniques, to make short-term "within cruise" observations with a range of

landers, and to deploy and retrieve longer-term moorings to measure and observe the particulate fluxes through the water column and onto the seafloor.

Cruise programme

Five cruises, each of about one month duration, were to be devoted entirely to the BENGAL objectives. The first of these, in September 1996, was intended to obtain baseline data, but was primarily to be a preliminary cruise to the main series, allowing techniques to be tested and developed and long term moorings to be deployed. The main series of four cruises was then planned to visit the study site in the early spring 1997, before the arrival on the seafloor of phytodetritus, in the early and late summer after the deposition, and finally in the spring of 1998. Additional opportunities to visit the site were possible on planned non-BENGAL cruises, particularly on *Meteor* in the summer of 1998 and on a *Discovery* cruise within the MAST III ALIPOR project, also in 1998. On each of the main cruises a basic set of samples was to be obtained: sediment and meiofauna with the multiple corer, macrofauna with the box corer, megafauna with a semi-balloon otter trawl (OTSB) and/or beam trawl. These cruises were also to service the long-term photographic, sediment trap, current meter, resuspension and recolonisation experiment moorings. On specific cruises, additional techniques were to be employed including short-term lander deployments, CTD and water sampling, near-bottom plankton sampling mid-water and seafloor photographic techniques.

Table 1. BENGAL cruises 1996-1997

Ship	Sailing date/place	Docking date/place
Discovery 222	29 August 1996 -Southampton	24 September 1996 - Falmouth
Discovery 226	12 March 1997 - Vigo	10 April 1997 - Vigo
Discovery 229	2 July 1997 - Vigo	31 July 1997 -Vigo
Challenger 135	15 October 1997 -Southampton	30 October 1997 - Southampton

So far, four of these cruises have been completed (see Table 1), the first three rather successfully (see below). The fourth cruise, originally planned on *l'Atalante* in September-October 1997, was disrupted at the last minute by a seaman's strike and was replaced as a matter of urgency by a short cruise on RRS *Challenger*. Inevitably, this replacement cruise was a poor substitute for the planned one, partly because the *Challenger* has neither the range of equipment nor the scientific accommodation of *l'Atalante*, but also because gear and equipment transported to *l'Atalante* was inaccessible and therefore unavailable for the *Challenger* cruise. The fifth cruise, on RRS *Discovery* in March 1998, is already planned, as is the sampling on the additional cruises later in 1998, partly to try to make good the gaps in the earlier cruises.

RESULTS

The core sampling programme has been achieved rather successfully, with adequate meiofauna (multiple corer) and megafauna (OTSB) samples having been obtained on all cruises. Despite the usual problems encountered with box core sampling, sufficient macrofaunal samples have also been obtained on each visit except that on the *Challenger* when unidentified problems with the gear prevented any samples being obtained. Other significant gear "failures" included the loss of the beam trawl on its first deployment on *Discovery* 222, the loss of the NIOZ lander on its final deployment on the same cruise and the loss of the Goteborg lander on its first deployment on *Discovery* 226. Despite these rather serious losses, and less significant malfunctions of other equipment from time to time, most of the required sampling has been accomplished to date. Many of the resulting samples and data

are still undergoing analysis, and since the sampling programme is still underway it is too early to report any final results. Nevertheless, significant preliminary results have been obtained in each of the Work Package areas. Although these are too disparate to summarise adequately here, the following highlights give an indication of the sorts of data which are emerging.

First the bad news. 1997 was a bad year for phytodetritus!

Achieving the overall BENGAL objectives was dependent upon being able to follow the consequences of the seasonal arrival of phytodetritus on the seafloor. It was essential, therefore, that there should be a significant deposition of organic matter at the BENGAL study site within the contract period. Since we had good evidence for such a strong seasonal input from sediment traps and/or time-lapse photography for the years 1989, 1990, 1992 and 1994 (with no adequate data for the intervening years), we felt rather confident that the same would be true for 1997. We were possibly wrong! Although the sediment trap data suggest that the phytodetrital flux in mid-water, peaking in late June 1997, was almost as big as any we had previously detected (Fig. 1), all other indicators suggest that this was not so. Thus, a successful bathysnap deployed from 8 April until 9 July, 1997 showed no evidence of any phytodetrital material reaching the bottom in this period. Similarly, analysis of chloroplastic pigment content of the sediments (Fig. 2) show rather high total levels in September 1996, consistently decreasing through March, July and October 1997. During the same period, the chlorophyll/phaeophorbide ratio, an indication of the relative "freshness" of the material, also decreased consistently, suggesting that a significant input during the summer of 1996 was not followed by a similar input during 1997. Finally, the sediment infaunal foraminifera tell a similar story. Throughout the BENGAL period, the foraminiferal densities show no significant seasonal changes, though a higher proportion were inhabiting the surficial layers in September 1996. The near surface September samples were dominated by a *Quinquiloculina sp* which appears to utilise somewhat degraded phytodetritus. This species decreased in abundance consistently over the next 13 months. Another species, *Epistominella exigua*, which was abundant in the presence of fresh phytodetritus in 1989, remained relatively uncommon in all the BENGAL samples (Fig. 3). Since earlier studies indicated that *E. exigua* increases rapidly in abundance after the arrival of phytodetritus, its rarity in 1997 suggests that no significant phytodetrital drop occurred.

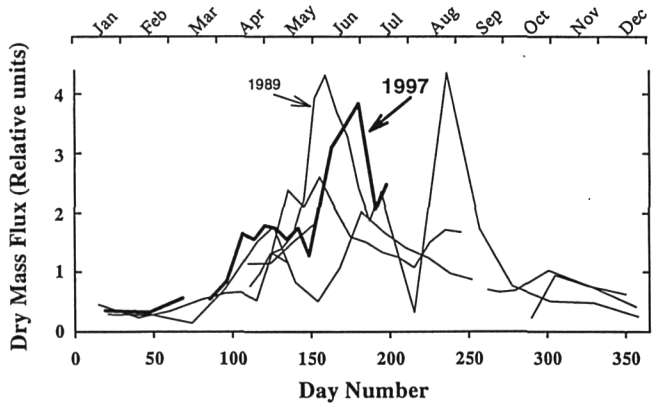


Figure 1. Seasonal variations in the total dry mass flux to sediment traps at a depth of 3000 metres at the BENGAL site in the period 1989 to 1997. The peak flux recorded in 1997 (bold line) was almost as high as the largest value recorded, which was in 1989.

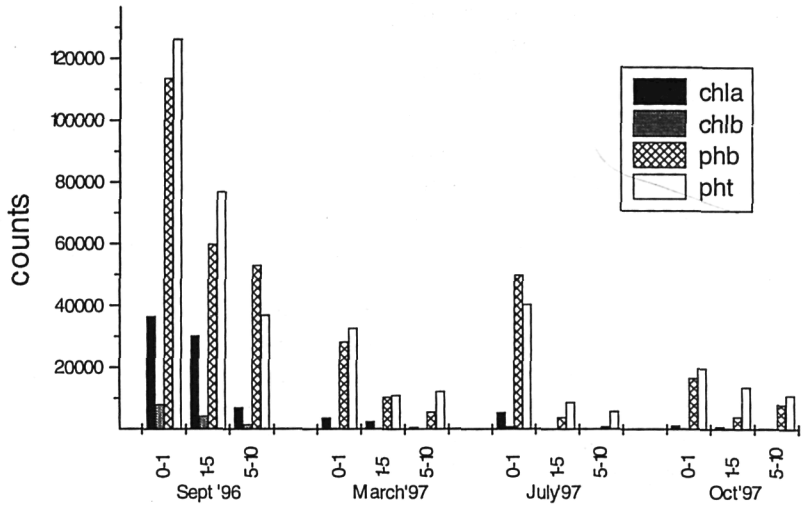


Figure 2. Changes in the chloroplastic pigments (Chlorophyll *a* and *b,* phaeophorbides and phaeophytines) in the surficial one centimetre of sediment cores taken on each of the BENGAL cruises. For each core, three layers are represented, 0-1mm, 1-5mm and 5-10mm. (We are grateful to Rob Witbaard of NIOZ for allowing us to use these data.)

The good news. 1997 was a great year for Amperima!

One of the principal objectives of BENGAL is to monitor the composition of the benthic fauna through a full year in an effort to discover any changes caused by the arrival of phytodetritus. Any such changes are expected to be most readily recognised within the smaller organisms with their generally faster turnover rates than among the larger animals. Nevertheless, although we were reasonably familiar with the megafauna at the study site as a result of earlier visits (Thurston *et al,* in press), the work plan included regular trawl sampling, partly to confirm the earlier data but also to provide abundance data and samples for other BENGAL tasks. In the event, the samples provided us with our biggest surprise which may turn out to be the most important outcome of the project.

As noted above, prior to BENGAL the study site had been visited on several occasions. Among other samples, a total of ten good trawl samples had been obtained during three separate cruises between September 1989 and April 1994. Gratifyingly, but not too surprisingly, these samples exhibited a good deal of internal consistency, revealing what seemed to be a fairly "typical" abyssal benthic megafauna dominated both numerically and in terms of biomass by holothurians (Table 2). Within the holothurians, represented by a total of some fifteen species, the dominant form in this area, again both in numbers and biomass, was the elasipod *Oneirophanta mutabilis.*

In contrast, the eleven trawl samples taken within the BENGAL programme and analysed so far (Table 2) also exhibit high internal consistency but indicate a dramatically different megabenthic community structure. Most major taxa show no significant changes from the previous situation and the community is still dominated by the holothurians, though numerically even more so than before. But along with the holothurians, the *Actiniaria,*

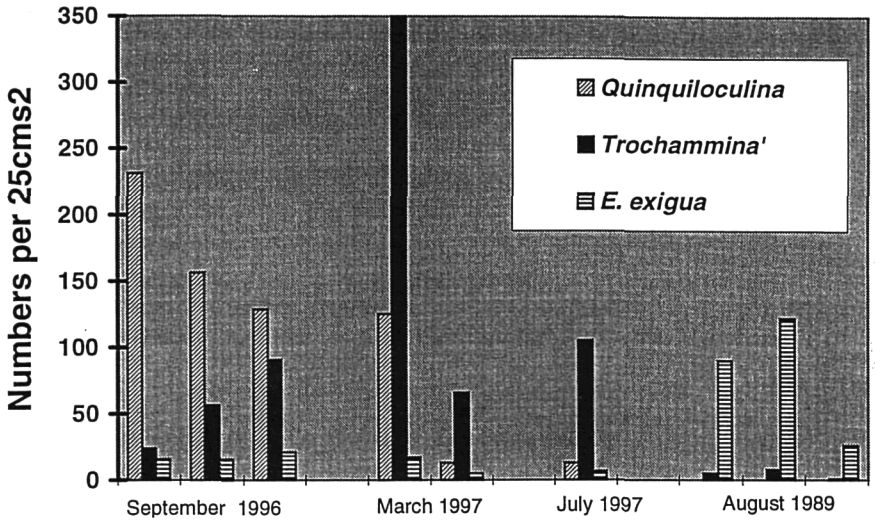


Figure 3. Abundance of key epifaunal and shallow infaunal foraminiferal species in multiple core samples from three BENGAL cruises and, for comparison, in 1989 samples when fresh phytodetritus was present. (Data from Gooday, submitted.)

Madreporaria, Annelida and *Tunicata* are all significantly more abundant in the new samples than in the earlier ones. More interestingly, the make up of the holothurian community is quite different (Table 3). Most species, including *Oneirophanta mutabilis*, are still present in much the same numbers as before. But three of the elasipods, the large species *Psychropotes longicauda* and the two much smaller species *Kolga hyalina* (included in "Varia" in Table 3) and *Amperima rosea*, have all increased in abundance very significantly. In fact *A. rosea*, previously a relatively uncommon constituent of the community, has now become by far the most abundant.

Clearly, something has happened to cause these changes between 1994 and 1996, but what? At the moment we have no idea, but first we must eliminate the remote possibility that it was the impact of our own activities. Consequently, during the upcoming March 1998 cruise we hope to trawl both within the BENGAL study area, where all our previous trawl catches have been obtained, and at similar depths within the Porcupine Abyssal Plain but away from any possible influence of our earlier actions. Assuming that the "new" benthic community is found outside the BENGAL area we will feel more confident that we have witnessed a "natural" rather than scientist-induced change. We will not necessarily be any nearer to an explanation, but this is not too important. The real significance of the result will be that such major changes in the community structure of the deep ocean floor can take place so quickly, and for natural reasons - whatever they are. The conclusions are two-fold. First, that our knowledge of deep sea biology is still very fragmentary and that further long-term studies such as BENGAL and its predecessors are required. Second, it would be unwise to attribute observed changes to anthropogenic impact until we know more about the scale of natural temporal variability.

CONCLUSION

BENGAL is progressing rather well. Although we will undoubtedly fail to achieve some of the tasks we set ourselves, most will be accomplished. Moreover, the accumulating mass of data is already resulting in discoveries that were unforeseen when the programme was

originally envisaged. Such unexpected added value will more than compensate for the programme's shortcomings.

Table 2. Mean abundance (individuals/ha) of the major invertebrate taxa obtained in otter trawl samples at the BENGAL study site before and during the BENGAL programme. The highlighted taxa show significant differences in the data from the two sets of samples.

	Pre-BENGAL			BENGAL		
TAXON	Sept 89	May 91	April 94	Sept 96	April 97	July 97
PORIFERA	0.17	0.08	0.13	0.26	0.07	0.37
PENNATULACEA	0.15	0.18	0.15	0.23	0.41	0.45
ACTINIARIA	**6.01**	**8.68**	**6.39**	**9.63**	**11.66**	**11.94**
MADREPORARIA	**0.29**	**0.29**	**0.08**	**0.63**	**0.89**	**1.22**
ZOANTHIDEA	5.40	3.61	0.49	1.51	1.81	2.32
ECHIURA	0.51	2.82	2.30	3.54	3.71	3.22
SIPUNCULA	0.22	0.59	0.75	0.61	0.85	0.63
ANNELIDA	**3.55**	**3.83**	**4.39**	**10.95**	**8.16**	**13.74**
CIRRIPEDIA	0.12	0.60	0.36	0.45	0.26	0.23
MYSIDACEA	0.35	0.12	0.11	0.25	0.00	0.07
PYCNOGONIDA	0.12	0.08	0.06	0.07	0.15	0.24
GASTROPODA	0.07	0.35	0.16	0.09	0.35	0.25
BIVALVIA	0.07	0.11	0.07	0.14	0.29	0.24
CEPHALOPODA	0.24	0.03	0.12	0.02	0.11	0.14
ASTEROIDEA	3.57	7.36	3.48	3.01	2.85	3.16
OPHIUROIDEA	0.60	2.50	2.04	1.03	0.97	2.03
HOLOTHURIOIDEA	**43.05**	**53.94**	**39.26**	**145.74**	**337.90**	**244.15**
CRINOIDEA	0.71	0.08	0.09	0.30	0.13	0.37
TUNICATA	**0.89**	**0.32**	**0.62**	**4.45**	**2.71**	**6.50**
NATANTIA	2.90	0.93	0.68	0.66	0.17	0.47
PALINURA	0.29	0.60	0.18	0.06	0.10	0.30
ANOMURA	0.49	0.40	0.44	0.17	0.41	0.27
VARIA	**2.73**	**0.31**	**0.17**	**0.17**	**0.09**	0.08

Table 3. Holothurian abundance (individuals/ha) from otter trawl samples before and during the BENGAL programme. The highlighted categories show significant differences between the two sets of samples. Category "Varia" includes *Kolga hyalina* and several unidentified entities.

	Pre-BENGAL			BENGAL		
	Sept 89	May 91	April 94	Sept 96	April 97	July 97
Amperima	**1.88**	**4.52**	**3.80**	**74.29**	**233.28**	**160.61**
Benthodytes	0.12	0.00	0.05	0.07	0.17	0.17
Deima	0.25	0.33	0.47	0.22	0.67	0.43
Mesothuria	1.20	1.78	0.94	0.66	0.69	0.95
Molpadia	0.02	0.52	0.47	0.21	0.18	0.35
Oneirophanta	23.42	25.96	17.63	14.94	21.69	23.24
Paroriza	0.33	1.06	0.99	0.60	0.78	0.97
Peniagone	6.57	4.69	0.29	5.63	0.29	0.64
Pseudostichopus	3.45	12.61	10.15	8.32	15.33	14.27
Psychropotes	**2.91**	**1.31**	**4.02**	**5.94**	**17.41**	**14.87**
Varia	**2.14**	**0.17**	**0.29**	**32.27**	**45.35**	**22.36**

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Title : Azores Mid-Oceanic Ridge Ecosystem Studies : An integrated research programme on deep-sea hydrothermal transfers and fluxes (project **AMORES**)

Contract NO : MAS3-CT950040

Coordinator

Dr. D. Desbruyères
Département « Environnement Profond »
IFREMER, Centre de Brest
BP 70
29280 Plouzané
France
Tel.no.(Fax) : +33 298224301 (757)
E-mail : ddesbruy@ifremer.fr

Partners :

Dr. C. R. German
The Challenger Division for Seafloor Processes
The Southampton Oceanography Centre
Empress Dock
Southampton
SO14 3ZH U.K.
Tel.no. (Fax) : +44- 1703-596542 (554)
E-mail : cge@soc.soton.ac.uk

Dr. H. Elderfield
Department of Earth Sciences
University of Cambridge
Downing Street
Cambridge
CB2 3EQ UK
Tel.no. (Fax) : +44-1223-333406 (450)
E-mail : HE101@rock.esc.cam.ac.uk

Prof. Dr. F. Dehairs
Department of Analytical Chemistry
Vrije Universiteit Brussel
Pleinlaan 2
B-1050 Brussels
Belgium
Tel.no. (Fax) : +32 2 629 32 63 (274)
E-mail : fdehairs@vnet3.vub.ac.be

Dr. Y. Fouquet
Département « Géosciences Marines »
IFREMER, Centre de Brest
BP 70
29280 Plouzané
France
Tel.no.(Fax) : +33 298224254 (570)
E-mail : fouquet@ifremer.fr

Dr. M. R. Palmer
Department of Geology
Wills Memorial Building
University of Bristol
Quen's Road
Bristol
BS8 IRJ UK
Tel.no. (Fax) :+44-117-928-8205 (3385)
E-mail : m.r.palmer@bris.ac.uk

Dr. P. Jean-Baptiste
Laboratoire de modélisation du climat et de l'environnement
Centre d'études de Saclay
BAT 709 - Orme de Merisiers
91191 Gif sur Yvette Cédex
France
Tel no (Fax) : +33 169 08 77 14 (716)
E-mail : pjb@asterix.saclay.cea.fr

Pr. P. Appriou
Département de Chimie URA 322
UFR Sciences
Université de Bretagne Occidentale
6, Av. Le Gorgeu
BP 809
29285 Brest Cédex
France
Tel no (Fax) : +33 2 98 01 62 96 (594)
E-mail : appriou@cassis-gw.univ-brest.fr

Dr. L. Dosso
Laboratoire de Géochimie isotopique du groupement de recherche Génèse et Evolution des Domaines Océaniques.
Université de Bretagne Occidentale
BP 70
29280 Plouzané
France
Tel no (Fax) : +33 2 98 22 4261 (570)
E-mail : Laure.Dosso@ifremer.fr

Dr. C. Mével
Laboratoire de Pétrologie - CNRS URA 736
Université Pierre et Marie Curie
4 Place Jussieu
tour 26, 3ème étage
75252 Paris Cédex 05
France
Tel no (Fax) : +33 1 44 27 51 92 (39 11)
E-mail : cam@ccr.jussieu.fr

Dr. D.R. Dixon
Plymouth Marine Laboratory
Prospect Place Plymouth
PL1 3DH UK
Present DRD's address :
The Southampton Oceanography Centre
Empress Dock
Southampton
SO14 3ZH U.K.
Tel no :
Fax no :
E-mail : David.R.Dixon@soc.soton.ac.uk

Pr. P. Dando
School of Ocean Sciences
University College of North Wales
Menai Bridge
Gwynedd
G8-LL59 5EY UK
Tel no (Fax) : +44 1248 392904 (620)
E-mail : oss109@sos.bangor.ac.uk

Pr. R. Sharp
Microbial Technoloy Department
Research Division
Centre for Applied Microbiology and Research
Porton Down
Salisbury
Wiltshire
SP4 OJG UK
Tel no : +44 1980 612443
Fax no : +44 1980 611320
E-mail : richard.sharp@camr.org.uk

Pr. P.A. Tyler
Department of Oceanography
University of Southampton
Southampton Oceanography Centre
European Way
Southampton, Hampshire
SO14 3ZH UK
Tel no (Fax) : +44 1703 593292 (059)
E-mail : p.a.tyler@soton.ac.uk

Dr John Patching
The Martin Ryan Marine Science Institute
University College Galway
Galway
Ireland
IE
Tel no : +353 91 524411 ext 2398
Fax no : + 353 91 750456
E-mail : john.patching@ucg.ie

Pr. L. Saldanha†
Pr. Armando de Almeida
Laboratório Marítimo da Guaia
Universidade de Lisboa
Estrada do Guincho
2750 Cascais - Portugal
Tel no (Fax) : +351 1 4869833 (833)
E-mail : aalmeida@fc.ul.pt

Pr. R. Searle
Department of Geological Sciences
University of Durham
Old Shire Hall
Durham
DH 1 3HP UK
Tel no (Fax) : +44 191 374 25 20 (510)

Dr D. Coller
ERA-MAPTEC Limited
5 South Leinster Street
Dublin 2
Ireland
Tel no : + 353 1 676266
Fax no : 353 1 6619785
E-mail : dcoller@mekquake.era.ie

Dr. F. Lallier
CNRS-UPR 9042 Centre d'Etudes
d'Océanographie et de Biologie Marine
Station Biologique
29682 Roscoff Cédex
France
Tel no (Fax) : +33 2 98 29 23 23 (324)
E-mail : lallier@sb-roscoff.fr

Azores Mid-Oceanic Ridge Ecosystem Studies : An integrated research programme on deep-sea hydrothermal transfers and fluxes (project **AMORES**).

D. Desbruyères[1], Y. Fouquet[2], C.R. German[3], R. Searle[4] and AMORES participants.

1. Département « Environnement Profond », IFREMER, Centre de Brest, BP 70, 29280 Plouzané, France.
2. Département « Géosciences Marines », IFREMER, Centre de Brest, BP 70, 29280 Plouzané, France
3. The Challenger Division for Seafloor Processes, The Southampton Oceanography Centre, Empress Dock, Southampton, SO14 3ZH UK.
4. Department of Geological Sciences , University of Durham, Old Shire Hall, Durham, DH 1 3HP UK.

SUMMARY

AMORES aims to identify and quantify the fluxes within and from the hydrothermal vent ecosystem, the interactions between lithosphere and seawater, and their impact on ecosystems of the Mid-Atlantic Ridge (MAR) south-west of the Azores Triple Junction. To date, three cruises have been completed to study (1) the physical, geochemical and biological dispersion of the neutrally-buoyant hydrothermal plume at a segmental scale (2) the high- and low-temperature fluxes (physical and chemical) and internal structure of the hydrothermal system at the vent field scale, (3) the influence of depth through chemical physical and biological processes on hydrothermal vent ecosystems, on three-four active segments.

1. INTRODUCTION

Hydrothermal activity, resulting from ocean/lithosphere interaction, represents one of the key issues today for understanding biogeochemical cycles in the oceans. Its importance is on a par with studies of land-sea exchanges on continental margins and with air-sea exchanges of dissolved gases. Although poorly constrained, hydrothermal fluxes are a major carrier to the oceans of heat and mass from fresh-formed underlying oceanic crust and the hydrothermal sites play host to ecosystems of originality and evolutionary significance perhaps unequalled anywhere on the surface of the earth.

One of the major objectives of the MARFLUX/ATJ MAST 2 project was to locate a hydrothermal site in the area of the Azores Triple Junction. Two hydrothermal sites were discovered: LUCKY STRIKE at 37°15'N and the MENEZ GWEN at 37°45'N. In addition, hydrothermal anomalies in the water column have been detected at several locations along various segments of the Mid-Atlantic Ridge (MAR) south-west of the Azores Triple Junction (ATJ). The properties of these two hydrothermal sites and the anomalies in the water column tell us that there is a gradient of the properties of the ocean crust from the ATJ southward. These properties of the crust are (i) depth (from 800m to 2800m), (ii) chemical properties of rocks, (iii) the nature of volcanism (explosive at depths shallower than 900m), and (iv) certain characteristics of the segmentation of the ridge axis, all properties being directly or indirectly the consequence of the Azores Hot Spot- These discoveries call for both (a) detailed studies of known hydrothermal sites, including locating and studying sites where strong seawater anomalies were found and (b) to define better the role of various parameters contributing to the construction of the ocean crust and consequently of the exchanges between the Ocean and the Lithosphere and the Biosphere. AMORES aims to study (i) the physical, chemical and biological fluxes from contrasted hydrothermal fields as heat and matter are dispersed through a hydrothermal plume into the adjoining MAR rift-valley (ii) high- an low-temperature fluxes (physical and chemical) and internal structure of the hydrothermal system at the vent field scale (iii) the influence of depth through chemical, physical and biological processes on hydrothermal vent ecosystems. In addition, some supporting studies are proposed to provide a regional perspective for the detailed investigations.

2. WORKPLAN

(A) STUDY AREA

Four targets with specific distinct characteristics were selected :

1- *Amar* segment is the deepest among our targets. The hydrothermal site (RAINBOW) has not been precisely located before the beginning of the programme and need detailed submersible investigations. Its characteristics are the depth (2300 m), the control of the site by a cross cutting fault system, the very high particle content in the plume. This type of hydrothermal activity is probably similar (i.e. interaction between basalt and sea water) to other deep hydrothermal sites along the MAR.

2- *Famous* segment (2250-2600m) is characterised by the presence in the water column of very large methane anomalies possibly related to discharge through ultramafic rocks as known from off-axis regions in this area.

3- *Lucky Strike* vent field is one of the largest hydrothermal area known in the modern ocean The main characteristics are the relatively shallow depth (1700 m) and the control

of the hydrothermal system by a lava lake. The maximum temperature (320°C) is close to the boiling point (340°C) for this depth. The lava are highly vesicular indicating a high gas content of the underlying magma. Preliminary investigations also show a high gas content of the fluid, indicating phase separation. The unusual importance of low temperature diffuse flows in the vent field has to be underlined.

4- *Menez Gwen* vent field is very shallow (800 m) and the temperature (278°C) is close to the boiling point. Evidence of a recent start of the activity was given recently. This site gives a unique opportunity to monitor the evolution of hydrothermal activity on a slow-spreading ridge.

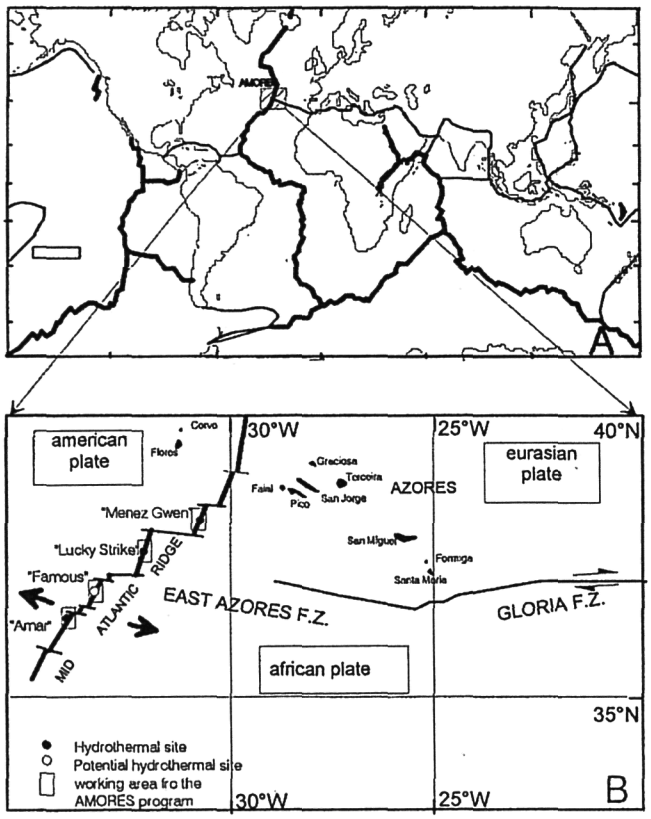


Fig. 1 : Working area of the AMORES programme.

(B) WORK AT SEA and EQUIPMENT

Three cruises which frame the core of the programme were completed during 1997.

(i) FLAME cruise aboard RRS « Discovery » sailed from Vigo (Spain) on May 21st 1997 returning to Ponta Delgada (Portugal) on June 28th. The principal objectives of the cruise were to study the dispersion of the hydrothermal plume and the interacting processes within the plume itself. Measurements of the physical environment were made using a Conductivity-Temperature-Depth (CTD) sensor equipped with a lowered Acoustic Doppler Current Profiler

(LADCP) which provided *in situ* information about current velocities (speed and direction) at different locations within the dispersing plume. In all, 22 full depth casts were made in the RAINBOW segment together with reference stations to the East and West of the ridge. Vertical sections of temperature, salinity and suspended plume-particle concentrations (from optical backscatter - "nephels") were obtained with BRIDGET a deep towed vehicle carrying a CTD, optical sensors and a 12-bottle sampling rosette (German *et al.*, 1998). As BRIDGET was tow-yoed through the water column, dissolved methane samples were collected at regular intervals for shipboard analysis (Charlou and Donval, 1993). Deep plankton trawls (RMT 1+8) were completed in the Southern AMAR, AMAR, FAMOUS, North FAMOUS and LUCKY STRIKE segments to sample the pelagic propagules of benthic or benthopelagic organisms associated with hydrothermal venting.

(ii) FLORES cruise aboard N/O « L'Atalante », mother vessel of the manned submersible « Nautile » sailed from Ponta Delgada on July 6th 1997, returning to the same port on August 10th 1997 with a intermediary port-call on La Horta to exchange scientists and equipment. The principal objectives of the cruise were to document and quantify the variability of hydrothermal activity and sulphide formation on the four selected vent fields. During the night, an important mapping programme was accomplished using EM12 multibeam system and a series of vertical hydrocast was performed to prepare diving. Twenty nine dives of the submersible were accomplished during the cruise. Specific equipment was associated with the submersible (CTD and minirosette water sampler , H_2S *in situ* analyser, nephelometer), telemanipulated (titanium syringes, gas tight titanium samplers for hot fluids) or disposed by the submersible on the bottom for « long » term measurements or sampling (MEDUSA system for diffuse flow sampling, time lapse temperature probes, specific bottles for particles sampling, push core system and markers to identify the site).

(iii) MARVEL cruise aboard N/O « L'Atalante », mother vessel of the manned submersible « Nautile » sailed from Ponta Delgada on August 13th, returning to the same port on September 13th 1997 with a intermediary port-call on La Horta to exchange scientists and equipment. The principal objectives of the cruise were to (1) explore the newly discovered RAINBOW vent field and to describe communities organisms associated with the hydrothermal vents (2) to compare the influence of depth range between 800m and 2500m on three vent fields (RAINBOW, LUCKY STRIKE and MENEZ GWEN). Nineteen successful dives were carried out among twenty five initially planned due to weather conditions : A sampling strategy combining video observation, chemistry, physiology and ecotoxicology was used. Working sites were chosen and equipped when possible with 1 m^2 frames and long term temperature probes. Water sampling, video observations, microdistribution studies and organisms collections were done within those frames to allow a multidisciplinary approach. Nine moorings of free falling baited traps were carried out. Three lines of sediment traps (five sequential sediment traps in total) associated with thermistor chains and current-meters were moored close to RAINBOW vent field. Four moorings and recoveries of telemanipulated sediment traps and two moorings of the automatic station SAMO were performed. Four moorings and one recovery of the *in situ* sequential pump PLASMA were done. Eight pelagic trawls (RMT 8+1) were completed in LUCKY STRIKE and RAINBOW areas. « Colonisation experiments », temperature recorders (HOBO and MICREL), a time lapse camera, diverse tagging experiment were disposed on the bottom and will be recovered during the PICO (summer 1998) cruise as will be the sediment trap lines.

3. PHYSICAL DISPERSION OF THE HYDROTHERMAL PLUME AT RAINBOW VENT FIELD.

The temperature/salinity characteristics of the deep water at RAINBOW show that this water originates from the eastern basins of the N.Atlantic (Sy, 1988). The horizontal component of the LADCP-derived velocity at plume height (2100-2200m) is shown in Figure 2a. The velocity vectors show a general flow through the segment towards the Northeast. Speeds are typically 5-6 cm/s although they do reach as high as 20 cm/s directly over the vent site. Both the Rossby number, R_o=U/fL, and the Froude number, Fr=U/hN, are less than one, being 0.25 and 0.1 respectively. We would therefore expect the flow to be topographically controlled. This is borne out by the optical backscatter data. The tow-paths of the BRIDGET lines are shown in Figure 2b. We will concentrate on 5 tows; BGT07 and BGT15 (Fig. 3) running approximately north/south and east/west, respectively, over the NW flank of RAINBOW Ridge and three long lines BGT03, 02/05/16 and 04 (Fig. 4) each 30-40 km long, running SW to NE across RAINBOW Ridge and into the adjacent basin. Maximum plume anomalies were observed in lines 07 and 15. The location of the subsequently discovered RAINBOW vent site (Fouquet *et al.*, 1997) is clearly indicated in BRIDGET Tow 07 (Fig.3, lower) with an abrupt termination to the high nephel signal at 36° 14.06'N 33° 54.22'W (approx. 9.5km along-track). The width of the plume close to its source (BRIDGET Tow 15) is 2km (Fig. 3, upper), in accord with the Rossby radius l = 3km (=ZN/f) based on the plume rise height, Z. Turning to the lines which extend across RAINBOW ridge and into the adjacent basin (Fig. 4) we see a high nephelometer plume signal down the western side of the basin (Eastern flank of RAINBOW ridge) which reappears to the east (BRIDGET Tows 03, 02/05/16). In the southernmost line (Tow 04) the plume signal is patchy but there is evidence of continuous dispersion, W-E, across the basin.

Dissolved methane concentrations in bottle samples collected from BRIDGET at plume-height confirm the evidence from nephelometer data. Close to the vent site (BRIDGET Tows 07, 03) dissolved CH_4 concentrations in the range 1000-5000nl/l are observed (Fig.2b). These concentrations are exceptionally high compared to concentrations found in other areas such as at 13°N on the East Pacific Rise or at other known sites of activity along the Mid-Atlantic Ridge where concentrations of just 300nl/l and 1000nl/l have been found (Charlou *et al.*, 1991; Charlou and Donval, 1993). Along the east flank of RAINBOW Ridge and into the southern bight of the adjacent basin, dissolved CH_4 concentrations decrease progressively from 900 to 300 nl/l at plume height, whilst toward the north and east decreasing dissolved CH_4 concentrations in the range 300-150nl/l are observed. Even here, however, concentrations remain significantly above the background values of 15nl/l which are typical for the MAR rift-valley (Charlou and Donval , 1993).

Our observations are all consistent with flow advecting the plume around the northern tip of RAINBOW ridge, anticlockwise around the edge of the adjacent basin and out through the gaps to the Northeast. Whenever nephelometer plume signals were present in the lowered CTD data, the LADCP observations indicated that the flow was generally following the topography with the higher topography to the right of the flow direction. The strength of both the nephelometer and the methane signals decreases along the path of the plume.

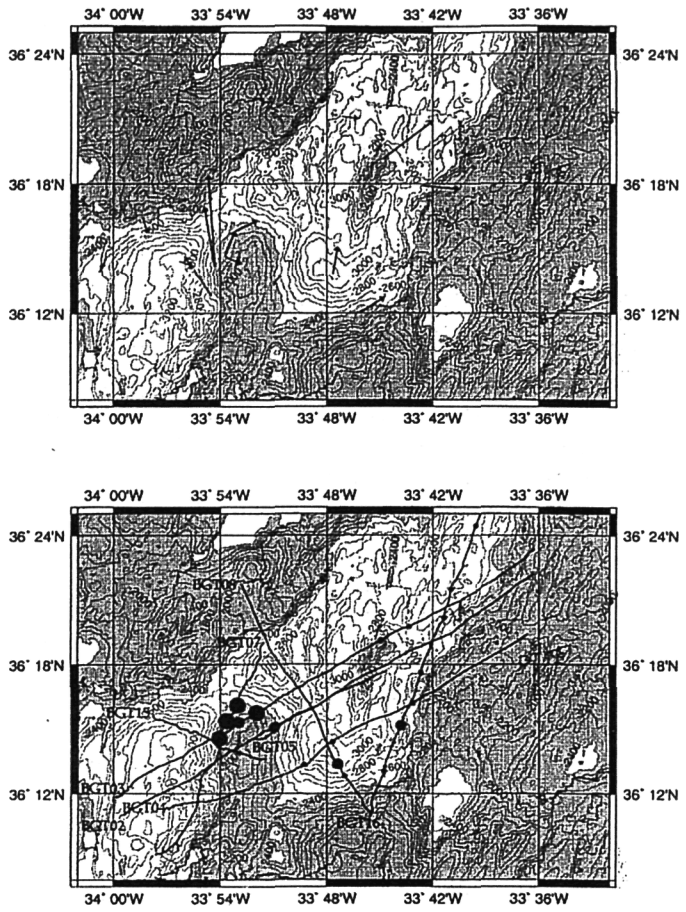


Fig. 2 a) Bathymetric map of the RAINBOW hydrothermal field near 36°15'N (all depths < 2400m shaded) with LADCP-derived plume-height (2100-2200m) current velocity vectors. Current directions as indicated, speeds proportional to arrow length. Typical velocities: 5-6cm/s; max. velocity directly above vent-site: 20cm/s. RAINBOW ridge is the topographic high which extends N-S into the rift-valley; 36°12-16'N, 33°51-54'W.

Fig. 2 b) Bathymetric map as above but with deep-tow BRIDGET track lines and along-track dissolved methane concentrations. Circle sizes reflect decreasing concentrations downstream (Large: >1000nl/l; medium: 300-1000nl/l; small 100-300nl/l). All samples are significantly enriched with respect to North Atlantic deep-water concentrations of 15nl/l. Bathymetric data from Needham *et al.* (1992).

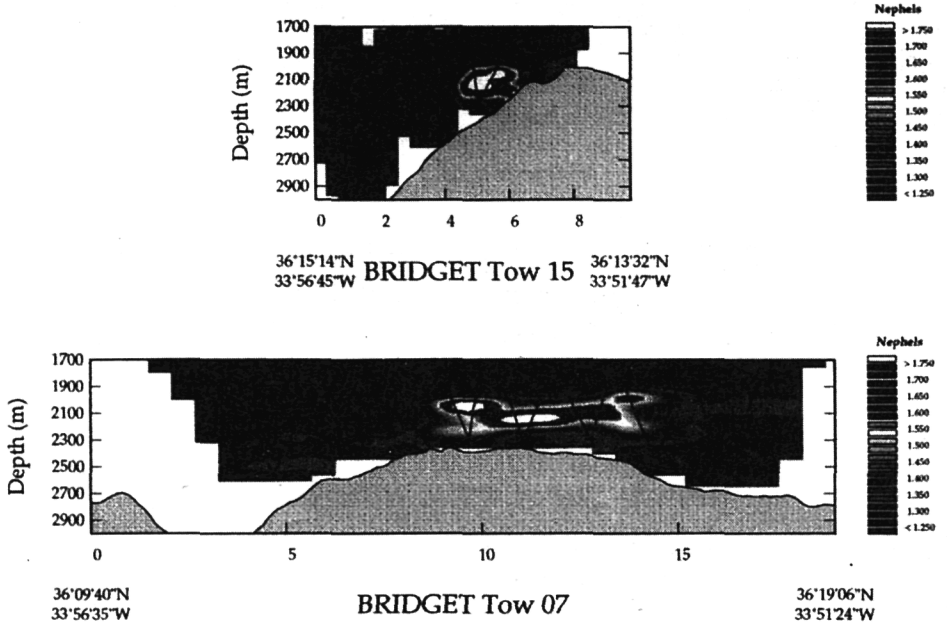


Fig. 3. Two-dimensional cross sections of nephelometer (optical backscatter) anomalies showing the dispersion of hydrothermal plume particles as detected from BRIDGET tow-yos approximately W-E (Tow 15) and S-N (Tow 07) immediately adjacent to the source of the RAINBOW hydrothermal plume. Gridding has been performed using a 50-point nearest neighbour method with a 1/(1+r2) weighting (Rudnicki, 1997). Scarlet saw-toothed lines show tracks of BRIDGET tow-yos. Distances along section are in km.

The methane concentration has decreased more than 10-fold as it exits the adjacent basin to the north-east (Tows 03, 02/05/16), a distance along-plume of ~25km from the source. Indeed, the full extent of BRIDGET Tow 16 (appended to Tow 02/05, Fig.3) runs along the eastern side of the basin up to a sill of water depth 2650m at 36°25'N 33°39'W. We have found that significant anomalies in both dissolved methane and nephelometer signals extend this far, some 50km along the identified flow-path from the RAINBOW hydrothermal site. The timescale for plume waters to reach the northeastern end of the basin at around 36°20'N is expected to be determined by advection by the boundary current. Based on an average speed of 5 cm/s this time is around 4 days. Eddying activity, which may be expected as the flow rounds the northern end of RAINBOW ridge, will tend to increase the residence time in the basin itself by moving plume waters away from the slope and into the centre. Long term moorings which are to be recovered in summer 1998 have been laid to monitor flow in the RAINBOW hydrothermal plume over a period of a year. These data, including time-series optical backscatter records, will provide confirmation on the short-term variability, long-term stability and fluxes associated with the dispersion trends elucidated here.

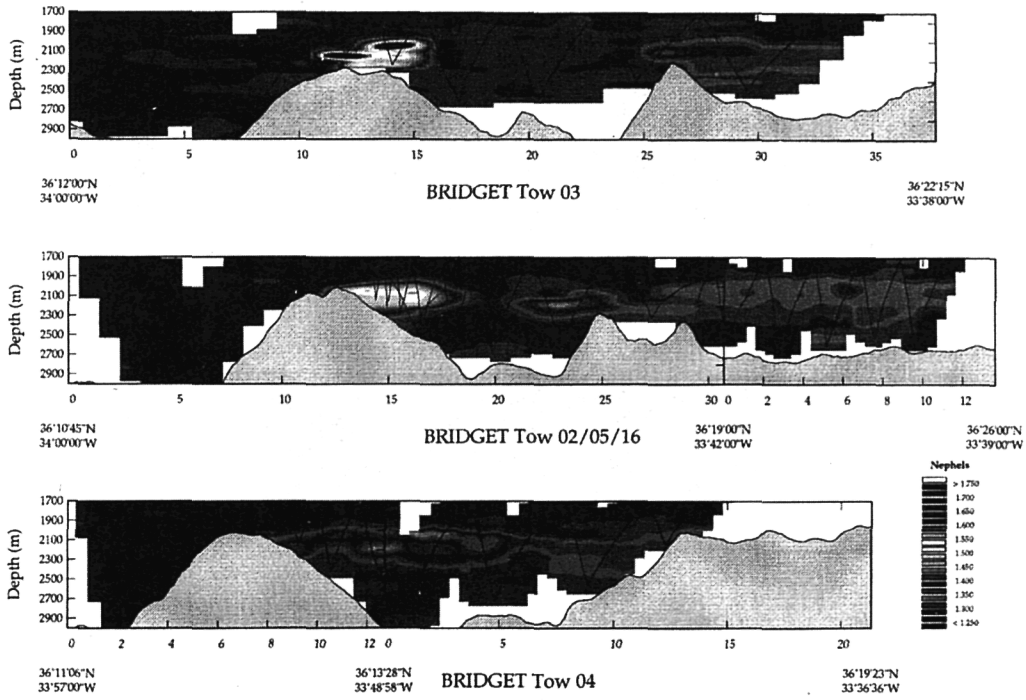


Fig. 4. Two-dimensional cross sections of nephelometer (optical backscatter) anomalies showing the dispersion of hydrothermal plume particles as detected in BRIDGET tow-yos 03, 02/05/16 and 04 running from SW to NE across RAINBOW Ridge, into the adjacent basin and (for 02/05/16) continuing north into the southern portion of the AMAR segment (vertical bar at 31km/0km represents intersection between Tow 05 and Tow 16 at 36°19'N 32°42'W). Gridding has been performed using a 50-point nearest neighbour method with a $1/(1+r^2)$ weighting (Rudnicki, 1997). Scarlet saw-toothed lines show tracks of BRIDGET tow-yos. Distances along section are in km.

4. GEOLOGICAL AND GEOCHEMICAL STUDIES. GEOLOGICAL SETTING, VARIABILITY OF HYDROTERMAL ACTIVITY, FLUID AND SULFIDE CHEMISTRY.

After the completion of the FLAME cruise (June 1997) diving operations were fundamental to precisely study the various aspects of hydrothermal processes on the Mid Atlantic Ridge near the Azores. The main objectives of the FLORES cruise were to document and quantify the variability of hydrothermal activity and massive sulphide formation on four selected sites near the Azores. This domain is a unique locale where several key parameters that can influence the style and intensity of hydrothermal fluxes can be studied on a relatively small area. Between 36°N and 37°N two major parameters were taken into consideration to select dive targets for the FLORES cruise : Depth and nature of the substratum (basalt *versus* ultramafic rocks).

From CH_4 and nephel anomalies discovered during the FLAME cruise, ten dives were made in July 1997 at the RAINBOW ridge on the AMAR segment during the FLORES cruise. An active vent field (RAINBOW, 36°13,80N & 33°54,12W) was discovered on the western flank of the RAINBOW ridge, at water depth between 2270 and 2320m, and covers a surface of 250m x 60 m. Diving investigations (Fouquet *et al.*, 1997) have demonstrated several originalities for this field :

(i) It is one of the most active hydrothermal field along the MAR, about 10 groups of extremely active black smokers are dispersed over the field.

(ii) High resolution EM12 bathymetric maps (slow speed and narrow beam) and detailed submersible investigations show a clear tectonic control of the field that is located at the intersection between the non transform system faults (N40) and the ridge faults (N00). The western border of the field is a 25 m high fault scarp where stockwork mineralisation is observed.

(iii) The entire vent field is located in an ultramafic environment; only a small veneer of old basalt occurs at the east tilted summit of the RAINBOW ridge 1 km east of the active vents.

(iv) Fluid collected have a maximum temperature of 362°C and are extremely enriched in gas (Charlou *et al.*, 1997).

(v) Chimneys and massive sulphides are enriched in Cu and Zn when compared with other sites in basaltic environments.

RAINBOW and FAMOUS represent two sites of quite distinct hydrothermal activity (German *et al.*, 1997, Charlou *et al.*, 1997). Both are located in second order discontinuities cutting the Mid-Atlantic Ridge south of the Azores (Parson *et al.*, 1997) and have been surveved and sampled during FLORES cruise. The high temperature venting at the RAINBOW site occurs along the shoulder of a W-facing hanging wall of a tilted ultrabasic block, the shoulder of which is cut by a network of intersecting N-S and NE-SW faults. Active and relict hydrothermal activity shows persistent and precise tectonic control of this very vigorous site at a range of scales. Around the site, and throughout the NTD, a relative chronology of normal dip-sfip extensional faulting, conjugale transtensional faulting and Riedel populations can be determined in the context of the evolution of the offset and the venting. At the southern end of the FAMOUS segment investigated during FLORES following identification of strong CH_4-rich hydrothermal plume signals (Charlou *et al.*, 1997), the combination of new high-resolution multibeam bathymetry, sidescan sonar and diving data indicate that the venting is associated with serpentinisation of an unroofed ultrabasic diapir. Similarly elevated crustal blocks mapped within NTDs on the MAR further point to significant tectonic/ultrabasic controls on hydrothermalism at slow spreading ridges.

RAINBOW fluids exhibit temperatures exceeding 360°C with pH ranging from 2.9 to 3.1 and having a uniform chemical composition (Charlou *et al.*, 1997, Donval *et al.*, 1997). Chlorinity exceeds 750mmol/kg and silica is *c.a.* 7 mmol/kg. Whereas H_2S content is relatively low all fluids display unusual high H_2, CH_4 content, as compared those collected along MAR (Charlou *et al.*, 1997, Donval *et al.*, 1997).. The chemistry of the revisited LUCKY STRIKE and MENEZ GWEN active fields is similar to that found in 1993 and 1994. An inter-site variability in chemical composition is still observed at LUCKY STRIKE vent field. As previously, MENEZ GWEN fluids display a uniform chemical composition. Pressure and lava lake proximity influence the chemistries of both sites, controlled by phase separation process. On AMAR segment, the RAINBOW fluids are issued from an ultramafic environment and are significantly influenced by the serpentinization process occurring in this area and generating a hudge amount of H_2 and CH_4. These results show that fluid chemistry can be greatly affected

by serpentinization occurring on the walls of the MAR, and which undoubtedly generates a high flux of H_2 and CH_4 along the axis of slow spreading oceanic ridges.

The RAINBOW hydrothermal site, is hosted by serpentinite, which compose the RAINBOW crest. Basalts were found to the East of the RAINBOW site, covering the serpentinites. The rocks consist mostly of coarse- and finegrained, porphyritic and non-porphyritic serpentinites with well developed mesh textures. Additionally, a few samples show brittle and/or ductile deformation, with at least partial preservation of the original mesh structure. The main components of the R.AINBOW serpentinites are serpentine group minerals (antigorite / lizardite + fibrous chrysotile in late fractures), magnetite (chromite) and aragonite in late veins (Barriga *et al.*, 1997). Bastite phenocrysts are present in some specimens. No relics of igneous silicates were found in any of the specimens. The lack (or scarcity) of brucite suggests that most serpentinisation took place at temperatures between 350-500°C (Barriga *et al.*, 1997).The textures of the serpentinites support well that they may derive from a serpentinite diapir and not from a major shear zone, such as a transform fault. This is in good agreement with the local ridge topography.

5. ECOLOGY AND BIOLOGY OF COMMUNITIES ASSOCIATED WITH HYDROTHERMAL VENTS.

LUCKY STRIKE and MENEZ GWEN hydrothermal vent fields dominated by mussels, differ from other and southerly located MAR active fields dominated by shrimps (Desbruyères *et al.* 1994). Our objective is to determine the role of local conditions *versus* isolating mechanisms on biological composition of MAR communities (Desbruyères *et al.* 1994). Knowledge of the recently discovered RAINBOW hydrothermal field, located like LUCKY STRIKE and MENEZ GWEN fields northwards of the Oceanographer fracture zone, and situated at intermediate depth (2300 m) between « deep » (3000-3600m) and « shallow » (800 - 1700 m) vent fields will help us in this sense. Differences in community structure may be also related geological and geochemical characteristics of each vent field, as well as their age or stage of activity. RAINBOW hydrothermal field is considered as the most active of the MAR (Fouquet et al 1997) and present a distinguish geochemical environment with ultramafic rocks enriched in Cu and Zn and hot fluids enriched in gas and with high salinity (Charlou *et al.* 1997).

In the LUCKY STRIKE area, several sites located at the periphery of the central lava lake were surveyed during LUCKY-STRIKE (1993), DIVA 2 (1994) and MARVEL cruises. All sites were dominated by beds of a new species of Mytilid belonging to the genus *Bathymodiolus*. In this vent field, nearly all individuals were infested by one to three commensal scale-worms (Van Dover *et al.* 1996) belonging to *Branchypolynoe* near *seepensis* (a cryptic species). Mussels were distributed in patches of thousands of individuals, the smaller ones being located on the outer part of the beds whereas the largest are located in the middle (max. observed size 113mm). Mean size of the mussels varies between patches according to their position within the site, largest individuals located in the warmest areas. All the frequency distributions are plurimodal and show 3 to 6 modes. The population structures are different from site to site within an active zone and there is spatial segregation at a given site. Temperature time series (from one day to two weeks duration) are recorded using HOBO probes at different places within mussel beds : Temperature displays rapid variations with a

maximum of 18°C; several periods being superimposed. Shrimps are living in small swarms on smoker walls or within the mussel beds. They belong to three species (*Chorocaris chacei, Mirocaris fortunata* and *Rimicaris exoculata*). Bythograeid crabs belonging to *Segonzacia mesatlantica* are abundant within mussel clumps and on active sulphides. Several species of limpets and coiled gastropods are found on Mytilid shells. Non-vent fishes are seen penetrating inside the vent areas. The most common is belonging to *Cataetyx laticeps*; a pink fish, *Gaidropsarus mauli,* is living in cracks within mussel beds and is rather common. Several rat-tail fishes, deep-sea sharks, chimaeroids are observed at the periphery of the sites. Urchins (*Echinus alexandri*) is observed at the border of several vent fields.

The environment surrounding the organisms is a dilute hydrothermal medium (88 to 100 % of seawater) with a pH between 6.2 and 8, H_2S concentrations from 0 to 62 µmol l^{-1}. Dissolved organic carbon (DOC) concentrations are high (up to 550 µmol l^{-1}, 100 µmol l^{-1} in seawater) suggesting a highly productive ecosystem. Mixing lines of seawater and hydrothermal fluid were plotted for each compound against the magnesium concentration to highlight the possible interactions between the diluted fluid and the hydrothermal communities. The patterns suggest that the medium is not only modified by temperature, chemical reactions and dilution but also by the organisms themselves as evidenced by high DOC production (up to + 450 µmol l^{-1}), and anomalies in phosphate distribution in the vicinity of the mussels communities. Sulphide removal is also observed (up to 100 µmol l^{-1}) and can happen by different means : Chemical oxidation, precipitation with metals present in the fluid and consumption by the organisms.

In the MENEZ GWEN vent field, maximum venting temperature is 281°C inside a smoker but diffuse venting (up to 25°C) occurs through the whole area. Sulphide mounds are covered with populations of Mytilids. Mussel-beds contain a mixed size range of individuals and belongs to the same species than in LUCKY STRIKE but the infestation rate by scale-worms is low. Bresiliid shrimps (*Mirocaris fortunata*), serpulids, ophiuroids and crabs (a geryon crab belonging to *Chaceon affinis*) are also present. This last species, of commercial value, is likely attracted by active venting. Abundant bathyal fauna is observed at the periphery of the site including pandalid shrimps (*Plesionika* spp.), fishes (*Etmopterus pusillus, Lepidion schmidti, Epigonus telescopus, Synaphobranchus* sp., *Photostomias* sp., *Scorpaena* sp., *Malacocephalus laevis, Beryx splendens, Neocyttus helgae*), squids (*Omastrephes pteropus* ?) and living and dead black coral (*Anthipates sp).*

Contrary to LUCKY STRIKE and MENEZ GWEN vent fields, communities of the RAINBOW field are dominated by shrimps. Very dense swarms of the caridean shrimp *Rimicaris exoculata* (Bresiliidae) as occurring at TAG, Snake Pit and Broken Spur are observed at two sites (a few m^2 in total at each site), and at a third site at a lower level. This species is considered to be fairly adapted to hydrothermal environment, using bacteria as a major source of nutrition (Van Dover *et al.* 1988). Two other species occur, *Mirocaris fortunata* (Bresiliidae), showing an opportunistic mode of nutrition (mixed diet) at LUCKY STRIKE sites is located on sulphide chimneys as observed at LUCKY STRIKE and MENEZ GWEN sites, and the necrophagous, common at the MAR sites, *Chorocaris chacei,* in lower abundance than other species. Mussel-beds are smaller and the densities of Mytilid lower than in shallower areas.

Vent mussels *Bathymodiolus* sp. were collected during Nautile dives in the MENEZ GWEN and LUCKY STRIKE vent fields. At sea they were successfully maintained for 12 days in

refrigerated aquaria and some individuals have now been kept alive in the laboratory for 6 months at 9°C and atmospheric pressure, when provided with sulphide and methane. The behaviour and movements of the mussels were monitored using a time lapse camera and video recorder. The mussels regularly extended their foot, often waving it around in the water. This action was often followed by a relocation of the mussel towards a sulphide source. Uptake rates of methane were determined for isolated gills of the mussels. Rates of over 1 μmole $gill^{-1}$ h^{-1} were determined at methane concentrations of 100 μM, with the uptake rates being directly proportional to the dissolved methane concentration. Sulphide uptake rates were up to 3.3 μmole $gill^{-1}$ h^{-1}. Histological studies of the endosymbionts in mussel gill tissue demonstrate that the LUCKY STRIKE mussels contain both sulphide - oxidising and methylotrophic bacteria as do Mytilids from Snake Pit (Cavanaugh *et al.*, 1992). Enzymes studies showed that the gills, but no other tissues of the mussels contained methanol dehydrogenase an enzyme found in methane-oxidising bacteria, adenylsulphate reductase and ATP sulfurylase enzymes usually found in sulphur oxidising bacteria. Isolated gills removed both sulphide and methane from the water at an appreciable rate. Different enzymes of the nitrogen metabolic pathways were tested including enzymes of nitrogen assimilation or dissimilation.

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TITLE: SAPROPELS And PALAEOCEANOGRAPHY: Palaeoceanographic, Palaeo-climatic, Palaeo-environmental and Diagenetic aspects of sapropel formation in the eastern Mediterranean **(SAP)**

CONTRACT NO: MAS3-CT97-0137

COORDINATOR:
Dr. Gert J. De Lange
Institute for Earth Sciences
Department of Geochemistry
Budapestlaan 4
3584 CD Utrecht, Netherlands
Tel.: +31-30-2535034, fax: +31-30-2535030
E-mail: gdelange@earth.ruu.nl

PARTNERS:

Elisabetta Erba
Universita degli Studi di Milano
via Mangiagalli, 34
20133 Milano, Italy
Tel.: +39-2-23698257
Fax: +39-2-70638261
E-mail: erba@imiucca.csi.unimi.it

George Anastasakis
National and Kapodistrian
University of Athens
Penepistimiopolis
15784 Athens, Greece
Tel.: +30-17284161
Fax : +30-17241888
E-mail: ganastas@atlas.voa.gr

Ana Maria Ferreira
Instituto de Investigacao das
Pescas e do Mar
avenida Brasilia
1400 Lisboa, Portugal
Tel.: +351-1-3010814
Fax : +351-1-3015948
E-mail: valec@ipimar.pt

John Thomson
Southampton Oceanography Centre
Empress Dock
Southampton SO14 3ZH, United Kingdom
Tel. : +44-1703-596548
Fax : +44-1703-596554
E-mail : john.thomson@soc.soton.ac.uk

Annie Michard
Laboratoire de Geosciences de
l'Environnement
Centre d'Activité du Petit Arbois
13545 Aix-en-Provence
Tel.: +33-0442971527
Fax : +33-0442971549
E-mail: amichard@cerege.fr

SAPROPELS And PALAEOCEANOGRAPHY:
Palaeoceanographic, Palaeo-climatic, Palaeo-environmental and Diagenetic aspects of sapropel formation in the eastern Mediterranean
(SAP)

[1]Institute for Earth Sciences, Utrecht, Netherlands; [2]Universita degli Studi de Milano, Milano, Italy; [3]Southampton Oceanography Centre, Southampton, United Kingdom; [4]National and Kapodistrian University of Athens, Athens, Greece; [5]Laboratoire de Geosciences de l'Environnement, Aix-en-Provence, France; [6]Instituto de Investigacao das Pescas e do Mar, Lisboa, Portugal

I. INTRODUCTION

During the last twenty years the scientific community has considered the Mediterranean Sea to be an important natural laboratory for research in physical, chemical and biological oceanography and marine geology. This relies on the particular features of the Mediterranean Sea, being an semi-enclosed marginal sea, having a negative hydrological budget, and thus being an unstable biogeochemical palaeo-environment. Furthermore, its geological history is long and complex; and during the late Holocene has fashioned a unique cradle of civilisation. Eighteen million years ago, in the Early Miocene, the Mediterranean Sea was a wide channel between the Atlantic and the Indo-Pacific Oceans; during the Miocene the basin was gradually transformed by plate tectonic movements into a broad Atlantic gulf. Near the end of the late Miocene (Messinian), it underwent a major biogeochemical crisis with isolation and disappearance of marine faunas and floras. This was the so-called 'Messinian salinity crisis' that resulted in the deposition of several tens to hundreds of metres of salt that presently underlie Mediterranean sediments. Since the lower Pliocene the Mediterranean Sea, again connected to the Atlantic Ocean, has attained its present morphological character. A peculiarity of the Mediterranean basin is the presence of several sills with depths between a few dozens to several hundreds meters. These sills, from west to east, divide the Mediterranean Sea into a series of smaller basins: the Alboran Sea, the Balearic Basin, the Tyrrhenian Sea, the Eastern Mediterranean and the Aegean Sea.
The geographical position of the Mediterranean Sea is unique: at present it is surrounded by arid regions to the south and east and by more humid regions in the north. All these features influence the individual basins in different ways, and salinity and temperature gradients that increase eastward are reported. The individual basins will have a different evolution during a major climatic change : i.e. the transition from a glacial stage to a interglacial stage. The end member of the model to the east (the Black Sea), the most isolated, has changed its condition from a fresh water environment to a brackish water one, with permanent anoxic conditions in the water column. The end member of the transect to the west (the Atlantic Ocean) only

underwent minor changes in temperature and salinity. During this time the eastern Mediterranean remained a marine environment where regional and global variations in climatic signals were recorded in the sediments. Due to its unique regional basin environment, the recordings of regional and global change have been preserved much better in the sediments of the eastern Mediterranean than in those of the open ocean.
Mediterranean sediments are ideal for high resolution studies, because of the excellent control on stratigraphic time (due to ash layers and sapropels, most of which have been extensively dated). This, in combination with palaeomagnetic, isotopic (both stable and radiogenic), micropalaeontological, and geochemical markers, tuned with astronomical parameters, gives an unprecedented precision for chronostratigraphy over the last few million years. Such high precision allows the accurate comparison, in high detail, of identical time intervals in the sedimentary record of different cores.

Pelagic sedimentation in the Mediterranean

The deep sea pelagic record in the Eastern Mediterranean is notable for the existence of numerous layers of dark-coloured pelagic sediments rich in organic carbon, known as sapropels. Most sapropels occur during the warming trend or just at warm peaks of the isotopic curve. A few sapropels however fall in cold episodes. Different models have been proposed for the origin of Eastern Mediterranean sapropels, related to climate changes which occurred in the Late and Middle Pleistocene. Sapropel deposition is a short duration regional phenomenon and no sapropels occur in the same period of time in the Atlantic Ocean or in the Holocene western Mediterranean.
The origin of the formation of sapropels has been debated from the time of their discovery until the present-day. Bottomwater anoxia due to stagnation, and/or enhanced productivity have been put forward as possible explanations. In view of the rare presence of benthic organisms in sapropel intervals, bottomwater anoxia seems likely to have occurred. There is, however, considerable evidence for enhanced productivity as well. All models are related to global climatic variations that have occurred, such as those referred to as 'astronomical forcing' models. These climatic variations may have resulted in distinct changes in the physical water mass circulation, and/or chemical fluxes to the water column. The former could have caused water column stagnation or a change from anti-estuarine to estuarine circulation.The latter may have been caused by an increased amount of nutrient input, for example through enhanced river input. All of these potential changes result in nutrient accumulation, and consequently enhanced biological productivity, and/or enhanced preservation. The Eastern Mediterranean remained a marine environment during sapropel formation, and recorded and amplified the climatic signal in its sedimentary record as shown by oxygen isotope stratigraphy of planktonic foraminifera.
With the tools developed and the cores recovered during previous MAST programmes, it will now be possible to compare in a high resolution multi-disciplinary study the spatial and temporal variability in sediments, deposited under varying environments (high/low sedimentation rate, varying water depths, oxic/anoxic conditions, and terrestrial versus marine input, etc.). This will be done for sediments from the last 10 000 years, followed by studies from older sediment units at decreasing spatial resolution. In addition, we will compare the composition of sediments deposited under similar pelagic fluxes, but preserved

under contrasting bottomwater redox conditions. The strength of our approach is not only the comparison between deposition in two contrasting environments (oxic versus anoxic), but also the highly interdisciplinary research done on sediments from boxcores, multicores, gravitycores and a large diameter long piston core, using a high resolution sampling interval. Despite the large amount of disciplinary sub-samples needed per sample, these cores allow almost all studies to be done on identical samples. Not only the amount of material per sample, i.e. the 'multidisciplinarity', but also the emphasis on the most recent sediments distinguishes the present proposal from that of ODP, where more restrictions apply as to the amount of available sample per interval, and where most effort is devoted to older sediment units and longer time-scales.
The understanding of the conditions leading to the onset and ending of sapropel formation are of vital importance for the long term management and sustainable use of the (eastern) Mediterranean.

Sediments as a recorder of natural and anthropogenic changes

As a result of the unique history and configuration of the Mediterranean, gradients in geochemical, sedimentological and biological parameters exist which provide important information on the kind of natural and anthropogenic biogeochemical processes in the region. The Eastern Mediterranean is the largest body of seawater where primary production is phosphate-limited, and the degree of P limitation increases from west to east across the basin. It has been suggested that this unusual P limitation may be due to inorganic processes adsorbing phosphate in the Levantine deep water on to labile iron hydroxides carried by Saharan dust and by River Nile particulate matter and depositing them in the sediment. The process is thought to be important because the Eastern Mediterranean has one of the highest fluxes of atmospheric dust to the sea surface in the world's oceans, while at the same time has the lowest overall concentration of dissolved nutrients (phosphate and nitrate). The sediments of the east Levantine Basin are dominated by fine-grained particulate matter supplied by the annual flood of the river Nile while further west it is principally atmospherically-derived Saharan dust.
One of the most significant anthropogenic effects worldwide is the change in the natural flow of rivers. Hardly any river flows naturally any more with the flux of water and particulate matter often being drastically reduced and its chemical composition being significantly altered. Nowhere is this effect more dramatically shown than in the River Nile where the water and particulate matter flux decreased by an order of magnitude as a result of the completion of the Aswan dam in 1965. Such dramatic change in Nile water-supply has recently been suggested to be of critical importance for the Global ocean circulation system, i.e. for future Global climate. The particulate matter from the Nile which used to flow east and then north spreading over most of the Eastern Levantine basin no longer exists. This is likely to have a major impact on biogeochemical processes including inorganic P uptake throughout the basin. The surficial sediments of the Eastern Mediterranean represent the only record now available of the geochemical processes that occurred in the Levantine Basin prior to the building of the Aswan dam. Details of this record will be relatively well preserved because of the minimal diagenetic changes which occur at the benthic interface.

The importance of fluid fluxes in the Mediterranean

We have discussed above the climatically induced changes in physical water mass circulation as one of the possible mechanisms that may have resulted in sapropel formation. One of the possible reasons why the Eastern Mediterranean is more sensitive to such distinct changes, may be the salinity fluxes that originate from the underlying Messinian salt layers. Such salt fluxes into the deep Mediterranean may have a stabilising effect on the water column, i.e. they may enhance stagnation. The most important fluxes seem to occur from i) 'mud diapir areas', ii) 'cobblestone areas', iii) 'brine lake areas', and iv) 'normal sediments'. A first estimate has been given recently, which needs to be made more precise to be useful as a boundary condition for physical modellers of the circulation of eastern Mediterranean water-masses.

2. OBJECTIVES

The overall aim of SAP is to better understand the (paleo) functioning of the eastern Mediterranean and to determine the role in the global environment by studying the characteristic biogeochemical processes. SAP also contributes to a better understanding of how the oceans function and how marine geoscientists can better interpret the marine sedimentary record. The improved understanding of the functioning of the palaeoc-eanographic and sedimentary system of the eastern Mediterranean will be a valuable contribu-tion to the European (palaeo)oceanographic and marine (geo)science communities, and to the future management for the sustainable use of the Mediterranean.
Important new concepts on the interpretation of the significance of sapropel units have been developed recently, based on detailed geochemical studies of the most recent sapropel (S1). Specifically, the importance of barium as an adequate palaeoproductivity indicator in the eastern Mediterranean has to be mentioned, which will allow us to identify start and finish of sapropel formation independent from postdepositional oxidation. In addition, various elements initially associated with sapropels have been found to form peaks in a particular sequence from which the extent of the oxidation process can be defined. On the basis of these concepts, it has been demonstrated that substantial amounts of the sapropel-unit originally deposited have been altered by post-depositional oxidation. Consequences of this finding are i) the S1 sapropel was originally much thicker than now observed, ii) S1 formation continued for much longer than previously accepted (5-9 ky BP rather than 7-9 ky BP) and iii) the trace element associations with this sapropel have already been heavily modified by diagenesis in the 5 ky since formation. This process has been proved in a limited number of cores up to 350 km apart. By implication, a similar process must have affected earlier sapropels. Using the diagenetic techniques developed from the S1 studies, SAP will explore further validation of the oxidation concept, both on S1 over a much wider area and in older sapropel units. The recent quantitative study of nanno-fossils has demonstrated its potential tool to increase our insight in the (paleo) watercolumn conditions. SAP will not only continue to improve along these lines, but will also explore the potential use as palaeo-indicator of more exotic trace / redox-sensitive elements such as Tl and Re. In addition, a significant Organic Geochemical component will contribute to the innovative and multidisciplinary approach of the SAP

project by studying a few 'type' intervals using the same high-resolution multidisciplinary approach as all partners, and by applying improved innovative Organic Geochemical methods. The data will be evaluated in terms of paleo-environmental variations, such as: paleo-temperatures, paleo-watercolumn stratification, paleosalinity, and algal / bacterial assemblages, and terrestrial input / humidity. This innovatiove approach will come to full value by integration of results from all disciplines within SAP, notably inorganic and organic geochemistry, micro-paleontology, and sedimentology.
Fluxes of atmospheric dust from the Sahara and particulate matter from the river Nile to the Eastern Mediterranean may give important contributions to the sediment and water-column chemistry. Detection of different sources of particulate matter in the eastern Mediterranean will be applied and further developed in the **SAP** project so as to detect possible riverine (>Nile=) and eolian (>Sahara=) contributions.
The possible relation of phosphate limitation and eolian / riverine fluxes will be evaluated in relation to sedimentary nutrient and salinity fluxes.

The specific objectives of SAP are:

1a. Determine composition, preservation, and environmental signals recorded in sediments deposited under different (oxic and anoxic) bottomwater conditions in the eastern Mediterranrean
1b. Determine composition, preservation, and environmental signals in some intervals of sediments from a core in the S Aegean Sea and a core in the western Mediterranean
2. Determine the relative contributions of aeolian and fluvial material and the associated biogeochemical fluxes to sediments of the eastern Mediterranean
3. Quantify salinity and nutrient fluxes from the sediment to the deep water of the eastern Mediterranean

WORKPLAN

The research of SAP is focussed on the understanding of the (paleo) functioning of the eastern Mediterranean and to determine the role in the global environment by studying the characteristic biogeochemical processes. Data collected, analysed, and interpreted during SAP will complement data collected by other projects and in some cases, will provide valuable additional data in areas not being investigated by the field programmes of other international projects. The improved understanding of the functioning of the palaeoceanographic and sedimentary system of the eastern Mediterranean will be a valuable contribution to the European (palaeo)oceanographic and marine (geo)science communities, and to the future management for the sustainable use of the Mediterranean.

Because part of the core material is already available, we can start immediately with the subsampling, preparations, and 'Data Production', whereas subsequently during two cruise participations, and one, possibly two, cruise(s) supplemental samples and data will be

collected. In addition, on-board porewater analyses and measurements of redox potential, dissolved oxygen, manganese, iron, and sulphide in subrecent porewaters will be done and compared to results from traditional squeezing and gel techniques. On-board some high-resolution sampling of sediments will be undertaken, but most of it will occur in the home laboratorium : After sampling, and internal mixing of each sample, subsamples will be distributed to the relevant partners, thus ensuring that each partner works on 'identical' samples, permitting a fully multidisciplinary study.
Recently, it has become clear that the Eastern Mediterranean is the largest body of water in the world which is phosphate limited. It has been suggested that this unusual nutrient limitation is due to the effect of atmospheric dust from the Sahara and particulate matter from the river Nile, which may remove dissolved phosphate. Novel developments in sequential extraction methods for phosphorus as well as the recently demonstrated potential of radiogenic isotopes (e.g. Sr, Nd/Sm) for the detection of different sources of particulate matter in the eastern Mediterranean can now be fully applied and further developed in the SAP project so as to detect possible riverine (>Nile=) and eolian (>Sahara=) contributions.

The following discrete tasks have been defined :

Task 1.A.1 Comparison of biogenic and non-biogenic components in sediments deposited under similar pelagic fluxes, but preserved under contrasting bottomwater redox conditions i.e. from the same region (i.e. from within and immediately outside of the Anoxic Basin Region).

Task 1.A.2 To study the biogenic and non-biogenic composition and preservation of contemporaneous sediments deposited along bathymetric, latitudinal, and longitudinal transects.

Task 1.A.3 To detect environmental signals recorded in sapropel and non-sapropel sediments so as to determine possible controls on sapropel formation conditions along bathymetric, latitudinal, and longitudinal transects.

Methodology :

To understand the controls on the composition of contemporaneous sediments deposited in contrasting oxic and anoxic environments, it is necessary first to study at high-resolution the composition and preservation of recently deposited sediments (0-2 kyr). On the basis of these results it is possible to interpret a more complicated signal combining 'normal' preservation under oxic conditions and the major change in the depositional environment which led to sapropel formation (0-10 kyr; including the last glacial/interglacial transition) in the widest possible spatial and temporal distribution. To fully discriminate preservation and various environmental effects, it is necessary not only to compare contemporaneously-deposited sediments from a transect in the eastern Mediterranean basin, but also to include similar sediments from at least one site in the Aegean Sea, the SE Adriatic Sea, and the Western Mediterranean. Once this combined effect of preservation and depositional environment is fully understood, it will be possible to extrapolate further back into the past, namely to the 0-200 kyr time-frame (which includes a full glacial/interglacial cycle), and the Quaternary (0 - > 1 Myr; including several glacial/interglacial cycles).

Task 1.B.1 To compare results obtained from Tasks 1A with those from sediments in some selected contemporaneous intervals of one gravity core (over 0-10 kyr) from the S Aegean Sea.

Task 1.B.2 To compare results obtained from Tasks 1A to those from sediments in some selected contemporaneous intervals of at least one gravity core (over 0-10 kyr) from the W. Mediterranean.

Methodology :

The samples for the above tasks will come from a gravity- core from the Aegean Sea, and from the W. Mediterranean. The gravity core from the Western Mediterranean has already been collected, whereas the core from the Aegean Sea will be collectred in 1997 or 1998. It will be possible, therefore, to compare the results from the Eastern Mediterranean (Tasks 1A) with those from one site in the Western Mediterranean, and with a site in the Aegean Sea.

The present-day bottomwater in the Eastern Mediterranean has been thought to originate mainly from the Adriatic Sea. However, major influx from the Aegean Sea has recently been reported. Contemporaneously (approx. 6-9 kyr) deposited organic-rich intervals (sapropels), similar to those in the deep Eastern Mediterranean, are found in the Aegean Sea and in the SE Adriatic Sea. For an improved understanding of past deep and bottomwater properties and dynamics of the Eastern Mediterranean. We will, therefore, compare sediments from the Aegean Sea, with those deposited in the Eastern Mediterranean at the same time and using the same methods (see Tasks 1A). The high sedimentation rates in the Aegean Sea would allow a high-resolution study, but only for the sub-recent (0-10 kyr) if normal gravity or piston cores are used.

One of the unresolved questions in the Mediterranean is the occurrence of organic-rich intervals in sediments of the Eastern, but not in those of the Holocene deep Western Mediterranean. In a pilot study we will compare some selected intervals from one site in the Western Mediterranean, with contemporaneous sediments deposited at the sites studied in the Eastern Mediterranean, using a high-resolution multidisciplinary approach.

Task 2.1 To determine the relative contributions of recent (0-2 ky BP) aeolian and fluvial material and the associated fluxes of biogeochemically important elements, including nitrogen and phosphorus, to the sediments in the Eastern Mediterranean

Task 2.2 To detect past variations (0-10 kyr BP) in aeolian and fluvial fluxes related to palaeoenvironmental variations and the resultant changes in the associated elemental fluxes to the sediments in the Eastern Mediterranean.

Task 2.3 To compare results obtained from Tasks 2.1 and 2.2 with those from some selected intervals in one gravity core (over 0-200 kyr) in the Eastern Mediterranean.

Methodology:
Tasks 2.1 and 2.2 will be accomplished by using clay, bulk mineralogy and radiogenic isotopes to determine the sources of particulate matter, and using major and minor elements and sequential leaches to quantify the elemental fluxes. The analyses will be carried out on the sediments from a series of high quality box cores or multicores collected in the widest possible lateral distribution (see Objective 1A).
The relative amounts of Saharan dust and Nile particulate matter in the sediments of the eastern Mediterranean will be estimated using not only major and minor elements, but in particular radiogenic isotopes (Nd/Sm and Rb/Sr, which have the potential for differentiating particulate matter from these two sources to a high degree of precision.

Task 3.1 To quantify the salinity fluxes to the deep water of the eastern Mediterranean in a few key areas, using porewater squeezing and analysis of major dissolved elements.

Task 3.2 To quantify nutrient fluxes in the same areas, using porewaters and on-board autoanalyzer techniques.

Methodology:
The circulation in the Eastern Mediterranean, as calculated from water and salt budgets, seems to be in a delicate balance at present. Thus far, bottom-derived salinity fluxes have not been taken into account during physical modelling, but these could have considerable effect on the stabilisation and stagnation process. On the basis of a few recently determined fluxes, and best estimates of unknown fluxes, we have been able to demonstrate that bottomwater salinities of 40 ‰ may have been possible during formation of the most recent sapropel. Not only salinity but also considerable nutrient fluxes occur from the sediments into the bottomwater. Not only changes in the bottomwater circulation, but also in its redox state, have a profound effect on the amounts of nutrients that can accumulate in the deep basin. Therefore, a lower circulation rate may result in a considerable increase in productivity. In a few boxcores from some selected areas we will determine the redox potential of the sediment, the porewater nutrient and salinity content. In the same cores we will test the revolutionary Multi-element Micro Electrode and will compare its results with those from traditional porewater.

In addition to these scientific tasks, cruise participations will be be prepared and undertaken, and bi-annual Workshops will be organized during which results of the preceding period will be discussed, integrated and interpreted. Furthermore, a WWW site will be opened with information on the SAP project, which will subsequently be updated at least monthly.

I.2.2. The ice-covered seas

TITLE: Local Ice Cover Deformation and Mesoscale Ice Dynamics (project ICE STATE)

CONTRACT NO: MAS3-CT95-0006

COORDINATOR:

Dr. Kaj Riska
Helsinki University of Technology, Ship Laboratory
P.O. Box 4100
FIN-02015 HUT, Finland
Tel.no.: +358 9 451 3498
Fax.no.: +358 9 451 3493
E-mail: kaj.riska@hut.fi

PARTNERS:

Dr. Jukka Tuhkuri
Helsinki University of Technology
Ship Laboratory
P.O. Box 5300
FIN-02015 HUT, Finland
Tel.no.: +358 9 451 3509
Fax.no.: +358 9 451 3493
E-mail: jukka.tuhkuri@hut.fi

Mr. Stein Sandven
Nansen Environmental and Remote Sensing Center
Edvard Griegsvei 3A
N-5937 Solheimsviken, Norway
Tel.no.: +47 55 297 288
Fax.no.: +47 55 200 050
E-mail: stein.sandven@nrsc.no

Dr. Matti Leppäranta
University of Helsinki
Department of Geophysics
P.O. Box 4, FIN-00014
University of Helsinki, Finland
Tel.no.: +358 9 1912 2028
Fax.no.: +358 9 1912 3385
E-mail: matti.lepparanta@helsinki.fi

Dr. Peter Wadhams
University of Cambridge
Scott Polar Research Institute
Lensfield Road
Cambridge CB2 1ER, England
Tel.no.: +44 1223 336 542
Fax.no.: +44 1223 336 549
E-mail: pw11@cam.ac.uk

Mr. Björn Erlingsson
Laboratory of Oceanic and Atmospheric Sciences
University of Iceland
IS-107 Reykjavik, Iceland
Tel.no.: +354 525 4951
Fax.no.: +354 525 4079
E-mail: be@enrich.halo.hi.is

LOCAL ICE COVER DEFORMATION AND MESOSCALE ICE DYNAMICS "ICE STATE"

Tuhkuri, J.[1], Lensu, M.[1], Riska, K.[1], Sandven, S.[2], Thorkildsen, F.[2], Haapala, J.[3], Leppäranta, M.[3], Doble, M.[4], Aksenov, Y.[4], Wadhams, P.[4], Erlingsson, B.[5]

[1]Helsinki University of Technology, Ship Laboratory, FIN-02015 Finland
[2]Nansen Environmental and Remote Sensing Center, N-5937 Norway
[3]University of Helsinki, Department of Geophysics, FIN-00014 Finland
[4]University of Cambridge, Scott Polar Research Institute, CB2 1ER England
[5]University of Iceland, Laboratory of Oceanic and Atmospheric Sciences, IS-107 Iceland

SUMMARY

The ICE STATE project is a study on local sea ice deformation and characterisation of the local state of an ice cover. The connection between the local ice mechanics and the mesoscale ice modelling is also studied. The project includes theoretical modelling work, laboratory tests, computer simulations, field observations, and remote sensing. The potential applications of the results include prediction of encountered ice conditions for ship routes and offshore structures.

1. INTRODUCTION

Sea ice covering the northern seas creates many technical challenges and scientific questions. Examples of such problems are determination of ice loads on ships and offshore structures, analyses of trafficability of ships in ice covered seas, and understanding of dynamics and deformation characteristics of the ice cover at different scales. Ice problems are typically multidisciplinary in nature; ice covers are studied by engineers and geophysicists and the research results are used by designers and operators of ships and offshore structures, shipyards, and by scientists studying the ocean-ice-atmosphere energy exchanges.

At present, a problem in ice cover mechanics is characterisation of the local state of an ice cover. This should include description of the dynamics and ice cover morphology, and also description of the local deformation processes where the morphology is changed due to the dynamics.

In geophysics, the basic equations to model ice cover dynamics in the mesoscale (10 - 100 km) are the momentum and mass balance. The quantity to be solved is the velocity field of the ice due to the forcing mainly from wind and ocean drag. The main component in the momentum balance equations is the rheological term which determines how the ice cover behaves in deformation. The quantity to describe the mass balance is the thickness distribution of ice which is changed by the mechanical deformation of the ice cover and by ice growth and melting. The thickness distribution is usually described by average values for a few thickness categories in a grid cell and the local variation is smoothed out. A similar smoothing applies for floe size, ridge distributions and lead dimensions. Inclusion of the local variation of these parameters into mesoscale ice models requires knowledge on how mechanical processes in the local scale (1 m - 1 km) are connected with dynamical processes in the mesoscale.

The ice cover deformation has been studied either in the mesoscale or in the local scale. Serious attempts to integrate these to a coherent theory of the ice cover do not exist. However, such a theory would be very valuable. For example, the mesoscale models of ice dynamics would greatly benefit from a correct formulation of how the thickness distribution changes due to ridging and rafting of ice cover. All earlier attempts to this direction have been empirical generalisations rather than true representations of the poorly known physical reality. A theory connecting the local scale and mesoscales would also have engineering applications, as then the models could be used to forecast local ice conditions, such as ridges or compressive stresses in the ice cover, which both are hazards to ships and offshore structures.

In the ICE STATE project the interconnection between the local scale and mesoscale is approached from two directions, from the mesoscale by the strategy of *downscaling* and from the local scale by the strategy of *upscaling*. Downscaling involves derivation of the local dynamical and morphological characteristics from the results of meso scale ice models. It has been observed that the mesoscale stresses in an ice field are about two orders of magnitude less than the local stresses. Upscaling involves determination of the mesoscale deformation characteristics from local deformation processes and ultimately derivation of the rheological terms of the mesoscale model equations from them.

An objective of this project is to characterise the local state of an ice cover. In other words, the objective is to define an *ice state*. In this context an ice state is analogous to a sea state. The set of parameters defining an ice state should be predictable by mesoscale ice dynamics models, observable by remote sensing, and applicable to practical purposes. This objective is a challenge to sea ice research. It is something that is not exactly known but which is everyday life in ice-covered seas.

The project includes theoretical modelling work, laboratory tests, computer simulations, field observations, and remote sensing. The research performed is introduced below and some results are highlighted. A discussion of the ice state concept is also included.

2. MAIN ACTIVITIES

2.1 LOCAL SCALE ICE COVER DEFORMATION

The processes involved in local ice cover deformation have been studied by using laboratory tests and discrete element modelling. In this context the local ice cover deformation means: (i) rafting of ice floes, (ii) rafting of ice sheets, and (iii) formation of ridges. The aims of the local scale work are to identify the central parameters in the ridging and rafting processes and to merge the local scale information into mesoscale ice models. One of the main results of this research is that for the first time pressure ridges have been produced in laboratory conditions, and thus relations between morphological features and forcing can be formed.

Parmerter (1975) has suggested that ice sheets thinner than a crossover ice thickness t* will raft and ice sheets thicker than t* will ridge. t* is a function of the bending strength and Young's modulus of the ice cover. Although several attempts, no laboratory tests have been able to produce ridges from uniform ice sheets, even though the ice sheets have been considerably thicker than t*. However, in nature the ice thickness may seldom be as uniform as in the laboratory, and our results suggest that, in addition to ice thickness and Young's modulus, the non-homogeneity of the ice cover is an important parameter in ridging.

Figure 1 shows an example of the ridges formed in the refrigerated ice model basin at the Helsinki University of Technology (Tuhkuri and Lensu, 1997b). Non-homogenous ice

fields consisting of floes of thickness t_2 and thin ice of thickness t_1 connecting these floes were used. Before each test, a 6 m wide strip of ice was cut loose from the surrounding sheet by cutting parallel slots, leaving the far end uncut. Then a strip was divided into equal parts by making a transverse cut. During an experiment a strip was compressed with a pusher plate and the load on the plate was measured. At first the two ice sheets rafted at the initial transverse cut and formed fingers. With continued deformation this rafting process changed into a ridging process as shown in Figure 1. Note that the ridge has both pressure zones and shear zones. The horizontal shape of the ridge that formed was very similar to those seen in the field, with typical arches. The process was a function of the non-homogeneity ratio t_1/t_2: If t_1/t_2 was close to unity, the ice sheets only rafted and did not form a ridge. An example of the force-displacement records is given in Figure 2.

The ridging/rafting of ice sheets has been studied also by using a discrete element model (DEM), which is a computer program that models the dynamics of a system of discrete particles. Recently, DEM has been used to simulate mechanical processes occurring in sea and river ice (Hopkins, 1994, 1996). That method has been developed further and used for the present analysis of deformation of non-uniform ice sheets. Figure 3 shows a snapshot from a simulation where both rafting and ridging were observed.

In both the laboratory tests and in the computer simulations ridges with large keels but almost no sails at all were observed. In addition, the small sail formations were significantly displaced from the keels. This result suggests that the amount of ice in a ridge can be seriously underestimated if information of the ridge sail only is used. Comparisons with field observations (Weeks et al., 1971; Lensu et al., 1998) support this reasoning.

Rafting of ice floes under uniaxial compression has also been studied by using both laboratory tests and discrete element simulations. The experimental results are reported by Tuhkuri and Lensu (1997a) and Hansen and Tuhkuri (1997a, 1997b). The test results and DE simulations have been compared by Tuhkuri and Hopkins (1997).

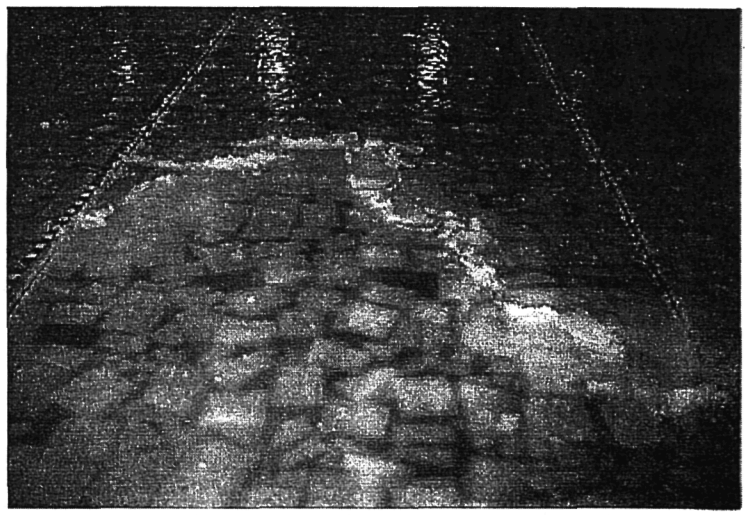


Figure 1. An ice ridge formed in test basin. Average thickness of the model ice was 69 mm. Width of the ridge was 6 m. The photo was taken after displacement of about 6.5 m.

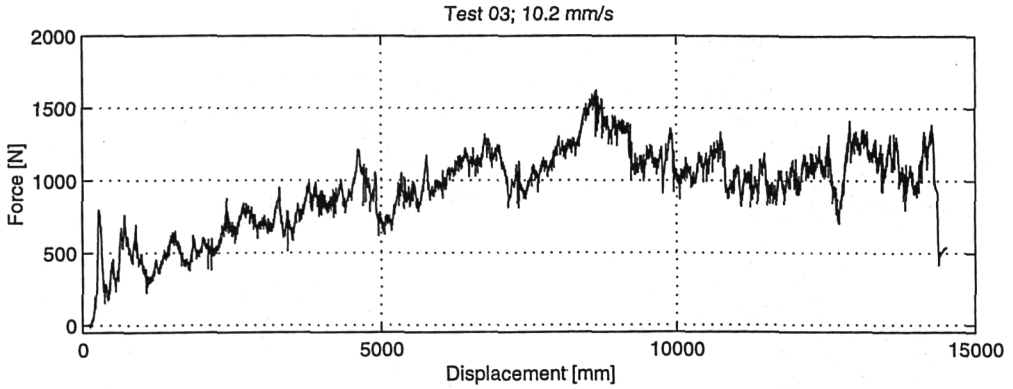
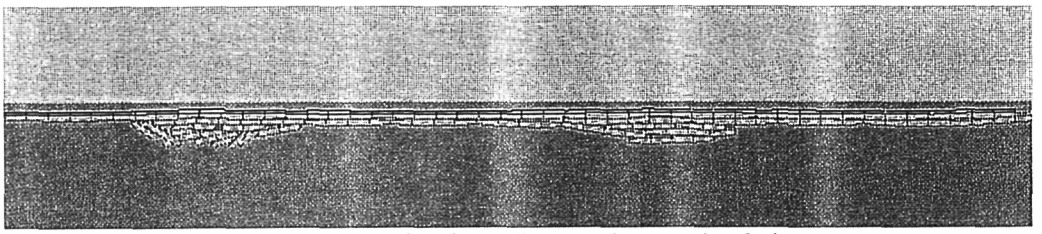


Figure 2. An example of measured ridging force. Width of the model scale ridge was 6 m.


Figure 3. A snapshot from discrete element simulations.

2.2 FIELD EXPERIMENTS

A field campaign entitled ZIP-97 (Zooming of Ice Physics) was organised in the Bay of Bothnia during March 1997. The central aims of the field experiments were to study ice cover morphology and dynamics in different scales and especially the interconnection between the scales. The work focused on three scales as shown in Figure 4: the basin scale, the mesoscale, and the local scale.

Weather favoured the experiments. Strong winds occurred and intensive ridge building was observed. The main data obtained consist of satellite SAR imagery, aerial photographs, ice thickness mapping, ridge characteristics by laser and drilling, GPS drift buoy array ice kinematics, and local tilt and strain within the ice sheet. A key feature in this field data is that the measurements in different scales were performed during the same two week period. ZIP-97 was a joint effort of 27 scientist from eight countries. The first results of the experiment are published in Haapala and Leppäranta (1997).

Basin scale observations

The satellite data consist of nine Synthetic Aperture Radar (SAR) images from ERS-2 and RADARSAT and four Russian Resurs and two Okean imagery. These data are used for ice type classification and ice kinematics studies. In addition, the ERS-2 and RADARSAT images received in near real-time were successfully used in planning of the field work.

Two helicopter flights with a laser profilometer were made for the basin wide statistics of ridge occurrence and ridge sail height. The floe sizes and lead widths can also be obtained from the data. More detailed mapping was made in the surroundings of the field camps.

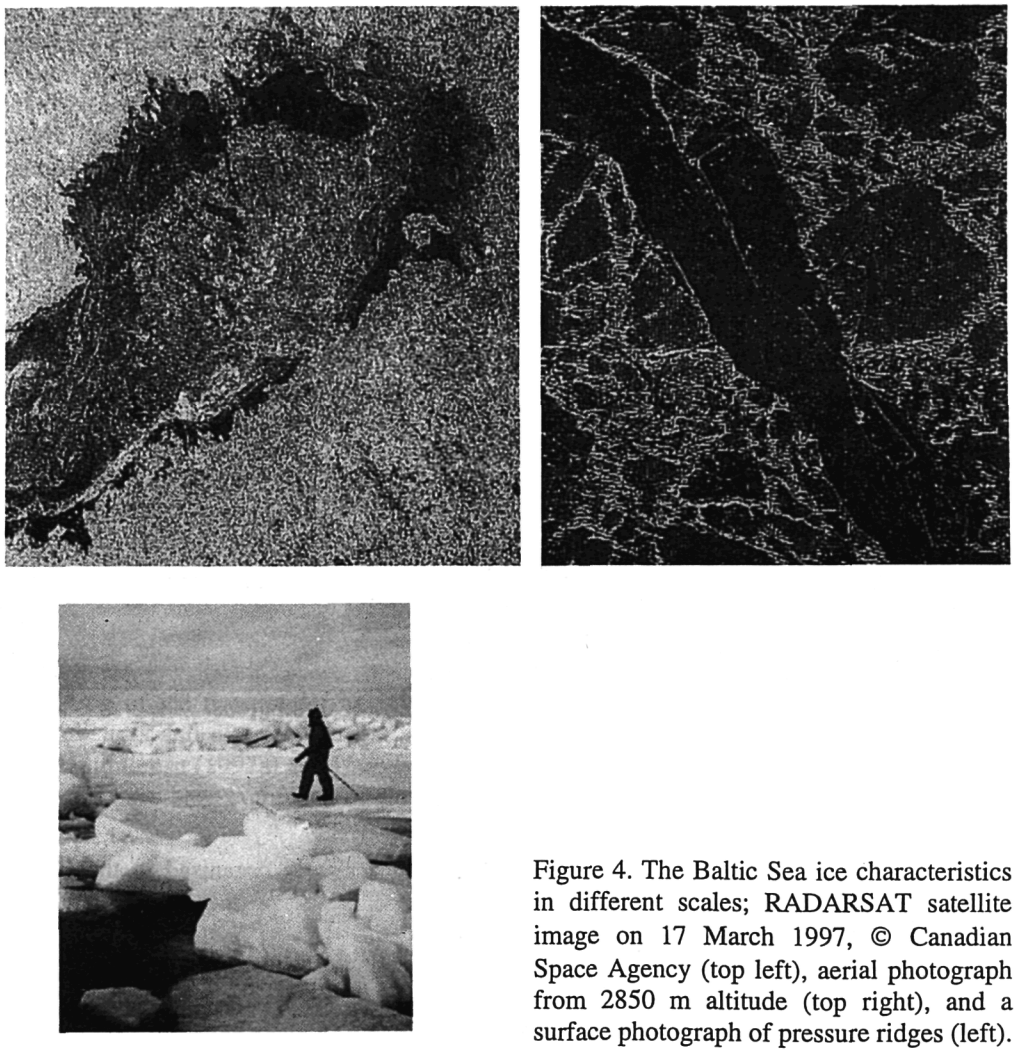


Figure 4. The Baltic Sea ice characteristics in different scales; RADARSAT satellite image on 17 March 1997, © Canadian Space Agency (top left), aerial photograph from 2850 m altitude (top right), and a surface photograph of pressure ridges (left).

Mesoscale observations

New ice drifter technology was developed for the ZIP-97 experiment. The drifters have a Global Position System (GPS) for accurate localisation and a radio modem which allows real-time monitoring of ice drift. Figure 5 shows tracks of the five drifters deployed. The drifter time series are used for ice kinematics research and for verification of ice models and SAR products. Ocean currents and hydrography were also measured. Four Aanderaa current meters and thermistor chains were installed on same ice floes as some GPS-drifters. An Acoustic Doppler Current Profiler (ADCP) was used to measure the current structure in the boundary layer beneath the ice.

Aerial photography was used for identification of ridges and determination of ice floe type, size and shape inside the GPS-drifter array. The study area was photographed three times during the campaign in order to monitor evolution of the ice conditions. Airborne radar measurements were made with a Ground Penetrating Radar and ground and helicopter reconnaissance data were collected.

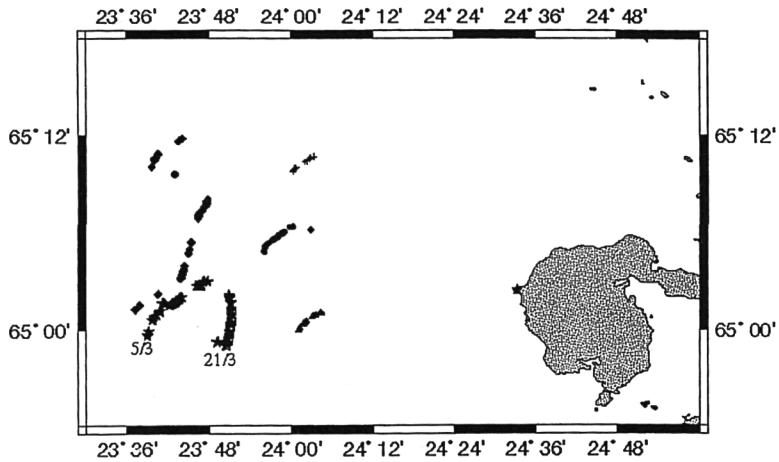


Figure 5. Ice drift measured by GPS drifters in the Bay of Bothnia during 5 March - 21 March 1997. The island shown in Hailuoto.

Local scale observations

During the ZIP-97 campaign, the local ice thickness characteristics were observed along an 8 km calibration line by drilling, ground penetrating radar and by electromagnetic methods. A detailed ridge morphology study to serve as a comparison with laboratory experiments was also made.

The local stress state of the ice cover was recorded using tiltmeters, three-component (delta) strainmeters, stress gauges and accelerometers. Additional data from a previous field campaign, the Sea Ice Mechanics Initiative (SIMI) in the Beaufort Sea, during autumn 1993 to spring 1994, is also used in the analysis. Recordings were made over the period of several days to months, allowing study of both short period ice failure processes and long period trends related to intra-annual variability in the mechanical properties and stress state of the ice cover.

Analysis has shown that this data has a sophisticated spectral structure with a long period non-linear trend and periodic oscillations in the range of 10^{-3} Hz to 10 Hz. Cyclic loads due to ocean waves and tides have already been shown to play a major role in ice deformation and fracturing in the polar seas (Wadhams, 1986; Czipott et al., 1991), but the present results show an additional contribution; short-period shear waves with differing polarisation, for which an example spectrum is shown in Figure 6.

Recent views of ridge building processes state that high-frequency seismic and acoustic waves are accompanied by waves of high amplitude and low frequency - 0.1 Hz to 1 Hz, possibly as high as 4 Hz (Farmer and Xie, 1995; Wadhams and Wells, 1995). Many papers discuss short period oscillations with reference to ice fracturing or ridge building, but none achieve a full understanding of the mechanisms of short period wave emission. It is hoped that further analysis of these short period oscillations combined with stress observations will provide better understanding of energy emission during ridge building.

Non-periodic long-term variations are related both to ice motion under wind and current forcing, and thermal expansion and contraction with temperature changes. Comparison between deformation on 10 km and local scales (~100 m) shows little relation between the two, with large deformations on the 10 km scale often leading to no significant deformation on the local scale.

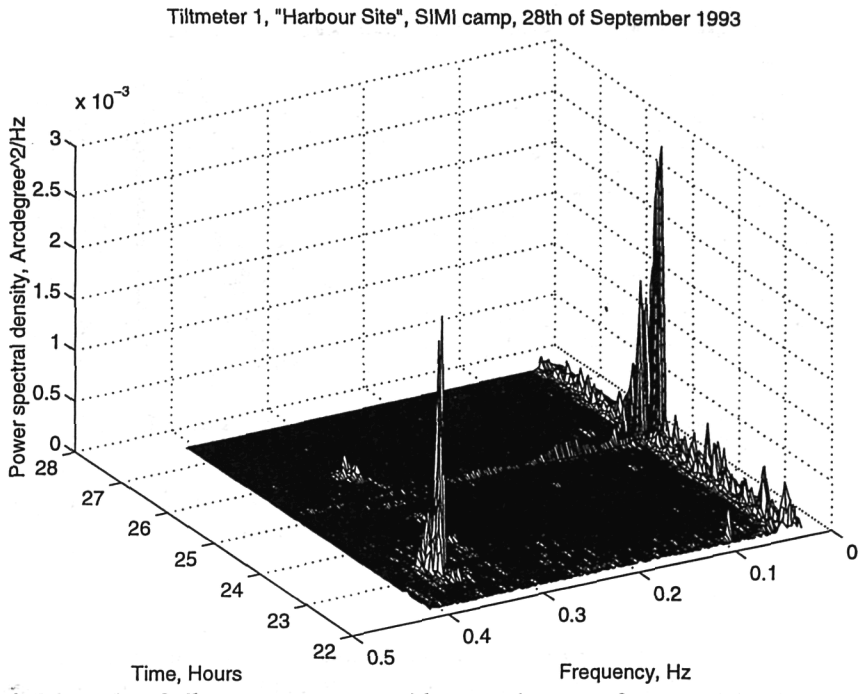


Figure 6. Example of tiltmeter spectrum with several types of waves. The data shows that energy is concentrated at $4 \cdot 10^{-2}$ Hz (swell like waves). Spectral peaks at 0.32 and 0.36 Hz represent the emission of short period waves related with ridge building process. The signal measured by local strainmeters shows a similar spectrum.

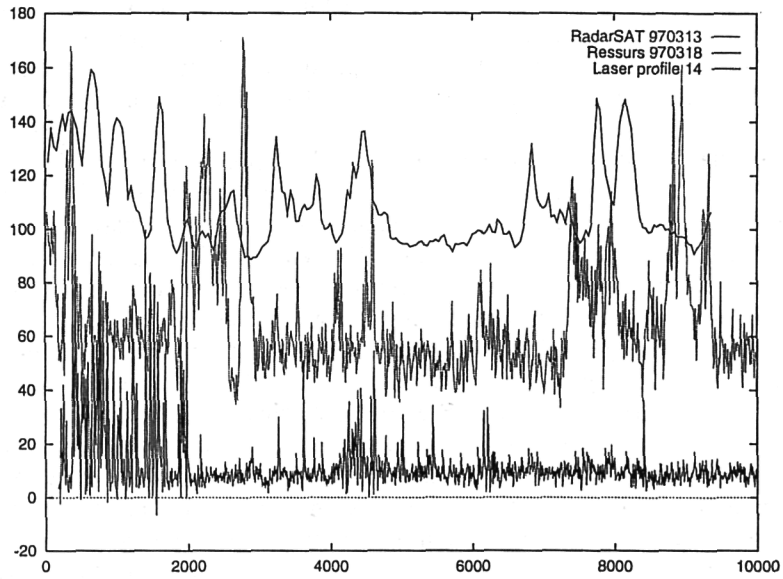


Figure 7. Example of profiles of RADARSAT SAR (middle), optical image from Resurs (top), and airborne surface profile measurements (bottom) taken in a 10 km long section west of Hailuoto during ZIP-97. The horizontal axis is in m, and the vertical axis is in cm showing the height measurements from the laser. The vertical scale of the satellite data is arbitrary.

2.3 REMOTE SENSING

Remote sensing of sea ice is an essential method in the studies of local ice cover deformation and mesoscale ice dynamics. Satellite information can be used to obtain quantitative ice parameters on large scale and mesoscale, and these parameters can be used in the coupling of satellite images with local scale observations from the field experiment. The main advantage of satellite data is the possibility to get synoptic images of large ice areas and synoptic ice motion estimates.

Figure 4 showed a RADARSAT ScanSAR image which covers the whole northern Baltic Sea. The image was taken during the ZIP-97 field campaign, which offered the first opportunity to study sea ice in the Baltic Sea with both ERS and RADARSAT (Sandven et al., 1997). From RADARSAT different modes of images were used; the highest resolution was 6 m. In addition, several cloudfree days during ZIP-97 made it possible to use high resolution optical images from the Russian satellite Resurs-O1, with pixel size down to 40 m, and aerial photographs. The data can be used for ice type classification, ridge mapping, identification of floes, leads, shear zones, drifting ice, fast ice, and to study both basin wide as well as meso scale ice dynamics.

Comparison of the different images is useful for evaluation of the ability of SAR images to classify ice types and to identify ridges and other small ice features which reflect the dynamic nature of the sea ice. Figure 7 gives profiles of SAR backscatter, optical radiation and airborne surface profile measurements from an east-west section just west of Hailuoto island. The surface profile shows the ridge heights directly, while the satellite data include also the effects of rafting, snow cover, and other small scale features. Repeated satellite images can also provide estimates of ice motion to be compared with the GPS drifters used during ZIP-97.

In another field campaign of the ICE STATE project, an upward looking sonar installed on a Royal Navy submarine was used to determine the ice thickness during a cruise in the Greenland Sea and Arctic Ocean (Wells, 1997). Simultaneous SAR images from the area were obtained from ERS-1 and ERS-2. The correspondence between the submarine track and the images obtained is shown in Figure 8. The aim of the simultaneous submarine/satellite imaging is to obtain a transform from SAR brightness to ice thickness which will allow a synoptic mapping of the statistical ice thickness distribution to be carried out from satellite measurements. The submarine sonar ice profile data is also being extensively processed to determine the statistical properties of the ice draft and the various features seen; pressure ridges, level ice, deformed ice and leads or polynynas.

2.4 MESOSCALE MODELLING

A mesoscale sea ice model has been implemented in the ICESTATE project. The model is an important part of the upscaling and downscaling work and will be used to model the ZIP-97 field experiment period. The model results will be compared with the satellite observations and the GPS drifter data.

The sea ice cover consists of many floes and is thus assumed to be a large scale granular material in slow continuous motion. When an ice field is strained by external loads, internal forces arise from interactions between the floes. These forces deform the ice horizontally and generate leads, ridges and rafting. Following the work of Erlingsson (1991) and Tremblay and Mysak (1997) the continuum momentum equation of the mesoscale ice model assumes a granular material rheology. The ice advection is driven by atmospheric loads from wind drag

and also drag from the general ocean circulation. Principal directions of the stress and strain link the components of the stress strain-rate tensors. The yield curve reduces the invariants of the stress tensor to one, e.g. normal pressure.

For each grid cell in the model, the thickness distribution of ice cover is discretised into thickness classes. Each class is advected with the mean ice velocity calculated with the momentum equation. Between the classes the ice is distributed due to rafting and ridging processes. This is parametrised with a thickness redistribution function. One goal of this modelling work is to investigate the possibilities to improve this parametrisation, using upscaling from the local scale ice experiments and numerical simulations.

3. ICE STATE

The ICE STATE project started from a need to characterise the ice cover in view of ship or offshore operations. Many of the current ice charts use the WMO standard. In this system boundaries of different ice types are shown and additional numerical information is given with the egg code for concentrations, thicknesses, and floe sizes of the ice types. The WMO system is good for general ice information but is not so good for geophysical research or for ship and offshore operations. The unsuitability of the WMO system stems from the low resolution and poor description of ridging, ice thickness, and convergence of the ice cover.

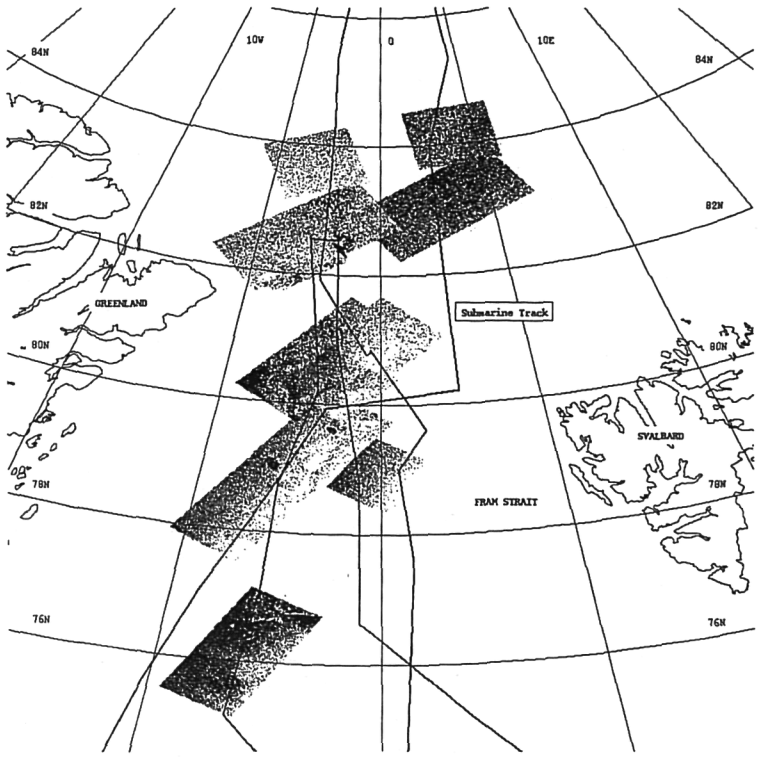


Figure 8. Map showing simultaneous coverage of SAR imagery and submarine ice profile data in the Greenland Sea and Arctic Ocean.

The central objective of this project is to identify an ice state which, as described here, is analogous to a sea state and refers to the local description of an ice cover. Further, the ice state should be predictable by mesoscale ice models and observable by remote sensing methods. As a resolution of 5 km is at the lower limit of the present mesoscale ice models, definition of an ice state requires sub-grid scale information, which can be derived from mesoscale if a downscaling structure for ice cover is known. Thus an ice state can be defined in a conceptual level as a function of two entities:

$$\textit{ice state} = \mathrm{F}(\textit{mesoscale ice condition, downscaling structure})$$

In this approach the mesoscale ice conditions are described by a set of variables for each grid cell. Haapala and Leppäranta (1997) have suggested the use of six key variables for the Baltic Sea ice. Table 1 gives these variables together with description how they can be solved by mesoscale ice models or observed by remote sensing. In principle, all the key variables can be solved by mesoscale ice models.

Table 1. Key mesoscale ice variables for the Baltic Sea and how they can be observed with remote sensing methods or solved by mesoscale ice models.

Variable	Remote sensing	Model
Ice compactness	Good	Good
Ice thickness distribution	Rough	Rough
Ice floe size	Good	No data
Ridge size and ridge density	Bad	Bad
Ice velocity	Control fields	Good
Ice stress	No data	Large scale

The second part of an ice state definition is the downscaling structure and description of local ice conditions. Sea ice cover has scale invariant features. For example, aerial photographs from an area at different scales look often very similar. If this scale invariance reaches from local scale to the scale of mesoscale ice models, it provides a way to connect these two scales, and a downscaling structure can be formulated and used to estimate the variation of local ice conditions. The mesoscale ice variables can be interpreted as average values $\langle x \rangle$ in a grid cell. If the cell is then divided into smaller cells, the values of the variables x for the smaller cells have some distribution $f(x)$ the mean value of which is $\langle x \rangle$. A mesoscale model predicts the future ice conditions in the cell from the present ice conditions as: $\langle x(t_i) \rangle \rightarrow \langle x(t_{i+1}) \rangle$. With the downscaling structure it is possible to derive from this the corresponding time change for the distributions defined in the cell: $f(x,t_i) \rightarrow f(x,t_{i+1})$.

The downscaling structure can be derived from the population balance equations (Ramkrishna, 1985; Lensu, 1997, 1998). This theory has been used to derive equations for the time change of distributions $f(x)$; the distribution is the solution of such an equation. On the other hand, if there is enough measured data, the form of $f(x)$ may be fixed on the basis of data only. Then an equation having $f(x)$ as a solution is sought. This equation is usually unique and can be used to predict the change in $f(x)$.

An explicit formulation of the downscaling structure has been made for the case where $\langle x \rangle$ is ridge density. Taking a short segment of the track, the "local ridge density" x can be defined for the segment while $\langle x \rangle$ for the whole track may represent "mesoscale ridge density". The local density x is proportional to the number of ridges in the segment. Thus the

distribution of local ridge density can be studied by dividing the track into segments and counting the ridges in each segment. This defines an empirical distribution $f(x)$ which is found to be well modelled by the discrete geometric distribution (the linear slope in the semilogarithmic plots of Figure 9). This property is also independent of the length of the segments, that is, it is scale invariant. Lensu (1998) has demonstrated that this determines the equation describing the time change of $f(x)$. The main result is that when new ridges are formed along the track, the probability for the ridges to appear at a certain location is proportional to the local ridge density. The results can also be generalised to two dimensions. Thus if a mesoscale model predicts that a certain volume of ice is deformed into ridges, it is possible with the ridge density downscaling structure to predict the probability that new ridges are formed to a certain location.

Figure 9 shows further that a similar downscaling structure found for the ridge density can also be discerned in SAR images. In addition, for SAR images, the scale invariant properties range from the scales of few meters to kilometres. Thus it is possible to some extent quantify ridging from imagery by studying the downscaling structure.

Another approach to the characterisation of an ice state from images and ice profiles has been proposed by Kerman (e.g. Kerman and Johnson, 1998). In this method the brightness of each pixel in the SAR image is compared with that of its neighbours and a characteristic information curve for the image is obtained. The central assumption of the method is that this brightness difference has a negative exponential distribution, similarly to a Gibbs process, and can be equated with the damage or deformation undergone by the ice cover. It has been found that the information curves obtained for both SAR imagery and ice thickness have a similar geometrical form, suggesting that a transformation between the two sets of curves could be used to provide ice thickness from SAR imagery. Examination of the validity of the method centres on answering weather the different ice states are really identifiable by the Kerman algorithm and what is the effect of the random noise, known as 'speckle', in the SAR image on the Kerman algorithm results.

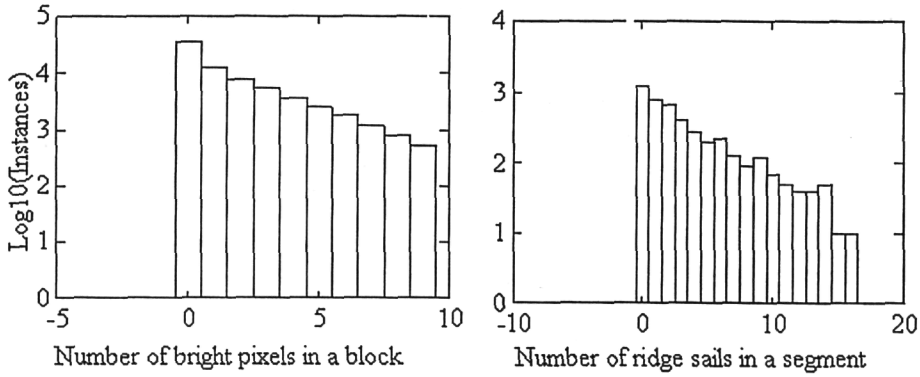


Figure 9. Statistics of a SAR image (left) and surface profile data (right) from the same area in the Baltic Sea. From the SAR image, blocks of 3x3 pixels or 94x94 m were formed and the number of pixels belonging to the brightest 16 % of the intensity histogram were counted in each block. From the laser profilometer data, the number of ridge sails in 94 m long segments of the profile were counted. Both numbers show the same type of distribution.

4. SUMMARY AND CONCLUSIONS

This paper has reviewed some of the research performed in the ICE STATE project. In this project the local ice cover deformation and the area connecting the local scale ice mechanics and the mesoscale ice modelling have been studied and new results have been obtained.

In the local scale work ice ridges were produced for the first time in laboratory conditions. As the ridging force was also measured, a connection between ice cover morphology and local forcing can be formed. Thus, if the ice thickness and local forcing are known, the size of ridges can be estimated, or if the size of ridges in a sea area is known, the local stresses that were active in the ice cover during the ridging event can be estimated. The mesoscale model used in this project is directly addressing the local scale processes in an ice cover. As the local scale ridging/rafting information is used in the mesoscale model, the small scale information derived from the model has a sound basis.

As one of the aims of this project is to obtain local scale information from mesoscale ice models, a link between a mesoscale model and local ice cover forcing *or* morphology need to be formulated. The morphological downscaling strategy introduced above is a new approach in which a structure is given for the sub-grid scale ice properties. Following such a morphological downscaling, a realisation of possible sub-grid scale ice conditions can be formed. Further, the downscaling structure, or downscaling rules, can be used to characterise the morphology of the ice cover and in this way define an ice state. This kind of downscaling approach is closely related to remote sensing work and image analysis. If an image, for example a SAR image, has a similar scaling structure as an ice cover, then this structure of the image can be used to characterise the ice cover and to obtain local scale ice information.

Other important aspects of the downscaling work are results from the field experiments and remote sensing work. The ice kinematics measurements performed by using GPS-drifters make an important link between information from SAR images and field conditions. Another valuable set of data is the simultaneous submarine/satellite imaging which will allow a synoptic mapping of statistical ice thickness distribution to be carried out from satellite measurements. The field data is also valuable in verifying the results from mesoscale modelling work.

Results of this project have several potential applications. These include the prediction of ice conditions encountered by ships and offshore structures. The local scale results for ice ridging can be applied in determining the ice forces and ice pile-up on offshore structures. The improvement of the characterisation of local ice cover processes is also crucial for more reliable mesoscale modelling of ice cover dynamics.

ACKNOWLEDGEMENTS

The work described here was supported by the European Commission, DG XII, through the Marine Science and Technology programme 1994-1998 (MAST III) under contract MAS3-CT95-0006. The participants in this joint project entitled "ICE STATE" are Helsinki University of Technology, Nansen Environmental and Remote Sensing Center, Scott Polar Research Institute, University of Helsinki, and University of Iceland.

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TITLE: European Subpolar Ocean Programme, Phase 2 (ESOP 2)
The Thermohaline Circulation in the Greenland Sea

CONTRACT NO: MAS3-CT95-0015

COORDINATOR:
Dr E Jansen
Department of Geology, University of Bergen
Allég 41, N-5007 Bergen, Norway
Tel.no: (47) 55 58 34 91
Fax no: (47) 55 58 94 16
E-mail: eystein.jansen@geol.uib.no

PROJECT MANAGER:
Mr V Opheim
Centre for Studies of Env. and Resources, Univ. of Bergen
Bergen High Technology Centre, N-5020 Bergen, Norway
Tel.no: (47) 55 58 43 24
Fax no: (47) 55 58 96 87
E-mail: vegard.opheim@smr.uib.no

PARTNERS:

Dr Truls Johannessen
Centre for Studies of Env. and Resources,
University of Bergen
Bergen High Technology Centre,
N-5020 Bergen, Norway
Phone: (47) 55 58 43 27
Fax: (47) 55 58 96 87
E-mail: truls.johannessen@smr.uib.no

Dr Andrew J Watson
University of East Anglia,
School of Environmental Sciences
Norwich NR 4 7TJ, England
Phone: (44) 1603 593761
Fax: (44) 1603 507719
E-mail: a.j.watson@uea.ac.uk

Dr Leif G Anderson
Gothenburg University
Departm. of Analytical and Marine Chem.
S-412 96 Gøteborg, Sweden
Phone: (46) 31 772 2774
Fax: (46) 31 772 2785
E-mail: leif@amc.chalmers.se

Dr Elisabet Fogelqvist
Gothenburg University
Departm. of Analytical and Marine Chem.
S-412 96 Gøteborg, Sweden
Phone: (46) 31 772 2282
Fax: (46) 31 772 2785
E-mail: elisabet@amc.chalmers.se

Dr Jean-Claude Gascard
LODYC
Université Pierre et Marie Curie,
4 place Jussieu, 75252 Paris 05,
France
Phone: (33) 1 44277070
Fax: (33) 1 44273805
E-mail: gascard@lodyc.jussieu.fr

Dr Lilliane Merlivat
LODYC
Université Pierre et Marie Curie,
4 place Jussieu, 75252 Paris 05,
France
Phone: (33) 1 44273248
Fax: (33) 1 44277159
E-mail: merlivat@lodyc.jussieu.fr

Dr Grant Miller Raisbeck
Centre de Spectrom. Nucleaire et de Spectrom. de Masse,
Batiment 108, Orsay 91405, France
Phone: (33) 1 69 15 5264
Fax: (33) 1 69 15 5268
E-mail: raisbeck@csnsm.in2p3.fr

Dr Helge Drange
Nansen Environ. and Remote Sensing Center,
Edvard Griegsvei 3A, N-5037 Solheimsviken,
Norway
Phone: (47) 55 29 72 88
Fax: (47) 55 20 00 50
E-mail: helge.drange@nrsc.no

Dr Jon Olafsson
Marine Research Institute
Skulagata 4, IS-121 Reykjavik
Iceland
Phone: (354) 552 0240
Fax: (354) 562 3790
E-mail: jon@hafro.is

Dr Francisco Rey
Institute for Marine Research
P.O. Box 1870 - Nordnes
N-5024 Bergen, Norway
Phone: (47) 55 23 85 00
Fax: (47) 55 23 85 84
E-mail: francisco.rey@imr.no

Dr Knut Yngve Børsheim
The Norwegian University of Science and Technology
Laboratory of Biotechnology
N-7034 Trondheim, Norway
Phone: (47) 73 594058
Fax: (47) 73 591283
E-mail: borsheim@kjemi.unit.no

Dr Peter Wadhams
Scott Polar Research Institute,
Cambridge University,
Lensfield Road, Cambridge CB2 1ER, England
Phone: (44) 1223 336542
Fax: (44) 1223 336549
E-mail: pw11@cus.cam.ac.uk

Dr Barry Uscinski
Dep. of Appl. Math. and Theoretical Physics
Cambridge University,
Silver Street, Cambridge CB3 9EW, England
Phone: (44) 01223 337900
Fax: (44) 1223 337918
E-mail: rita@amtp.cam.ac.uk

Dr Flavio Fiorigi Parmiggiani
IMGA-CNR,
Via Gobetti 101, 40129 Bologna,
Italy
Phone: (39) 51 639 8009
Fax: (39) 51 639 8132
E-mail: parmi2@ghibli.imga.bo.cnr.it

Dr Gereon Budéus
Alfred Wegener Institute für Polar- und Meeresforschung
P.O.Box 120161, D-27515 Bremerhaven,
Germany
Phone: (49) 471 4831702
Fax: (49) 471 4831724
E-mail: gbudeus@awi-bremerhaven.de

Dr Jan Backhaus
Inst. für Meereskunde, Hamburg Univ.
Troplowitzstrasse 7, D-22529 Hamburg,
Germany
Phone: (49) 40 4123 2604
Fax: (49) 40 4123 4644
backhaus@dkrz.de

Dr Detlef Quadfasel
Inst. für Meereskunde, Hamburg Univ.
Troplowitzstrasse 7, D-22529 Hamburg,
Germany
Phone: (49) 40 4123 4206
Fax: (49) 40 4123 4644
E-mail: quadfase@ifm.uni-hamburg.de

Dr Jens Hesselbjerg Christensen
Danish Meteorological Institute
Lyngbyvej 100, DK-2100 Copenhagen
Denmark
Phone: (45) 39 157428
Fax:(45) 39 157460
E-mail: jhc@dmi.min.dk

Dr Torgny Vinje
Norwegian Polar Institute
P.O. Box 5072 Majorstua
N-0301 Oslo, Norway
Phone: (47) 229 59587
Fax: (47) 229 59501
E-mail: torgny.vinje@npolar.no

Dr Howard Cattle
UK Meteorological Office,
Hadley Centre for Climate Predict. and Res.
London Road, Bracknell, Bershire RG12
2SY, England
Phone: (44) 1344-856209
Fax: (44) 1344 854898
E-mail: hcattle@meto.govt.uk

Dr Leif Toudal
Technical University of Denmark
Danish Center of Remote Sensing
DK-2800 Lyngby, Denmark
Phone: (45) 45 25 3791/881444
Fax: (45) 45 931634
E-mail: ltp@emi.dtu.dk

Dr Erland Bo Rasmussen
Danish Hydraulic Institute
Agern Allé 5, DK-2970 Hoersholm,
Denmark
Phone: (45) 45769555
Fax: (45) 45 762567
E-mail: ebr@dhi.dk

Dr Thor Jakobsson
Iceland Meteorological Office
Bustadavegur 9, IS-150 Reykjavik
Iceland
Phone: (354) 560 0600
Fax: (354) 552 8121
E-mail: thor@vedur.is

Dr Harry Dooley
International Council for the Exploration of
the Sea,
Palaegade 2-4, 1261 Copenhagen K,
Denmark
phone: (45) 3315 4225
fax: (45) 3315 4215
harry@ices.dkE-mail: harry@ices.dk

EUROPEAN SUBPOLAR OCEAN PROGRAMME, PHASE 2 (ESOP 2): THE THERMOHALINE CIRCULATION IN THE GREENLAND SEA

V. Opheim[1] and E. Jansen[1] with input from L.G. Anderson[2], J. Backhaus[3], H. Drange[4], J-C. Gascard[5], T. Johannessen[1], L. Toudal[6], P. Wadhams[7], A.J. Watson[8], and the rest of ESOP-2 scientific team

[1] *Centre for Studies of Environment and Resources, University of Bergen, Norway*
[2] *Department of Analytical and Marine Chemistry, University of Ghotenburg, Sweden*
[3] *Inst. für Meereskunde, Hamburg Univärsitet, Germany*
[4] *Nansen Environmental and Remote Sensing Center, Norway*
[5] *LODYC, Université Pierre et Marie Curie, France*
[6] *Dep. of Electrom. Systems, Danish Center of Remote Sensing, Techn. Univ. of Denmark*
[7] *Scott Polar Research Institute, Cambridge University, UK*
[8] *University of East Anglia, School of Environmental Sciences, UK*

SUMMARY

The European Subpolar Ocean Programme, Phase 2, a study of the thermohaline circulation in the Greenland Sea, started on 1 January 1996 and runs for 36 months. A short description of the background, objectives and organisation of the project is given. A summary of main scientific achievements so far is also outlined. The results presented are preliminary and should not be treated as final.

1. INTRODUCTION

One of the main issues in marine research today is to understand whether the thermohaline circulation is stable in its present mode of operation. Despite many years of extensive research, only a crude and qualitative understanding is at hand today, and many fundamental questions related to the basic nature of convective overturning in high latitudes are not resolved: what are the mechanisms, what are the driving forces, what are the quantities and ventilation rates, and what are the quantities of the associated fluxes of carbon? This calls for a novel approach to the study of thermohaline circulation, and it is the ambition of ESOP-2 to overcome the shortcomings of previous attempts by the implementation of a completely new interdisciplinary research strategy: ESOP-2 combines the purposeful release of an anthropogenic tracer, the launching of isobaric floats, the observation of standard hydrographic parameters and transient tracers, partly from a permanently moored, internally recording CTD, a complete coverage of the carbon cycle, remotely sensed and directly measured sea ice fluxes, and an integrated small, meso and large scale modelling effort, which will allow a quantitative assessment of convection and thermohaline circulation.

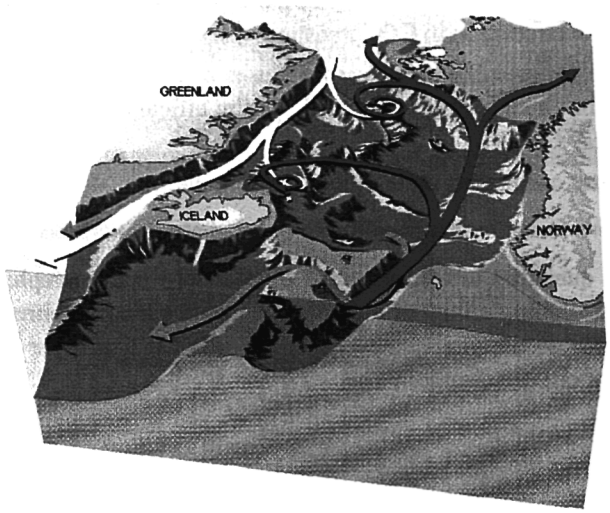


Figure 1: Main features of ocean circulation in the Nordic Seas.

2. OBJECTIVES

The goal of ESOP-2 is to understand the thermohaline circulation in the Greenland Sea, its sensitivity, and impact on global ocean circulation, building on a unique combination of novel experimental techniques, modelling and experience gained under ESOP-1.

Specific objectives:

- To understand the oceanic thermohaline circulation on meso and large scales and its dependence on surface fluxes of heat, fresh water and momentum.
  - → To follow the fate of the newly formed waters as they leave into the Norwegian Sea, the Iceland Sea, and over the Denmark Strait, thus contributing to the global ocean circulation.
  - → To obtain a quantitative estimate of both the depth and the integrated extent of the deep winter-time mixing.
  - → To quantify rates of mixing in summer at shallow (approx. 300 m) levels in the Greenland Sea gyre.
  - → To quantify the importance of internal mixing processes for the transformation of water masses.
  - → To assess the lateral exchanges between the rim and the central gyre of the Greenland Sea.
- To study fresh water fluxes into and out of the central Greenland Sea region.
  - → To study ice growth and decay and consequent salt fluxes and overturning within the central Greenland Sea region.

- Evaluate the role of convection areas in ocean-atmosphere gas exchange and investigate the role of thermohaline circulation in CO_2 transport.
  - → To provide precise calculations of carbon fluxes and carbon budgets in active convection areas like the Greenland Sea, and evaluate the efficiency of the convection areas in the oceanic uptake of CO_2.
  - → To provide better constraints on the global carbon budgets.
- To use observations to improve and calibrate coupled atmosphere-ocean models.

The project address questions left unanswered by standard oceanographic techniques. The combined field and modelling efforts of the project constitute a comprehensive attempt, both to understand the role of the Greenland Sea in the «Global Conveyer Belt» and to make realistic predictions of climate change.

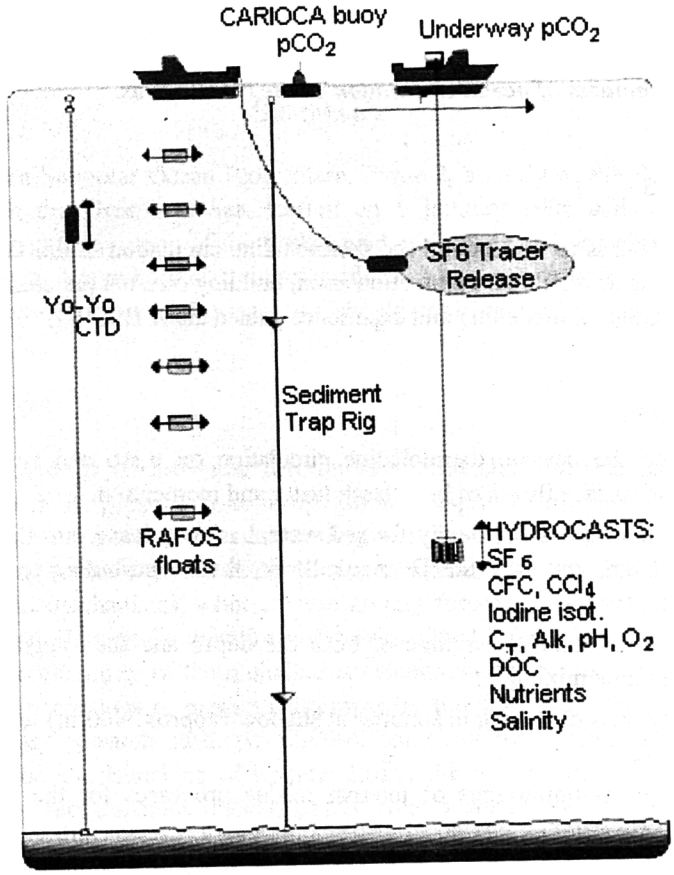


Figure 2: Schematic of activities in the Greenland Gyre. The use of oceanographic and sea ice measurements combined with novel automated measurement techniques and the tracer and floats release, make ESOP-2 a unique oceanographic experiment.

3. ORGANISATION

The project is divided into four Task Groups (TG): *TG 1: Tracer experiment and Ocean Physics. TG 2: Ice-ocean interaction, TG 3: Carbon cycle, TG 4: Modelling.* The Task Groups are closely linked and there is much mutual dependence between them. To ensure an efficient management, a management infrastructure is set up to administer the project and its data.

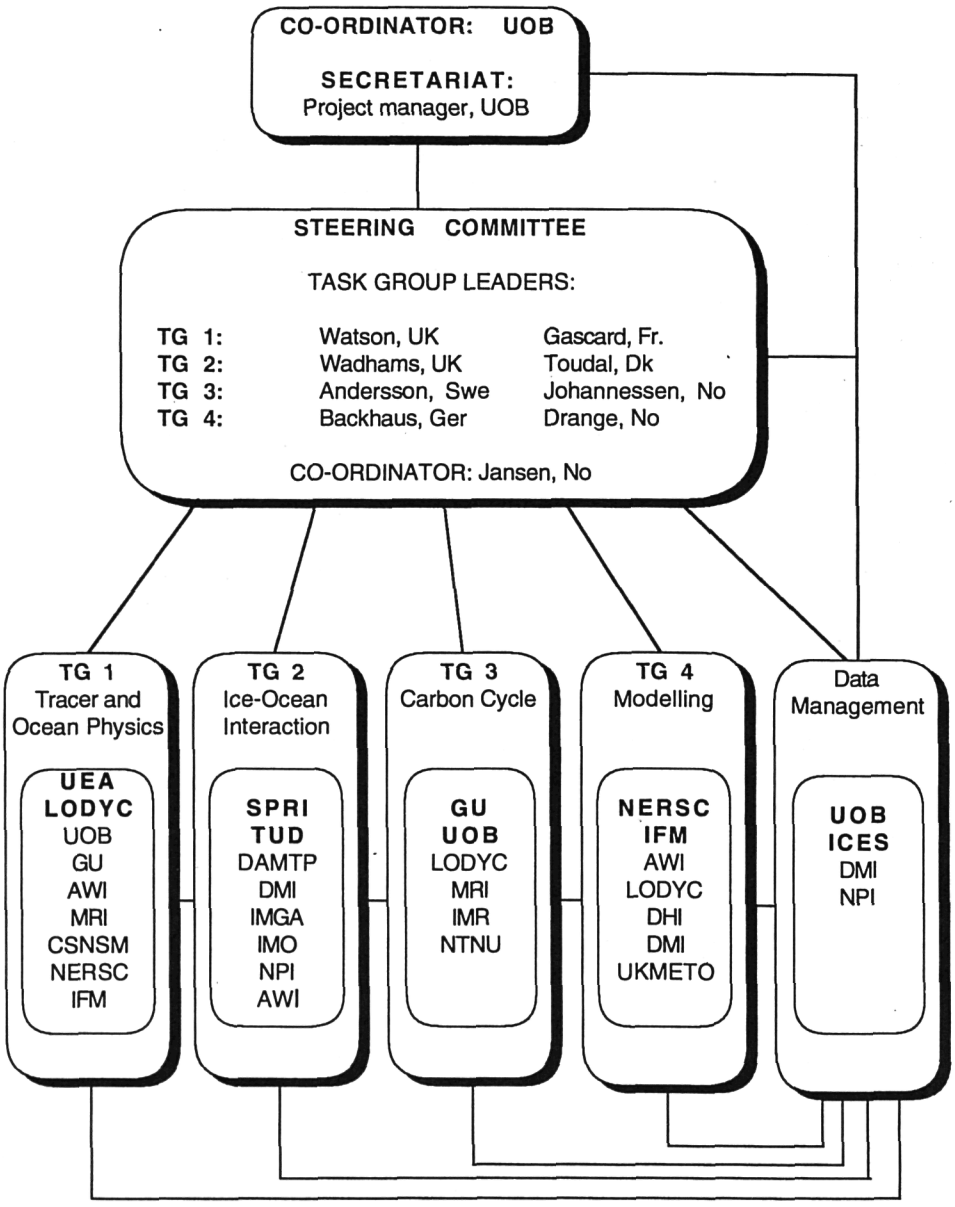


Figure 3: ESOP-2 management structure

4. ACHIEVEMENTS SO FAR

In the following sections we will give a short summary of the main scientific achievements at this stage of the project. These are preliminary results used here to illustrate the results of the project and should not be treated as final. The final results will be published in relevant journals and reports.

4.1. TRACER EXPERIMENT AND OCEAN PHYSICS

1. The *tracer release experiment* has been technically audacious; the largest such experiment so far undertaken by oceanographers and the first to be attempted in a dynamically active region. Three full-scale surveys of the tracer distribution have so far been carried out, plus one transect using stored samples and quarterly monitoring near Iceland.

   The tracer release has yielded graphic and quantitative estimates of the mixing, both in summer and winter, of the upper waters of the gyre. Recent data have begun to illuminate exchange with surrounding water bodies.

   → Rates of summer-time mixing are an order of magnitude more rapid compared to earlier tracer release experiments in quieter regions of the ocean.

   → Winter-time rates associated with deep convection are more rapid still; rates averaged over 75 days covering the convection period were about five times more rapid than summer rates, but measured scaling arguments suggest that much of this activity was actually concentrated into very short time period.

   → Overall however, mixing rates are revealed to be more modest than might have been expected in a region of active deep convection; actively convecting plumes rapidly homogenise the water they contain, but the upper gyre water as a whole was not homogenised in this way during the convection period. Much of the observed homogenisation of the upper water column seems to be due to mixing acting year round.

   → In the horizontal, after spreading into the gyre itself within a matter of months, further spreading has been rather slow and indications are that the gyre is rather tightly isolated from the surrounding water bodies.

See also Figure 4.

2. The *RAFOS float experiment* was another substantial technical achievement, with 18 out of 25 floats popping up after 300 days of drifting, and 15 being re-deployed for a second year.

   The float experiment has given the following unexpected results:

   → A very dynamic eddy field exists within the gyre, at scales from 5 km up to 50 km and lifetimes ranging from months up to > 1 year. These eddies seem to be persistent, coherent, and mostly anticyclonic.

   → None of the recovered floats escaped from the gyre, even after 300 days of drifting. This observation argues clearly for the gyre as an isolated water body.

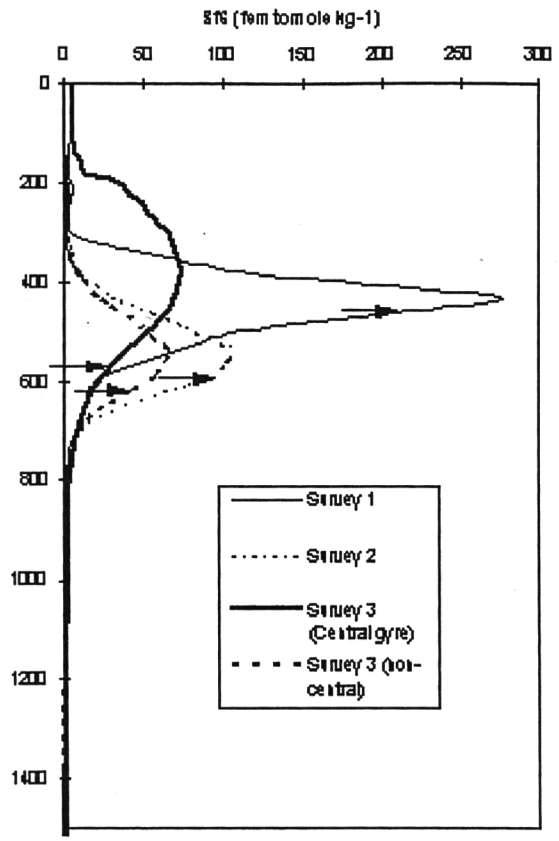


Figure 4: Mean profiles of tracer against depth in the water column for three surveys between August 1996 and May 1997. Arrows indicate the approximate depths of the «target» isopycnal on which the tracer was released.

3. Substantial *hydrographic surveys* have been undertaken on numerous cruises covering all seasons of the year. What is unusual about this series of measurements has been its intensity; by combining resources from the many different partners we have been able to provide a quasi-continuous record of the region under study. The *transient tracer* programme has produced a comprehensive monitoring of the concentrations of CFCs which are important constraints on models of the oceanography. The Iodine - 129 measurements clearly show the potential of this tracer.

   The intense hydrographic and transient tracer programmes have yielded a rich variety of results.

   → There is evidence for deep convection caught «almost in the act» where deep water penetration in the northern Greenland sea is documented to occur close to the Ice edge.

   → The April-May cruise located a deep chimney stretching to about 2000 m, similar (and in a similar location) to those reported in earlier years. These chimneys seem to be qualitatively distinct from the more areally extensive convection going on in the gyre centre. They penetrate deeper as a result of local intense cooling of comparatively salty water.

→ 1997's CFC transient tracer data from the J. Hjort cruise clearly show that the water in the chimney is of near-surface origin. The chimney penetrates clear through the SF_6 marked layer lying between 200 and 600 m, but apparently entrains none of the tracer-marked water. These data must provide powerful constraints on models of the chimney forming process. The lack of SF_6 above background in the chimney clearly points to an origin outside the gyre, in the waters of the West Spitsbergen current.

→ Long term, warmer and more saline water is apparent in the central Greenland sea below 2000m. A characteristic temperature maximum and salt minimum, observed throughout the nineties, has been slowly moving downward in the water column.

→ Results of monitoring of the Denmark strait and region round Iceland to date is consistent with exchange between the Greenland sea and Denmark strait being rather slow and indirect. The new transient tracer Iodine - 129, being tried in earnest for the first time during ESOP-2, shows I-129/I127 ratios that are larger at the Denmark strait than any observed in the Greenland sea. Furthermore, our observations have so far failed to reveal any of the SF_6 tracer arriving at these locations. More data are obviously needed however; arrival of a large tracer signal in the near future would modify the picture substantially.

4. The *yo-yo deployments* were the one innovative technical development which has not gone as planned. The daily CTD records originally hoped for would have been a substantial addition to our knowledge, but at least we got a record of surface conditions at the gyre centre from this exercise.

5. *Analysis of historical (past 10 years) data* has been an essential aspect of the programme, enabling us to test hypotheses from our present measurements against the historical context.

4.2. Sea Ice - Ocean Interaction

The mapping of the 1996-7 Odden by remote sensing was carried out by the reception, archiving and analysis of AVHRR imagery (DMI), SSM/I passive microwave imagery (DTU) and SAR imagery (DTU, SPRI) and their merging to create a composite picture. DMI also generated digital surface temperatures for the sea and sea-ice surfaces. In the analysis of the remote sensing data the SSM/I imagery was the prime source for mapping, and from it contour maps of ice concentration were generated (DTU).

After the exceptional ice year of 1995-6, when the Odden formed very late but stayed in existence until late in the summer (mid-August), the 1996-7 Odden was more conventional, forming in late November and lasting until spring. Its main unusual characteristic was the large quantity of old ice floes (10-20%) embedded in the matrix of frazil-pancake ice which normally composes the whole of Odden.

The cruise of «Jan Mayen» in March 1997 was most fruitful, this being the only opportunity to carry out direct field investigations of the ice in Odden (SPRI and collaborators). The composition of the ice cover was studied by observation and direct sampling, with frazil being sampled for thickness, concentration and salinity, and pancake ice for size, shape, thickness, nature of snow cover, temperature-salinity profiles, ice fabric (by thin and thick section analysis) and meteoric ice/snow content (by O-18 analysis). Near-surface water

structure was measured by a hand-held CTD deployed from a rubber boat away from the ship, while normal CTDs were done to 2000 m. Several ERS-2 passes were validated to yield the relationship between SAR signatures of young ice and ice volume. Three «pancake buoys», designed to resemble pancakes hydrodynamically, were deployed in the ice and tracked by Argos/GPS.

Results are still being analysed and merged with data from the remote sensing programme, but preliminary findings from the buoy data suggest that there is a net flux of pancake ice (mainly wind-driven) away from a formation region on the NW side of Odden, near Nordbukta, and towards the SE where melt occurs. This would give a net salt flux into the ocean in the vicinity of Nordbukta, and a net fresh water flux near the open ocean ice edge. The magnitudes, and possible role in stimulating overturning in the Nordbukta area, are still being computed.

On the larger scale, NPI collected upward sonar data from moored systems in Fram Strait, some also providing current data, and in collaboration with AWI (data from Argos buoys and sequential AVHRR images) generated ice velocity fields and mass transport estimates for Fram Strait and for the Greenland Sea as a whole. This provides a measure of the fresh water flux entering the Greenland Sea from the Arctic Ocean as sea ice, which when released tends to stabilise the water column and hamper convection.

A development programme for a remote sensing technique to estimate pancake ice thickness in Odden was continued by IMGA-CNR and SPRI, with help from the «Jan Mayen» cruise, in which a directional wave buoy was deployed at each ice station. This gave validation data for the technique, which depends on deriving the wave spectrum inside and outside the ice from the analysis of SAR imagery, then determining the change in wavelength of the principal component, which is a function of ice thickness.

Surface measurements in the open sea, relevant to the cooling and convection processes, were carried out by IMO, which measured surface energy fluxes from «Bjarni Saemundsson» in February 1997 in the Iceland Sea; and by DAMTP, which carried out one-ship acoustics experiments during the same cruise to demonstrate the ability of the acoustic shadowgraph technique to detect sub-surface convective structures and other small-scale water structure fluctuations.

4.3. Carbon Cycle

Dissolved carbon species will by the deep water formation in the Greenland Sea be transported from the surface to deeper layers and thus be sequestered for up to several hundred years. Another transport mechanism of carbon from the surface to deeper layers, that is independently of the vertical mixing, is through sinking biogenic particles and respiration of migrant plankton. An important question concerning these sinks of carbon is: What are the sources? The answer depends on the scale we use, both in time and space. In a global system more or less in steady state, the oceans loose carbon to the atmosphere in some regions and take it up in others. However, if we look at the present system and set our boundaries around the Nordic Seas, a significant fraction of the sinking carbon has its source in the sea water flowing into our region, while the rest is taken up from the atmosphere. The air-sea exchange of carbon dioxide is a function of the partial pressure difference (ΔpCO_2) and the

piston velocity, with the latter mainly being a function of wind speed. Changes in ΔpCO_2 is mainly caused by processes in the surface water (the atmospheric pCO_2 is relatively constant) and include biological production, temperature changes and vertical mixing. These three processes are all seasonally dependent, with maximum effect at different seasons, and they will together produce the observed pCO_2 field.

The timing of the different fluxes is such that the mixing and convection occur during the winter, when the density gradient is small, while the sedimentation is coupled to the productive season, when the density gradient is large. By using the variation of the different properties over the year, we can estimate what the main drivers are and their timing. In Figure 5 the salinity, temperature, dissolved inorganic carbon and phosphate are plotted versus days of the year for the surface mixed layer (thickness varies over the year, with summer values around 30 m) in the central Greenland Sea. During the summer season the nutrients are low because of primary production, also reflected in the dissolved inorganic carbon signal. The total alkalinity showed a very constant concentration when normalised to a constant salinity.

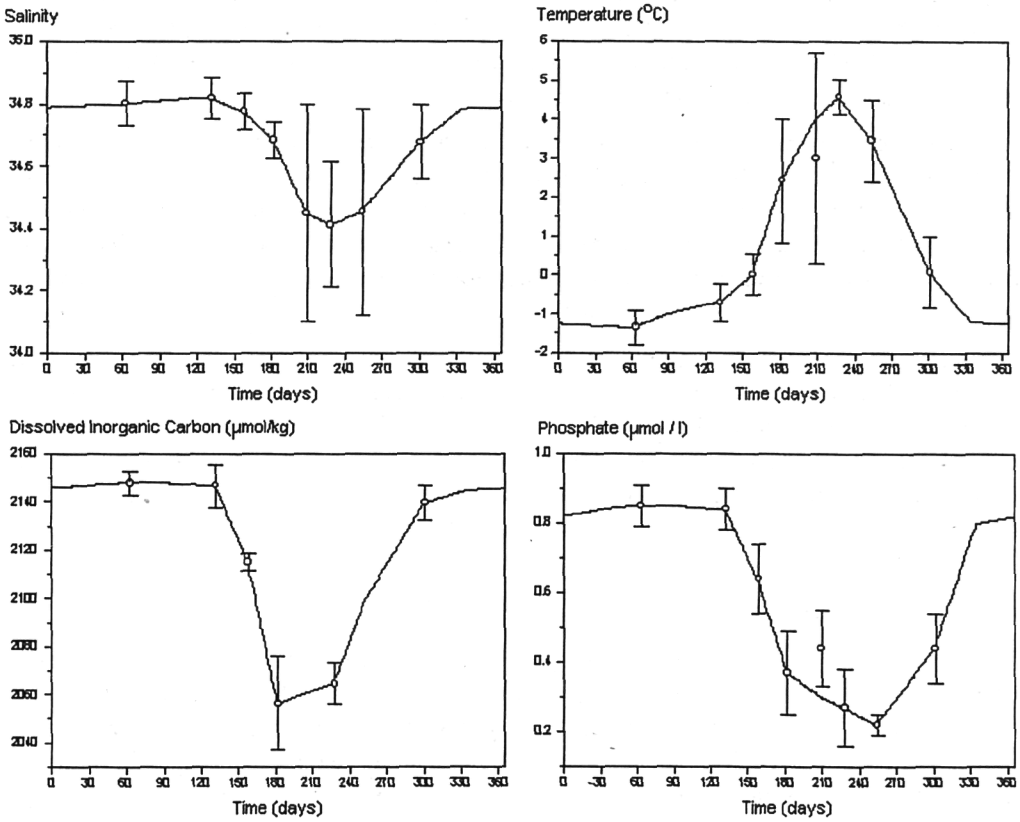


Figure 5: Mean salinity, temperature, dissolved inorganic carbon and phosphate properties in the surface mixed layer of the Greenland Sea. Different data sets are shown as points, with the scatter within each data set illustrated by the vertical bars (standard deviation). Lines are fitted to the mean measured data, in order to get the evolution over the year.

Day to day concentration changes of nutrients are computed assuming vertical mixing and primary production / decay of organic matter as the driving forces. Adding the daily changes

in nutrient concentration, due to biological processes, over one year and converting them to carbon equivalents by applying the stoichiometric relationship in organic matter, gives an annual consumption of 8 - 12 gC m^{-2} when the thickness of the surface mixed layer is set to 50 m. The calculated consumption corresponds to the nutrients mixed up from below during one year and if no other sources or sinks of nutrients were present it would equal the export production. However, we have no information about the difference between the advective influx and outflux, or the atmospheric deposition, but as the carbon consumption agrees fairly well with other estimates of export production it indicates that the vertical mixing is the dominant source of nutrients to the surface layer.

The fugacity of carbon dioxide, calculated from the line fitted to the dissolved inorganic carbon concentration of Figure 5 and the total alkalinity, is illustrated in Figure 6.a together with the atmospheric record from weather ship M.

In Figure 6.b it is seen that the flux is very variable, but with a mean which is fairly constant over the year. The latter is because the lower wind in the summer compensates for the higher difference in fugacity. Also it is seen that the Greenland Sea always acts as a sink of atmospheric carbon dioxide. When the whole year is added together the net sink gets close to 50 gC m^{-2} y^{-1}. This agrees well with the other approaches of estimating the air - sea exchange of the Greenland Sea. Biological export production as shown above, is in the order of 20 % of this carbon sink, and this indicates that the main driving factor is the cooling of the surface water that flow into the Greenland Sea.

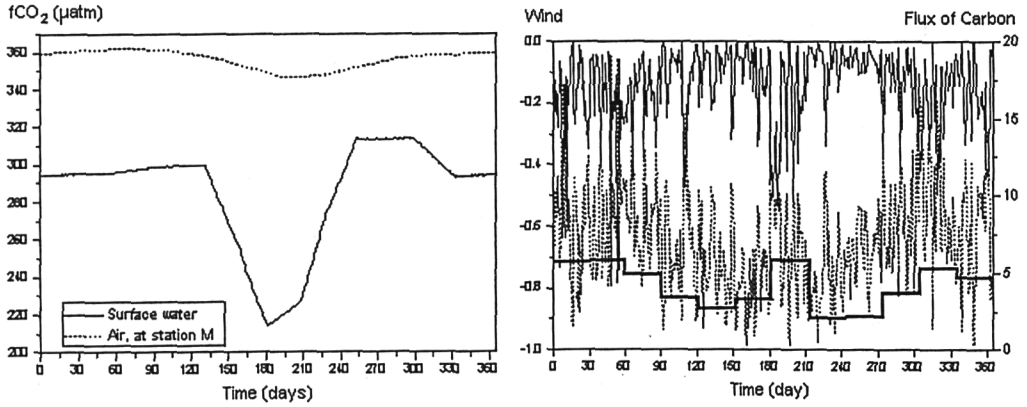


Figure 6: The distribution of, (a) fCO_2 (lower line) as computed from dissolved inorganic carbon and total alkalinity over the year in the Greenland Sea together with the atmospheric record at weather ship M in the Norwegian Sea (upper line) and (b) the daily wind field (lower line) together with the computed flux of carbon dioxide (upper line), based on the fCO_2 in (a), the wind field and Wanninkhof algorithm for the piston velocity. The thick, squared line represent the monthly sink in gC m^{-2}, with the scale on the right axis.

4.4. MODELLING

Simulations with several state-of-the-art 2- and 3-dimensional modelling tools are performed, covering basin scale, mesoscale, and fine scale processes with an ocean only model, a sea ice only model, several coupled sea ice and ocean models, and a coupled atmosphere, sea ice and ocean model.

The main objectives for the modelling groups are to simulate, in space and time, the

- dynamics and thermodynamics of the processes in the Greenland Sea during the ESOP-2 period;
- advective transport and dispersive mixing of the injected tracer SF_6; and
- seasonal cycling of dissolved carbon dioxide, including making estimates of the air-sea exchange of CO2.

During 1997, a coupled atmosphere, sea ice and ocean model has been used to study the effect cold air outbreaks have on the exchange of heat between air and sea at the ice edge in the Greenland Sea. For a specific simulation (starting in March 13, 1997), an upward directed heat flux of more that 100 M/m^2 is obtained. Such a heat flux, together with an optimal pre-conditioning situation, may trigger convective mixing in the Greenland Basin.

The large-scale dynamic-thermodynamic sea ice model has been set up to simulate ice conditions off the coast of Greenland for the years 1979 to 1995, and quantitative agreement between satellite data and modelled ice drift velocities is obtained.

The fine scale modelling is process oriented, and aims at describing convective mixing, and the associated vertical mixing of carbon dioxide and SF_6. The experiments performed indicate that convection to a depth of 1300 m is possible for the conditions observed during the ESOP-2 period. The SF_6 simulation indicate that the tracer released at a depth of 300 m in August 1996, is spread over the uppermost 750 m in December 1996.

The meso and large scale modelling include several OGCMs, ranging in spatial resolution from 20 km to about 100 km. All of the models have been set up to simulate the general circulation and the thermodynamics (including sea ice) for the ESOP-2 period. The models are, or will shortly be, in the phase of production simulations. Comparison with observations show that the models are able to describe the main features of the Greenland Sea and large scale circulation.

5. STATUS AND PLANS

Up to 1998, the partners have mainly been engaged in field work and model testing and devlopment. ESOP-2 is a «high-risk project» with many new and daring elements, conducted under adverse conditions in a very hostile environment. As is seen by the short description of main achievements above, a great number of experiment and field tasks have been succesfully executed. Some key data sets are being obtained in 1998, but most of the data from the three field elements are now secured from the work in 1997 as planned, and the modelling efforts are in the phase of production runs.

In 1998 the focus will be on the interpretative side of the activities, where the pressing needs are to secure publication of results, finalisation and quality control of data sets and deliverables, interaction and synergy among partners and across task groups in time to secure a successful outcome of the project.

Information:

- The UOB WWW-server provides information to the community at large on ESOP-2 results. (http://www.smr.uib.no)
- ESOP-2 newsletters are circulated to interested parties.

Final products:

- The proceedings of the final workshop will be published in a suitable high-profile scientific journal.
- A synthesis of the results of ESOP-2 will be submitted for publication in a suitable peer reviewed journal.
- Publication of CD-ROM which contains all data from ESOP-2.
- Special reports will be made on the Technological aspects and Technological Innovations of ESOP-2. This will include submission of papers on the utilisation of ESOP technologies, in particular experience with the operation of remote/unmanned observation techniques in harsh environments.
- ESOP-2 will ensure close contact with the European efforts on designing ocean observation systems. A close contact will be obtained with GOOS (Global Ocean Observing System) activities to provide assessment of unmanned technologies for permanent ocean monitoring systems.
- Model results and model documentation will be provided as a special dissemination item in the final report.

TITLE: Variability of Exchanges in the Northern Seas (Project **VEINS**)

CONTRACT NO: MAS-3 CT 96 00 70

CO-ORDINATOR:

Prof. Dr. J. Meincke
Institut für Meereskunde der Universität Hamburg
Troplowitzstr. 7, D-22529 Hamburg, D
Tel.no.: +49 40 4123 5986
Fax no.: + 49 40 4123 4644
E-mail: meincke@ifm.uni-hamburg.de

PARTNERS:

2. Dr. Eberhard Fahrbach
Alfred-Wegener-Institut
Columbusstraße, Postfach 12 01 61
D-27515 Bremerhaven, D
Tel.no.: +49 471 4831 820
Fax no.: +49 471 4831 425
efahrbach@awi-bremerhaven.de

3. Mr. Bruce Hackett
Norwegian Meteorological Institute
P.B. 43 Blindern, N-0313 Oslo, N
Tel.no.: +47 22 96 3300
Fax no.: +47 22 69 6355
bruce.hackett@dnmi.no

4. Prof. Peter Davies
University of Dundee
Dep. of Civil Engineering
Nethergate, Dundee DD1 4HN, UK
Tel.no.: +44 1382 344 346
Fax no.: +44 1382 344 816
p.a.davies@dundee.ac.uk

5. Prof. Pentti Mälkki
Finnish Institute of Marine Research
P.O Box 33, Lyypekinkuja 3 A
FIN-00931 Helsinki, FIN
Tel.no.: +358 9 613 941
Fax no.: + 358 9 613 94494
malkki@fimr.fi

6. Dr. R. R. Dickson
CEFAS Lowestoft Laboratory
Pakefield Road
Suffolk NR33 OHT, UK
Tel.no: +44 1502 562 244
Fax no.: +44 1502 513 865
r.r.dickson@cefas.co.uk

7. Prof. Martin Mork
Geophysical Institute
University Bergen
Allégaten 70, N-5007 Bergen, N
Tel.no.: +47 55 58 2642
Fax no.: +47 55 58 9883
martin.mork@gfi.uib.no

8. Dr. Karin Borenaes
Goeteborg University
Dep. of Oceanography
S-41381 Goeteborg, S
Te.no.: +46 31 773 2857
Fax no.: +46 31 773 2888
kabo@gvc.gu.se

9. Dr. Harry Dooley
Oceanography Secretary
ICES
Palaegade 2-4
DK-1261 Copenhagen K, DK
Tel.no.: +45 33 154225
Fax no.: +45 33 934215
harry@ices.dk

10. Prof. Elisabet Fogelqvist
Goeteborg University
Analytical + Marine Chemistry
S-41296 Goeteborg, S
Tel.no.: +46 31 772 2282
Fax no.: +46 31 772 2785
elisabet@amc.chalmers.se

11. Mr. Harald Loeng
Institute of Marine Research
P.O. Box 1870 Nordnes
Nordnesgaten 50, N-5024 Bergen, N
Tel.no.: +47 55 23 8466
Fax no.: +47 55 23 8584
harald.loeng@imr.no

12. Dr. Anna Luchetta
Instituto Sperimentale Talassogr.di
Trieste, Chem. Oceoanogr.
Viale Romolo Gessi 2
I-34 123 Trieste, I
Tel.no.: +39 40 305506
Fax no.: +39 40 308941
luchetta@itt.ts.cnr.it

13. Dr. Svend Aage Malmberg
Marine Research Institute Reykjavik
P.O. Box 1390, Skúlagata 4,
121 Reykjavik, ICELAND
Tel.no.: +354-552-0240
Fax no.: +354-562-3790
svam@hafro.is

14. Dr. Paul Budgell
Norsk Polarinstitutt
Storgata 25A, Box 399
N-9001 , Tromsø, N
Tel.no.: +47 77 60 6733
Fax no.: +47 77 60 6701
paul.budgell@tromso.npolar.no

15. Dr. Cliff Law
Plymouth Marine Laboratory
Prospect Pl. West Hoe
Plymouth PL1 3DH, UK
Tel.no.: +44 1 752 633 438
Fax no.: +44 1 752 633 101
csl@wpo.nerc.ac.uk

16. Prof. Peter Lundberg
Stockholm University
Dep. of Meteorology and Oceanography
S-10691 Stockholm, S
Tel.no.: +46 8 161735
Fax no.: +46 8 157956
peter@misu.su.se

17. Dr. Karen Heywood
University of East Anglia
Norwich, Norfolk NR4 7TJ, UK
Tel.no.: +44 160 35 92555
Fax no.: +44 160 35 07719
k.heywood@uea.ac.uk

18. Peter Haugan
University Courses of Svalbard
Geophysics Marine Research
Postboks 156/157
N-9170 Longyearbyen, N
Tel no.: +47 7902 3338
Fax no.: +47 7902 3301
peter@unis.no

VARIABILITY OF EXCHANGES IN THE NORTHERN SEAS VEINS

J. Meincke

Institut für Meereskunde der Universität Hamburg
Troplowitzstr. 7, D-22529 Hamburg, Germany

SUMMARY

The MAST III-Project VEINS started its execution phase in July 1997 and runs for 37 months. By means of moored current meter arrays and repeat-hydrography in the major passages between the Arctic and Ocean and the North Atlantic and by means of meso- to large-scale modelling the project aims at developing an efficient observational design for long-term measurements of oceanic fluxes. They are considered crucial for advancing the predictive capabilities for decadal climate changes.

INTRODUCTION

Exchanges between the North Atlantic and the Arctic Ocean result in the most dramatic water mass conversions in the World Ocean: Warm and saline Atlantic waters flowing through the Nordic Seas into the Arctic Ocean are separated by cooling and freezing into shallow fresh waters (and ice) and saline deep waters. The outflow from the Northern Seas to the south provides the initial driving of the global thermohaline circulation cell, the one to the north is of major impact to the large scale circulation of the Arctic Ocean. Measuring these fluxes is a major requirement to quantify the turnover-rates within the large circulation cells of the Arctic and the Atlantic Oceans and a basic condition to understand the role of these ocean areas in climate variability on interannual to decadal scales.

There are ongoing national, European and international research projects which focus on processes relevant to forming the characteristics of the individual regions of the Northern Seas. However, a study on the climate control of the Northern Seas primarily requires information on integrated fluxes from the Atlantic Ocean through the Nordic Seas into the Arctic Ocean and vice versa. This can be achieved by obtaining synoptic time series of water and property transports through the key passages. The VEINS-project has started such a programme by a three-year concerted effort of both sea-going and modelling activities.

OBJECTIVES AND METHODOLOGY

The general objective of VEINS is to measure and to model the variability of fluxes between the Arctic Ocean and the Atlantic Ocean with a view on implementing a longer term system of

critical measurements needed to understand the high-latitude oceans steering role in decadal climate variability.

This objective is based on the fact that interannual to decadal climate variability has an important cause in the water mass conversion processes of the Northern Seas, the effects of which are propagated by the fluxes through the boundaries into the global ocean.

Therefor the ultimate goal is to obtain time series measurements of the relevant oceanic fluxes up to decadal period. However, such a long-term commitment can only be taken up after a conceptual model on the fluxes and their variability has been established to answer the following questions: - What are the relevant parameters? - Do we have the most efficient method of measuring them? - Do we have the modelling tools to assist in measurement interpretation? - Do we have an optimal experimental design for such a long-term activity?

This set of questions leads to the VEINS-specific objectives.

- To obtain time-series of heat, salt and water fluxes for the exchange routes through the Northern Seas, i.e. between the Atlantic Ocean and the Nordic Seas and between the Nordic Seas and the Arctic Ocean.
- To quantify the magnitude of the variability of these fluxes.
- To improve the understanding of processes responsible for the variability.
- To develop a conceptual model of exchanges and water mass alterations between the Atlantic Ocean and the Arctic Ocean. It will be used to estimate the integrated effect of the exchanges from the four measurement areas and to design an optimised measurement programme to be continued up to a decadal period.

The method designed to achieve the VEINS goals is illustrated in Figure 1. It shows the four major passages between the Arctic and the Atlantic, i.e. the Iceland-Scotland Ridge, the western Barents Shelf, the Fram Strait and the Denmark Strait. They will be monitored by

Repeat hydrographic sections:

- Physical and chemical parameters with CTD/Rosette for 4-6 times per year along the lines Greenland/Svalbard/Norway and Greenland/Iceland/Faroes/Shetland.

Special hydrographic cruises:

- Physical parameters and tracers (CFC's, SF6, O18) with special emphasis on the Iceland-Scotland and the Denmark Strait overflows.

Current measurements:

- Deployment of long-term moored current meters across the passages, partly with additional high-quality salinity sensors.
- Deployment of long-term moored upward looking sensors to establish the thickness-variability of the overflows.
- Acoustic Doppler Current Measurements from ships operating the repeat-sections.

The measurements in the four passages cannot resolve all scales relevant to fluxes directly. Therefor *Regional Models* and *Process Models* will be employed as a means of intelligent interpolation between the discrete moored measurements.

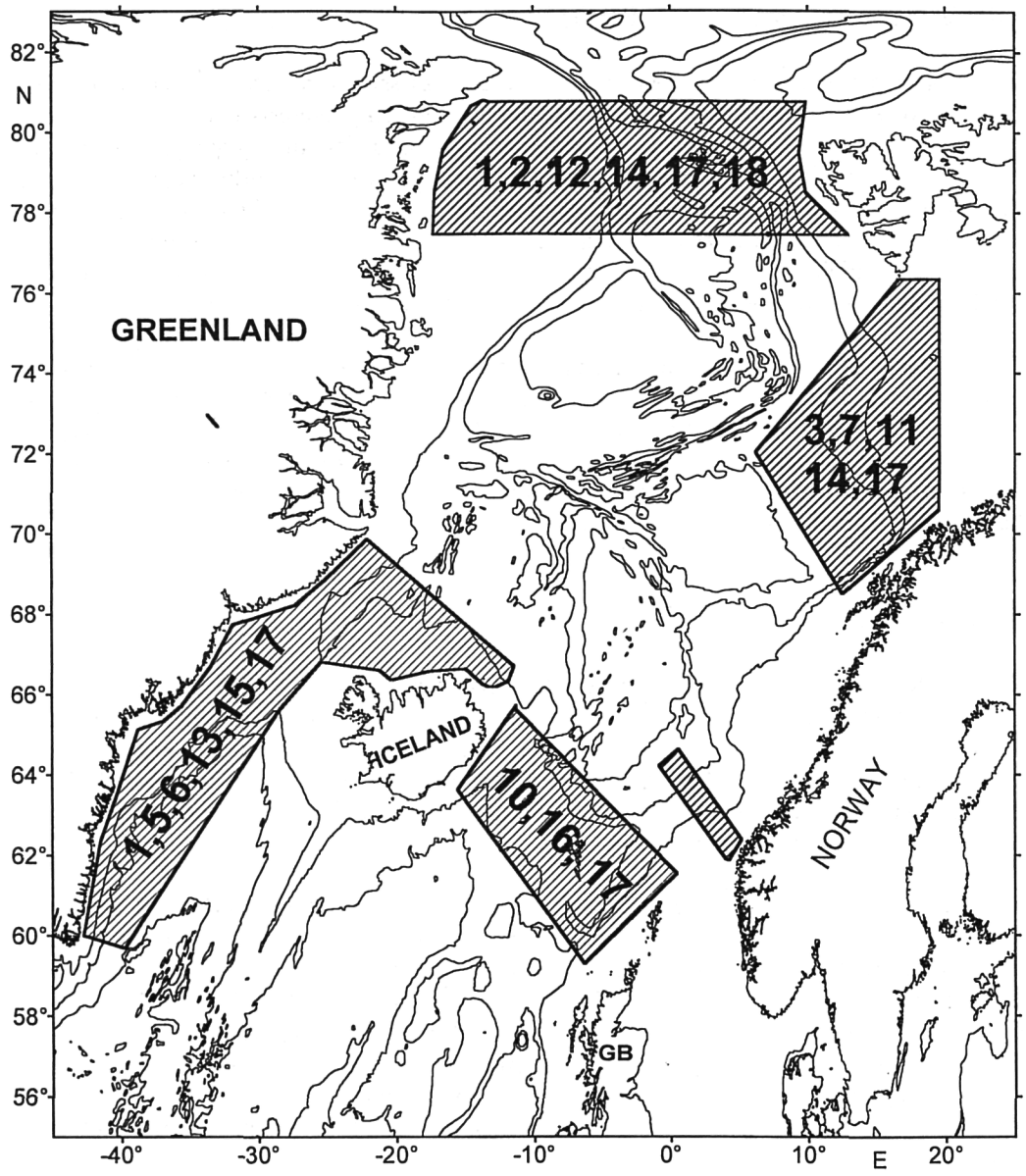


Figure 1: The VEINS-Observation Areas. The numbers denote the partners (acc. to the listing on the title page).

For the understanding of the controls for the flux variability a *Large Scale Circulation Model*, covering the North Atlantic and the Arctic Ocean and including run-off, ice and real wind-forcing in being set up. This model will be the major tool for the synthesis of the data and will be used for the design of a *Conceptual Model*, which will form the basis for the design of a longer-term monitoring array for decadal flux variability.

ORGANISATION OF THE PROJECT

The project partners are organised in workpackages as shown in Table 1. There are four regional workpackages manned by partners who have standing interests in the hydrographical conditions and who can provide shiptime and logistics for the geographical and the climatological specifics of the relevant passages. There is a separate workpackage comprising the modelling activities. Initially the modelling will focus on the regional modelling to assist in the integration of the measurements, but gradually its effort well turn into simulation of the larger scale variability. Finally, the large scale model will be major tool for the project synthesis and the formulation of a conceptual model for the variability of exchanges.

The combined effort of measurements and modelling requires an efficient sharing of data and data products. This task is given to the Data and Information Management workpackage which is at a level above the regional and the modelling workpackages. This workpackage is also responsible for data qualitycontrol and data dissemination. Table 1 shows the tasks for the workpackages as well as the partners participating. The partners are given as numbers and can be identified from the listing on the title page.

DISCUSSION

The VEINS project is designed to identify low frequency signals and their propagation from the Atlantic into the Arctic and vice versa. Since the major passages are only instrumented since summer 1997, there are no results as yet. However, from the long-term engagement of most partners in hydrographic variability of the Northern Seas there are several events documented which provide the VEINS-consortium with the necessary realistic exceptance for signals to pass the measurement arrays.

The well known mid 70's 'Great Salinity Anomaly' (Dickson et al, 1988) was an excess freshwater and ice release from the Arctic Ocean through Fram Strait. Subsequently it exited through Denmark Strait into the Atlantic portion of the subpolar gyre, capped the Labrador Sea convection for the period 1968-1972, re-entered the Northern Seas through the Faeroese Channels in 1976 and finally reached the Barents Sea in 1980, greatly influencing the cod fisheries of this region (Loeng et al, 1997). Another low salinity anomaly in the mid 80's (Belkin et al, 1998) and a possible generation of a new anomaly in the 90's (Vinje et al, 1998) show active freshwater signals to propagate through the VEINS-area at decadal time-scales.

Two other significant signals were recently identified: The first one was an enhanced inflow of Atlantic water into the Arctic, causing the present "Arctic Warming" (Carmack et al, 1998) at intermediate depths. The second one is a cooling of the Atlantic water in the Westspitsbergen Current in 1988/89 which can be tracked with the recirculating Atlantic component in the East Greenland Current, passing a moored array in the western Greenland Basin and exiting through Denmark Strait as a cold overflow-event three years later (Dickson et al, in prep.).

Most of these longer-term changes have recently been shown to correlate with the North Atlantic Oscillation NAO (Hurrell, 1995), i.e. the intensity of the North Atlantic westerlies. Dickson et al (1996) have shown the NAO to not only directly affect the convection activity in the Labrador and the Greenland Seas, but they could proof its effects to reach across the

whole Arctic Ocean. There are in particular the meridional humidity transport and the wind pattern, resulting in NAO-cycles of Fram Strait exports from the Arctic and Atlantic water input into polar regions (Dickson et al, subm.).

This list of oceanic time series information and their relation to atmospheric circulation pattern will hopefully put the expected VEINS-observations into a sequence of signals which then by means of the VEINS-modelling can be composed into a dynamically consistent framework of high latitude variability relevant to decadal climate changes.

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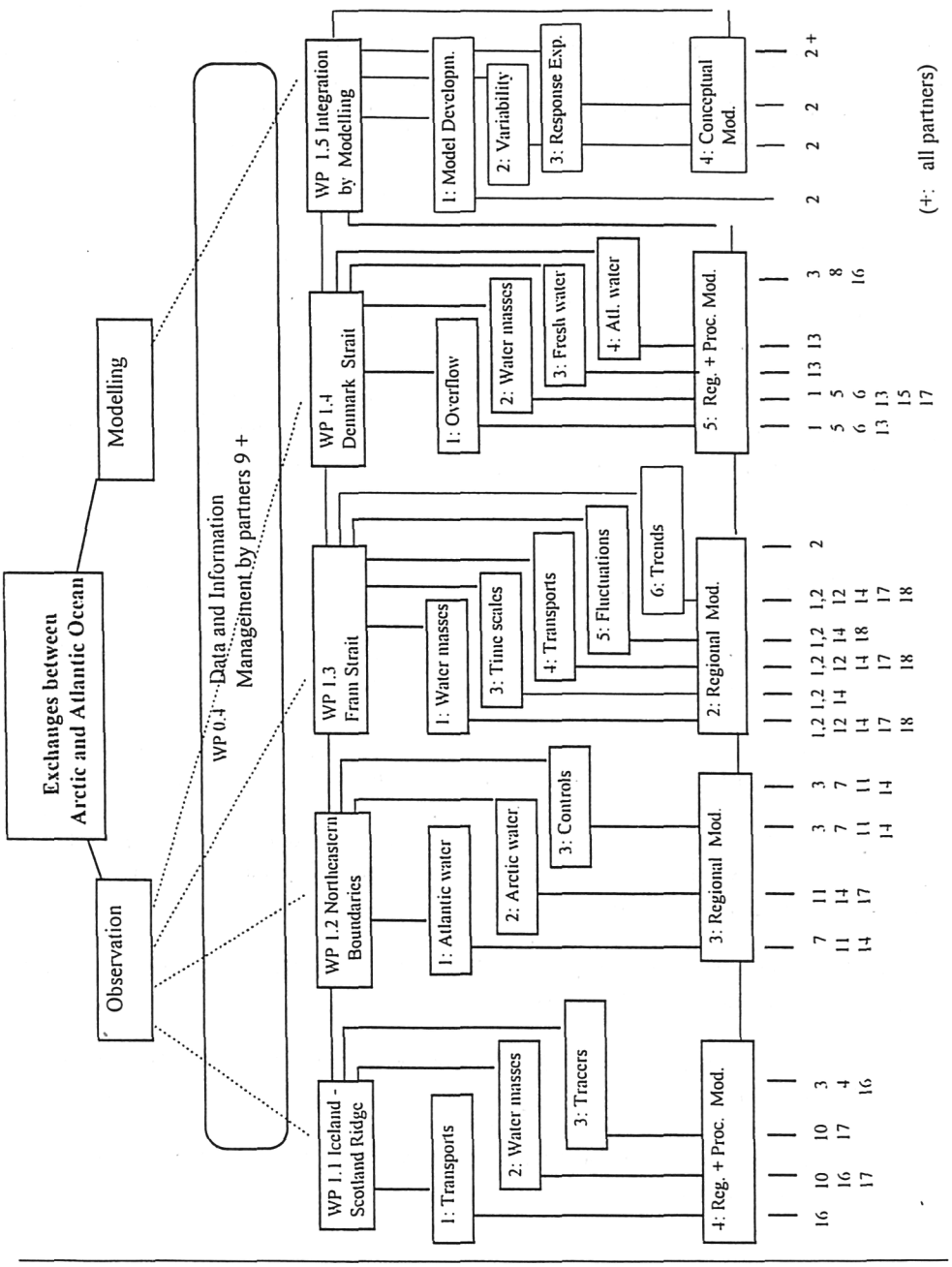
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Table 1: Organisation of the VEINS-Project, its tasks and its scientific participation



TITLE: **Baltic Air-Sea-Ice Study (BASIS)**

CONTRACT: MAS3-CT97-0117

COORDINATOR:
Prof. Dr. Jouko Launiainen
Finnish Institute of Marine Research
P.O. Box 33, FIN-00931 Helsinki, Finland
Tel.no. + 358 9 61394420
Fax: + 358 9 331025
E-mail: launiainen@fimr.fi

PARTNERS:

Prof. Dr. Burghard Brümmer
Universität Hamburg / Meteorologisches Institut
Zentrum für Meeres- und Klimaforschung
Bundesstrasse 55, D-20146 Hamburg, Germany
Tel.no. +49 40 4123 5083
Fax: +49 40 4117 3350
E-mail: markshausen@dkrz.de

Prof. Dr. Rainer Roth
Institut für Meteorologie und Klimatologie der Universität Hannover
Herrenhäuserstrasse. 2, D-30419 Hannover, Germany
Tel.no. +49 511 762 2678
Fax: +49 511 762 4418
E-mail: nhbkwode@rrzn-user.uni-hannover.de

Prof. Dr. Ann-Sofi Smedman
Department of Meteorology, Uppsala University
Box 516, S-75120 Uppsala, Sweden
Tel.no. +46 18 542 792
Fax: +46 18 544 706
E-mail: annsofi@big.met.uu.se

Dr. Bertil Håkansson
Swedish Meteorological and Hydrological Institute
S-60176 Norrköping, Sweden
Tel.no. +46 11 158 385
Fax: +46 11 170207
E-mail: bhakansson@smhi.se

BALTIC AIR-SEA-ICE STUDY - A FIELD EXPERIMENT OF BALTEX

J. Launiainen and T. Vihma, *Finnish Institute of Marine Res., POB 33, 00931 Helsinki, Finland*
B. Brümmer, *Universität Hamburg, Meteorol. Institut, Bundesstr. 55, D-20146 Hamburg, Germany*
R. Roth and C. Wode, *Inst. für Meteor., Univ. Hannover, Herrenhäusstr. 2, 30419 Hannover, Germany*
A.-S. Smedman, *Dept. of Meteorology, University of Uppsala, Box 515, S-75120 Uppsala, Sweden*
B. Håkansson, and A. Omstedt, *Swedish Meteorol. and Hydrol. Institute, 60176 Norrköping, Sweden*

SUMMARY
The Baltic Sea Air-Sea-Ice Study (BASIS) is a process study of the BALTEX programme. A winter experiment to be carried out in February-March 1998 forms the central experimental element in the project aimed to study physical processes for optimization of the coupled atmosphere-ice-ocean models. The report outlines the plans of the study just started.

1. INTRODUCTION

The Baltic Sea is located in the seasonal sea ice region with an ice cover forming and melting each year. By acting as a thermal insulator and a mechanical cover, the sea ice influences the sea-atmosphere interaction in a dramatic way. Sea ice also has a large climatic importance as a sensitive indicator of a climatic change and can act as a feedback mechanism for the change. Considering the winter navigation, sea ice is of first-rate importance to various Baltic Sea countries.
Mathematical modelling of the dynamics and thermodynamics of sea ice is vital for understanding and predicting the processes affecting the climate and winter navigation, but the models also need verification and optimization by observations. A detailed and multidiscplinary observational data set of various physical processes in the wintertime atmosphere, ice and the sea is still lacking.
The BALTEX program, a sub program of GEWEX, aims to explore, model and quantify the main physical processes that control the energy and water exchange within the Baltic Sea and its drainage area. The overall objective of the Baltic Air-Sea-Ice Study (BASIS) is to create and analyse an experimental data set for optimization and verification of coupled atmosphere-ice-ocean models. The specific objectives cover

1) Investigation of water budget and momentum and thermal interaction at the air-ice-sea interfaces
2) Investigation of the atmospheric boundary layer (ABL), especially close to the sea ice margin
3) Investigation of the ocean boundary layer (OBL)
4) Investigation of the sea ice and its dynamics
5) Validation of coupled atmosphere-ice-ocean models.

2. WORK CONTENT

The field experiment is carried out in the Gulf of Bothnia in February-March, 1998 (Fig.1). Experiments are concentrated in the ice edge zone, and the land-fast ice - land boundaries form

additional horizontal boundaries in the study problematics. Airborne measurements of the ABL are made using both a research aircraft and a helicopter, the latter carrying the Helipod measuring device. Those measure the properties of atmospheric turbulence and radiation in various heights, and clouds (Table 1). Ground-based measurements of the ABL include radiosonde soundings at five stations at the coasts of the Gulf of Bothnia. The soundings are made four times a day. The central working platform is *R/V Aranda* anchored in the sea ice. Meteorological buoys, two meteorological masts, a sonic anemometer, radiation sensors, and the ship weather station are used to observe the ABL properties at this ice station. A meteorological mast, various turbulence instruments and radiation sensors measure on the land-fast ice at the Swedish coast. The ice and surface properties are investigated by remote sensing and surface-based measurements. The latter include thermistor chains through the ice and snow, laser profilometry of the surface roughness, and snow and ice sampling. The sea ice concentration and movement are studied by remote sensing and buoy observations. Totally, some 10 drifters detect the ice motion. The ocean boundary layer is studied by large-scale hydrographic sections before and after the 3-week-long ice station. Current measurements are made using ADCPs and current meters below the ice, and thermistor chains are mounted below the ice. The OBL turbulence is investigated by ultrasonic and electromagnetic eddy flux measurements below the ice.
The scale of the various experiments varies from microscale to meso-γ-scale, i.e. the spatial scale from 10^{-1} to 10^{2} km and the temporal scale from hours to days.

The duration of the project is 1997-2000 and a preparatory experiment pre-BASIS was carried out in March 1997 in the Gulf of Bothnia.

3. OUTCOME EXPECTED

The field data supported by various modelling studies shall yield data sets and information of:

- atmospheric water, heat and momentum budgets
- turbulent and radiative fluxes in the ABL above inhomogeneous ice and water surface
- ice and snow properties, ice concentration and drift, ice roughness
- ground truth data for remote sensing
- turbulent fluxes and OBL structure below the ice
- oceanic heat budget
- improved process parameterizations for the coupled atmospheric and marine models.

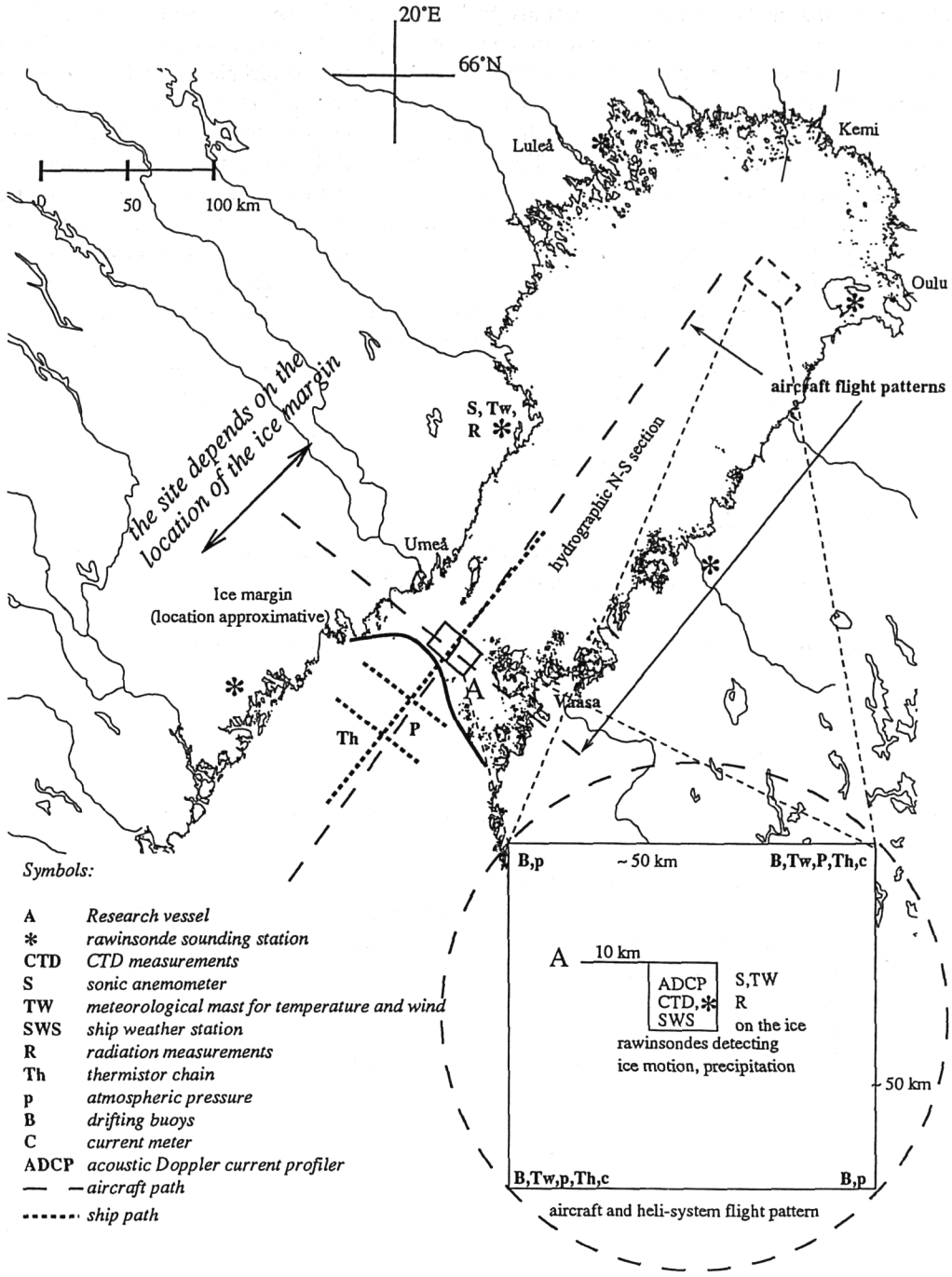


Figure 1. Map of the research area in the Gulf of Bothnia. The measurement activities at the main experiment site are shown in the lower right-hand corner. The experiment data will be completed by meteorological synoptic and sounding station data.

Table 1. Airborne measurements in BASIS

measurement quantity	heli-system	research aircraft
Wind speed	- five-hole probe	- five-hole probe (100 Hz)
Air temperature	- sensor with long-time stability - fast sensor (100 Hz)	- sensor with long-time stability (10 Hz) - fast sensor (100 Hz)
Air Humidity	- dewpoint mirror - capacitive sensor - Lyman-Aplha sensor	- dewpoint mirror (10 Hz) - Humicap (10 Hz) - Lyman-Alpha sensor (100 Hz)
Surface temperature	- infrared thermometer	- infrared thermometer
Surface roughness	- laser profilometry	none
Turbulent fluxes	- eddy-correlation technique	- eddy-correlation technique
Radiative fluxes	none	- short- and longwave radiation (10 Hz)
Cloud droplets	none	- two particle size probes - liquid water sensor (10 Hz)
Navigation	- 3 x GPS - inertial platform	- GPS - Omega - inertial platform (100 Hz)

I.2.3. The surf and swash zone

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

CONTRACT NO: MAS3-CT95-0012

COORDINATOR:
Prof. Guido Chelazzi
Consorzio Nazionale Interuniversitario
per le Scienze del Mare
Unità Locale Ricerca Firenze
Via Romana 17
I-50125 Firenze
Tel.: +39-55-2 28 82 90, fax: +39-55-2 28 82 89
E-mail: dibagefl@idg.fi.cnr.it

PARTNERS:

Prof. Stephen Hawkins
University of Southampton
Department of Biology
Bassett Crescent East
GB-Southampton SO9 3TU
Tel +44-1703-592208
Fax +44-1703-594269

Prof. Alan Myers
University College Cork
Department of Zoology
Lee Maltings, Prospect Row
IE-Cork
Tel +21-276871-2455
Fax +21-270271

Dr. Per Åberg
Göteborg University
Department of Marine Botany
Carl Skottsbergs Gata 22
S-41319 Göteborg
Tel +46 31 7732701
Fax +46 31 7732727

Dr. José Paula
Universidade de Lisboa
Lab. Maritimo da Guia
Faculdade de Ciencias
Estrada do Guincho
P-2750 Cascais
Tel +351-1-4869211
Fax +351-1-4869720

Dr. Julio Arrontes
Universidad de Oviedo
Dept. de Biologia de Organismos y
Sistemas
Catedratico Rodrigo Uria s/n
E-33071 Oviedo
Tel +34 8 5104776
Fax +34 8 5104777

INTERACTIONS OF PHYSICAL AND BIOLOGICAL FACTORS IN THE SURF AND SWASH ZONE OF EUROPEAN ROCKY SHORES EUROROCK

Guido Chelazzi

Consorzio Nazionale Interuniversitario per le Scienze del Mare

University of Firenze

50125 Firenze, Italy

SUMMARY

Within the context of the MAST III scientific area dealing with extreme environments, EUROROCK focuses on the intertidal and shallow sublittoral fringe of rocky shores. The strategic objective of EUROROCK is to adopt the European rocky coast as a model system to understand the functioning of the extreme marine environment represented by the intertidal zone in relation to dominant physical factors and their influence on biological interactions. A key feature of this project is linking behavioural responses at the individual level to population dynamics and community structure. Most importantly, it includes comparative studies made at Atlantic sites from Scandinavia to the Iberian Peninsula, and into the Mediterranean in Italy. The very different physical characteristics of the wave swept littoral zone across the geographical gradient require a broad-scale integrated European perspective. Integrated studies on the generality of ecological processes on continental scales have not previously been attempted anywhere in the world. The consortium of scientists from six European countries enables such variations to be investigated in a co-ordinated fashion for the first time.

1. INTRODUCTION

Littoral systems are subject to important changes on various temporal and spatial scales, due to physical and biological factors, including direct or indirect human disturbance. The intertidal zone is particularly affected by such changes due to its critical position at the interface between marine and terrestrial environments, and its pronounced exposure to human activities. As such the intertidal zone is worth studying as an extreme environment whose dynamics result form a complex blend of stochastic and deterministic factors.

Rocky shores have been extensively used as a convenient model for ecological studies dealing with the relative importance and reciprocal influence of physical and biological factors in generating community patterns (Underwood, 1985). As such, studies on rocky shores have made considerable contributions to general ecological theory, particularly in the field of population and community ecology (see Paine, 1994). They also provide a superb natural laboratory for studies of behavioural ecology (Chapman & Underwood, 1992; Hughes, 1989;

Chelazzi et al., 1988) as they have steep and definable environmental gradients and are ideal for experimental manipulation.

From the Arctic to the Strait of Gibraltar rocky shores are the dominant feature of wave-swept eastern Atlantic coasts. With the exception of the North Sea, the Bay of Biscay and the South Atlantic coast of Portugal and Spain rocky shores occur both on headlands and in more sheltered localities such as fjords and rias. Rocky shores are also common throughout much of the Mediterranean. Thus a more or less continuous habitat occurs throughout Europe allowing regional comparisons of the generality of ecological processes.

The European coast exhibits an interesting biogeographic gradient from the North to the South (see Hawkins et al., 1992). This is essentially mediated by climatic factors and also reflects distributional changes in response to glaciation. There is a suite of essentially northern species (*Nucella, Semibalanus balanoides*, fucoids, kelps) many of which may have originated in the North Pacific. There are also southern forms which probably invaded the Atlantic from the South northwards (*Chthamalus, Patella, Gibbula*, grapsid crabs). The result is a diversity gradient of increasing species numbers for space occupying animals, grazers and consumers from north to south. Brown algae however, are more dominant in the north. In addition to diversity gradients the balance between plants and animals changes in the eulittoral zone from northern to southern Europe (Ballantine, 1961; Hawkins & Hartnoll, 1983a; Hawkins et al., 1992), with barnacles and associated grazers becoming prevalent on increasingly sheltered shores further south and large fucoid seaweeds disappearing from the midshore. This pattern is interrupted by local areas of upwelling, with the re-emergence of essentially northern conditions in the north Iberian peninsula, with the Basque coast very southern in character. There are also changes in productivity of coastal waters in terms of both magnitude and seasonal pattern. Northern waters are highly productive for a short time in spring or summer (Barnes, 1956; Hawkins & Hartnoll, 1982), and for many species, larvae are released as single broods. Further south there is a more continuous production cycles and animals routinely brood several times (Burrows et al., 1992). Thus, in the north pulses of recruitment occur which can be highly variable. In the south we suspect that recruitment is more of a trickle and less variable between years. The Atlantic also provides interesting contrasts with the Baltic and Mediterranean. Physically there is a major difference in tidal amplitude which emphasise the vertical environmental gradient and perhaps exaggerate the effects of topographically generated spatial heterogeneity and wave action. The Baltic and Mediterranean coast encounter more extreme conditions than the open Atlantic: on the west coast of Sweden winter ice scour can be important; in the Mediterranean calm summer weather exaggerates heat stress.

The strategic objective of EUROROCK is to adopt the European rocky coast as a model system to understand the functioning of the extreme marine environment represented by the intertidal zone in relation to dominant physical factors and their influence on biological interactions. Physical factors (desiccation and extreme temperatures on the vertical axis and wave action horizontally) were traditionally viewed as "limiting factors" to which intertidal organisms evolved adaptations. In recent years much field experimental work has shown the importance of biological interactions in structuring communities. It is now widely accepted that both physical factors and biological interactions affect populations and communities: often physical factors act indirectly by mediating the intensity of interactions. The general aim of EUROROCK project is to show how the physical environment influences the activities of key consumers and the consequences of this for the community. It also examines the role of different recruitment regimes for community structure.

2. STRUCTURE OF EUROROCK AND METHODOLOGY

EUROROCK integrates field observations and experiments at different levels of the biological complexity (from individual to population and community), with theoretical analysis based on mathematical models. According to its strategic and specific objectives, the project addresses two experimental plus one theoretical tasks, through specific interlinked research sub-tasks (modules). Moreover, a common technical task will provide original instruments and techniques for recording both physical and etho-physiological parameters, as well as specific image-analysis systems. Thus the scientific structure of EUROROCK comprises four distinct but interconnected parts.

Part T develops instrumentation for acquiring critical information on (a) the environment, (b) behaviour and physiology of individuals, and (c) recruitment and population dynamics in the wave swept zone. Part T is divided into two modules specifically dealing with telemetric instruments (module T1), and image-analysis techniques (module T2).

Part A analyses the individual adaptation to physical and biological factors acting in the rocky intertidal, by examining the behaviour of (a) key grazers, and (b) predators having an important influence on community structure. This part of the project largely deploys equipment developed in module T. Part A is articulated in two distinct but interconnected modules, dealing with the temporal and spatial organisation of foraging behaviour of grazers (module A1), and with the foraging behaviour of invertebrate predators (module A2). Field work relies upon telemetric devices developed as part of the project and designed to record automatically behavioural and physiological parameters from intertidal mobile animals in the field. Laboratory studies include assessment of grazing activity of limpets under different experimental conditions, prey choice by crabs and dogwhelks, and analysis of different aspects of metabolism to quantify energetic costs of consumers.

Part B basically examines the geographic variation in community-structuring processes. In particular, investigations concern (a) the importance of recruitment fluctuations using barnacles as a model, and (b) the way in which the physical environment modifies community patterns and processes on the geographic gradient of the European coast. Part B is organised in two distinct but interconnected sub-tasks: module B1 and module B2, dealing respectively with geographic variation in patterns of recruitment and with the role of physical and biological factors in the organisation of intertidal communities. Field work of this task is based on the following methodologies: a) recruitment and mortality, and subsequent population dynamics are assessed by quadrat monitoring in all study sites, aided by image-analysis systems; b) experimental manipulation to investigate the role of physical and biological factors in the organisation of intertidal communities is performed using removal, caging and transplantation techniques according to a nested design in all the study sites. Field work is done jointly by the different participants in nine study areas (Fig. 2) according to a nested design and common protocols to allow for effective discrimination of regional and European-scale effects.

Part C provides integrative models to link individual adaptation to physical and biological factors, to population dynamics and community structure on rocky shores. Accordingly, this task is organised in three modules: module C1 dealing with individual-level models; module C2, dealing with population-level models, and module C3, dealing with community-level models. Models are done in parallel with field experimentation to enhance generation of hypotheses for specific testing. Modelling techniques include: a) Montecarlo techniques and

dynamic optimization models to be applied to the individual-level phenomena; b) matrix techniques including deterministic and stochastic parameters to model population dynamics; c) cellular automata and risk-sensitive models for the community-level theoretical analysis.

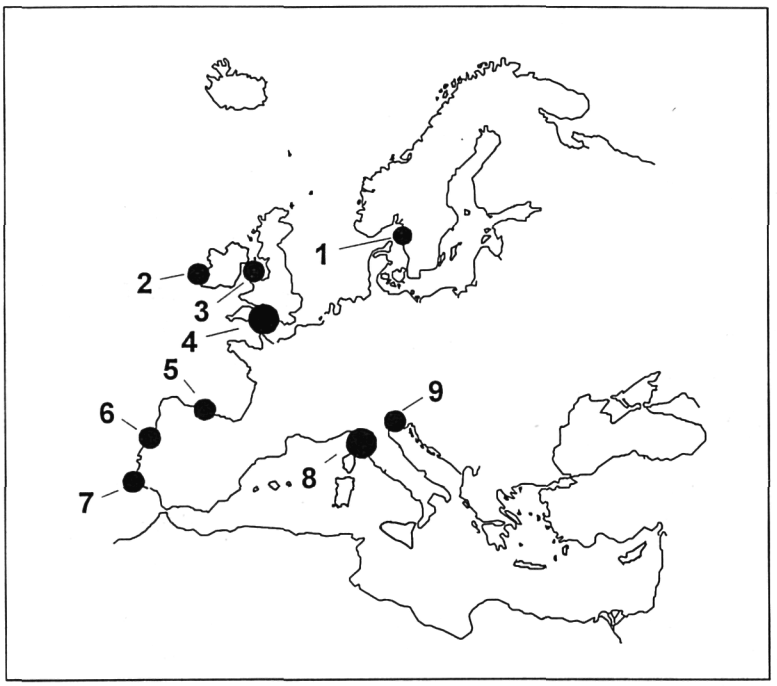


Fig. 1. Main areas where activities of part B are performed: Scandinavian (area 1), Celtic (areas 2,3,4), Iberian (areas 5,6,7) Mediterranean (areas 8,9).

3. MAJOR OUTCOMES

The EUROROCK program started in February 1996 and is now in the third and final year. Activities pertaining to the different tasks proceeded according to the initial schedule and although general conclusions are still to be obtained, some major outputs are already available. Here follows a synthetic presentation of some major outcomes.

Module T1. This module is devoted to develop automatic stations for recording environmental parameters on the shore, and behavioural and physiological parameters from intertidal animals.

A system for monitoring the wave frequency and height based on radiotransmitters, was developed during the first year and tested in different localities for long times. The transmitter unit is composed by a two stage radio transmitter (derived from the transmitter Televilt TXH-2) enclosed with batteries into a waterproof package of 40x35x25 mm (length, width, height), and bearing a linear antenna of 180 mm. The interval between two successive pulses of the

transmitter changes according to the on-off status of a magnetic external detector (reed switch). The waterproofed reed, connected to the transmitter via a cable, is mounted onto a vertical support at a selected level of the shore), and a cylindric floater including a magnetic ring is placed free to move up and down along the package containing the reed, thus changing the inter-pulse period according to the water movements (fast or slow period for submerged or uncovered status, respectively).

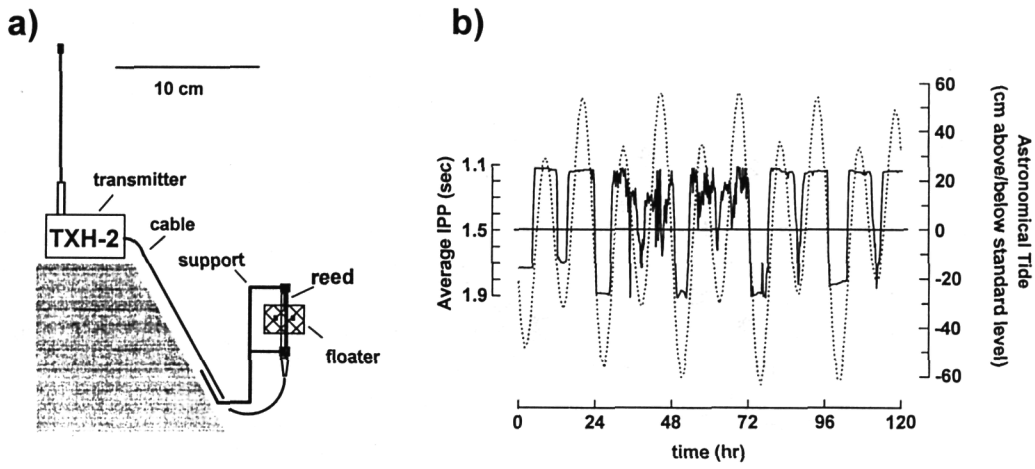


Fig. 2. (a) Schematic representation of the radiotransmitter used for automatic monitoring of sea level oscillations. (b) Sea level oscillations recorded during five days on a shore in Northern Adriatic (average Inter-Pulse Period of one transmitter, solid line) and concomitant predicted tides (dashed line).

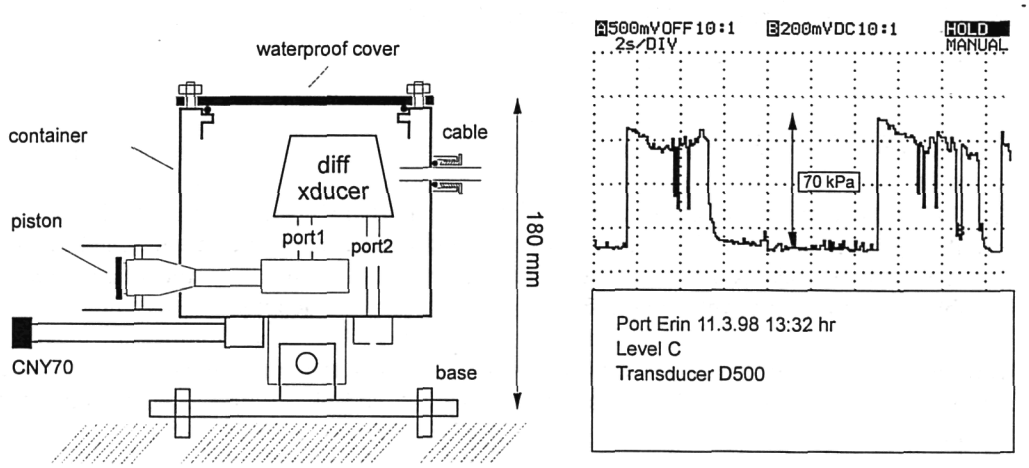


Fig. 3. Schematic view of the wave impact recorder (left). An example of measures taken during tests on the breakwater at Port Erin (Isle of Man) (right); two wave impacts are evident.

The signals from several units placed at different levels on the shore are received by a Televilt RX900 scanner-logger, and periodically downloaded using a portable computer. The receiver, connected to an omnidirectional or a 3 elements Yagi antenna can be placed far from the swash zone, to scan automatically the frequencies corresponding to the single units, according to a programmed schedule. Typically, each transmitter is received for about 10 sec. If during this time the pulse period remained constant, only one record is stored, including date, time, frequency, pulse period, pulse width, and signal strength. If during the scanning time the pulse period changed, more records are stored accordingly. Original software has been developped to clean the sequential files obtained by the scanner-logger, in order to remove noise. Additional software has been developed to process raw data for obtaining the pertinent time-series of the parameters. A schematic representation of the system is reported in Fig. 2 a. An example of data obtained during five day testing in Trieste (Northern Adriatic) is reported in Fig. 2 b.

Module A1. This module includes the analysis of temporal and spatial organisation of activity of limpets, and the assessment of costs incurred and on gains obtained by individual grazers during each foraging excursion. Moreover, it includes estimates of the amount and the spatial distribution of microbial film removed during foraging by different species throughout their European ranges.

Field recording of temporal organisation of foraging has been performed on *Patella. caerulea* and *P. vulgata* from different sites in the Mediterranean and in the Isle of Man, respectively, using an original actographic technique based on radiotransmitters similar to those used for monitoring sea level oscillations. The reed of the transmitter is mounted over the rest site of the limpet, and switched on/off by a magnet glued to the shell, thus giving the resting-foraging status of the limpet in time. This is important to assess total time spent by grazers foraging on the microbial film, and to investigate the organisation of grazing activity with respect to tides and day/night (Fig. 4).

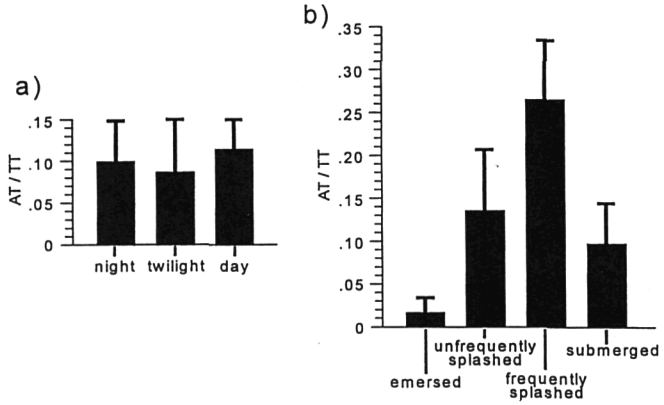


Fig. 4. Organisation of grazing activity in *Patella caerulea* (Gulf of Trieste, northern Adriatic). a) fraction of available time used under different day/night conditions. b) fraction of available time used during different submersion/emergence phases.

Module A1 includes also the study of limpets' metabolism in order to assess costs incurred by grazers. Multi-factor experiments performed on different species of limpets permitted to assess the importance of size, temperature, activity, and their interaction, on metabolic rate.

Moreover, recording of heart rate, as a reliable indicator of metabolic rate, is performed in the field using a non-invasive optoelectronic technique (Fig. 5). Experiments are performed on limpets maintained in the laboratory to monitor variations in metabolic pathways following different degrees of starvation and dehydration.

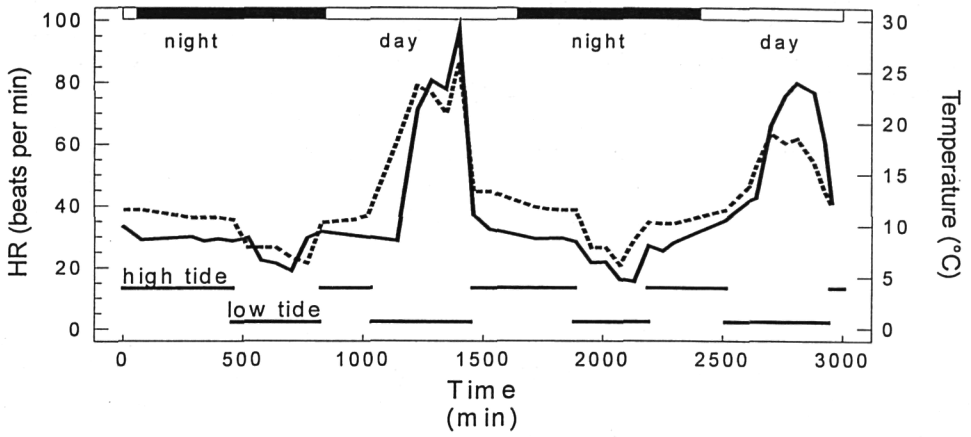


Fig. 5. Two day recording of heart rate (solid line) and body temperature (dashed line) on a specimen of *Patella caerulea* from the Gulf of Trieste (norther Adriatic). Herat rate was continuously monitored using a non-invasive optoelectronic tecnique.

Module B1. This module, central in the EUROROCK project, specifically addresses the following problems, using barnacles as model organisms: a) importance of cyprid availability for settlement density; b) relative importance of deterministic and stochastic factors on settlement over this geographical range; c) geographic variation in seasonal patterns of recruitment, and implications for the structure and dynamics of populations and communities. Recruitment and subsequent population dynamics of barnacles are assessed by common techniques at all sites (Fig.1), and within region nesting of sites enables pan-European comparisons. The main method is monitoring of quadrates at a spatial scale to satisfy statistical tests of significance, and at different tidal levels. Direct observation and photographic documentation is used to determine the presence of cyprids, juveniles and adults, and to assess growth and mortality. Photographic data are processed by computer image analysis.

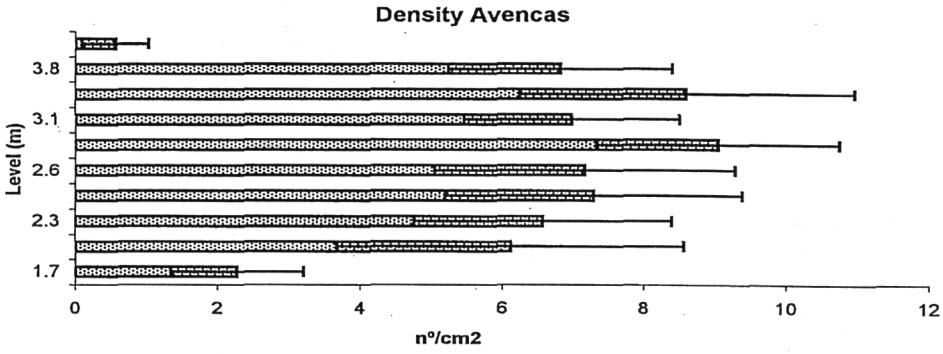


Fig. 6. Distribution of *Chthamalus montagui* at different levels of the shore at Avencas (Portugal).

The distribution of *Chthamalus* species within shores was carried out on three shores in S.W. England at six shores in Cork (Ireland) at three shores in Lisbon and two shores in Sines (Portugal), at four shores in the Adriatic and one shore in the Gulf of Genoa (Italy). Some exemplificative results are shown in Fig. 6.
Recruitment to cleared surfaces was assessed at each of three sites (1-4m^2) per shore, six quadrats (5x5cm) were hand scraped each month with a paint scraper and then rinsed with sea-water. After one month, all cyprids and recruits were collected from the cleared squares and preserved in alcohol. New, randomly selected squares were cleared each month.

Recruitment of *Chthamalus* species was assessed on different shores within areas shown in Fig. 1. In both Cork and in Devon (Fig. 7), *Chthamalus* settlement was first noted in July. Cyprid numbers were generally low (Cork maximum = 16 per 5x5cm, Devon maximum = 8 per 5x5cm). Metamorph densities reached a peak in September at both locations with a maximum of 283 per 5x5cm quadrat in Cork. In North Spain, settlement began in April, but very few cyprids were recorded during the study period. Metamorph numbers peaked there in August-September. In the Ligurian sea, settlement commenced in early April but in the Adriatic it commenced at the end of May, with a maximum of 8 cyprids per 5x5cm quadrat in both locations. On the Ligurian shores, metamorph numbers peaked in July. In the Adriatic there were clearly two peaks, the first in June the second in October. Metamorph numbers were higher in June, with a maximum number of approximately 300 per 5x5 cm quadrat.

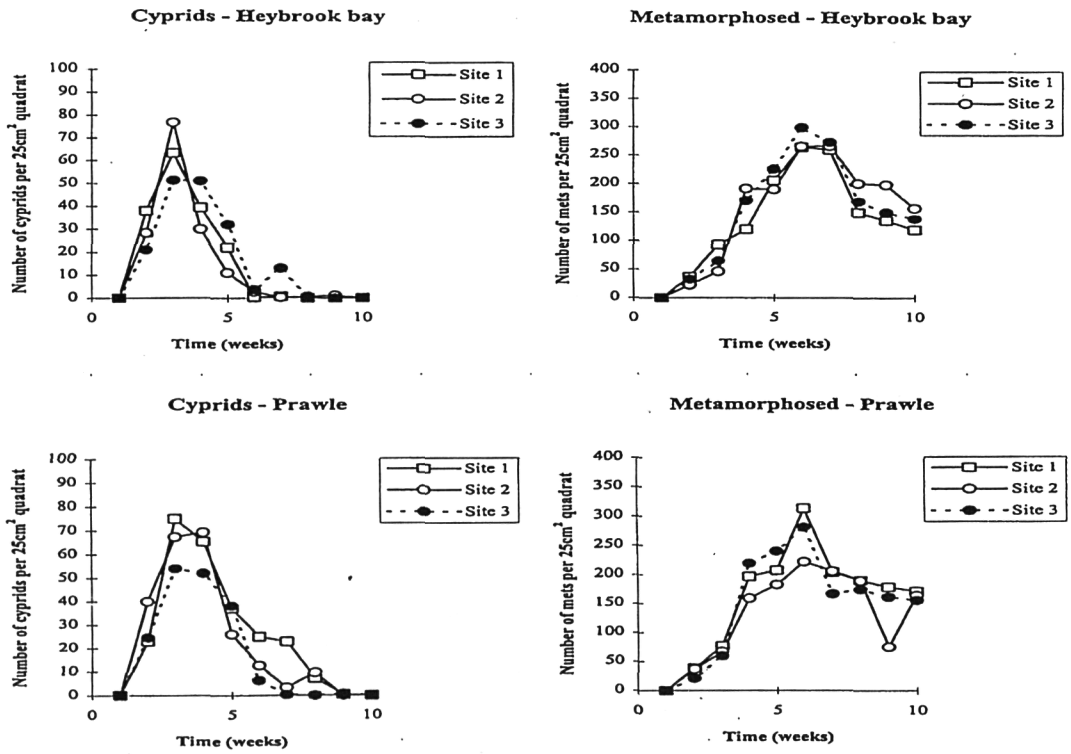


Fig. 7. Density of chtamalid cyprids and metamorphs recorded in different sites at two shores in SW England.

Settlement of *S. balanoides* was studied in five 5x5cm quadrats randomly located at three sites within each of three shores. Cyprids, metamorphs and percentage cover bare rock were recorded weekly throughout the settlement period. Settlement was first recorded in both Cork and S.W. England in April 1997, and continued until the end of June. Settlement reached a peak at the end of April at both locations, with maxima of 126 cyprids and 360 pink metamorphs per 5x5cm.

Module B2. This module is part of Task B of EUROROCK. The role of task B is to examine the geographic variation in community-structuring processes. Module B2 deals with the role of physical and biological factors in the organisation of intertidal communities. The specific items of this module are:

a) To investigate the relative importance of direct and indirect effects of grazers and physical constraints on mid-shore algal abundance and community structure in barnacle-dominated and fucoid-barnacle mosaic areas.
b) To study the regeneration of canopies in algal-dominated systems and the effects of canopy removal in the presence or absence of grazers.
c) To investigate patch dynamics in mussels/barnacle mosaics at exposed sites, particularly the relative importance of predation and physical disturbance in generating free space.
d) To investigate the role of spatial heterogeneity in stabilising community dynamics.

Grazer exclusion experiments is the major integrated activity of the Eurorock team in Module B2. This is undertaken using the same experimental design by all partners involved. Sites are as shown in Fig. 1. Following the successful establishment of all experimental plots during the first year, as required by the protocols, monitoring has continued until spring 1998.

Formal analysis of the results of the limpet exclusion experiment will be undertaken during the third year of the project. However, a qualitative comparison of the figures so far obtained reveal the major following outcomes (see Fig. 8 as an example). There is very little algal growth in most of the controls whereas algal growth occur in most of the treatments; therefore there appears to be a clear effect of limpet grazing throughout Europe. This effect appears most strong in the Isle of Man and least strong in Portugal with intermediate levels of effect in Oviedo (North Spain) and on the British South Coast. There are also differences in the algal colonisation of exclusion areas initiated in the winter and summer: these are both in terms of algae and the rate of colonisation. For example in the Isle of Man, green algae are more prevalent in the experiments initiated in the winter; whereas *Fucus* colonises more rapidly in the summer (also in Oviedo). In Portugal, rate of colonisation of ephemeral algae were more rapid in winter than in summer.

There were also striking differences in the types of algae colonisation following the exclusions: on the Isle of Man ephemeral greens and fucoids predominated; in southern England and Oviedo, crustose algae such as *Ralfsia* also occurred in addition to *Fucus* and ephemerals; in Portugal there was very little colonization by available species of Fucus (*F. spiralis*) and the exclusion areas were colonized by ephemeral algae and various crust. In general, there appeared to be much more variation in the outcomes of the experiments in Southern Europe.

Particular experiments were conducted in Sweden, where littorinids are the only grazers present, and in the Mediterranean, where micro-tidal conditions occur. Limpet exclusion experiments has been performed on 3 Mediterranean shores 100-200 km apart along the Ligurian coast, and includes comparisons of the effects of grazers at different spatial and

temporal scales and in relation to the inclination of the substratum. The experiment, initiated in July 1996, consisted of 16 sites on each shore and a total of 504 plots. Preliminary results indicate that the effect of grazing is extremely variable in space and time (Fig. 9). After 3-4 months from start, the exclusion of limpets significantly increased the abundance of the filamentous algae but only on one shore (Baratti) and on nearly horizontal substrata. On the same shore the exclusion of limpets determined a significant increase in the abundance of encrusting coralline algae, again only on nearly horizontal substrata. Thus, on this particular shore, limpets reduce the coverage of filamentous and encrusting coralline algae on nearly horizontal substrata while other factors, probably related to desiccation, control the abundance of these organisms on vertical substrata.

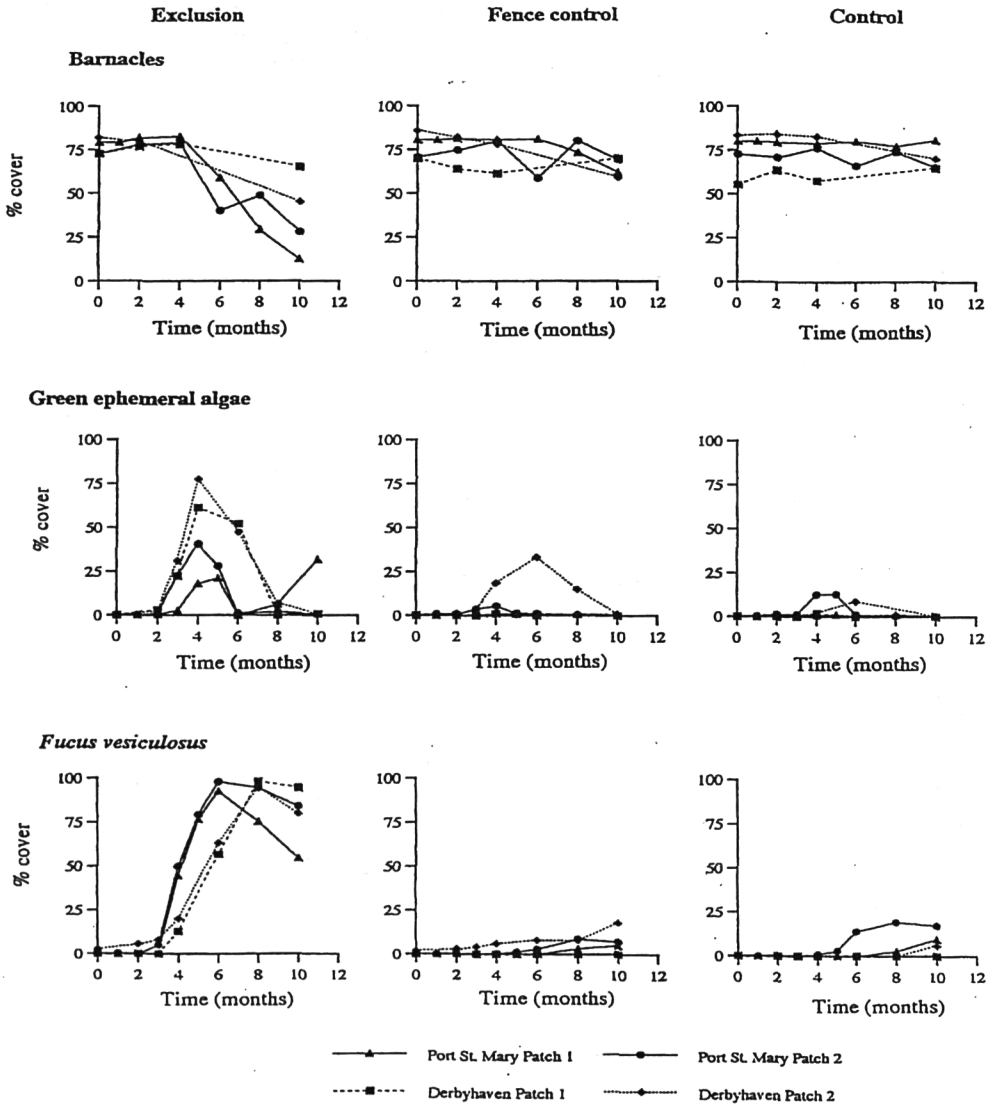


Fig. 8. Results of grazer exclusion experiments performed on the Isle of Man. Variation in the percent cover of barnacles (top), green ephemeral algae (mid), and *Fucus* (bottom) during the first year after the start of the experiments are shown.

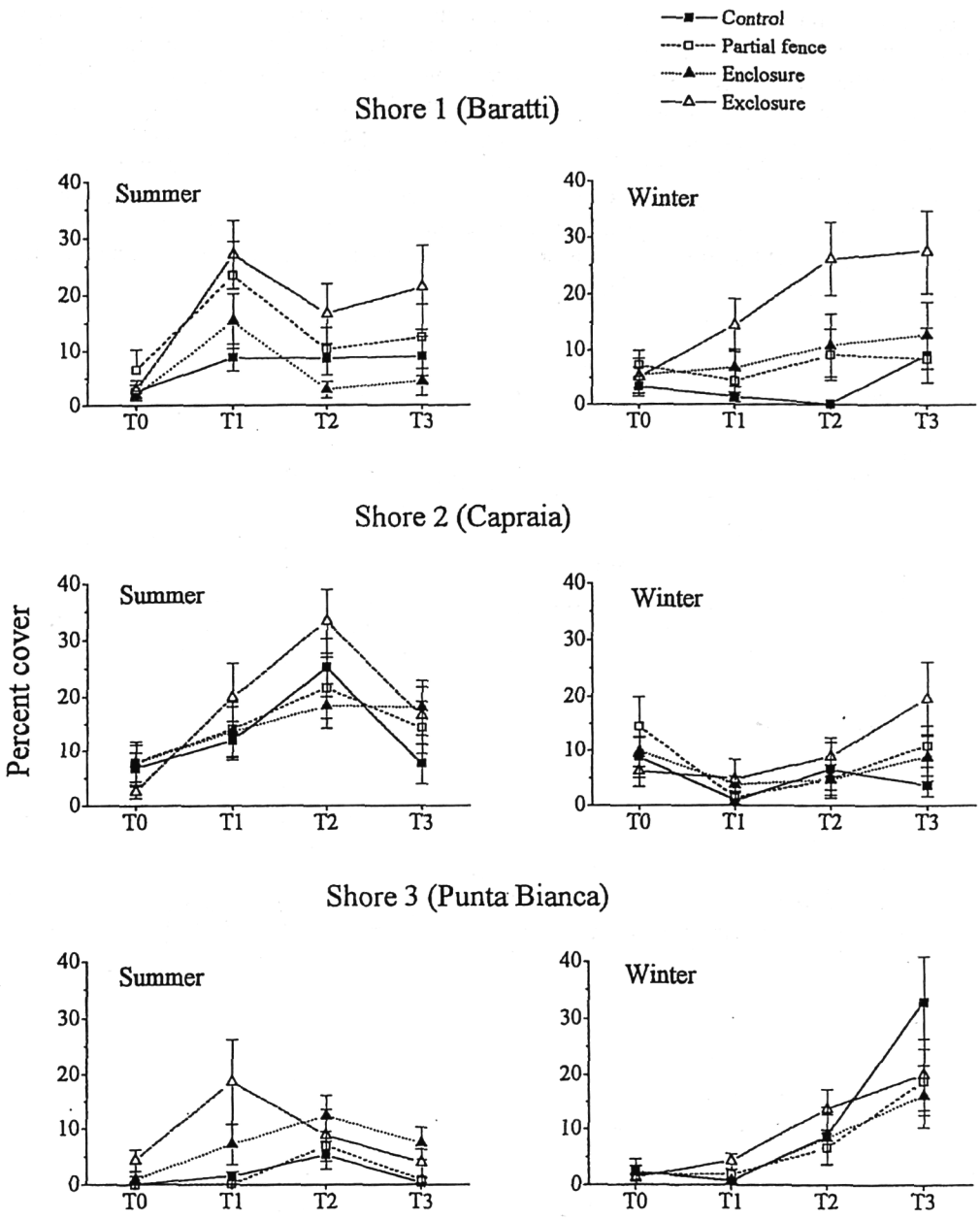


Fig. 9. Results of grazer exclusion experiments performed on nearly horizontal surfaces at three shores along the Tyrrhenian and Ligurian coast. Variation in the percent cover of filamentous algae is shown. T0-T1 and T1-T2: two months; T2-T3: four months.

Part C of EUROROCK is devoted to modelling individual behaviour of consumers (C1), and to link individual adaptation to physical and biological factors to population dynamics (C2) and community structure (C3) on rocky shores. The first module of this part is particularly dedicated to develop mechanistic models of foraging in simulated environments, and models of foraging behaviour including physical constraints, prey availability and risk associated with foraging excursions. A compartmental model of the limpet alimentary system was designed to simulate the effects of functional constraints and substrate's characteristics on the temporal patterning of grazing in these gastropods. Limitations are imposed by gut capacity and processing time. When holding constant the "morpho-functional" parameters of the model, variations in the "richness" of the substrate (i.e. in the amount of matter extracted per single rasp) generated different patterns of grazing activity, from constant grazing at different frequencies, to the appearance of distinct grazing-non grazing sub-phases with a periodicity corresponding to the processing time. Predictions of the model were tested by recording grazing activity in specimens of *Patella caerulea* kept under seminatural conditions in the laboratory (Chelazzi et al., in press).

To investigate the role of factors (energy costs, mortality risks, digestion and storage capacity) affecting the foraging activity of limpets M.T. Burrows and G. Santini (Dunstaffnage Laboratory and University of Firenze) formulated a dynamic programming model which determines optimal decisions by maximising a hypothetical fitness function of the state of the forager. The model predicts that the risk of mortality during a given tidal phase represents the strongest constraint to forage during that tidal phase, while metabolic costs are usually less effective. Moreover, the relative importance of the risk of mortality over metabolic costs increases as standing crop increases, but it is also influenced by maximum energy storage capacity (Fig. 10).

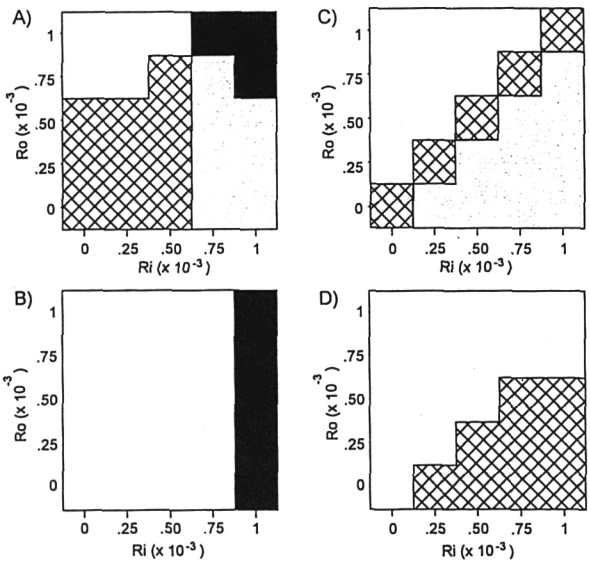


Fig. 10. Examples of predictions of a model of foraging in limpets based on dynamic optimisation. Optimal timing is predicted to occur during tide-in (white areas), tide-out (grey areas), both during tide-in and tide-out (cross hatched areas). Black areas indicate optimality

for no-foraging. Optimal timing depends on relative risk incurred by foraging during tide-out (Ro) and during tide-in (Ri). Moreover, optimal timing changes depending on standing crop values (A and B: standing crop = 0.05 joule/cm^2; C and D: standing crop = 0.30 joule/cm^2), and when costs of foraging during tide-in is equal to cost during tide-out (A and C) or when cost during tide-in is lower than foraging during tide-out.

Other individual-level models, based on cellular automata, were used to investigate the effect of different behaviours of predators (dogwhelks) on the population structure of the prey (barnacles). These models suggest that quantitatively different effects on barnacle size structure will be produced by dogwhelks showing and not showing size selective predation. Furthermore, it is predicted that the spatial structure of the shore can influence barnacle size structure via its effect on dogwhelk foraging activity. Other models were devoted to the analysis of the importance of refuges used by predators, on the small scale gradients in the populations of the prey, and to simulate the effect of grazers on distribution of macroalgae.

The models of the module C2 concern mainly population dynamics of barnacles and limpets, and are tested by using the data from the experimental module B1. Several models based on transition matrices (P. Åberg and co-workers, Göteborg University) have been designed, for predicting the effect of deterministic and stochastic process on population dynamics. General models were also produced for testing different mechanistic hypotheses from a demographic model of open populations with space-limited recruitment.

A first goal of module C3 is modelling of simple two and three species interactions. More complex models incorporate both the behaviour of individuals and populations as well as physical factors such as climate (temperature, precipitation, tidal regime) and disturbance (waves, sand and ice). Finally, multi-species models concern successional trends, non-equilibrium situations, and temporal effects of large scale phenomena on European rocky shores. For example, M.P. Johnson and co-workers (University of Southampton) analysed the spatial dependence in Markov models of rocky shores using cellular automata. Examples of interesting dynamics which theoretically relate to the patterns in real spatially extended ecosystems can be generated by a class of models known as cellular automata (CA). Such models represent space with a simple grid and usually use simple biological abstractions. However, the underlying similarity between CA and matrix transition models shows that CA rules can be defined empirically. We test whether empirically defined CA rules lead to simulated rocky shores dynamics different to those projected from a non-spatial model.
A system was examined where fluctuations in algal cover are thought to be driven by the spatial arrangement of limpet grazing pressure. Annual field surveys of 25 m^2 grids divided into 0.01 m^2 cells were used to define transition probabilities between different types of cover. The collection of data in a grid also allowed definition of transition probabilities dependent on the presence or absence of limpets in neighbouring cells. Transition matrices derived from different areas all showed that, even when sites are classified into a limited number of possible states, the shore has complex dynamics. At least 70% of all possible transitions occurred in a single year. Spatial effects of limpets were detected, affecting local transition probabilities at all the sites.

Although simple deterministic models of the shore generate patchiness, empirically derived spatial simulations did not generate patchiness and their dynamics were generally similar to non-spatial Markov model projections. There were slight differences in equilibrium cell state frequencies between model types, but no spatio-temporal structure was generated in empirically derived spatial models. An arbitrary choice of simple CA rules may therefore lead to misleading conclusions about pattern and process in ecology and direct empirical definitions of model rules should be more widely considered.

Another model was developed by a team from the Universities of Southampton and Liverpool for simulating the establishment of fucoid zonation on algal dominated rocky shores. The growth of intertidal algae with photosynthesis simulated both in air and in tidal water column. Morphological data on dry mass per unit area (thallus specific mass, TSM, g m^{-2}) and length-area relationships were used to separate the growth of different fucoid species. The relative growth rate of fronds at any height on the shore depended on a trade-off between net photosynthetic performance and tolerance to desiccation.

The simulated zonation patterns and growth rates were consistent with those observed previously for *Fucus* spp. and *Pelvetia canaliculata*. The simulated growth of *Ascophyllum nodosum* was always slower than the other species. This species could not form zones in simulations without including further processes in the model. However, *Ascophyllum* collected from the field could be separated into upper and lower shore morphologies which formed separate zones when they were simulated in competition with each other. A variety of hypotheses could be proposed concerning the relative locations and sharpness of interspecies boundaries on the shore. Zonation patterns were relatively insensitive to changes in most model parameters except the desiccation rate.

In conclusion, although experimental activity and modelling have not yet been concluded, EUROROCK is already becoming a standard for the analysis of interaction between physical and biological factors in structuring intertidal communities. Original techniques for monitoring physical factors and animal activity, individual-level information on behaviour and physiology of grazers and predators, results accumulating from large scale observations on recruitment and demography of sessile animals, and the many data from manipulative experiments on impact of grazers on intertidal communities, performed according to a standard experimental design, are constituting a unique piece of intertidal ecology made possible by the strong integration between the different partners. EUROROCK is the baseline of European rocky shore ecology from which different kinds of applied research - including assessment of environmental quality, management and conservation of coastal systems, and analysis of consequence of large scale climatic changes - can stem in the future.

This paper is largely based on the documents produced by the co-ordinators of the different modules of EUROROCK for ongoing reporting to the European Union DG XII. I wish to thank the collaborators which help me in the conduction of the project: P. Åberg, J. Arrontes, R.G. Hartnoll, R.N. Hughes, S.J. Hawkins, A. Myers, J. Paula.

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TITLE: Assessing the biological and physical dynamics of intertidal sediment ecosystems: A remote sensing approach (project BIOPTIS)

CONTRACT NO: MAS3-CT97-0158

COORDINATOR:
Dr David M. Paterson
Sediment Ecology Research Group
Gatty Marine Laboratory
University of St Andrews
Fife, KY16 8LB, Scotland, UK
Tel: 00-44-1344-463467
Fax: 00-44-1334-463443
E-Mail: d.paterson@st-andrews.ac.uk

PARTNERS:

Dr Roland Doerffer
Remote Sensing
GKSS Research Centre
Max Planck Str.
DE-21502 Geesthacht.
Tel: 00-49-4152-872485
Fax: 00-49-4152-871888
E-Mail: doerffer@gkss.de

Gerard Morgan
Aquatic Services Unit
Department of Zoology
University College Cork
Lee Maltings
Prospect Row
Cork, Ireland
Tel: 00-35-3-21-904179
Fax: 00-353-21-278020
E-Mail: asu@ucc.ie

Dr Jacco Kromkamp
Netherlands Institute of Ecology
Centre for Estuarine and Coastal Ecology
Vierstraat 28
4401 EA Yerseke, The Netherlands
Tel: 00-31-50-362241
Fax: 00-31-50-3635205
E-Mail: kromkamp@cemo.nioo.knaw.nl

Dr Winfried Gieske
Department of Marine Biology
University of Groningen
Biologisch Centrum
Kerklaan 30, P.O. Box 14
9750 AA Haren, The Netherlands
Tel: 00-31-50-363-2259
Fax: 00-31-363-5205
E-Mail: W.W.C.Gieskes@biol.rug.nl

ASSESSING THE BIOLOGICAL AND PHYSICAL DYNAMICS OF INTERTIDAL SEDIMENT ECOSYSTEMS: A REMOTE SENSING APPROACH

BIOPTIS

[1]D.M. PATERSON, [2]R. DOERFFER, [2]F. SHROEDER, [3]G. MORGAN, [4]J. KROMKAMP, [5]W. GIESKES, [5]K.H. WILTSHIRE

[1]Sediment Ecology Research Group, Gatty Marine Laboratory University of St Andrews, Fife, KY16 8LB, UK. [2]Remote Sensing, GKSS Research Centre, Max Planck Str., 21502 Geesthacht. [3]Aquatic Services Unit, Department of Zoology, University College Cork, Lee Maltings, Prospect Row, Cork, Ireland. [4]Netherlands Institute of Ecology, Centre for Estuarine and Coastal Ecology, Vierstraat 28, 4401 EA Yerseke, The Netherlands. [5]Department of Marine Biology, University of Groningen, Biologisch Centrum, Kerklaan 30, P.O. Box 14, 9750 AA Haren.

0. SUMMARY

Improvements in the analysis of data obtained by remote sensing systems (airborne and satellite) has provided the opportunity to examine the ecology and dynamics of intertidal sediment ecosystems in a new way. The BIOPTIS project will attempt to maximise the information on intertidal systems that can be obtained from the analysis of RS data. This work requires skilful ground truthing support which will incorporate the analysis of the physical properties of the substratum with the measurement and understanding of the biological dynamics of the system. This integrated approach will provide a basis for future developments in the RS analysis of the coastal zone and has wide potential for a number of end-user groups with a statuary role in the management of the coastal zone.

1. INTRODUCTION

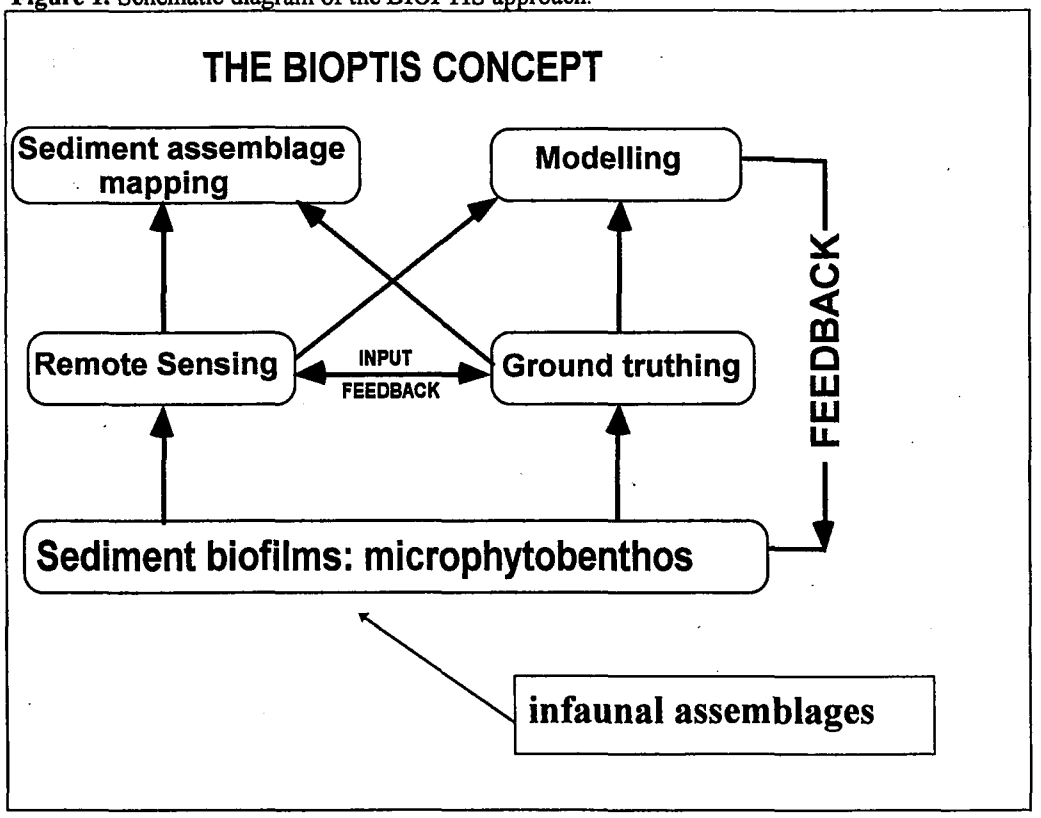
The estuaries and coastal seas of Europe are of great commercial and ecological significance which have, for centuries, been exploited by man for communication, transportation, waste disposal, power generation and amenity development. These areas are under increasing demographic pressure and 50% of the world's population now lives within 60 km of the coast. An understanding of the dynamics and ecology of coastal systems is a fundamental requirement to the understanding of this human impact. Despite the extreme conditions of periodic exposure to air and variations in salinity, coastal deposits are one of the most productive natural ecosystems on Earth, with a gross primary productivity of up to 10 Kcal/m^2 year (Kennish, 1995). The major primary producers of European coastal deposits are micro- and macro-algae (phytobenthos) supporting infaunal grazing organisms, wading birds and demersal fish. Phytobenthic populations on intertidal sediments therefore have a major influence on the ecosystem dynamics but are generally studied on very small spatial and temporal scales making the prediction of carbon fixation over large areas dubious and the investigation of environmental change difficult. It is timely to attempt to connect these small-scale measurements with the large scale distribution of algal populations and associated infauna to examine the changes occurring within these systems either naturally or as a result of human impact. The scales involved are very large but recent developments in remote sensing, in conjunction with ground measurements and process modelling, have shown that synoptic mapping can lead to a better understanding of system dynamics and environmental change. The BIOPTIS programme, beginning early in 1998, will address the use of remote sensing for the interpretation of intertidal systems and the assessment of environmental change.

The BIOPTIS project aims to maximise the discrimination of tidal flat characteristics by remote sensing and examine the importance of scale in actual measurements and modelled predictions of sediment processes. Links between pigment distribution, primary productivity and grazing in tide-influenced sediment systems will be examined. The specific objectives of the BIOPTIS programme are outlined below. The general concept of the programme is shown in Figure 1.

- *To map the spatial distribution of sediment type and "related" assemblages from tidal flat systems by ground truthing and associated remote sensing.*
- *To refine the interpretation of remote sensing data with respect to temporal and spatial variations in assemblage productivity, diversity and structure.*
- *To examine the scale relationships linking RS data with ground measurements on a micro (μm), meio (mm) and meso (dm) scale.*
- *To input RS derived data to benthic primary production models and examine the validity of this feedback mechanism by ground truthing.*
- *To use synoptic maps to investigate anthropogenic and natural change in sensitive coastal zones.*

1.1. The BIOPTIS concept

Figure 1. Schematic diagram of the BIOPTIS approach.



1.2. The sites

The Eden Estuary, Scotland

The Eden Estuary on the East Coast of Scotland (Figure 2) is a small but biologically varied estuary of local and European importance in terms of wading bird populations. Primary production is represented by biofilms, algal mats (*Enteromorpha*) and seagrass (*Zostera*). Infauna is equally varied with populations varying from dominance by *Corophium* and *Nereis* to cockle and mussel beds. Recent surveys of the Eden for Scottish Natural Heritage and by St Andrews University will provide a valuable database for the BIOPTIS project. The Eden is a also UK Site of Special Scientific Interest (SSSI) and under pressure from increasing nutrient loading.

The Sylt-Romo Basin

The Sylt-Romo basin is part of a European nature reserve in the Wadden Sea (Figure 2). It has been studied extensively over the period of 1991-1995 (Sylter Wattenmeer Austausch Prozesse, SWAP) to assess exchange processes between the Wadden Sea tidal flats, atmosphere and land. This involved hydrodynamics, ecological modelling, gaseous exchange processes, long-term geological processes and short-term productivity and flux processes. The study area is approx. 100 km² with a diverse array of biotopes and represents an anthropogenically-influenced intertidal coastal system, in contrast to the Eden system in terms of size, biotope, salinity regime and adjacent land use.

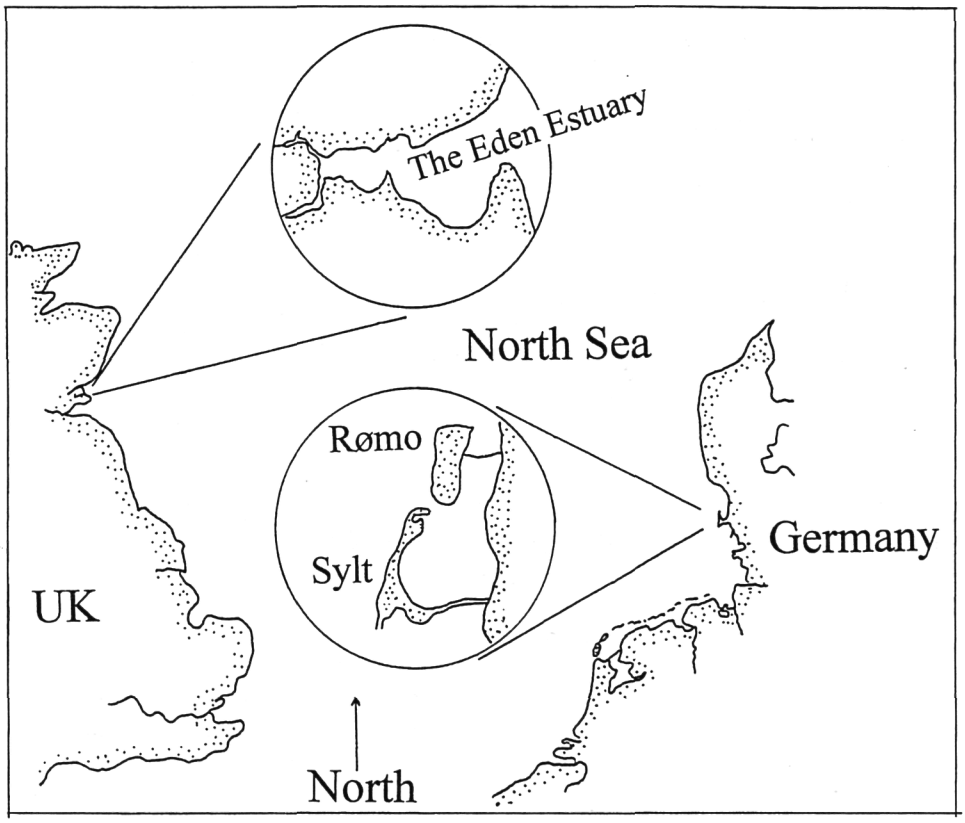


Figure 2. The sites selected for intensive study as part of the BIOPTIS programme.

2. BIOPTIS METHODOLOGY

The BIOPTIS programme involves a number of state-of-the art techniques involving the interdisciplinary partnership bringing together remote sensing, sediment systems ecology, macrofaunal abundance analysis, *in situ* analysis of photosynthesis by microsensor and non-invasive surface techniques, microscale pigment analysis and sediment microbiology. A major advance arising from the BIOPTIS programme will be the improved discrimination of intertidal areas, supported by expert ground truthing of surface assemblages, by remote sensing (RS). The input of RS data to existing sediment process models has important implications and represent an exciting advance in the exploitation of models (e.g. for evaluation of sediment oxygen dynamics, calculations of primary productivity, and diatom migration).

2.1 Mapping of sediment distribution by remote sensing techniques

Synoptic maps of the distribution of sediments on tidal flats (Figure 3) have been in use since the early 1980's (Bartholdy & Folving 1986). These approaches usually involved decision-making algorithms based on supervised classification such as the 'maximum likelihood classification technique'. This consists of taking representative ground samples at specific sites for supervising the classification of the information contained in the spectral channels. Recently Doerffer and Murphy (1989) have devised an unsupervised classification technique (i.e. without ground truths) to separate the land, sea and cloud mass signals from that of tidal flats. Such a method produces a discrete mask for the tidal flats, whereby all 'non-tidal flat' information can be removed for a subsequent Factor Analysis. Using ground truth measurements, information concerning the covariability of the components of this mixture will be related to the remotely sensed data for a more specific mapping of habitat types.

2.2. The determination of the spectral properties of sediments

The spectral properties of a sediments surface are dependant on the viewing geometry. Considering the radiative transfer from the sun to an airborne or spaceborne sensor, the interaction with the surface is described by its bi-directional reflectance factor. This is a function of wavelength, the solar incident and viewing angles. This is difficult to measure and data exist for only a few natural surfaces. More data, especially for coastal areas is available as simple reflectance factors, assuming a Lambertian reflector (SFB 149). However, this assumption is not valid and may lead to large errors for wet mud surfaces, which are known to reflect in a highly anisotropic way. The error in the evaluation of remotely sensed data, which is introduced by the assumption of a Lambertian reflector, has been estimated to be greater than 10% for a wide band, nadir-looking spectrometer (Krueger & Fischer, 1994). In MAST I and II a high resolution spectrometer capable of simultaneously measuring scalar and vector irradiance as well as radiances at different locations and under different angles was developed (MARAS, Marine Radiometric Spectrometer). This system has been designed for the *in situ* analysis of water samples but has already been tested for reflectance measurements from an aircraft and on the ground in a Wadden Sea Environment. Several short-comings have been identified, but the first bi-directional reflectance spectra of algae on different sediments have been sampled. Combining measurements of the optical properties of the sediment from different heights by radiative transfer calculations will be used to improve the interpretation of airborne and spaceborne images of the investigation areas.

2.3. Improvements in ground truthing protocols for remote sensing

At present no standardised protocol exists for taking ground truth samples in tidal flat areas for remote sensing purposes. For a reliable interpretation of remotely sensed data detailed protocols are necessary and will be common for all BIOPTIS working groups. The protocols must take into consideration the various spatial scales involved and the improvement of protocols will consist of two aspects: those related to the optical measurements and; those related to the habitat description (see SWAP report 1996). Ground optical measurements are point measurements, whereas, depending on the flight height, the pixel size of an aerial photograph is in the order of tens of

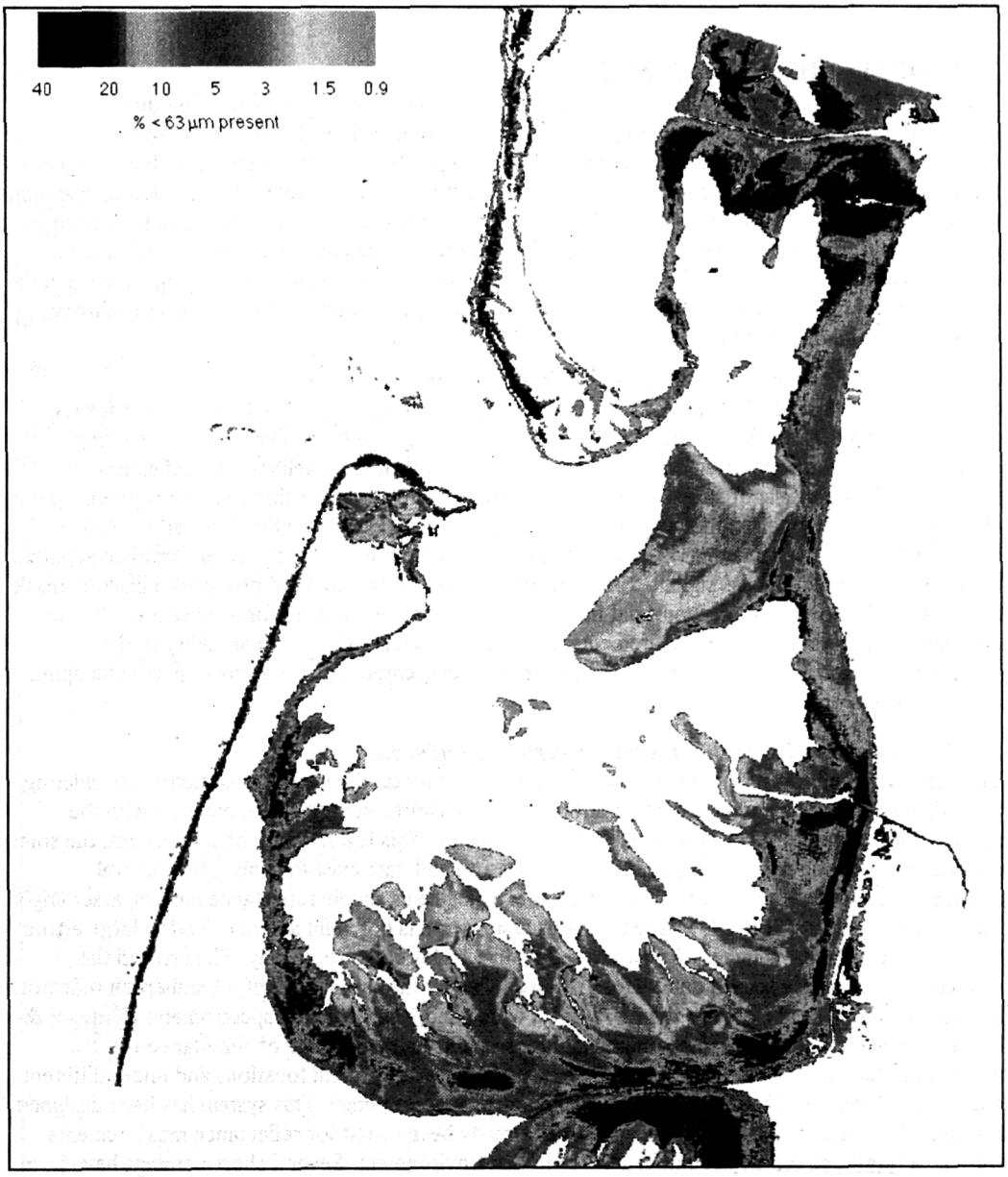


Figure 3. Synoptic map of sediment size distribution for one of the study areas (Sylt-Romo basin).Source: GKSS, Germany

centimetres and for the Thematic Mapper an area of 30m x 30m on the ground. It is, therefore, important to have as detailed a description as possible of the habitat around the point measurement. In addition, for the subsequent use in the radiative transfer model all influences effecting the radiances and absorbency measurements must be listed. Correlation of large scale sediment features to macrofaunal diversity and density will be carried out. As far as the mapping of microbial mats is concerned, remote sensing can reveal the appearance and disappearance of patterns on tidal flats. The spectral information collected by the airborne sensors is only accurate for mapping these patterns when ground-truthing is complete. This can be achieved by the spectral analyses of the colour of the sediment (Figure 4). This signature is made up of microbial pigments, and the pigments of detritus (non-living matter, degraded substances). HPLC analyses will be used to determine the range of pigments, their position and influence on RS signal.

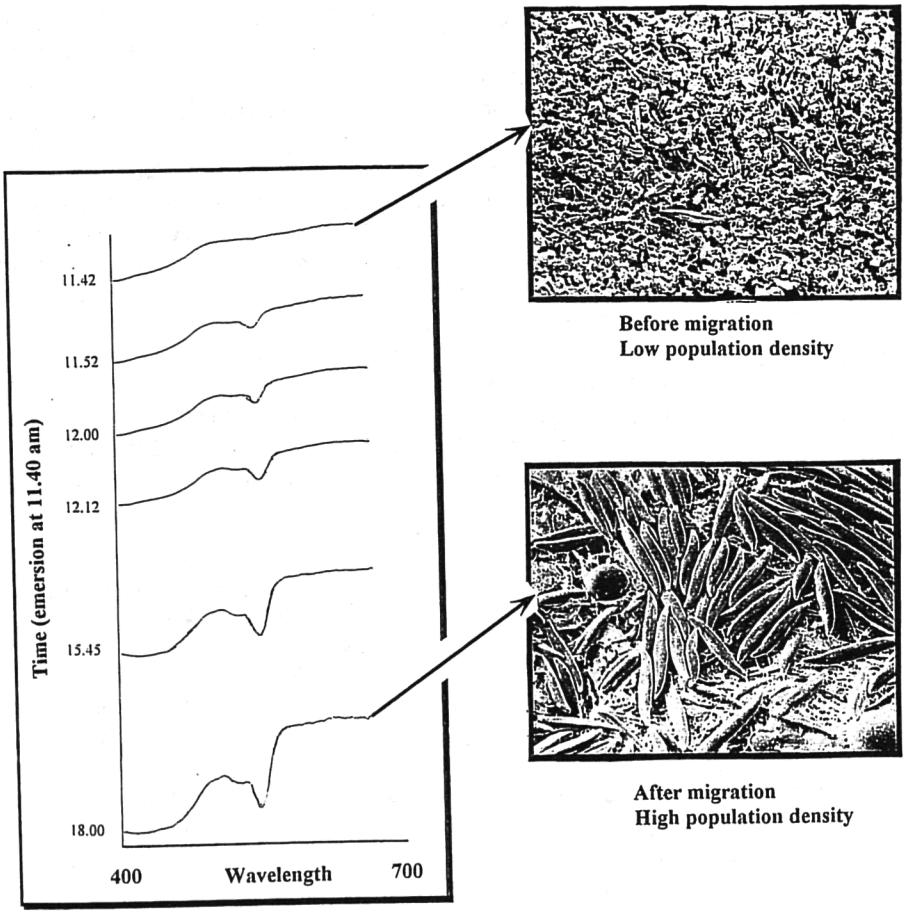


Figure 4. Variations in reflectance from the surface of intertidal mud. The spectral components of the reflected signal change in intensity with time depending on the migratory cycle of the microphytobenthos assemblages.

2.4. The light field within sediments

The nature of the light field within a sediment is influenced by absorption and scattering. Light can be described as directional (field radiance) or scattered. Scalar irradiance can now be measured directly by the addition of a spherical diffusing tip to a fibre-optic (Lassen *et al.* 1992). These systems can now provide an inexpensive measure of spherically integrated photosynthetic photon flux density (PPFD) on a scale suitable to microbial mat and biofilm studies. The importance of these measurements for the understanding of the light climate in sediments and light reflected from them cannot be overstated. Measurement of the light climate within the sediment will employ fibre optic technology for the determination of directional and scalar light within surficial sediment layers. Spectral quality of the light will be analysed by spectroradiometry. Simultaneous measurements of the light field within a sediment and the spectral reflectance from the surface of the sediment represents an advance to the state-of-the art.

2.5. Assemblage structure and scaling of pigment distribution

The structure and composition of the surficial sediment layers is critical to the optical properties of the sediment system and hence the interpretation of productivity by RS. The intense absorption at the sediment/air interface are partly induced by the accumulation of organisms in this region. The technique of choice to visualise the fine structure of surficial sediment micro-fabric is the use of low-temperature scanning electron microscopy (LTSEM, Paterson 1995, Figure 5). Pigment analysis must also be carried out on a spatial scale of relevance to the proposed study. Thin-sectioning (freezing microtome) of sediment cores frozen in the field followed by examination by HPLC has recently been developed as a method for determining the microspatial distribution of pigments (Wiltshire et al. 1996). A correlative technique is required to bridge the gap between the microscale of pigment sampling and description of a biotope-size scale. The most promising approach is based on the principle of Pulse Amplitude Modulated (PAM) fluorescence. PAM-fluorescence can be used to map the algal distribution on a tidal flat based on photosynthetic activity. PAM measurements are rapid and non-intrusive and can be used to measure the primary productivity of benthic algae at a mesoscale during tidal emersion. There is evidence that estimates of chlorophyll content acquired by pulsed fluorescence are more accurate than normal fluorescence methods. In BIOPTIS PAM-fluorescence will be instrumental in scaling up from microscale measurements to synoptic measurements (remotely sensed measurements).

2.6. Model studies

Two areas of modelling are inherent within BIOPTIS. Firstly modelling aimed at increasing the range and value of information gained from RS comprising numerical modelling of the radiative transfer in the system atmosphere/surface the relationships between independent and dependent variables (Brockmann, 1992, Doerffer *et al.*, 1989). The Matrix Operator Method of Fischer and Grassl (1984) and LOWTRAN will be adapted to this specific application. Both models output spectral radiances which will also be adapted to the specifications of the instruments used in the project. The resulting data-set of simulated radiances for well-defined surface, atmospheric and environmental conditions will be subjected to a statistical analysis. This will determine the information that can be extracted from the remote sensing data (e.g., pigment distributions), and the precision possible. Algorithms to retrieve the information from remotely sensed data will be developed and tested. The second area of modelling concerns the input of data derived from RS radiative transfer modelling into sediment process models. The feedback of data from remote sensing into process models of benthic activity is an integral and innovative part of the BIOPTIS programme (see Figure 1). The modelling of sediment oxygen consumption and algal productivity and have been selected as areas of primary importance and lightly to reflect environmental change.

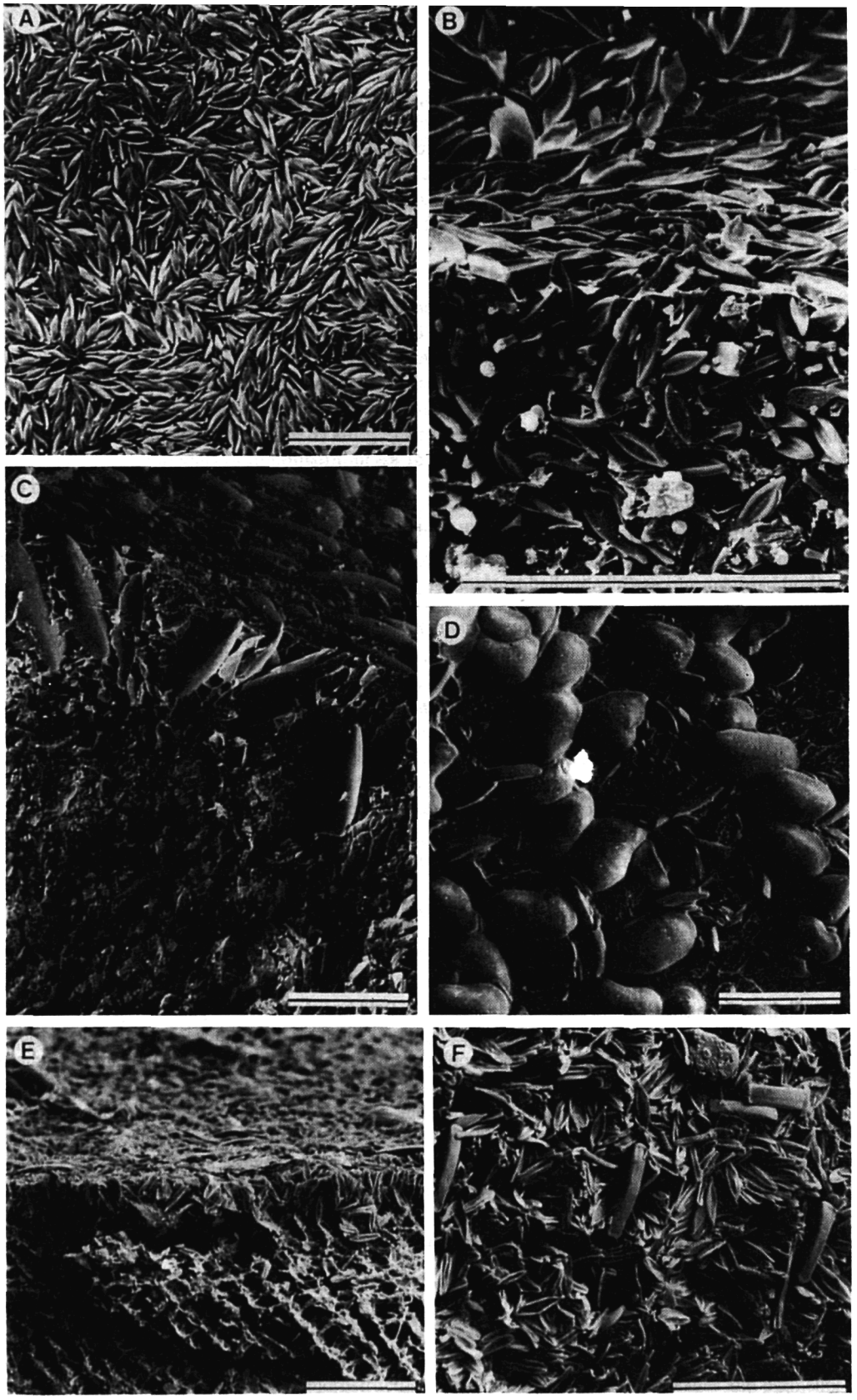


Figure 5. Low-temperature Scanning Electron Micrographs of sediments. A. Algal biofilm. B. Edge of biofilm. C. Cell migration. D. *Euglena* sp, (rich in Chl a and b). E. *Nitzschia* sp. F. Surface detail of assemblage. (All bar markers = 100 um).

The first uses a two-layer model (Wiltshire,1992; Wiltshire *et al.*, 1996) which is based on the principle of steady state but will be adapted to include the changes of oxygen concentration over time in sediments. This model will also be extended to include the evaluation of kinetics for oxygen consumption in sediments. RS data will also be tested in the productivity model of Pinckney and Zingmark (1991). This feedback approach in BIOPTIS is a new paradigm for the analysis of system dynamics and the consequences of environmental change and represents a significant advance.

3. THE BIOPTIS TASKS

3.1. Mapping the spatial distribution of sediment and "related" assemblages.

Sites will be mapped according to their sediment distribution, algal cover and infaunal assemblages. Algal species pigment distributions will be determined by high performance liquid chromatography. Chlorophyll *a* will be examined as an algal biomass indicator and the presence of primary consumers documented. Protocols developed in relevant European programmes will be used to aid in the classification of the intertidal areas from the ground (e.g. INTRMUD). The diversity and spatial patchiness will be recorded for the interpretation of RS information.

3.1.1. The variation in algal assemblage with sediment grain size

The biodiversity of the algal assemblages will be determined by light and electron microscopy. In addition, algal assemblages will be classified according to pigment ratios as analysed by HPLC. This method has been successfully applied to plankton and is routine for the examination of sediments.

3.1.2. The distribution and variability of primary consumers

Abiotic and biotic variables greatly influence the composition of intertidal macrobenthic infaunal communities. Prime amongst these are grain size spectra and microphytobenthic primary production. The 'bio-sedimentary approach' of Ducrotoy *et al.* (1989) will be adapted to study the distribution patterns of the macrobenthic infauna. This approach uses remote sensing data to arrive at a sedimentary-dynamics parameter map onto which morpho-sedimentary units and bio-sedimentary facies are overlaid to arrive at a complete picture of benthic variability over the whole study area. This will allow a study into the predictability of large scale macrofaunal distribution patterns on the basis of remote sensing data. The sampling strategy will be adapted to take into account the relative substratum homogeneity and heterogeneity on the tidal flats in Königshafen and the Eden Estuary. Use of multivariate analysis techniques will be used to study the relative importance and contribution of each factor to the distribution pattern of the macrobenthic primary consumers.

3.1.3. Classification of large tidal flat areas with respect to biofilms using airborne photography, airborne video systems and satellite images.

Overflights of the sites will be co-ordinated with the field based studies on productivity, assemblage distribution and structure. The employment of simple planimetric techniques is not suitable in the case of the microphytobenthos due to the problem of differentiating different biofilm areas. Radiative transfer modelling will be used to produce radiances adapted to the spectral characteristics of the various remote sensing instruments and form the link between these. The model will be fed with ground-based reflectance and absorbance measurements of the biofilms. Four aerial campaigns will be undertaken providing simultaneous aerial photographs, video imagery, and RS data sets. Furthermore, both aerial photography and video systems have a very high spatial resolution (cm). The development of digital evaluation methods (vegetation indices and numerical classification), therefore, is a priority which will be addressed. All digitised and evaluated data will be integrated into a GIS (Kleeberg 1992)

3.2. Interpretation of remote sensing data.

3.2.1. Determination of the attenuation, reflectance and absorption of light by sediments.

The amount and quality of light being absorbed by sediments is directly related to the reflectance and scattering of light. It is this light which is used for colour and grey scale analyses in remote sensing. Analysis of the attenuation, reflectance and absorption of light will be carried out initially under controlled conditions in the laboratory with defined sediment. Further analysis will be carried out to examine light penetration and attenuation within sediments under natural conditions using fibre-optic microsensors.

3.2.2. Relating in situ *optical properties to remote sensing by radiative transfer modelling*

Numerical modelling of the radiative transfer in the system atmosphere/surface is a proper tool for evaluating the relationships between independent and dependent variables (Brockmann 1992). In this proposal, the optical properties of the surface, namely the spectral absorption and the bi-directional (or Lambertian) spectral reflectance of different biofilms and sediments are the main independent variables. Existing models [Matrix Operator Method of Fischer and Grassl (1984) and LOWTRAN] will be adapted to this specific application. Both models output spectral radiances which will also be adapted to the specifications of the instruments used in the project. Test scenarios which cover the expected (and later measured) range of optical properties of the surface will be defined and the radiances measured at the instruments will be calculated. The atmospheric (aerosol type, pressure) and environmental conditions (flight height, sun elevation) can be varied for each surface type and small random variations of all parameters will be introduced to account for natural variations. The result will be a large data set of simulated radiances for well-defined surface, atmospheric and environmental conditions. A statistical analysis of this data set will determine the information that can be extracted from the remote sensing data (e.g., different algae), and the precision possible. Algorithms to retrieve the information from remotely sensed data will be developed and tested.

3.2.3. Examination of macrofaunal bioturbation effects on pigment distribution and primary production

Resin casting of field populations has been successfully applied in the intertidal and subtidal to study species-specific burrow structures in great detail, while X-radiography has been applied to laboratory set-ups to study more specifically the size relationships between burrowers and burrows. Together with the more recently developed fluorescent particle incorporation technique these will allow an estimation of the total amount of water-sediment interface increase on a community scale. The Swift (1993) bioturbatory activity scoring system will be adapted to intertidal fauna and used to weight an abundance matrix in order to spatially map the total bioturbating capaçity of the infaunal macrobenthos.

3.2.4. Grazing influence

Three aspects of grazing will be investigated *in situ*: species-specific grazing rates, total community grazing pressure and the correlation between them and environmental variables, such as grain size, inundation time and microphytobenthos standing stock. Macrobenthic species-specific grazing rates will be determined by micro-coring grazing trails, feeding depressions and the immediate area surrounding bivalve siphon-holes. Total community grazing pressure will also be estimated, *in situ*, by employing chemical treatments to clear areas from macrobenthos, a technique which has been shown to have a more transient effect on microphytobenthos (Underwood & Paterson 1993). In conjunction with this, experimental predator-inclusion experiments will be run, a method that has been successfully used by Warwick *et al.* (1982) to remove all macrofauna.

3.2.5. The relationships between pigments in sediments and sediment optical properties,

Attenuation coefficients derived above will be compared to sediments colonised by natural and characterised assemblages of autotrophic microbes. These experiments will also analyse directional and scalar light as well as the spectral composition of light at different depths. These studies will be related to SEM examination of the microstructure of the sediment algal assemblages and pigments

analysis using HPLC. Data will be used for models of light penetration depths in the sediments and also to improve models of the oxygen penetration of sediments particularly during photosynthesis by microphytobenthos (Wiltshire et al.1993).

3.3. Scale relationships linking RS data with ground measurements

The scale relationships between actual productivity measures, pigment distribution (photoautotrophic biomass) and estimates from the analysis of spectral reflectance data is critical to BIOPTIS. Therefore a nested hierarchy of measurements is to be established to examine scale relationships. At the smallest level, *in situ* microsensor and freeze sampling techniques will be used to describe the microscale patchiness of pigments and production. These measurement will be grouped within replicate PAM fluorescence measurements on a slightly larger scale (mm-cm). Ground based RS instrumentation (spectoradiometry) will be used to relate pigment distribution on a metre scale to productivity measurements and these, once established, will be co-ordinated with over-flights to assess the broader distribution of pigments on the surface of the flats.

3.4. To input RS derived data to benthic primary production models

3.4.1. Production and consumption measurements- rates and fluxes of oxygen.

In BIOPTIS, a variety of methods will be used to measure the fluxes of oxygen in sediment-water systems (e.g. microsensors, incubations). Knowing the diffusion coefficients and porosity of the sediments, it is possible to calculate the flux of oxygen to the overlying system using Fick's law of diffusion. However, in order to determine the gross oxygen production of a system it is necessary to measure the oxygen consumption rates of sediments. Consequently, the consumption rates will be measured using microsensor profiles. These results will be compared with data from the incubation measurements and used for modelling oxygen sediment penetration in the systems using a two layer model. This model is at present based on the principle of steady state but will be extended to include the changes of oxygen concentration over time in sediments within the BIOPTIS study. The data generated from this will be tested in models such as that of Pinckney and Zingmark (1991) for productivity under a variety of environmental conditions over larger areas.

3.5. Synoptic maps to investigate anthropogenic and natural system change

3.5.1. Data banking.

Data banking for the RS material will be the responsibility of Partner 2. The data from overflights and ground measurements will be collated to provide synoptic overlays giving the maximum discrimination of system change. Information from the GIS data will indicate areas of maximum change and the relative ecosystem stability.

3.5.2. The assessment of change to intertidal environments.

In seasonal terms, the BIOPTIS project is relatively short but the sites have been selected to allow the maximum potential to realise this objective. Regular ground truthing and RS mapping will be used to provide and assessment of the changes to the system while the application of the modelling studies will examines the influence of these changes on biological processes.

4. WORK PROGRAMME

The work programme and timetable for BIOPTIS is outlined in Table 1.

Table 1. BIOPTIS program and timetable

Month	0-6	7-12	13-18	19-24	25-30	31-36	
Protocols	XXX						
Field studies		XXX	XXX	XXX	XXX		
Lab. Studies	X	X	XX	XX	X	XX	
Overflight		X	X	X	X		
Modelling	X	X	X	X	X	XX	
Data collation		X		X		XXX	
Reports			X				XXX
qaqc	X		X		X		XX

5. ECONOMIC AND SOCIAL IMPACTS.

Demographic changes and tourism have lead to increasing pressure on vulnerable coastal systems. The economic impact of the deteriorating coastal environment is virtually impossible to estimate. The viability of the coastal system has a direct impact on:

- Fisheries
- Tourism
- Transport
- Health

The BIOPTIS approach will help to provide information leading to the prediction of change in the intertidal and this data towards a valid management strategy for the threatened coastal zone is of high priority to the EU as outlined in The Council Resolution of 25/2/92 requesting such a development. Equally from a social perspective, knowledge gained during the BIOPTIS project could have considerable implication to the health and life style of coastal inhabitants and incoming tourists. In addition to helping to establish guidelines for the management of coastal zones, a move towards more "ecofriendly" tourism supported by relevant data would be a valuable contribution towards sustainable economic development of these regions. Information toward these goal is therefore of high social priority.

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I.3. Regional seas research

I.3.1. The Mediterranean Sea

TITLE: Mediterranean Targeted Project II -
MAss Transfer and Ecosystem Response (MTP II-MATER)

CONTRACT NO: MAS3-CT96-0051

COORDINATOR: Dr. Pierre Marie Lehucher (Project Manager)
CETIIS, Cabinet d'Etudes Techniques Industrielles et d'Innovations Scientifiques
Aix Métropole Bat.D, 30 avenue Malacrida
13100 Aix en Provence, France
Tel. : +33-4-42934707
Fax : +33-4-42265219
e-mail: pml@cetiis.fr

Dr. André Monaco (Scientific Coordinator)
Centre National de la Recherche Scientifique
Laboratoire de Sédimentologie et Géochimie Marines,
Université de Perpignan
52 avenue de Villeneuve
66860 Perpignan, France
Tel. : +33-4-68662088
Fax : +33-4-68661713
e-mail: monaco@univ-perp.fr

PARTNERS:

Julian Icarus Allen
Natural Environment Research Council
Plymouth Marine Laboratory
Prospect Place, West Hoe
PL1 3DH, Devon Plymouth, England
Tel. : +44-175-2633468
Fax : +44 175 2633101
e-mail : jia@pml.ac.uk

Vincenzo Artale
Ente per le Nuove tecnologie, l'Energia e l'Ambiente,
Dipartimento Ambiente
Divisione Ambiente globale e Mediterraneo
P.O.Box 2400, via Anguillarese 301
00060 S. Maria di Galeria Rome, Italy
Tel. : +39-6-30483096
Fax : +39-6-30484264
e-mail: vincenzo@canaletto.casaccia.enea.it

Antonio Artegiani
Consiglio Nazionale delle Ricerche
Istituto di Ricerche sulla Pesca Marittima
Largo Fiera della Pesca 1
60125 Ancona, Italy
Tel. : +39-71-2078842
Fax : +39-71-2055313
e-mail : pesca@vm.cnuce.cnr.it

Mario Astraldi
Consiglio Nazionale delle Ricerche
Istituto per lo Studio della Dinamica
delle Grandi Masse Stazione Oceanografica
La Spezia, Forte Santa Teresa
19036 Pozzuolo di Lerici, La Spezia, Italy
Tel. : +39-187-536301
Fax : +39-187-970585
e-mail : fisams@est409.santateresa.enea.it

Job Baretta
Vand Kvalitets Instituttet
Ecological Modelling Centre
Agern Allé 5
2970 Hørsholm, Denmark
Tel. : +45-45-769555
Fax : +45-45-762567
e-mail : baretta@dhi.dk

Sanzio Bassini
Consorzio Interuniversitario per la gestione del centro di calcolo elettronico dell'Italia Nord orientale
Gruppo Supercalcolo
Via Magnanelli 6/3
40033 Casalecchio di Reno, Bologna, Italy
Tel. : +39-51-6599514
Fax : +39-51-6592581
e-mail : bassini@cineca.it

Jean Marie Beckers
Université de Liège
GeoHydrodynamics and Environment
Research laboratory, B5 Sart Tilman
4000 Liège, Belgium
Tel. : +32-43-663358
Fax : +32-43-662355
e-mail : JM.Beckers@ulg.ac.be

Jean Pierre Béthoux
Centre National de la Recherche Scientifique
Laboratoire de Physique et Chimie Marines
Observatoire Océanologique de Villefranche
sur Mer, BP 8, Quai de la Darse
06230 Villefranche sur Mer, France
Tel. : +33-4-93763727
Fax : +33-4-93763739
e-mail : bethoux@ccrv.obs-vlfr.fr

Davide Bregant
Consiglio Nazionale delle Ricerche
Istituto Sperimentale Talassografico di
Trieste
viale romolo Gessi 2
34123 Trieste, Italy
Tel. : +39-40-305403
Fax : +39-40-308941
e-mail : A0290@PDAR1.PD.CNR.IT

Ioanna Bouloubassi
Centre National de la Recherche Scientifique
Département de Géologie et Océanographie
Université de Bordeaux I, URA 197,
avenue des Facultés
33405 Talence, France
Tel. : +33-5-56848960
Fax : +33-5-56840848
e-mail:bouloubassi@geocean.u-bordeaux.fr

Miquel Canals
Universitat de Barcelona
GRC Geociencies Marines
Departament de Geologia Dinamica
Geofisica i Paleontologia
Campus de Pedralbes
08071 Barcelona, Spain
Tel. : +34-3-4021360
Fax : +34-3-4021340
e-mail : miquel@natura.geo.ub.es

George Chronis
National Centre for Marine Research
Institute of Oceanography
Agios Kosmas
16604 Helleniko (Athens), Greece
Tel. : +30-1-9820214
Fax : +30-1-9833095
e-mail : gchronis@edp.ncmr.ariadne-t.gr

Michael Collins
Southampton University
Department of Oceanography
Southampton Oceanography Centre
Dockside Campus, European Way
SO17 1BJ Southampton, United Kingdom
Tel. : +44-170-3592786
Fax : +44-170-3593059
e-mail : mbc@soton.ac.uk

Michel Crépon
Université Pierre et Marie Curie, Paris VI
Laboratoire d'Océanographie Dynamique et
de Climatologie
Case courrier 100, 4 place Jussieu
75252 Paris, France
Tel. : +33-1-44277274
Fax : +33-1-44277159
e-mail : mc@lodyc.jussieu.fr

Norberto Della Croce
Università di Genova
Facoltà di Scienze
Istituto di Scienze Ambientali Marine
CP 79, Corso Rainusso 14
16038 S. Margherita Ligure, Genova, Italy
Tel. : +39-185-283415
Fax : +39-185-281089
e-mail : ligursea@promix.shiny.it

Pierre De Mey
Centre National de la Recherche Scientifique
Mouette, UMR 5566
18, avenue Edouard Belin
31055 Toulouse, France
Tel. : +33-5-61332928
Fax : +33-5 61253205
e-mail : demey@nanook.cst.cnes.fr

Alain Dinet
Centre National de la Recherche Scientifique
Observatoire Océanologique de Banyuls
Laboratoire Arago, BP 44
66651 Banyuls sur Mer, France
Tel. : +33-4-68887344
Fax : +33-4-68887395
e-mail : adinet@arago.obs-banyuls.fr

Gerard Duineveld
Nederlands Instituut voor Onderzoek
der Zee, Department of Marine Ecology
P.O. Box 59
1790 Ab Den Burg, Nederland
Tel. : +31-222-369533
Fax : +31-222-319674
e-mail : duin@nioz.nl

Walter Eifler
European Commission
Joint Research Center
Institute for Remote Sensing Applications
Marine Environment Unit, TP 690
21020 Ispra, Italy
Tel. : +39-332-789326
Fax : +39-332-789648
e-mail : walter.eifler@jrc.it

Bouchta El Moumni
Université Abdelmalek Essaâdi
Faculté des Sciences et Techniques de Tanger, Département des Sciences de la Terre et d'Océanologie
Ancienne rue de l'Aéroport, BP 416
90000 Tanger, Morocco
Tel. : +212-9-3359 55 / 54
Fax : +212-9-335953
e-mail : moumni@challenger.fstt.ac.ma

Marta Estrada
Consejo Superior de Investigaciones Cientificas, Institut de Ciencies del Mar
Departament de Biologia Marina
Passeig Joan de Borbo s/n,
08039 Barcelona, Spain
Tel. : +34-3-2216416
Fax : +34-3-2217340e-
mail : marta@icm.csic.es

Laurence Eymard
Centre National de la Recherche Scientifique
Centre d'étude des Environnements Terrestre et Planétaires
10/12 avenue de l'Europe
78140 Velizy, France
Tel. : +33-1-39254902
Fax : +33-1-39254922
e-mail : laurence.eymard@cetp.ipsl.fr

Jordi Font
Consejo Superior de Investigaciones Científicas Instituto de Ciencias del Mar
Departamento de Geología Marina y Oceanografía Física
Passeig Joan de Borbõ s/n
08039 Barcelona, Spain
Tel. : +34-3-2216416
Fax : +34-3-2217340
e-mail : jfont@icm.csic.es

Slim Gana
Institut National Scientifique et Technique de l'Océanographie et des Pêches
Département Milieu Marin
Laboratoire d'Océanographie Physique
28, rue du 2 mars 1934
2025 Salammbô, Tunisia
Tel. : +216-1-730420
Fax : +216-1-732622
e-mail : slimgana@instop.rnrt.tn

Paola Giordani
Consiglio Nazionale delle Ricerche
Istituto per la Geologia Marina
via Piero Gobetti 101
40129 Bologna, Italy
Tel. : +39-51-6398861
Fax : +39-51-6398940
e-mail : giordani@boigm2.igm.bo.cnr.it

Keith Haines
University of Edinburgh, Department of Meteorology
King's Building, Mayfield road
EH9 3JZ Edinburgh,United Kingdom
Tel. :+44-131-6505096
Fax : +44-131-6624269
e-mail : kh@ed.ac.uk

Bruno Hamelin
Centre National de la Recherche Scientifique
Laboratoire de Géosciences de l'Environnement
Europôle Méditerranéen de l'Arbois, BP 80
13545 Aix en Provence, France
Tel. : +33-4-42971522
Fax : +33-4-42971540
e-mail : hamelin@cerege.fr

Rodney Herbert
University of Dundee
Department of Biological Sciences
Nethergate, DD1 4HN Dundee, United Kingdom
Tel. : +44-138-2344279
Fax : +44-138-2322318
e-mail : R.A.HERBERT@dundee.ac.uk

Lydia Ignatiades
Demokritos National Centre for Scientific Research, Laboratory of Hydrology
Institute of Biology
P.O. Box 60228, Aghia Paraskevi, Attiki
15310 Athens, Greece
Tel. : +30-1-6511767
Fax : +30-1-6511767
e-mail : igna@cyclades.nrcps.ariadne-t.gr

Alex Lascaratos
University of Athens
Department of Applied Physics
Laboratory of Meteorology and Oceanography
Ippocratous 33, 10680 Athens, Greece
Tel. : +30-1-3613504
Fax : +30-1-3608518
e-mail : alasc@pelagos.ocean.uoa.ariadne-t.gr

Pierre Yves Le Traon
Collecte Localisation Satellites
Space Oceanography Division
Parc Technologique du Canal
8-10 rue Hermes,
31526 Ramonville Saint-Agne, France
Tel. : +33-5-61394758
Fax : 33-5-61751014
e-mail : Pierre-Yves.Letraon@cls.cnes.fr

Catherine Maillard
Système d'Information scientifiques pour la Mer, IFREMER centre de Brest, B.P. 70
29280 Plouzane, France
Tel. : +33-2-98224279
Fax : 33-2-98224644
e-mail : Catherine.Maillard@ifremer.fr

Claude Millot
Centre National de la Recherche Scientifique
Laboratoire d'Océanographie et de Biogéochimie, Centre d'Océanologie de Marseille, Antenne de Toulon, BP 330
83507 La Seyne sur Mer, France
Tel. : +33-4-94304884
Fax : +33-4-94879347
e-mail : millot@com.univ-mrs.fr

Renzo Mosetti
Osservatorio Geofisico Sperimentale
Dipartimento di Oceanologia e Geofisica Ambientale, Borgo Grotta Gigante 32
34010 Sgonico (Trieste), Italy
Tel. : +39-40-2140268
Fax : +39-40-2140266
e-mail : mosetti@rs2oga.ogs.trieste.it

François Nyffeler
Université de Neuchâtel Institut de Géologie
Laboratoire de Minéralogie et Pétrographie
11 rue Emile Argand
2007 Neuchâtel, Switzerland
Tel. : +41-32-7304665
Fax : +41-32-7303150
e-mail : Francois.Nyffeler@geol.unine.ch

Stefano Pierini
Istituto Universitario Navale
Facoltà di Scienze Nautiche
Istituto di Meteorologia e Oceanografia
Corso Umberto I, 174
80138 Napoli, Italy
Tel. : +39-81-5475732
Fax : +39-81-207106
e-mail : PIERINI@NAVA1.UNINAV.IT

Nadia Pinardi
Consiglio Nazionale delle Ricerche
Istituto per lo Studio delle Metodologie Geofisiche Ambientali
Area della Ricerca CNR
via Gobetti, 101
40129 Bologna, Italy
Tel. : +39-51-6398015
Fax : +39-51-6398132
e-mail : pinardi@imga.bo.cnr.it

N. Brian Price
University of Edinburgh
Department of Geology and Geophysics
King's Building, West Mains road
EH9 3JW Edinburgh, United Kingdom
Tel. : +44-131-6504846
Fax : +44-131-6683184
e-mail : fsl@glg.ed.ac.uk

Sandro Rabitti
Consiglio Nazionale delle Ricerche
Istituto di Biologia del Mare
Castello 1364/A,
30122 Venezia, Italy
Tel. : +39-41-5207622
Fax : +39-41-5204126
e-mail : rabitti@vecnr8.ibm.ve.cnr.it

Fereidoun Rassoulzadegan
Centre National de la Recherche Scientifique
Universite Pierre & Marie Curie (Paris VI)
Laboratoire d'Oceanographie Biologique et Ecologie du Plancton Marin
CNRS URA 2077
Station Zoologique, BP 28
06230 Villefranche-sur-mer, France
Tel. : +33-4-93763821
Fax : +33-4-93763834 / 38 23
e-mail: rassoul@ccrv.obs-vlfr.fr

Wolfgang Roether
Bremen Universität
Bremen Institut für Umweltphysik
Fachbereich 1, PO Box 330440
28334 Bremen, Germany
Tel. : +49-421-2183511
Fax : +49-421-2187018
e-mail : wroether@physik.uni-bremen.de

J. Albert Sánchez Cabeza
Universitat Autònoma de Barcelona
Grup de Física de les Radiacions
Departament de Física, Edifici Cc
08193 Bellaterra, Spain
Tel. : +34-3-5811915
Fax : +34-3-5812155
e-mail : ja.sanchez@cc.uab.es

Uwe Send
Universität Kiel
Institut für Meereskunde
Düsternbrooker Weg 20
24105 Kiel, Germany
Tel. : +49-431-5973827
Fax : +49-431-5973821
e-mail : usend@ifm.uni-kiel.de

Nouri Soussi
Faculté des Sciences de Tunis
Département de Géologie
Laboratoire de Géologie Marine
Campus Universitaire de Tunis
1060 Tunis, Tunisia
Tel. : +216-1-512600
Fax : +216-1-885408

Joaquin Tintore
Instituto Mediterraneo de Estudios
Avanzados, CSIC-UIB
Dept. de Recursos Naturales
E-07071 Palma, Spain
Tel. : +34-9-71173227
Fax : +34-9-71173426
e-mail:dfsjts0@ps.uib.es

Anastassios Tselepides
Institute of Marine Biology of Crete
Department of Marine Ecology
Laboratory of Biological Oceanography
P.O. Box 2214
71003 Heraklion (Crete), Greece
Tel. : +30-81-342022 / 346647
Fax : +30-81-241882
e-mail : ttse@imbc.gr

France Van Wambeke
Centre Nationale de la Recherche
Scientifique
Laboratoire de Microbiologie Marine
Campus de Luminy, Case 907
163 avenue de Luminy
13288 Marseille, France
Tel. : +33-4-91269049
Fax : +33-4-91172800
e-mail : wambeke@luminy.univ-mrs.fr

Robert Vautard
Centre National de la Recherche Scientifique
Laboratoire de Météorologie Dynamique
Université Pierre et Marie Curie
Tour 15, Boîte 99
4 place Jussieu
75252 Paris, France
Tel. : +33-1-44277353
Fax : +33-1-44276272
e-mail : vautard@ella.ens.fr

Paul Wassmann
University of Tromsø
Norwegian College of Fishery Science
Breivika, 9037 Tromsøe, Norway
Tel. : +47-77-644459
Fax : +47-77-646020
e-mail : paulw@nfh.uit.no

Richard Guy Williams
University of Liverpool
Department of Earth Sciences
Oceanography Laboratories
Bedford Street North, P.O. Box 147
L69 3BX Liverpool, United Kingdom
Tel. : +44-151-7945136
Fax : +44-151-7944099
e-mail : ric@liverpool.ac.uk

MEDITERRANEAN TARGETED PROJECT II

MASS TRANSFER AND ECOSYSTEM RESPONSE (MTP II-MATER)

The MTP-MATER Group[1]

LSGM, Laboratoire de Sédimentologie et Géochimie Marines,
Centre National de la Recherche Scientifique, Université de Perpignan,
52 avenue de Villeneuve, 66860 Perpignan, France

SUMMARY

The Mass Transfer and Ecosystem Response (MATER) project started on August 1996 and runs for 36 months. The projects aims to examine the functioning of the Mediterranean Sea in all its aspects, considering physical, chemical and biological processes at the same time and with the same priority. The objectives, structure and methodologies are outlined and some early results stemming from the First Year Scientific Report are presented and discussed.

1. INTRODUCTION

Interest in ocean sciences has considerably risen during the last decades especially with regards to multidisciplinary studies and the global change problematic.
The Mediterranean Sea offers the opportunity to study, on a reduced and therefore more manageable scale, processes typical of the world oceans. It provides an excellent laboratory for the examination of a complex interplay of natural processes that operate on a broad spectrum of spatial and temporal scales, and represents an ideal system to evaluate the impact of human activity on the marine environment. The achievement of a better knowledge and predictive understanding of the functioning of the Mediterranean Sea requires the establishment of multidisciplinary studies and effective arrangements for international cooperation. Established by the European Commission in 1993 through the Marine Science and Technology programmme (MAST), the Mediterranean Targeted Project (MTP) represents a major effort in the understanding of the Mediterranean Sea today (EU publication 17787). During the MTP pilot phase (MTP I, 1993-1996), 10 joint research projects were conducted covering the disciplines of physics, chemistry, biology and geology. This large-scale research project is now in its second phase under the acronym of Mass Transfer and Ecosystem Response (MATER, 1996-1999). This phase is characterized by improved approaches closely integrating biogeochemical and physical studies and coupling experimental work and modelling.

2. SCIENTIFIC APPROACH

2.1 OBJECTIVES

The overall objective of MTP II - MATER is to study and to quantify the triggering and controlling transfer processes of mass (water, particles, natural and anthropogenic, stable and radioactive) between various compartments (e.g., land-sea, sea-atmosphere, water-sediment, living-non living, pelagos-benthos) and in contrasting trophic environments (from eutrophic to

[1] Synthesis prepared by the scientific coordinator (A. Monaco) in collaboration with the scientific assistant (S. Peruzzi) for the First Annual Scientific Report (August 1997) and based on the inputs given by the various partners and by the Workpackage representatives (M. Canals, G. Chronis, M. Crepon, R. Mosetti, B. Price)

oligotrophic) of the Mediterranean Sea, and to investigate the ecosystem response to such transfers. This program is designed to assess the processes at various time and space scales, from the entire basin down to the local scale, and from interannual variations to daily processes. Efforts are made on defining an approach of the long term evolution and thus on the analysis of current and historical data sets and the development of general models.

2.2 STRUCTURE

To meet these objectives, the MTP II - MATER project has been structured around seven main scientific topics or Research Tasks (RT):

1) Seasonal and interannual variability of the general circulation (RT I)
2) Water mass formation processes and thermohaline circulation (RT II)
3) Subbasin scale circulation and mesoscale dynamics (RT III)
4) Processes controlling particle dynamics (RT IV)
5) Biotic and abiotic processes controlling biogeochemical fluxes (RT V)
6) Benthic response to downward fluxes and sedimentary record (RT VI)
7) Ecosystem studies (RTVII)

and five implementation areas or Work Packages (WP) describing the operating strategies and combining either multidisciplinary field studies at subbasin and mesoscale level (WP 2, 3 and 4) or modelling at various scales (WP 1 and WP 5):

1) Basin scale circulation, modelling and strait monitoring (WP 1)
2) Western Mediterranean subbasin, with a particular emphasis on the southern areas-Alboran and Algerian Basin (WP 2)
3) Adriatic/Ionian subbasin (WP 3)
4) Eastern subbasin, particularly the Aegean and Levantine Seas (WP 4)
5) Ecological models (WP 5)

These subbasins represent the main sites of implementation for the coupled studies and provide the comparative basis for contrasting environments. The research strategies include: (i) investigations at the scale of the entire Mediterranean basin for which circulation studies in the main straits (Gibraltar, Sicily, Otranto and the Cretan Arc) will be strenghtened; (ii) research on mesoscale structures which give rise to a variety of physical-biogeochemical couplings; (iii) high resolution process studies in specific areas where large scale and general processes are already investigated; (iv) seasonal surveys, particularly for biological studies; and (v) monitoring at representative sites of physical parameters and biogeochemical fluxes to provide information at montly, seasonal and interannual scales.

To strengthen the links and interdependency between the different components of the program, MTP II - MATER is organised around a matrix-like structure (Figure 1). Seven horizontal Research Tasks describe the different scientific topics. They are accordingly represented within five vertical Work Packages which describe the operational strategy, implement the research tasks into the different field and laboratory works.

2.3 METHODOLOGY

MTP II -MATER uses various methodologies and the expected outputs will be quite diversified. The interactions between experimentalists and modellers will be fostered, developping appropriate *in situ* observations to generate, check and calibrate models. Furthermore sophisticated equipments are now becoming available and a strong instrumental effort will be made to make biogeochemical observations compatible with the dynamical ones. For example, the project will produce process and sensitivity numerical modelling and provide and analyse realistic simulations of the circulation through data assimilation in numerical models. Innovative data sets such as TOPEX/POSEIDON, ERS-1 and ERS-2 altimeter data will be exploited, in parallel to the use of remote sensing and "the composite diagnostics" methodology developed for meteorological weather regimes analysis.

Observations such as current time series, hydrology, and experiments by floats and transient tracers (CFCs, tritium, helium isotopes) will be extended and continuous hydrological and nephelometric mesoscale surveys (at the different straits and experimental sites) will be performed to calculate horizontal fluxes.

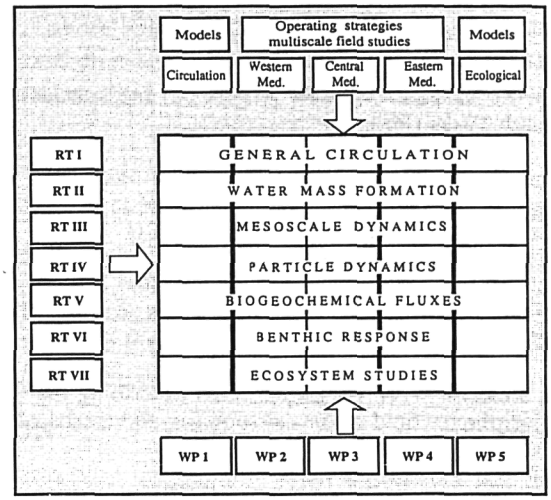


Figure 1. The MTP II-MATER matrix-like structure. Seven Research Tasks (RT) or scientific topics implemented through five Work Packages (WP) or operating strategies combining either multidisciplinary field studies (WP 2, 3 and 4) in the three Mediterranean subbasins or modelling at various scales (WP 1 and 2).

The photic zone will be investigated in terms of nutrients, dissolved and particulate organic matter, primary production (new, regenerated and export production), distribution of primary producers, taxonomic composition of phytoplankton. Biomass and metabolic activities of bacteria will be extensively studied, as will be the spatial and temporal variability of zooplankton biomass using the Continuous Plankton Recorder.
Distribution patterns and temporal variability of SPM will be described by transmissometers and in situ pumps, those of aggregates by means of an Underwater Video Profiler; the composition, source and fate of particulate matter will be determined using biogeochemical tracers such as metals, isotopes (thorium, neodymium, lead and polonium) and rare earth elements.
Downward fluxes of the major biogenic components, of the major constituents, of metals, biogeochemical and isotopic tracers will be quantified by means of moored and drifting sediment traps.
Temporal and spatial variability of the benthic standing stock will be assessed in terms of abundance, biomass, diversity and organic carbon content, megafaunal, macrofaunal, meiofaunal and microbial populations, using collections by USNEL and MULTI corers and Agassiz and Otter trawls. Pelagos-benthos coupling will be performed by studying a common set of water column and sedimentary parameters such as POC, PON, ATP, enzymatic activity, chloroplastic pigments, carbohydrates, lipids, proteins, phenols, amino acids, and radionuclides. These will be used to establish various budgets in the different environments and to quantify diagenetic processes. Finally benthic metabolism, O2 gradient within the sediment, nutrient fluxes between the sediment and overlaying water column will be used using a benthic chamber and the BOLAS lander.

2.4 DATA ARCHIVING AND MANAGEMENT

The data management structure is decentralised and related to the project field study organisation (WP). It consists of three regional data centres having in charge the regional data archiving and

distribution and of an animation group in charge of the data circulation. It is supervised by a data manager (SISMER), a Data Quality Group and the project scientific coordinator. The regional data centers are the following:

- Regional Data Center for the Western Basin-WP 2
  SISMER-Systéme d'Informations Scientifiques pour la Mer, Centre IFREMER de Brest,
- Regional Data Center for the Adriatic/Ionian-WP 3
  OGS-Osservatorio Geofisico Sperimentale,
- Regional Data Center for the Eastern Basin-WP 4
  HNODC-Hellenic National Oceanographic Data Center, National Center for Marine Research.

3. PROJECT STATUS AUGUST 1997

3.1 WATER MASS TRANSFER: DYNAMICS

Large Scale Circulation (Research Task I)
The first year was devoted to the use of already existing models, the analysis of ongoing experiments and the development of new tools. Satellite data analyses and simplified models were used to investigate the atmospheric pressure forcing and surface circulation variability of the overall Mediterranean. The Mean Sea Level response presented a significant departure from inverse barometer effect and confirmed the role of the straits (Gibraltar and Sicily) at high frequencies. As observed by TOPEX/POSEIDON combined with ERS-1, a wide range of temporal and spatial scales appeared to be due to both wind stress (seasonal) and topography (high variability). The two basins (West and East) are differentiated but mesoscale and eddies activity occur all year around in both basins. Altimetry assimilation by vertical adjustment of the water column has been implemented in a full GCM, an adapted version of GFDL MOM with a resolution of 1/4 degree and 19 vertical levels forced by varying winds and surface thermohaline relaxation. A fully functioning model with assimilation codes capable to reproduce some transient mesoscale features when a daily wind forcing is used has been completed. The implementation of the assimilation scheme into a higher resolution Mediterranean General Circulation model is underway.
Atmospheric forcing being an important ingredient of the circulation, an intercomparison between ECMWF and NCEP atmospheric model forcing over a 8 years period (1980-1988) has been undertaken. Significant differences appear the ECMWF presenting much more well defined structures but the interannual variability is well marked.
To allow a better estimation of this important atmospheric forcing, a field experiment called "FETCH" will be performed in an area of the Western Basin characterised by high occurrence of strong winds. *In situ* measurements, ship observations, moored ASIS (from Miami University) buoy to measure turbulent atmospheric fluxes and remote sensing observations using aircraft, are planned. An original point concerning the ship observations will be the estimate of the latent heat flux using a microwave system (a " refractometer ") which measures the refractive index of the atmosphere at a high frequency acquisition rate.

Transient tracers data can also be used to calibrate OGCMs and improve the understanding of deep and intermediate water formation mechanisms, as well as the variability and interactions with general and regional circulation (Figure 2). In the present model version with a resolution of 1/4*1/4, the effects of mesocale eddies have to be parametrized by implementing the Gent & McWilliams scheme (Gent & McWilliams, 1990) which allows the incorporation of isopycnal mixing in areas of steeply sloping found in overflow regions. Numerical experiments with the OGCM will be continued and a new advection scheme will be implemented to ensure valuable tracer concentrations and distributions.

It is well known that observing and understanding the dynamics of the major straits allow a better knowledge of the mechanisms controlling the basin scale circulation and its variability. During the first year special emphasis was placed on the Sicily Strait ; results of the monitoring

of this strait showed a very complex pathways of the MAW and the LIW waters and a strong seasonal variability. The directions and intensities of currents also varied at a high frequency, the frequent current reversals of the MAW layer being deeply influenced by the mesoscale activity. The topographic and hydraulic effects of the Strait on the basin scale circulation will be parametrized in OGCMs models but the first task was to model the locally generated dynamics through the implementation of a layer model with moving lateral boundaries intersecting topography and of a 3D high resolution model. The extended version developed for MATER included forcing by realistic winds and mass exchanges between water layers.
Finally, the long term monotoring of the Corsica Channel continued from 1985 and leads now to two important mentions: i) the transport decline observed for several years has stopped and has begun to increase again, ii) there seems to be a correlation between the currents in the channel and the atmospheric events affecting the whole western Mediterranean region, as observed in the North Atlantic Oscillation (NAO).

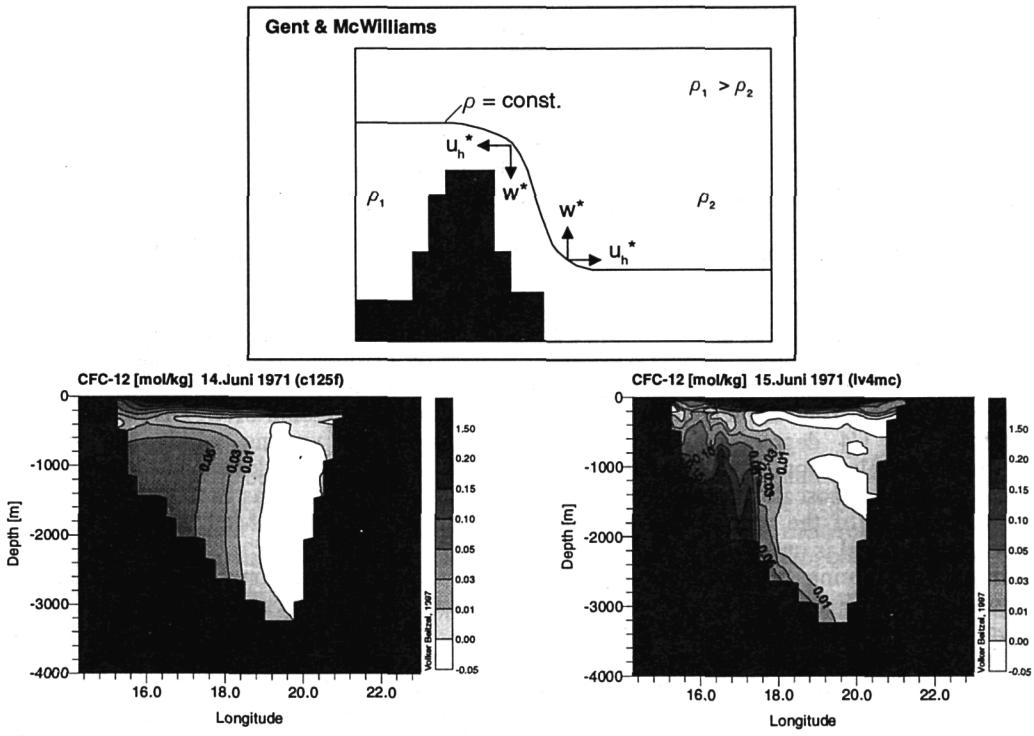


Figure 2. Improvement of Mediterranean General Circulation models. Transient tracers are used to evaluate the ability of an OGCM to simulate the formation and pathways of water masses in the Mediterranean Sea. Early versions of the model were unable to reproduce the overflow of water at the straits; the Gent and McWilliams scheme implementation allows the parametrization of the effects of mesoscale eddies into coarser resolution models. An example of performed preliminary model runs shows a modelled CFC-12 section along a West-East transect in the Ionian Sea behind the Strait of Otranto. Top figure: Gent and McWilliams scheme of the eddy-induced advection. Bottom left figure: Standard modelling of CFC-12 section. Bottom right figure: Modelling with the Gent and McWilliams scheme.

Water mass formation and thermohaline circulation (Research Task II)

This task was developed in the three workpackages with different approaches, through modelling and *in situ* measurements ; intense field work is planned during the second year of the programme.

Modelling
For example, within the frame of the WP2 in the Western Mediterranean, the temporal evolution of the vertical CFC distribution during winter 1990-1991 in the Gulf of Lions was modeled; various parametrizations for the air-sea-gas exchanges were used leading to different CFC concentrations in the deep water, the deep convection reaching 2000m depth. Concerning the vertical distribution of helium and tritium, data were provided from the cruise of RV *Poseidon* in May 1996 (stations in the Gulf of Cadiz, the Strait of Gibraltar and the Alboran Sea) and from Meteor cruise in January 1995. An interesting point which can be related to water column/sediment exchange studies, is the potential use of terrigenous bottom source helium, which is low in 3He, as a steady-state tracer of vertical mixing in the bottom layer and residence times. Therefore, it is apparent that Delta-He values below 500m are largely deviating in the western and eastern Mediterranean and discriminate, once more, the two basins in term of residence time.
In the Adriatic, numerical simultations reproduced the dense water formation process in winter, from the shelf to the southern basin in the center of the cyclonic gyre. Model results for the subsequent months show also the outflow of this dense water over the Otronto Sill. Further development of simulations will be carried out with an interannually varying surface forcing.
Furthermore, the recently observed formation of deep water in the Cretan Sea (CDW) is a well-known phenomenon. A 3-D numerical model of the Eastern Mediterranean has been developed for the study of the intermediate and deep formation mechanisms in the basin, with different atmospheric forcings (climatology *A* and *B*), i.e. the atmospheric conditions before and after 1987. Using climatology A, the model simulates intermediate water formation in both the Cretan Sea (CIW) and the Rhodes Gyre (LIW)and it will be continued with a higher resolution (10 km) for a better representation of mesoscale eddy activity and of the exchanges through the straits of the Cretan Arc. During the course of the next year the numerical studies will be focused on a better representation of the fresh water budget based upon available data and idealized scenarios.

Field work
In the Adriatic, the first interdisciplinary cruise carried out in March 1997 (MAI1/97), clearly identified the different water masses and their spatial variability. It was concluded that only the ADW observed within the layer between 600 and 700m at the Pit transect can flow out into the Ionian during the observed period. The chemistry of the water column, particularly the oxygen levels, indicated a lack of winter ventilation and that no winter deep water formation had occured. A comparison of the salt advecting into the Adriatic in the intermediate range by LIW and CIW between 1987 and 1995, shows important differences in the situation before and after the deep water production in the Aegean and a negative feedback on the Adriatic Deep Water formation which could explain the lack of deep reaching winter convection noted in March 1997. It would appear that the salt accrued from incorporation of LIW and CIW would be essential in achieving the typical ADW densities.

Although the planned winter cruise was posponed to the following winter, some CTD stations, complemented with dissolved oxygen and light transmissometry profiles and ADCP, were carried out in the Aegean Sea during the biogeochemical work in the period of March-April 97. The data revealed the presence of three water masses: the Black Sea water, the LIW between 50 and 200m and the bottom water of local origin. This indicates that the Cretan sea continues to produce large amounts of very dense water during the winter as shown by transient tracer data sets and hydrographic data from 1987 and 1995; there is no clear evidence of the causes of this change but indications exist that the cooling over the Mediterranean Sea and the reduced precipitation might be the major forcing mechanisms.

Strong field work effort will be continued in the entire Basin; in the Western Mediterranean intermediate RAFOS and ALACE floats will be deployed in 1997 during the ELISA and Poseidon cruises. During the later cruise, on board analyses of chlorofluocarbons will be carried out and water samples collected for tritium and helium. In the Adriatic Sea three cruises are planned for August and December 1997 and March 1998 performing CTD and mooring work. Finally, in the Eastern Mediterranean, two oceanographic cruises are planned in the

South Aegean and the adjacent seas (Ionian and Levantine) during late summer 1997 and winter 1998.

ERS-1/TOPEX/POSEIDON altimetric data revealed the dynamical differentiation in the main surficial structures between the two basins of the Mediterranean and the strong mesoscale activity in the Western, Ionian and Levantine basins.
The activity started with intense field studies and provided an important insight in the task dedicated to the temporal and spatial variability of dynamics; this task concerns essentially the Western Mediterranean with a particular effort on the southern part and the Algerian basin; thus it can be extended to the task I (general circulation) by means of the study of the Sardinia/Sicily strait.
The researches combined multidisciplinary and international campaigns and modelling, surveys and monitorings, satellite images (NOAA AVHRR, ERS-1, ERS-2 + TOPEX/POSEIDON), use of classical and innovative equipments such as CTD and XBT/XCTD, current meters, ADCP, surface satellite-tracked drifters, electronic counter analyser, SeaSoar, Longhurst Hardy Plankton Recorder, a prototype spectral light scattering/absortion instrument (SUMOSS) developed by SOC, as well as an HRPT satellite receiving station (SeaSpace Terascan TS-300).
The cruises were the following: Poseidon 96 in the Gulf of Cadiz, the Strait of Gibraltar and the Alboran Sea, Algers'96 on board the Spanish RV *Hesperides* in October 96 carried out in the western algerian basin, three days cruise of the British RRS *Discovery* two months later, Elisa-1 on board the french RV *Le Suroit* starting on July 97 in the eastern part of the basin and several cruises to survey the Balearic Channels.
All these works offered the opportunity to assess the instabilities in the Algerian current from a physical point of view but also to relate them with the variability in the distribution of chemical and biological parameters. For example, the maxima of chlorophyll and highest values of daily integrated primary production were found in the offshore cyclonic eddy, and more precisely correlated, in the case of chlorophyll, with the areas of strong velocity shear. The cyclonic eddies, although not persistent, may represent therefore structures of enhanced carbon flux affecting the functionning of the marginal ecosystem.
In the same way, studies on the general circulation of the water masses (MAW, WIW, LIW, TDW, WMDW) and the various kinds of mesoscale Algerian Current-induced eddies are undertaken with the consequences on the biogeochemical phenomena.
Infrared images and drifters trajectories describe the character of the Algerian Current and the mesoscale features (cyclonic and anticyclonic eddies) and their energetic variability. The data analysis completed the investigations giving access to various kinematic data which detail their temporal evolution and their various dimensions. At the level of the Sicily Strait, the trajectories of the drifters confirmed the previous theoritical and numerical modeling studies initiated during the MTP 1. A suitable representation of bathymetry shows that bottom topography enhances the coastal trapping of the Algerian Current and drives the current to flow eastward at all depths.
In another connection, regular spatial and temporal maps of residual sea levels anomalies (SLA) were used in order to provide information on two anticyclonic eddies produced by instabilities of the Algerian Current. A statistical analysis of SLA time series used to separate the variability into spatially coherent modes revealed the presence of two points of high variability which could correspond to detachment areas of eddies from the main current flowing along the African coast.
The pluridisciplinary surveys and monitoring of the Balearic Channels as well as a numerical study using Modular Ocean Model (MOM) evidenced the important role played by the accumulation of WIW, sampled for the first time within and to the north of the channels, on the general circulation of the Western Mediterranean, particularly on the MAW and LIW flows.

3.2 BIO-GEO-CHEMICAL TRANSFERS AND ECOSYSTEM RESPONSE

Pelagic/benthic coupling (Research Task IV, V, VI)

The researches related to investigation on biogeochemical cycles and fluxes giving access to the generic pelagos/benthos coupling were essentially based on experimental works carried out during winter-spring periods in the three main sub-basins (western, Adriatic/Ionian, Aegean/Levantine) using approximately the same field strategies and techniques inherited from the MTP- I pilot phase.

Figure 3 shows the overall station grid occupied during the cruises performed in the different sub-basins within the frame of the workpackages 2, 3 and 4, as well as the stations of surficial waters covered during the first transmediterranean cruise MINOS (Mediterranean Investigation of Oligotrophic Systems) which took place during May-June 96. The latter covered 20 stations splitted from the Western basin to the Levantine basin and was essentially devoted to give some lights on the fundamental characteristics of the oligotrophic regime and to investigate new and exportable production as well as nitrogen and carbon cycles. In this way, a synoptic view on some bio-geo-chemical characteristics at basin scale was offered.

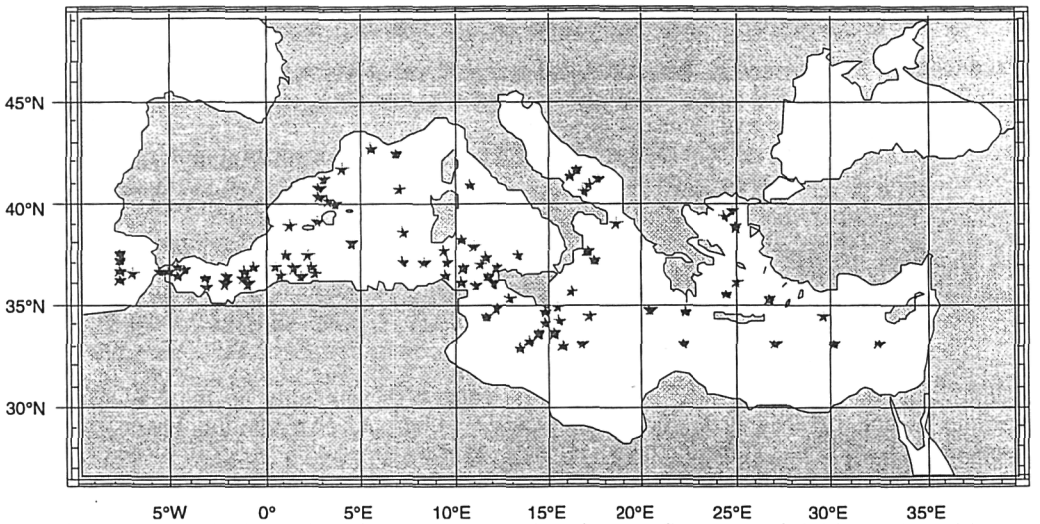


Figure 3. Hydrological stations investigated during the first year of field activity with a multidisciplinary approach

According to expectations, transmittance and *in situ* fluorescence corresponding to SPM and chlorophyll-a concentrations respectively, demonstrated the presence of a coastal-open sea gradient and, with respect to the trophic level, of a more "turbid" euphotic zone in all sites. Pronounced SPM concentrations in the northern part of the three subbasins, North Balearic, Adriatic and the Aegean Sea, as shown by satellite images and models were also highlighted. As confirmed by elemental composition of particulate matter, this phenomenon is due essentially to nearby river discharges, enhanced biological production and resuspension processes in the shelf/slope bottom layer, topographic effects (canyons) and spreading of intermediate nepheloid layers; in the particular case of the N Aegean, an input of Black sea waters is also invokated.
This shelf/slope advective transport plays an important role in the behaviour of chemicals, both metals and organic elements, in the marine environment including the particulate/dissolved interactions. There are several lines of evidence showing that chemical scavenging is concentrated at the boundaries of the ocean, as a result of the generally high particle concentrations. Particular attention was dedicated to the numerical study of such shelf/slope exchanges and to the understanding of modifications induced in coastal circulation by a canyon which indents the margin. In this configuration, the wind forcing induced important vertical and cross-shelf motions suggesting that ageostrophic circulation may be at the origin of the observed plankton and pollutants transport between the coastal zone and the open ocean.

The particularly strong effort made in field work during this first year allowed to obtain, for the first time, a synoptic view of the primary production in the overall Mediterranean based on *in situ* measurements performed at two different periods. 1) The three subbasins were investigated during springtime and produced some unexpected results: for the Northwestern basin, new and total production averaged 115 and 390 mgC m^{-2} d^{-1} respectively, in the central part of the Adriatic daily PP reached an overall rate of 340 mgC m^{-2} d^{-1}. Surprinsingly, the

Aegean recorded high productivity reaching mean values of 1784 and 554 mg m^{-2} d^{-1} in the northern and southern parts repectively.
2) The MINOS transmediterranean cruise took place during the stratification period and confirmed, on the other side, the west-east trophic gradient and the low productivity of the southern and central Mediterranean basin: >350 mgC m^{-2} d^{-1} in the western part and <250 mgC m^{-2} d^{-1} in the Levantine basin for the production rates and 200-800 mgat.m^{-2} and less than 80 mgat.m^{-2} for the levels of available nitrogen. Local enrichments occured during this period, such as in the Algerian current as shown by altimetric data.
Once more, the variability appears as a major characteristic, going so far as to recognize, at certain periods, the most productive zone in the Aegean Sea.

In the western Mediterranean, the spatial and temporal variability was approached through an High Frequency Flux Experiment (HFFE) conducted in the Gulf of Lions, coupling column water sampling, mooring of equipped lines and on a lesser extend sediment sampling ; it prepared the Experiment in the Alboran Sea and a preliminary investigation and mooring in the Alboran. Long term measurements of water flows and downward fluxes at selected sites in the North-Balearic basin continued the work undertaken during the MTP I (EUROMARGE NB).

The microbial approach which has been performed in the western and eastern basins comparatively shows the same trends : the bacterial integrated production (0-100m) of 81 to 131 mgC m-2 d-1 in the N.Western Mediterranean and the N. Aegean showing values from 56 to 164 mgC m-2 d-1 ; the values of this production as well as of biomass were found to be lower in the S. Aegean (63 to 81 mgC m-2 d-1). At a smaller scale and probably depending on the hydrological conditions, bacterial parameters presented high variability: in the NW Med., for example, a site off Marseille, under the Rhone influence, presents the lower range of oligotrophic conditions ; at the contrary, in the N. Aegean, the station under influence of Black Sea Waters reached the highest value of 164 mgC m-2 d-1.
Composition and biomass of zooplankton, as well as phytoplankton communities allowed to discriminate productive zones depending on the trophic regime.

As far as the carbon export is concerned, the use of drifting sediment traps in the Southern/Central Mediterranean Basin during the MINOS cruise, in the Southern Adriatic and in the Gulf of Lions (HFFE), demonstrated that a very low fraction of the biological fixed carbon left the euphotic zone. Preliminary results show very low fluxes, enhanced carbon cycling in the upper waters and high daily loss rates of phaeopigments and chlorophyll-a.

To anticipate the further developments in this task, a methodological remark can be done : recent works have demonstrated that the Th^{234} particulate flux exported from the euphotic zone may be a tracer of the flux of particulate organic carbon (using the ratio of POC to particulate Th^{234}); this approach has been developed during the HFFE experiment to be compared with those using standard techniques (C^{14} and N^{15}). Same investigation carried out in the Adriatic indicates that caution should be used, due to the affinity of Th^{234} with some inorganic particles, particularly with Fe most likely in the form of Fe hydroxide coatings. Further discussion are therefore needed around this specific point.

The so-called "benthic response" included: relationship between benthic biomass and particle fluxes, composition of the sedimented particulate matter, bacterial activity and related POM degradation processes, metabolism. In terms of meiobenthic response, it is possible to compare the first results obtained in the two opposite zones, Western and Eastern Mediterranean: surprinsingly, the recent evaluation of meiofaunal densities in the N. Western Mediterranean, rather low when compared to previous observations in the area, are lower (99 to 259 ind/10 cm^2) than those made in the Aegean Sea; additionally, North and South Aegean can be clearly distinguished : 980 ind/10 cm^2 and 294 ind/10 cm^2 respectively.
Bacterial densities in the near bottom waters and in the sediment as well as the hydrolytic activity will be compared, the first results leading to complex interpretations. Nevertheless, it already appears a large spatial and temporal heterogenity in all biochemical parameters measured in the sediment-water interface, even if, in the case of the Aegean Sea the northern and southern portion remained distinguishable. However, in this last example, sedimentary organic

compounds and benthic populations support the affirmation that "hot spots" or sites focussing "organic matter" exist in isolated deep basins of oligotrophic systems, reflecting differences in energy supply, in hydrological and topographical conditions, but also in mechanisms of particle transfers. Preliminary results obtained during HFFE confirmed the existence, due to these combined factors, of a focussed " organic zone " at mid-slope.
Further and complementary *in situ* experiments (benthic lander) in the various environments should bring original insights into the pelagos-benthos coupling mechanisms. Taking also into account the works undertaken and planned in this task in the Adriatic Sea, it appears the need of obtaining representative samples of bottom sediment and to know the basic physical, physico-chemical and mineralogical parameters allowing a reliable reconstruction of feeding mechanisms.

A network of moored stations for an overall flux experiment
A coordination between the different workpackages led to an experimental work on biogeochemical fluxes in the overall Mediterranean basin (Figure 4); the moored sites in the three subbasins became operative almost at the same time, between the end of February and early March 1997, and included: the HFFE experiment in the northwestern basin comprising 9 mooring lines equipped with sediment traps (20) and current meters (18) deployed into a 20x12 nm box for a two months period; from the end of June the equipment monitores, for a first period of six months, the Alboran basin. In the Central basin, the deployment of time series sediment traps and current meters took place, from 4 to 17 March, in the South Adriatic, Otranto Strait and Ionian Sea, each array comprising 2 sediment traps ; in the Aegean Sea, a deployment comprising two moorings in the South and three in the North, each array including two sediment traps and three current meters for six months occured in March and will last for six months. Some of these moored lines correspond to sites already occupied during the previous MTP I, ensuring therefore the long term interannual monitoring of particle fluxes in key zones of the Mediterranean. The valuable amount of data should allow to validate models on pelagic/benthic coupling and benthic ecosystem in response to energetic fluxes. Additionally, they should bring new insights on the relationships with the oligotrophic gradient and surface productivity as well as the physical forcing and climatological variability.

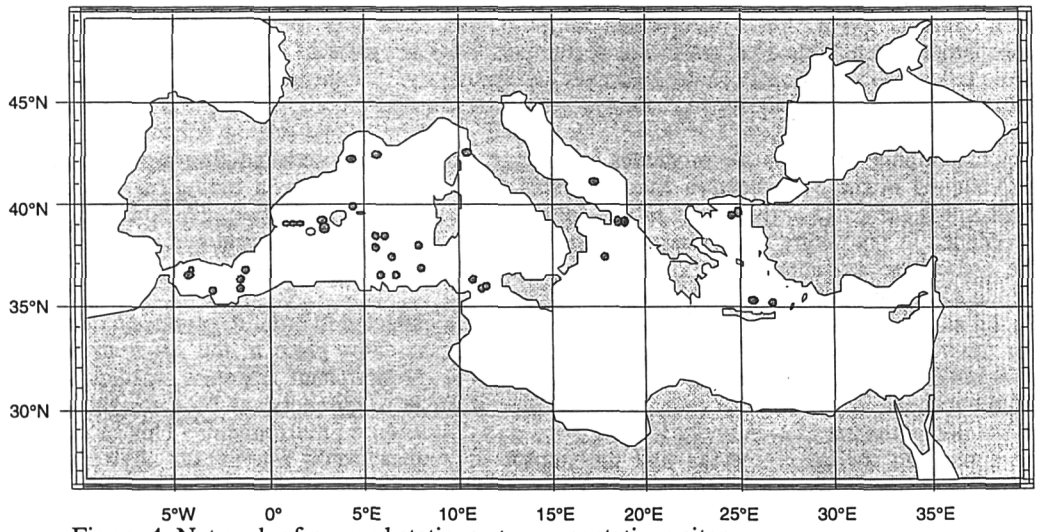


Figure 4. Network of moored stations at representatives sites

The analysis of sediment and use of molecular biomarkers will contribute to the understanding of such relationships in the Mediterranean and in relation to present and past events: concentrations of indicators of marine productivity (alkenones and Phytol) show, for example, the persistent upwelling south of Malaga and its intensity directly related to the variable water exchanges across the near Gibraltar Strait. Evolution of productivity and warming from the

glacial to interglacial periods as calculated from the marine proxies stored in the sediments is related to the changes of the Atlantic inflow transporting nutrient-rich waters. To conclude, data should be used to validate models of long term general evolution.

Ecosystem studies (Research Task VII)

The studies refering to this research task may be differentiated according to the scale of the researches and the level of the ecosystem studied. Three of them took up large time and space-scales; among these, one in particular refers to a three-dimensional coupled basin wide ecological model developed during MERMAIDS II/MAST II, at low trophic level and allowing an understanding of the seasonal cycles and of the nitrogen and phosphorous exchanges in the main basins. Total nitrogen and phosphorous fluxes through the Gibraltar and Sicily straits are obtained with evidence of wind stress input; two improvments are in progress which will take into account the Adriatic Sea and Aegean Sea inputs/outputs of inorganic matter as well as the Po and the Bosphorous inflows in order to balance part of the loss of nutrients through Gibraltar.

The work devoted to long-term biogeochemical modelling using natural and artificial radionuclides and will couple a 3D advective-diffusive model with a 1D biogeochemical model. During the first year, modelling and radiotracers bibliographic database works were undertaken. It must be remarked the fact that little information has been published or made available from the Eastern Mediterranean despite the importance of the Chernobyl event as well as on non conservative radionuclides such as Pb^{210} and plutonium. The model will reproduce the sedimentation of partially dissolved radionuclides contributing to predict the behaviour of artificially introduced elements.

Syntheses and statistical analyses carried out within the frame of " General evolution of the Mediterranean ecosystem " confirmed the relationship existing between hydrological and biogeochemical (nutrients, halocarbon, trace metals) changes with environmental global change and human impact. Looking ahead, an interesting point could be the monitoring of trace metal concentrations in intermediate waters coming from the eastern basin where a regulation of atmospheric inputs is not present yet. The activity focused on the processing of the Meteor data (1995) showed, like in the case of other investigations, the role of the hydrodynamical forcing on the phytoplankton structure ; accordingly, high integrated chlorophyll contents are associated with cyclonic gyres. On a basin-scale nutrient level, data sets from 1987 and 1995 were compared, and notable changes in the northern and eastern parts of the Ionian were found; in these areas, the nutricline became shallower and could provide enhanced nutrient concentrations into the euphotic layer supporting increasing biological activity.

The importance of mesoscale processes for primary production is underlined in a process study approached in the northwestern Mediterranean (Ligurian sea) using a biological model and concerning the onset of the spring bloom following deep winter convection. The simulation has succeeded in predicting the highest productivity and chlorophyll concentrations at the edge of the convective chimney. Sensivity studies bring important conclusions, particularly on the strong effect of winds on phytoplankton development.

As far as the pelagic ecosystem is concerned, data were collected in order to produce a data base for the validation of a simple model of food web at the same place in the Ligurian Sea ; a structured population model of *Centropages typicus*, a dominant copepod species in the Mediterranean, has been elaborated and simulates, in terms of numbers and biomass, the annual dynamics of the population under forcing food and temperature environments. This model will be applied to the main species and the impact of zooplanktonic activity on phytoplankton standing stock will be estimated.

One very relevant point was the strong collaboration between three groups involved in ecosystem modelling and which led to coordinated activities in model development and implementation results as well as transfer of expertise in the field of regional models. The first draft presented is a simplified multi-nutrient ecosystem model designed to describe the phytoplankton growth and nutrient cycling, with a very simple physical forcing. The model simulates the seasonal cycle of chlorophyll and reproduces the expected vertical distribution of phytoplankton biomass; the nutricline appeares permanent through the year as observed in parts of the southern Adriatic Sea. The next stage will be to couple this model to a more realistic

physical environment and to parameterise against existing data. Finally, it will be coupled to the existing MOM general circulation model.

The benthic/pelagic coupling plays an important role on ecosystem functioning and the coupled ERSEM (European Regional Seas Ecosystem Model)/ POM (Princeton Ocean Model) has been applied to sites in the Adriatic and Cretan Seas in which biogeochemical parameters measured during the MTP I (Euromarge AS and CINCS projects) were available. In the Adriatic the model simulated a seasonal cycle of chlorophyll and phosphate and reproduced the observed diatom spring bloom. The modelled benthic fluxes of phosphate ad ammonia show a clear seasonality and flux rates are of the same order of magnitude as the real observations. The same model set up in the CINCS site showed the seasonal cycles of benthic meiofauna and aerobic bacteria but underestimated the meiofauna biomass. At present time, one could argue that the models were set-up for coastal environments and need to be validated for increasing water depths and changing physical properties.
The POM/ERSEM code optimised for the CRAY C-90 has been used to define the sensitivity of the model to atmospheric forcing and river inputs in the Adriatic Sea. Biogeochemical state variables have been defined as profiles approximately consistent with the winter profiles derived from the Adriatic data set. Elevated chlorophyll-a concentrations appear along the coastal areas and particularly in the northern part affected by the river inputs in agreement with the CZCS satellite pictures. After the installation the ERSEM and SESAME on SUN workstations and application to a shallow lagoon in Greece, the model was applied in a 100 m site using physiochemical and biological data from CINCS project, and forced by monthly wind stresses. The model results are given for nutrients, chlorophyll and primary production.

4. DISCUSSION

4.1 STRATEGIES AND TECHNIQUES

Besides classical techniques, high technological equipment has been used during the course of the study. This included the following:

- Completely new tripod built by the NIOZ after the loss of the Benthic Lander BOLAS; new Lander was tested successfully in the Procupine Abyssal Plain at 4800 m depth. This equipment complement the Benthic Banyuls Lander used in the Western part and the pool of instruments for *in situ* measurements of benthic activity and sediment diagenesis which should improve the model validation.

- A series of innovative equipment from the SOC for *in situ* real time measurements, such as the SeaSoar undulating towed CTD profiler with Optical Plankton Counter, a prototype spectral light scattering/absortion instrument SUMOSS, Longhurst Hardy Plankton Recorder as well Video Profiler from LECM for zooplankton and aggregate determinations.

- A prototype of *in situ* large volume filtration pump (PERFILS by Technicap) allowing split on different type of adequate filters for diversified analyses of particulate matter and analysis of soluble elements.

- Almost real time acquisition and use of various type of satellite images to monitor the study area and design the best sampling strategy during the course of the cruises.

- Improvement of analytical and numerical models with implementation and development of new modules as well as the construction of new tools which will be worked during the next two years. It is also worth mentioning the altimetry assimilation in a full Mediterranean GCM and the validity of combined ERS-1+TOPEX/POSEIDON data sets to describe the surface circulation variability. Last but not least, the work on the implementation of a layer-

model including a numerical technique particularly usefull in areas with coplex topography like the straits.

4.2 ORGANISATION

Several examples of exchanges, collaborations, interdisciplinary effort, dissemination of information can be given:

- Large part of the field work was carried out in an mulidisplinary way in each experimental workpackage even if the cruise maintained more often a dominant disciplinary approach;

- It is a matter of fact that task carried out by the same team in different areas lead to easier and more elaborated interpretations, due to the uniformity in the methodological and technological approach used. With respect to this point, the particular examples of the microbiology or the CFC experiments could be cited;

- MTP 1 offered the opportunity to compare and discuss methodologies and results in the frame of a given research (due to the presence of separate projects) ; this made easier the rapid start of the works and the connection between the teams using the same strategies;

- In some case the cooperation betweem teams gave rise to exchange of equipment and particulary of research vessels ; another point had been the constitution of a common pool of equipment to perform, at one and the same time, long term and high frequency observations.

5. CONCLUSIONS AND OUTLOOK

Analysis of the great deal of new results stemming from the different works and pluridisciplinary and multiscale approach gave new insights in the general understanding of sensitive and changing systems. Among the strong points, the following could be cited:

The variability
This is a major input of the project and all kinds of results met expectations allowing the assessment of a wide range of spatial and temporal variability. Decadal, interannual, seasonal and high frequency signals are detected using the various techniques.
Spatially and at basin scale, physical, chemical and biological parameters clearly differentiated the western and eastern basins, either at the level of surficial waters or in deep waters, the latter in term of residence time and probably affecting the transformation processes and water/sediment exchanges. Different factors introduce the variability at a smaller scale too.

The factors influencing the oceanic processes
It seems that, independently of any coordination among the different disciplines, three factors are often invokated and used to explain the long and short-term variability and the mesoscale activity: wind stress, topography and rainfall/river discharge.

Winds : tipically represented at various scales in the different models, the next year an experimental and high technology work will be undertaken this coming year: a moored buoy will measure turbulent atmospheric fluxes but also the latent heat flux giving access to information on the high frequency spatial variation of the atmosphere;
Topography : is now represented in models with special use for marginal and channelized systems too; it plays an important role in the investigation of the shelf/basin transfers and ageostrophic processes;

Runoff/river discharge : are more and more suspected to influence bio-geo-chemical processes, the functioning of the ecosystem, the long term changes in the overall basin as well as the budgets; through this forcing, the land use and the man induced changes are approached.

All these parameters are represented in the models, making them more realistic; for example, the three-dimensional ecological model representing the time and space evolution of the nitrogen cycle in the Mediterranean analyses the atmospheric forcing on primary production on an interannual and decadal scale. High resolution numerical simulations with ERSEM/POM coupled system are also tested to define the sensitivity to atmospheric forcing and to river inputs and to reproduce primary production processes.

Concerning the importance of mesoscale activity, this point is very often underlined independently from the approach being used and the effects of these process are paramaterized in high resolution model versions. In some cases, spatial and temporal scales of the mesoscale activities are given. In addition, it became clear by *in situ* approaches and simulations that the dynamical features are associated with biogeochemical processes particularly in areas of enhanced productivity (see cyclonic eddies) and in areas of strong velocity shear. Even if the synoptic view of the biological parameters, especially the primary production, confirms the general oligotrophy and west-east trophic gradient, large spatial heterogenity still remains; In this view, the first set of data shows the maximum values of PP in the North Aegean and relatively high values in the South Aegean. Remember that strong mesoscale activity with high temporal variability appears in the Levantine Basin, a zone still not widely investigated. The preliminary results obtained reinforce the concept that these zones represent suitable systems for the development of multidisciplinary studies, possibly at high frequency, and the importance of mesoscale activity.

The factors influencing the general evolution of the ecosystem

- The Cretan Sea continues to produce large amounts of dense water and either experimental works or numerical studies will have to explain this significant change by using available data and by a particularly better representation of fresh water budgets;

- The hydrological and chemical (nutrients and metals) changes are confirmed and a clear demonstration can be brough that they are indeed linked, firstly and expectedly to greenhouse effects and, secondly to anthropogenic effects like the decrease of river runoffs due to increased freshwater extraction ; the analysis halocarbon allows to complete our knowledge on theses changes;

- Notable changes of nutrient distributions have been found from 1987 to 1995; in the northern and eastern parts of the Ionian the much more shallower nutricline could induce enhanced biological activity;
- Use of radiotracers along with the creation of a bibliographic database for the overall Mediterranean basin will be used to produce biogeochemical models leading to a better understanding of the processes influencing long-term changes.

ACKNOWLEDGEMENTS

This contribution has to be considered as a partial synthesis of the inputs given by the project's partners to the MTP II-MATER First Annual Scientific Report (August 1997). Those works which are not included have the same scientific merit and are equally interesting. We acknowledge all the contributors. We acknowledge the support of the European Commission's Marine Science and Technology Programme (MAST III) under contract MAS3-CT96-0051.

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I.3.2. The Baltic Sea

TITLE: Baltic Sea System Study (project BASYS)

CONTRACTS NO.: MAS3-CT96-0058 and IC20-CT96-0080

COORDINATOR:

Prof. Bodo von Bodungen
Baltic Sea Research Institute (IOW)
D-18119 Rostock-Warnemünde, DE
Telephone: ++49-381-5197-100
Facsimile: ++49-381-5197-105
Email: bodo.bodungen@io-warnemuende.de

PARTNERS:

Bodo von Bodungen Baltic Sea Research Institute Warnemuende Department of Marine Biology Seestrasse 15 D-18119 Rostock DE Tel.:+49 381 5197 100 Fax:+49 381 5197 440 Email:bodo.bodungen@io-warnemuende.de	Agneta Andersson-Nordstroem University Umea Department of Microbiology S-901 87 Umea SE Tel.:+46 90 167991 Fax:+46 90 167995 Email:Agneta.Nordstrom@umf.umu.se
Fredrik Wulff University Stockholm Department of System Ecology Universitetsvaegen 10 S-106 91 Stockholm SE Tel.:+46 8 16 42 50 Mobile: +46 70 731 00 26 Fax:+46 8 15 84 17 Email:fred@system.ecology.su.se	Ralf-Otto Niedermeyer Ernst-Moritz-Arndt University Greifswald Institute of Geosciences Friedrich-Ludwig-Jahn-Strasse 17a D-17489 Greifswald DE Tel.:+49 3834 864557 Fax:+49 3834 864572 Email:leek@rz.uni-greifswald.de
Wolfgang Krauss Institute for Marine Research Kiel Abt. Theoretische Ozeanographie Duesternbrooker Weg 20 D-24105 Kiel DE Tel.:+49 431 597 3800 Fax:+49 431 565 876 Email:wkrauss@ifm.uni-kiel.de	Ulrich Schiewer University Rostock Department of Biology/Ecology Freiligrathstrasse 7/8 D-18051 Rostock DE Tel.:+49 381 498 2010 Fax:+49 381 498 2011 Email:hendrik.schubert@biologie.uni-rostock.de

Bodo von Bodungen Baltic Sea Research Institute Warnemuende Department of Marine Biology Seestrasse 15 D-18119 Rostock DE Tel.:+49 381 5197 100 Fax:+49 381 5197 440 Email:bodo.bodungen@io-warnemuende.de	Agneta Andersson-Nordstroem University Umea Department of Microbiology S-901 87 Umea SE Tel.:+46 90 167991 Fax:+46 90 167995 Email:Agneta.Nordstrom@umf.umu.se
Anders Omstedt Swedish Meteorological and Hydrological Institute Research and Development Department S-601 76 Norrkoeping SE Tel.:+46 111 58284 Fax:+46 111 70207 Email:aomstedt@smhi.se	Ake Iverfeldt Swedish Environment Research Institute Ltd POB 21060 S-100 31 Stockholm SE Tel.:+46 8 7291500 Fax:+46 8 318516 Email:ake.iverfeldt@ivl.se
Matti Perttilae Finish Institute for Marine Research Helsinki Department of Chemistry Lyypekinkuja 3 A FIN-00930 Helsinki FI Tel.:+358 9 61394510 Fax:+358 9 61394494 Email:matti.perttila@fimr.fi	Gerrit de Leeuw Netherlands Organization for Applied Scientific Res. TNO Physics and Electronics Lab. Oude Waalsdorperweg 63, POB 96864 NL-2509 JG The Hague NL Tel.:+31 70 374 0462 Fax:+31 70 3280961 Email:deleeuw@fel.tno.nl
Peter Stoffers Christian-Albrechts-University Kiel Geological-Paleontological Institute Olshausenstr. 40 D-24118 Kiel DE Tel.:+49 431 8804376 Fax:+49 431 8807303 Email:pstoffers@email.uni-kiel.de	Ann-Sofi Smedman Uppsala University Dept. of Meteorology Kyrkogardsgatan 6, POB 516 S-751 20 Uppsala SE Tel.:+46 18 542792 Fax:+46 18 544706 Email:annsofi@big.met.uu.se
Michael Schulz University Hamburg Institut fuer Anorganische und Angewandte Chemie Martin-Luther-King-Platz 6 D-20146 Hamburg DE Tel.:+49 40 41234095 Fax:+49 40 41232893 Email:michael.schulz@dkrz.de	Piet Ruardij Netherlands Instituut voor Onderzoek der Zee Dept. of Biological Oceanography POB 59 NL-1790 AB Den Burg (Texel) NL Tel.:+31 222 369300 Fax:+31 222 319674 Email:rua@nioz.nl
Boris Winterhalter Geological Survey of Finland Espoo Department of Surficial Geology P.O.Box 96 FIN-02150 Espoo FI Tel.:+358-20550-2222 Fax:+358-2055012 Email:boris.winterhalter@gsf.fi	Lars Rahm University Linkoebing Department of Water and Environmental Studies S-581 83 Linkoeping SE Tel.:+46 13 282554 Fax:+46 13 133630 Email:larra@tema.liu.se
Michael Olesen University Copenhagen Faculty of Science, Marine Biological Laboratory Strandpromenaden 5 DK-3000 Helsingoer DK Tel.:+45 4 2211633 319 Fax:+45 4 9261165 Email:mblclmio@inet.uni-c.dk	Marke Hongisto Finish Meteorological Institute Helsinki Vuorikatu 19, P.O.Box 503 FIN-00100 Helsinki FI Tel.:+358-9-1929 3150 Fax:+358-9-1929 3146 Email:marke.hongisto@fmi.fi

Bodo von Bodungen Baltic Sea Research Institute Warnemuende Department of Marine Biology Seestrasse 15 D-18119 Rostock DE Tel.:+49 381 5197 100 Fax:+49 381 5197 440 Email:bodo.bodungen@io-warnemuende.de	Agneta Andersson-Nordstroem University Umea Department of Microbiology S-901 87 Umea SE Tel.:+46 90 167991 Fax:+46 90 167995 Email:Agneta.Nordstrom@umf.umu.se
Timo Tamminen Finish Environmental Agency Helsinki Impacts Research Division POB 140 / FIN-00251 Helsinki Kesaekatu 6, FIN-00260 Helsink FI Tel.:+358 9 40300321 Fax:+358 9 40300390 Email:timo.tamminen@vyh.fi	Juergen Suendermann University Hamburg Institut fuer Meereskunde Troplowitzstrasse 7 D-22529 Hamburg DE Tel.: Fax:+49 40 4123 2606 Email:
Gerd Becker Federal Maritime and Hydrographic Agency Hamburg Bundesamt fuer Seeschiffahrt und Hydrographie Bernhard-Nocht-Strasse 78 D-20359 Hamburg DE Tel.:+49 40 3190320 Fax:+49 40 31905000 Email:gerd.becker@m2.hamburg.bsh.d400.de	Jueri Elken Estonian Marine Institute Tallin Sector of Marine Physics and Commercial Resources Paldiski Road 1 EE-0001 Tallinn EE Tel.:+372 2 453598 Fax:+372 6 311069 Email:elken@phys.sea.ee
Gerald Geernaert National Environmental Research Institute Roskilde Dept. of Atmospheric Environment Frederiksborgvej 399 DK-4000 Roskilde DK Tel.:+45 46 301101 Fax:+45 46 301214 Email:glg@dmu.dk	Roman Marks Institute of Oceanology Sopot Polish Academy of Sciences Powstancow Warszawy 55 PL-81 712 Sopot PL Tel.:+48 48 517281 312 Fax:+48 48 512130 Email:marks@iopan.gda.pl
Wolfram Brenner GEOMAR Forschungszentrum für Marine Geowiss. Universitaet Kiel Wischhofstrasse 1-3 D-24148 Kiel DE Tel.:+49 431 600 2259 Fax:+49 431 600 2925 Email:wbrenner@geomar.de	Tarmo Kouts Estonian National Maritime Board Lighthouse and Hydrography Department Lasnamae street 48 EE-0014 Tallinn EE Tel.:+372 6 339 115 Fax:+372 6 339 166 Email:kouts@marine.emhi.ee
Erik Thomsen Geological Survey of Denmark and Greenland Department of Geochemistry Thoravej 8 DK-2400 Copenhagen DK Tel.:+45 31 106600 Fax:+45 31 196868 Email:et@geus.dk	Aivars Yurkovskis University of Latvia Salaspils Institute of Aquatic Ecology 6 Daugavgrivas Street LV-1007 Riga LV Tel.:+371 7614840 Fax:+371 9 345 412 Email:aivars@monit.lu.lv
Matti Leppaeranta University Helsinki Department of Geophysics POB 4 (Fabianink. 24 A) FIN-00014 Helsinki FI Tel.:+358 9 191 22028 Fax:+358 9 191 22385 Email:matti.lepparanta@helsinki.fi	Georgs Kornilovs Latvian Fisheries Research Institute Pelagic Fish Sector 6 Daugavgrivas St. LV-1007 Riga LV Tel.:+371 7613775 Fax:+371 7616946 Email:latfri@mailbox.riga.lv

Bodo von Bodungen Baltic Sea Research Institute Warnemuende Department of Marine Biology Seestrasse 15 D-18119 Rostock DE Tel.:+49 381 5197 100 Fax:+49 381 5197 440 Email:bodo.bodungen@io-warnemuende.de	Agneta Andersson-Nordstroem University Umea Department of Microbiology S-901 87 Umea SE Tel.:+46 90 167991 Fax:+46 90 167995 Email:Agneta.Nordstrom@umf.umu.se
Hans Hanson University Lund Department of Water Resources Engineering POB 118 S-221 00 Lund SE Tel.:+46 46 222 4435 Fax:+46 46 222 8987 Email:hans.hanson@tvrl.lth.se	Oleg Savchuk State Oceanographic Institute St. Petersburg Branch, Lab. of the Baltic Sea Problems 23d Line, 2 A RU-199026 St. Petersburg RUS Tel.:+78 12 2188123 Fax:+7 812 2188123 Email:oleg@ocean.spb.su
Ilppo Vuorinen University of Turku Archipelago Research Institute FIN-20014 Turku FI Tel.:+358 2 3335974 Fax:+358 2 333 6592 Email:ilppovuo@utu.fi	Stanislaw Musielak University of Szczecin Institute of Marine Sciences Felczaka Str. 3 A PL-71 412 Szczecin PL Tel.:+48 91226411 ex 217 Fax:+48 91 553120 Email:muss@sus.univ.szczecin.pl
Gerhard Petersen GKSS-Forschunszentrum Geesthacht Institue of Hydrophysics, Model System Unit (GMS) Max-Planck-Strasse D-21502 Geesthacht DE Tel.:+49 4152 87 1847 Fax:+49 4152 87 1888 Email:petersen@gkss.de	Jueri Kask Geological Survey of Estonia Department of Marine Geology and Geophysics 80/82 Kadaka Str. EE-0026 Tallinn EE Tel.:+372 2 538377 Fax:+372 6 579664 Email:peetermann@egk.ee
Helmar Kunzendorf Risoe National Laboratory Environmental Science & Technology Department POB 49 DK-4000 Roskilde DK Tel.:+45 4 6774276 Fax:+45 4 2370264 Email:kunzendorf@risoe.dk	Dalia Sopauskiene Institute of Physics Vilnius Aerosol Research Laboratory A. Gostauto 12 LT-2600 Vilnius LI Tel.:+370 2 641227 Fax:+370 2 617070 Email:arvisj@ktl.mii.lt
Jacob Steen Moeller Danish Hydraulic Institute Hoersholm Ecological Modelling Centre Agern Allee 5 DK-2970 Hoersholm DK Tel.:+45 4 5 7695557 Fax:+45 4 5762567 Email:jsm@dhi.dk	Algimantas Grigelis Lithuanian Institute of Geology Vilnius Department of Baltic Marine Geology Sevcenkos 13 LT-2600 Vilnius LI Tel.:+370 2 236504 Fax:+370 2 236408 Email:grigelis@geology.aiva.lt
Geir Evensen Nansen Environmental and Remote Sensing Center Edv. Griegsvei 3 a N-5037 Solheimsviken-Bergen NO Tel.:+47 55 297288 Fax:+47 55 200050 Email:geir.evensen@nrsc.no	Sergey Babichenko Institute of Ecology Tallin Laser Remote Sensing Group Kadaka Ave. 165 E-0001 Tallinn EE Tel.:+372 2 524385 Fax:+372 2 524385 Email:sergeyb@lidar.edu.ee

Bodo von Bodungen Baltic Sea Research Institute Warnemuende Department of Marine Biology Seestrasse 15 D-18119 Rostock DE Tel.:+49 381 5197 100 Fax:+49 381 5197 440 Email:bodo.bodungen@io-warnemuende.de	Agneta Andersson-Nordstroem University Umea Department of Microbiology S-901 87 Umea SE Tel.:+46 90 167991 Fax:+46 90 167995 Email:Agneta.Nordstrom@umf.umu.se
Anders Stigebrandt University Gothenburg Department of Oceanography, Earth Sciences Centre S-41381 Goeteborg SE Tel.:+46 31 773 2851 Fax:+46 31 773 2888 Email:anst@oce.gu.se	Arturas Razinkovas Klaipeda University Centre for System Analysis Manto 84 LT-5808 Klaipeda LI Tel.:+370 6 212936 Fax:+370 6 212940 Email:artr@samc.ku.lt
Adolf Stips Space Applications Institute Ispra Marine Environment Unit I-21020 Ispra (VA) IT Tel.:+39 332 789876 Fax:+39 332 789034 Email:adolf.stips@jrc.it	Ryszard Zeidler Polish Academy of Sciences Warszawa Institute of Hydro-Engineering 7 Koscierska PL-80 953 Gdansk PL Tel.:+48 58 522011 Fax:+48 58 524211 Email:zeidler@ibwpan.gda.pl
Graham Shimmield Scottish Association for Marine Science Dunstaffnage Marine Laboratory, PO Box 3 Argyll, PA34 4AD OBANUK Tel.:+44 1631 562244 Fax:+44 1631 565518 Email:g.shimmield@ed.ac.uk	Toomas Saat University Tartu Institute of Zoology and Hydrobiology 46 Vanemuise Street EE-2400 Tartu EE Tel.:+372 7 420214 Fax:+372 7 420214 Email:tsaat@math.ut.ee
Christian Christiansen Aarhus University c/o Univ. Copenhagen Øster Voldgade 10 DK-1350 Copenhagen K DK Tel.:+45 3532 2510 Fax:+45 3532 2501 Email:cc@geogr.ku.dk	

BALTIC SEA SYSTEM STUDY (PROJECT BASYS)

BODO VON BODUNGEN

Baltic Sea Research Institute (IOW)
D-18119 Rostock-Warnemünde, DE
Telephone: ++49-381-5197-100
Facsimile: ++49-381-5197-105
Email: bodo.bodungen@io-warnemuende.de

SUMMARY

The research project BASYS started at 01.08.1996 and will run for three years. It is devoted to the interdisciplinary study of the Baltic Sea ecosystem. An overview on the outline of the project as well as the actual state is given below.

1. INTRODUCTION

Recent evaluations have described the lack of capability to predict unequivocally future developments as the most serious gap in environmental research in the coastal oceans. It was identified that this is mainly due to insufficient quantification of fluxes of key elements and the inability to differentiate between the effects of climate variability and human interventions. Albeit the Baltic Sea is one of the best-investigated marine areas in the world, this, in general, holds also true for this semi-enclosed marginal sea.

The Baltic Sea is subject to an impressive external forcing both natural and anthropogenic. The present stage of the Baltic Sea is still influenced by postglacial processes, most notably the coastal uplift and down lift in the northern and western parts respectively, which result in a natural sediment transport of considerable magnitude. The water cycle is characterised by precipitation and river runoff exceeding largely evaporation and by the restricted exchange with the North Sea through the Danish Strait resulting in salinity gradients, which show strong seasonal and decadal varibility corresponding to the

metereologic forcing. Thus oxygen supply of deep water is strongly driven by natural external forcing. Similarly, formation of sea ice is highly variable up to 50% of the sea may be covered and regionally duration of ice cover may exceed 6 months.

Rivers deliver their water from a catchment area four times larger in extent than the surface area and inhabited by more than 80 million people. Urbanisation, industrial development, and intensive land use are the main causes for increased pertubation of the marine ecosystems during the last 100 years. Changes recently observed in the Baltic Sea are often categorically assigned to uncontrolled human interventions. However, more than 20 years of monitoring environmental and biological variables have shown that eutrophication and the effect of harmful substances are nonlinear processes and cannot be studied regionally at selected sites.

Therefore, to improve this situation two overall objectives were chosen for BASYS:

- to further the understanding of the susceptibility of the Baltic Sea to external forcing
- to improve the quantification of past and present fluxes through the Baltic Sea.

2. APPROACH

To achieve a significant progress towards these objectives a system approach was chosen which requires a multitude of scientific activities, handling of large amounts of data and close international co-operation. This is reflected by the large number of participants from EU-member countries and all riparian countries as well as by the according subdivision of BASYS into a Co-ordination-Data management subproject and 10 scientific subprojects.

The methodologies chosen in BASYS cover the application of a selected range of modern analyses of variables sampled in the field, data processing and model tools which are described in detail in the individual subprojects. Generally, the approach of BASYS to meet the objectives covers time scales from seasons, years, decades and centuries including the postglacial development of the ecosystem to which all subprojects will contribute individually as well as collectively (Figure 1).

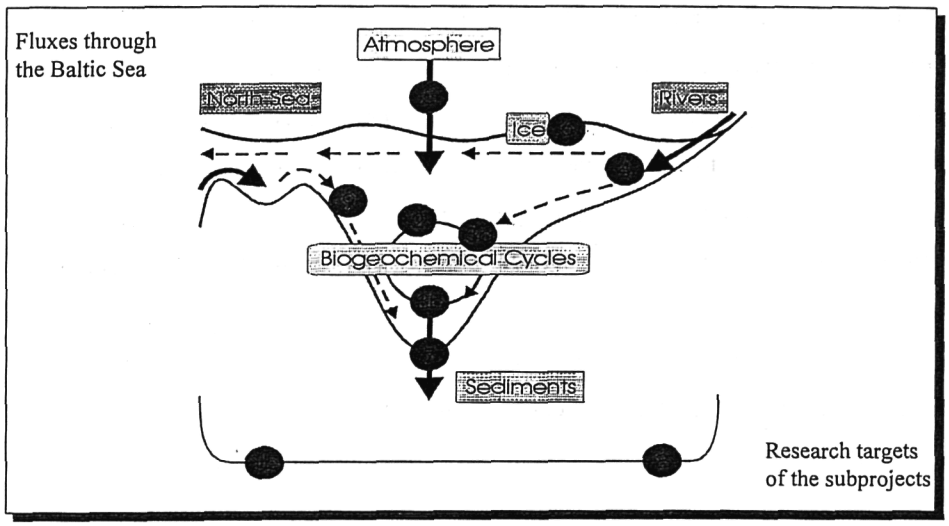


Figure 1: Fluxes through the Baltic Sea. Major external forcing is manifested through the exchange with the North Sea, atmospheric load, coastal and riverine discharge and deposition of matter in the sediments. Biogeochemical cycles are involved at each stage of description. Their numbers indicates the subproject activities.

The various subsystems in the Baltic Sea differ considerably in their biogeochemical behaviour. The field work on vertical and lateral fluxes in the pelagial and benthal, therefore, covers the major basins in the Baltic Proper and Bothnian Sea. Lateral fluxes will be studied from the Odra mouth into the Arkona and Bornholm Basin and from the Gulf of Finland into the Gotland Basin. Results from the field work, historical data sets and paleoecological studies are upscaled with numerical models. The atmospheric load scenario will encompass the entire Baltic Sea embedded in a Europe wide model. The studies on Basin circulation and diapycnal processes will be focused on the Arkona, Bornholm and Gotland basin. The effects of variations in sea ice formation in the northern Baltic will be investigated for the entire Baltic Sea circulation. The sample for the reconstruction of the paleoenvironment will be obtained from the central basins. See Figure 2.

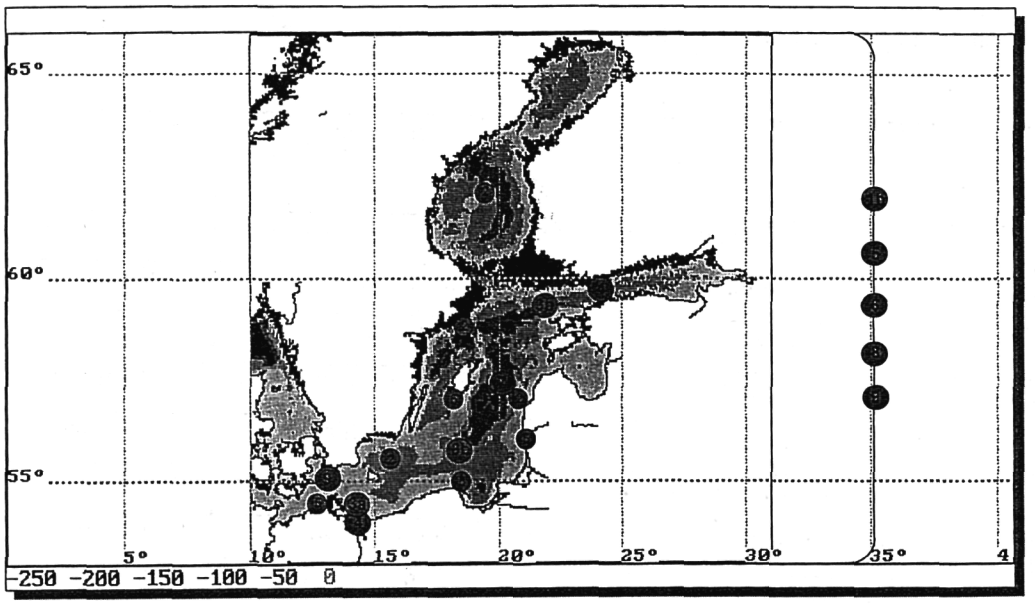


Figure 2: Target regions for BASYS subprojects

To meet the objectives we organised the work in analytical and synthetic parts:

Subproject tasks - analysis work:

Each subproject has tasks and subtasks according to the specific scientific questions (Tab. 1).

Sub-project	Title	Co-ordinator	Institute
1a	Coordination and data management	Bodo von Bodungen	IO Warnemünde
1b	Processing of historical Data	Juergen Alheit	IO Warnemünde
2	Pelagic fluxes	Ulf Larsson	U Stockholm
3a	Coast-basin Fluxes	Kay-Christian Emeis	IO Warnemünde
3b	Basin-basin fluxes	Matti Perttilae	FIMR Helsinki
4	Nearshore and coastline processes	Peter Stoffers	GPI Kiel
5	Atmospheric load	Michael Schulz	U Hamburg
6	Baltic sea ice	Wolfgang Krauss	IfM Kiel
7	Paleo-environment	Boris Winterhalter	GTK Espoo
8	System analysis and models	Fredrik Wulff	U Stockholm
9	Circulation and diapycnal exchange	Gerd Becker	BSH Hamburg

Table 1: BASYS Subprojects

Cross-project research foci - synthesis work:To enforce scientific, functional and operational links throughout the BASYS-Project beyond the commitment to the individual project's objectives a conceptual framework is established. This is established by the major research foci of BASYS - they are identified in the following Tab. 2.

Focus	Title
A	External and internal biogeochemical fluxes, matter balances and accumulation in the system
B	Assessment of spatial and temporal scales of significant changes
C	Differentiation between natural and anthropogenically induced climate variability
D	Upscaling of model hierarchies, nesting and data assimilation

Table 2: BASYS research foci

3. WORKPLAN

The combination between process oriented work, assembling of historical data, geological record and modelling will allow for robust testing for the predictive capability of modelling and for the development of generic strategies for ecosystem research in coastal oceans. An important tool to run the project is the establishment of cross-project groups for logistics and date management, research foci work and for finalising end products such as data CD-ROM, video and a comprehensive state of the art document. The methodological approach is depicted in Figure 3.

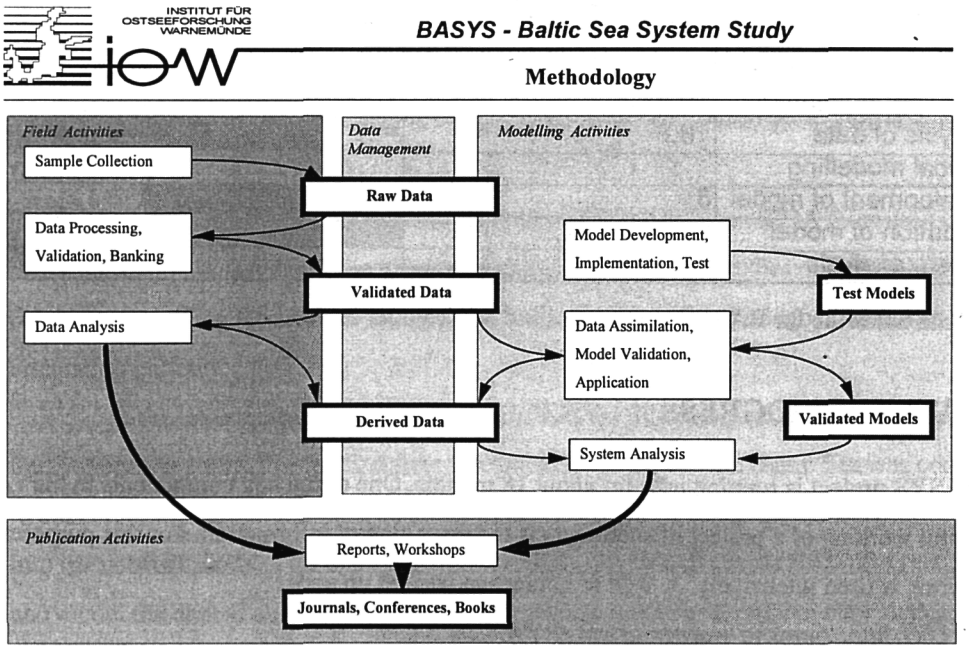


Figure 3: Methodological Approaches utilised in BASYS

The following Table 3 gives an overview on the time schedule of BASYS.

Analysis Work - Project Tasks							
	Months	1-6	7-12	13-18	19-24	25-30	31-36
		8/96-1/97	-7/97	-1/98	-7/98	-1/99	-7/99
	Subprojects						
I. Process field studies							
I.1: Collection of data	1B,3A,3B,4,5,7,9	>	>				
I.2: Processing, Validation	1B,3A,3B,4,5,7,9	=	=				
I.3: Analysis of data	1B,3A,3B,4,5,7,9		=				
II. Process modelling							
II.1: Development of model	3A,4,5,6,9	=	=				
II.2: Validation of model	3A,4,5,6,9	=	=				
II.3: System Analysis	3A,4,5,6,9						
III. Historical field studies							
III.1: Archiving, Validation	1B,8	>	>				
III.2: Analysis of data	1B,8	=	=				
IV. Historical modelling							
IV.1: Development of model	8	=	=				
IV.2: Validation of model	8	=	>				
IV.3: System analysis	8						

Table 3: Time Schedule for BASYS

4. STATE OF PROGRESS

The BASYS project is running now for about 18 months. One of the key components in the successful working of a project of such scale is the managing of information. For this purpose the Internet is used intensively. A WWW homepage was set up under

URL http://www.io-warnemuende.de/Projects/Basys/

From there general information can be obtained as well as specific operational communication. A BASYS NEWSLETTER is published three-monthly. In this way, a contribution to a network of Baltic scientists has been made.

The scientific progress in the project was according to planning and expectations. The nature of the progress is very different between the various subprojects (SP) corresponding to their tasks.

The coordination and management (SP1A) has set up a BASYS home page with a well-developed information system, which is intensively used by all scientists. As the synthesis part of the project becomes increasingly dominant a question and answer market will be installed to guarantee a fast flow of ideas and problems within the community.

Data have been sampled and made available for empirical and numerical studies in SP1B (Historical Data). First analysis of the biological data showed that there is a considerable variability in fish stocks and composition of the zooplankton that can be unequivocally ascribed to variability in the climate forcing.

Field sampling in SP2 (Pelagic fluxes) has been conducted in a joint cruise RV „Petr Kottsov" which was one of the highlights of the first years activities (see also SP3B and SP7). Crucial fluxes in the nitrogen cycle and export have been further quantified. An ad-hoc working group has been established to enable rapid progress towards the quantification of key fluxes.

A close cooperation in fieldwork has been achieved between SP3A (Coastal-basin fluxes) and SP4 (Coastal and nearshore processes). The regional studies delivered high resolution sampling for seafloor topography, sediment properties, biological variables and circulation patterns.

For the investigation of the atmospheric load the SP5 has gone through an intensive intercalibration study. For the first time a network study around the Baltic Sea was conducted to collect jointly samples. Also a novel was the integration of a Lagrangian study with to ship into the network study. This approach provides data, which will enable BASYS to estimate, and model the annual atmospheric input to the various sea areas for which only sketchy information are available as yet.

A joint cruise with RV „Petr Kottsov" by SP3B (Basin-basin fluxes) and SP7 (Paleoenvironment) was another outstanding event. Data for estimating a modelling horizontal transport have been obtained and locations were identified where goring will result in obtained wharfed sediments for paleoenvironmental studies with high time resolution for the last centuries.

The release and sampling of dye tracers in the Arkona and Bornholm Basin by SP9 (Deep currents and diapycnical mixing) was supported by the measurement of hydrographical properties and currents. A database was selected which allows empirical analysis and validation of numerical models of mixing and water transport.

To assess the role of ice coverage on Baltic Sea circulation patterns an ice model was successfully implemented into a free surface GFDL model by SP6 (Baltic sea ice). This and parameterisation of vertical diffusion, viscosity and pack ice mechanisms presents a step forward to prognostic calculations.

A database for forcing and state variables for the sea has been assembled by SP8 (System analysis and models) and is available throughout the BASYS community. There has been progress on data assimilation by starting to implement the data assimilation into simplified 0-D and 1-D ecosystem models as well as on handling variability of some properties. The development of mechanistic models is in a progressing phase. One of the highlights in Baltic Sea modelling is definitely the connection of empirical models with cost benefit-aspects in relation to abatement plans.

Cross-subproject activities have been started early in BASYS in subproject meetings where members of other subprojects took part. Herewith the various subprojects were able to define their input as well as their need for information to approach successfully the research foci. The results of these activities were documented during the First Annual Science Conference and also led to the establishment of working groups to foster the synthesis aspects of BASYS.

These are

WORKING GROUP 1)Nitrogen Fluxes. Aims to further the understanding of the sources and sinks of nitrogen.

WORKING GROUP 2)Deep Circulation and Sedimentation. Aims to connect dynamics of deep currents and vertical and horizontal sediment transports.

WORKING GROUP 3)Coupled Models. Aims to coordinate activities in ecosystem models at different locations and scales.

Besides these activities some progress towards the research foci of BASYS can already be identified:

FOCUS A)External and internal biogeochemical fluxes, matter balances and accumulation in the system. In the pelagial key fluxes have been measured from which a much better quantification particularly in the nitrogen cycle can be achieved. The input from atmospheric outfall to the Baltic Sea is an important source; Baltic wide quantification is approached. Accumulation in the basins is largely influenced by bottom near transport from the shallower areas.

FOCUS B) Assessment of spatial and temporal scales of significant changes. Analyses on long-term data sets will important information for focus as will the sediment analysis of the cores and model runs for periods of 20 years and more.

FOCUS C) Differentiation between natural and anthropogenic induced variability and changes. Historical data give empirical evidence that various components in the ecosystem do react with changes in biomass and/or species composition to climate variability.

FOCUS D)Upscaling of model hierarchies, nesting and data assimilation. Data assimilation tools have been developed and the atmospheric load scenario above the Baltic Sea is derived from nesting a regional model into a Europe wide atmospheric model.

The scientific progress of the project has been presented at the First Annual Science Conference at Warnemünde, 29.09.-01.10.1997. The successive review of the subprojects demonstrated the complexity of the tasks to the participants. By each subproject vital information available for and needed from other subprojects were lined out. Major forum for discussions were the poster sessions - about 55 posters have been presented. The complete collection of abstracts will be included as a technical report in the 1-YEAR SCIENTIFIC REPORT; it also is available through the BASYS WWW pages.

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

TITLE: **Canary Islands Açores Gibraltar Observations (CANIGO)**

CONTRACT NO: **MAS3-CT96-0060**

CO-ORDINATOR: Gregorio Parrilla
Instituto Español de Oceanografía
Corazón de María 8, 28002 Madrid, Spain
Tel. 34 (9)1 3473608
Fax 34 (9)1 4135597
E-Mail: gregorio.parrilla@md.ieo.es
Web site: www.marine.ie/datacentre/projects/canigo

PARTNERS:

Dr. Gerold Siedler
Institut für Meereskunde
Düsternbrooker Weg 20
24105 Kiel, Germany
Tel.: 49-431-597 3890; Fax: 49-431-597 3891
E-mail: gsiedler@ifm.uni-kiel.de

Dr. David J. Webb
Southampton Oceanography Centre
Empress Dock
Southampton SO14 3ZH, United Kingdom
Tel.: 44-1703-59 6199; Fax: 44-1703-59 6204
E-mail: david.webb@soc.soton.ac.uk

Dr. Madeleine Goutx
CNRS-Lab. Microbiologie Marine
Campus de Luminy, Case 907
163, Ave. de Luminy
F- 13288 Marseille Cedex 9, France
Tel.: 33-491-82 90 62; Fax: 33-491-82 90 51
E-mail: goutx@luminy.univ-mrs.fr

Dr. Isabel Luisa S.A. Ambar
Instituto de Oceanografía
Faculdade de Ciencias, Univ. de Lisboa
Campo Grande
1700 Lisboa, Portugal
Tel.: 351-1-750 0080; Fax: 351-1-750 0009
E-mail: iambar@fc.ul.pt

Dr. F. Xavier Niell
Universidad de Málaga
Dept. Ecología, Fac. Ciencias
Campus de Teatinos s/n, Apdo. Correos 59
29071 Málaga, Spain
Tel.: 34-5-213 1852; Fax: 34-5-213 2000
E-mail: fxn@uma.es

Dr. José J. Hernández-Brito
Univ. Las Palmas de Gran Canaria
Dpto. Química
Campus Universitario Tafira, Apdo. 550
35017 Las Palmas de Gran Canaria, Spain
Tel.: 34-28-45 29 20; Fax: 34-28-45 29 22
E-mail: jhdez@quimica.ulpgc.es

Dr. Fiz Fernández Pérez
Instituto Investigaciones Marinas (CSIC)
Eduardo Cabello, 6
36208 Vigo (Pontevedra), Spain
Tel.: 34-86-23 19 30; Fax: 34-86-29 27 62
E-mail: fizfperez@iim.csic.es

Dr. Fidel Echevarria
Universidad de Cadiz, Fac. CC. del Mar
Campus Rio de S. Pedro
11510 Puerto Real, Cadiz, Spain
Tel.: 34-56-47 08 36; Fax: 34-56-47 08 11
E-mail: fidel.echevarria@uca.es

Dr. Octavio Llinás González
Instituto Canario de Ciencias Marinas
Ctra. Taliarte s/n, Apdo. Correos 55
35200 Telde (Las Palmas de G.C.), Spain
Tel.: 34-28-13 33 12; Fax: 34-28-13 29 08
E-mail: ollinas@iccm.rcanaria.es

Dr. Ricardo Anadón
Universidad de Oviedo
Dpto. Biología de Organ. y Sis.
Catedrático Rodrigo Uría s/n
33071 Oviedo, Spain
Tel.: 34-8-510 47 90; Fax: 34-8-510 47 77
E-mail: ranadon@sci.cpd.uniovi.es

Dr. Alan Cantos
AINCO-INTEROCEAN
Costa Rica, 11 (1, A-26)
28016 Madrid, Spain
Tel.: 34-1-350 4394; Fax: 34-1-350 2414
E-mail: alan.cantos@ainco.es

Dr. Miquel Canals
Universidad de Barcelona
Dept. Gologia Din., Geo i Paleo.
Marti i Franques s/n, Nucli Univers.Pedralbes
08028 Barcelona, Spain
Tel.: 34-3-402 1375; Fax: 34-3-402 1340
E-mail: miquel@natura.geo.ub.es

Dr. José García-Braun
Universidad de La Laguna,
Dpto. Bilogía Marina
Astrofísico F. Sánchez s/n,
38206 La Laguna (Sta. Cruz Tenerife), Spain
Tel.: 34-22-60 37 57; Fax: 34-22-25 33 44
E-mail: ilozano@ull.es

Dr. Emilio Fernández Suárez
Universidad de Vigo, Facultad de Ciencias
Campus Lagoas-Marcosende,
36200 Vigo (Pontevedra), Spain
Tel.: 34-86-81 25 91; Fax: 34-86-81 25 56
E-mail: esuarez@uvigo.es

Dr. Catalina Gascó
CIEMAT, Instituto de Medio Ambiente
Avda. Complutense, 22
28040 Madrid, Spain
Tel.: 34-1-346 6568; Fax: 34-1-346 6121
E-mail: cata@ciemat.es

Dr. Egil Sakshaug
Trondhjem Biological Station, NTNU
7034 Trondheim, Norway
Tel.: 47-73-59 15 82; Fax: 47-73-59 15 97
E-mail: egil.sakshaug@vm.ntnu.no

Dr. Leo Nykjaer
Joint Research Centre
Space Application Institute
TP 272
21020 Ispra, Italy
Tel.: 39-332-78 97 15; Fax: 39-332-78 90 34
E-mail: leo.nykjaer@jrc.it

Dr. Karin Borenas
Earth Sciences Centre
Dept. of Oceanography
Guldhedsgatan 5A
S-41381 Göteborg, Sweden
Tel.: 46-31-773 28 57; Fax: 46-31-773 28 88
E-mail: kabo@gvc.gu.se

Dr. Sten Lindblom
Stockholm University
Dept. Geology and Geochemistry
S-106-91 Stockholm, Sweden
Tel.: 46-8-674 7837; Fax: 46-8-674 7897
E-mail: lindblom@geol.su.se

Dr. Carlo Papucci
ENEA, Ente per le Nuove Tecnologie,
l'Energie e l'Ambiente
P.O. Box 316
19100 La Spezia, Italy
Tel.: 39-187-53 62 67; Fax: 39-187-53 62 13
E-mail: papucci@estosf.santateresa.enea.it

Dr. Gerhard J. Herndl
Netherlands Institute for Sea Research
(NIOZ), Dept. Biological Oceanography
P.O. Box 59
1790 AB Den Burg, Texel, The Netherlands
Tel.: 31-222-36 95 07; Fax: 31-222-31 96 74
E-mail: herndl@nioz.nl

Dr. Hans R. Thierstein
ETH-Zentrum, Geolog. Institute
Sonnegg Strasse 5
CH-8092 Zurich, Switzerland
Tel.: 41-1-632 3666; Fax: 41-1-632 1051
E-mail: thierstein@erdw.ethz.ch

Dr. Gerold Wefer
University of Bremen, Geosciences FB5
Klagenfurter Str., Postfach 330440
28359 Bremen, Germany
Tel.: 49-421-218 3389; Fax: 49-421-218 3116
E-mail: gwefer@zfn.uni-bremen.de

Dr. W. Balzer
University of Bremen, FB2 Meeresche
Leobener Str., Postfach 330440
28334 Bremen, Germany
Tel.: 49-421-218 3232; Fax: 49-421-218
4542
E-mail: balzer@mch.uni-bremen.de

Dr. Rainer Reuter
Univ. Oldenburg, FB Physik
Carl von Ossietzky Str. 9-11
26111 Oldenburg, Germany
Tel.: 49-441-798 35 22; Fax: 49-441-798 32 01
E-mail: r.reuter@las.physik.uni-oldenburg.de

Dr. Donat-Peter Häder
Friedrich-Alexander Universität, Inst. für
Botanik und Pharmazeutische Biologie
Staudtstrasse 5
91058 Erlangen, Germany
Tel.: 49-9131-85 82 16; Fax: 49-9131-85 82
15
E-mail: dphaeder@biologie.uni-erlangen.de

Dr. Christoph Hemleben
Universität Tübingen, Institut und Museum für
Geologie und Paläontologie
Sigwartstrasse, 10
72076 Tübingen, Germany
Tel.: 49-7071-297 2496; Fax: 49-7071-29 5766
E-mail: christoph.hemleben@uni-tuebingen.de

Dr. Peter A. Davies
University of Dundee, Dept. Civil Engineering
Nethergate
Dundee DD1 4HN, United Kingdom
Tel.: 44-1382-34 43 46; Fax: 44-1382-34 48
16
E-mail: p.a.davies@dundee.ac.uk

Dr. David Robins
Plymouth Marine Laboratory
Prospect Place, West Hoe
Plymouth, PL1 3DH, United Kingdom
Tel.: 44-1752-63 32 71; Fax: 44-1752-63 31 01
E-mail: dbro@pml.ac.uk

Dr. John Johnson
University of East Anglia
School of Mathematics
Norwich NR4 7TJ, United Kingdom
Tel.: 44-1603-59 25 98; Fax: 44-1603-25 95
15
E-mail: j.johnson@uea.ac.uk

Dr. Nick J.P. Owens
University of Newcastle, Dept. Marine Sciences
& Coastal Management
Ridley Building
Newcastle Upon Tyne, NE1 7RU, UK
Tel.: 44-191-222 8885; Fax: 44-191-222 7891
E-mail: n.owens@ncl.ac.uk

Dr. Eric Des Barton
UCNW Marine Science Labs.
School of Ocean Sciences
Menai Bridge
Gwynedd LL59 5EY, Wales, UK
Tel.: 44-1248-38 2848; Fax: 44-1248.38 28 48
E-mail: oss041@sos.bangor.ac.uk

Dr. Dominique Renouard
LEGI-Coriolis
1025 R. de la Piscine, B.P. 53
38041 Grenoble Cedex 9, France
Tel.: 33-4-76-86 61 82; Fax: 33-4-76-87 97 93
E-mail: dominique.renouard@img.fr

Dr. Pierre-Yves Le Traon
CLS, Space Oceanography Division
8-10 Rue Hermes
Parc Technologique du Canal
31526 Ramonville Saint Agne, France
Tel.: 33-561-39 47 58; Fax: 33-561-75 10 14
E-mail: pierre-yves.letraon@cls.cnes.fr

Dr. Françoise Elbaz-Poulichet
CNRS, Geofluides, Bassins, Eau. Ura D1767
Place E. Bataillon, CC 57
34095 Montpellier Cedex 5, France
Tel.: 33-467-14 39 31; Fax: 33-467-14 47 74
E-mail: elbaz@dstu.univ-montp2.fr

Dr. Maria José Brogueira
IPIMAR
Av. Brasilia
1400 Lisboa, Portugal
Tel.: 351-1-301 08 14; Fax: 351-1-301 59 48
E-mail: mzb@ipimar.pt

Dr. Nicholas Morley
Univ. of Southampton, Dept. Oceanography,
Southampton Oceanographic Centre
European Way
Southampton SO14 3HZ, United Kingdom
Tel.: 44-1703-59 65 73; Fax: 44-1703-59 30 59
E-mail: nhm@soton.ac.uk

Dr. Gunther Krause
Alfred Wegener I. für Polar und
Meeresforschung
Columbusstrasse
27568 Bremerhaven, Germany
Tel.: 49-471-483 1703; Fax: 49-471-483 1724
E-mail: gunther_krause@awi-bremerhaven.de

Dr. Fabienne Gaillard
LPO, IFREMER, Centre de Brest
BP 70
29280 Plouzane, France
Tel.: 33-2-98-22 42 88; Fax: 33-2-98-22 44 96
E-mail: fabienne.gaillard@ifremer.fr

Dr. Françoise Martel
CETIIS, Aix Metropole-Bt D
30 Av. Henri Malacrida
13100 Aix En-Provence Cedex 3, France
Tel.: 33-442-93 47 07; Fax: 33-442-26 52 19
E-mail: fmartel@cetiis.fr

Dr. Fátima Abrantes
Instituto Geológico e Mineiro
Estrada de Portela
Alfragide, Portugal
Tel.: 351-1-471 89 22; Fax: 351-1-471 90 18
E-mail: icp6fatima@mail.telepac.pt

Dr. Mario Alves
Universidade dos Açores
Dept. Oceanografia e Pescas
Cais de Santa Cruz
9900 Horta Açores, Portugal
Tel.: 351-92-22988; Fax: 351-92-22659
E-mail: mario@dop.uac.pt

Dr. Zvy Dubinsky
BAR-ILAN University, Dept. Life Sciences
52900 Ramat-Gan, Israel
Tel.: 972-3-531 82 83; Fax: 972-3-535 18 24
E-mail: dubinz@mail.biu.ac.il
dubinsk@ibm.net

Dr. Bronwyn Cahill
Irish Marine Data Centre
80 Harcourt St.
Dublin 2, Ireland
Tel.: 353-1-475 71 00; Fax: 353-1-475 71 04
E-mail: bronwyn.cahill@marine.ie

CANARY ISLANDS AÇORES GIBRALTAR OBSERVATIONS (CANIGO).

GREGORIO PARRILLA
Instituto Español de Oceanografia
Corazón de María 8, 28002 Madrid, Spain

SUMMARY

CANIGO is the second largest project in the MAST III Program. It is a multi- and inter-disciplinary project with an important observational component and a significant modelling effort. A group of 45 partners from 12 countries and a JCR intervene in it. Its main goal is to understand the functioning of the marine system in the Canary-Azores-Gibraltar region of the Northeast Atlantic Ocean and its links with the Alboran Sea through comprehensive interdisciplinary basin scale studies. The project started on the 1st. of August of 1996 and it will last for 38 months.

1. INTRODUCTION

The oceanographic regime in the region is dominated by the North Atlantic subtropical gyre flow, the coastal upwelling processes and the exchange through Gibraltar (Fig. 1). Its diversity in hydrographic structures and dynamic processes gives place to a variety of situations, from eutrophic to oligotrophic, in which carbon exchange and cycling will be clearly different. The biogeochemical cycles and fluxes are significatively affected by the atmospheric input of mineral particles which can be also used as paleoclimatological indicators.

The eastern part of the subtropical North Atlantic gyre includes the Azores Current and the Canary Current. The Azores Current is the extension of the south-eastern branch of the Gulf Stream (Gould, 1985) and is thus an essential part of the large-scale oceanic circulation. The current is related to the Azores Front which separates colder and fresher water in the north from warm and salty water in the south. The Azores Current splits into three main southward recirculation branches which vary seasonally and interannually (Stramma and Siedler, 1989). Later they join the westward-flowing North Equatorial Current (Klein and Siedler, 1988). The easternmost branch feeds the Canary Current, an essential part of the Eastern Boundary Current System. While the large-scale flow pattern is known, the details of processes by which the Azores Current water is incorporated in the eastern boundary flow and then transported southward and westward are, however, not well understood. Also the volumes of water and the amounts of heat, salt and nutrients feeding the eastern boundary flows and their seasonal and interannual variations need to be quantified.

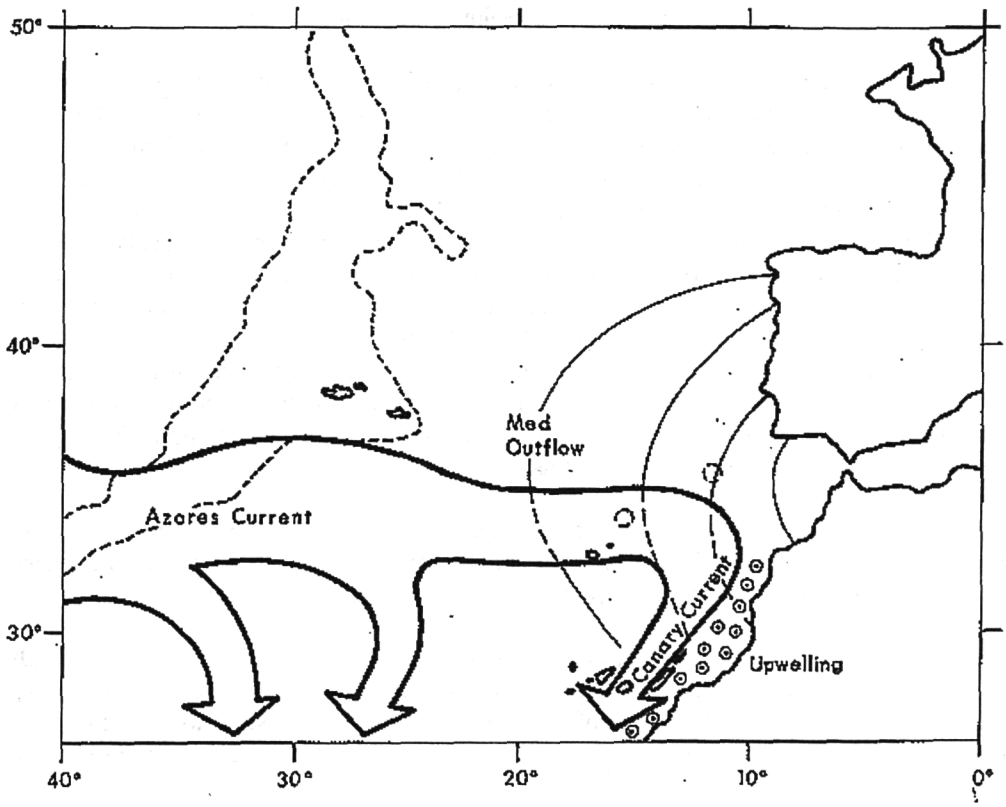
Coupling between the eastern boundary current and the coastal upwelling regime is another important question. A number of theoretical studies have shown that the coastal boundary conditions can control the interior flow (Pedlowsky, 1983; Csanady and Pelegri, 1995).

Mesoscale oceanic phenomena such as eddies, jets and filaments (having, by definition, length scales of the order of the Rossby deformation radius and time variability ranging from days to several weeks) are ubiquitous features of the Canary Basin. Field observations confirm that while some of these features (e.g. filaments off the African coast) may exist only in shallow

while some of these features (e.g. filaments off the African coast) may exist only in shallow layers close to the surface, others such as meddies, island wakes and jets may significantly affect the full water column. Filaments of cool and pigment-rich water from the upwelling regime often extend several 100 km offshore. The filaments reach and intrude into the eastern islands of the Canaries group and become distorted by interaction with individual islands and island groups. Such processes modify significantly the distribution of phytoplankton and organic materials within the Canary Basin

Much of the variability of the region is associated with the presence of isolated islands, island groups and large submarine topographic features. Such features deform the incident flow and density fields and lead to the generation of small scale eddy flow structures(Aristegui and Montero, 1994), island wakes (Sangrá, 1994), shear zones between well-mixed and stratified surface layers (Barton, 1994) and significant boundary mixing. In situ measurements show that these processes lead to an enhancement of chlorophyll and other biological parameters close to the island groups - developments that are also affected significantly by the influence of the cold nutrient-rich upwelling filaments generated at the NW African coast (Wild and Navarro Pérez, 1994).

Fig. 1.- Map of the CANIGO region showing the main oceanographic features



The presence of the Mediterranean water mass strongly influences the hydrology and the dynamic behaviour of the Atlantic Ocean (Richardson et al, 1989; Reid, 1979 and 1994).

The Mediterranean Outflow does not only alter the thermohaline field but it also has an important role as a carrier of particulate and dissolved matter and of living organisms originating in the Mediterranean Sea (Abrantes et al, 1994; Heezen and Johnson, 1969; Proni, 1978), this role being reinforced by the presence of submesoscale eddies which detach from the main stream and are able to carry the influence of Mediterranean Water much farther away from the source than if only "classical" advection/diffusion processes operated (Armi et al, 1989). There have been several attempts to estimate the in- and outflow transports through the Strait, the results obtained show that these transports are quite variable. There are still differences between the modes of exchange in the models and in the observations (Bryden et al, 1994).

The major energetic and dynamically-important signals in the Canary Basin at mid-depth are anticyclonic isolated vortices containing water mass properties typical of the hydrography in the Gulf of Cadiz (Armi and Zenk, 1984), the so-called meddies. They constitute a highly efficient agency for transporting salt from the generation region in the Gulf of Cadiz to the open ocean. The generation mechanisms of meddies constitute a subject under active investigation (Käse et al, 1989).

One of the main issues in marine research today is to understand the mechanisms of the ocean as a carbon sink (UNEP, 1992) and obtain accurate values of its importance in regional concrete areas. The potential capacity of the Canary-Azores region as sink of CO_2 remains unevaluated . Quantification until date have been carried out only through geochemical balance equations. Although there is a consistent body of physical studies in the Canary-Azores area they have not yet been coupled to the scarce biological data dealing with phytoplankton distribution and primary production (Fasham et al, 1985). It is necessary to understand the role of the living organisms in the sedimentation of the Carbon into deeper waters. Results suggest an export of organic matter, but not of nutrients, from the Eastern boundary upwelling to the open oceanic region. This last area is responsible for high respiration rates and very low productivity, being an important sink of dissolved organic carbon (DOC) due to mixing processes in the Subtropical Western Convergence, where heterotrophic activity is very high and production is supported by planktonic communities of high turnover, formed by small phytoplankters (Fernádez et al, 1994)

The Azores-Canary region oceanographic structures affect in different ways the exchange of nutrients, non-living particulate and biological matter. The Subtropical Convergence is characterised by the subduction of central waters with different degree of ventilation (US WOCE, 1992). From the upwelling region, off the North-western coast of Africa, filaments extend from the coast to offshore areas (Hernádez-Guerra et al, 1993; Barton, 1994). Both hydrographical features present seasonal changes. Extensive areas of oligotrophic waters exist between these regions on which nothing is known in terms of the importance of carbon cycle as sink of CO_2 in the oceans. Such succession of events allows the study in this area of a variety of situations, from eutrophic to oligotrophic, in which carbon exchange and cycling will be clearly different.

In the subtropical convergence and in the upwelling, high production is expected; carbon could be exported either in particulate or in dissolved form depending on the size and turnover of high productive plankton. In the extensive but low productive waters, DOC could be expected to be the form of carbon export from the photic zone, except when the heterotrophic activity is high. In this case packing and migration would be a possible way of carbon export by sinking and transport. Nutrient impoverished waters despite their low production occupy a large surface of the sea and, their global contribution to carbon export must be estimated.

In the Canary Islands region, the atmospheric input of mineral particles is of outstanding significance for the marine particle cycle (Duce et al, 1991). Far reaching transport and deposition of Saharan dust particles is an important feature not only for the Canaries but also over wide parts of the subtropical Atlantic Ocean . These particles influence the chemistry of the water column by both: partly dissolving and thus releasing trace elements and by providing adsorption sites for scavenging trace elements from the dissolved state (Kremlig and Streu, 1993; Wefer and Fischer, 1993).

Several of the components of the dust samples collected in the region can be used as indicator of past wind regime (freshwater and limnobiotic diatom species) and paleoclimatological conditions (pollen originating from characteristic vegetation zones on the NW African continent, opal phytoliths). Some of these components can be used also as proxy indices for upwelling and primary productivity, among them foraminifera and coccolithophorids (Berger et al, 1989; Summerhayes et al, 1992). Foraminifera could be used as indicators of the influence of upwelled water originating from the NW African upwelling zone into the mainly oligotrophic regime of the Canary Islands region. Such an advection from coastal upwelling water into low productivity regions has already been observed. In addition to planktonic foraminifera, benthic forms have also been used as fertility indicators in the fossil record Herguera and Berguer, 1991).

Coccolithophores play an important role in the CO_2/O_2 exchange between ocean and atmosphere and are peculiar because of their combined effects on both, the biological and the carbonate pumps. While the formation of organic carbon particulates decreases the CO_2 partial pressure in the surface layer of the ocean, the formation of carbonate skeletons increases CO_2 in the water and consequently in the atmosphere (Wefer, 1993). Because of their optical (albedo) and biochemical (DMS) effects they are likely to produce additional feedback to climate change. Population-dynamic and morphometric studies of coccoliths provide information on surface water temperatures and fertility (Bollman, 1995). Also, coccolithophorids contain alkenones, long-chained kentones incorporated in their cell membranes that can also be used as temperature indicators. The composition of these alkenones is a function of environmental temperatures and can be analysed in the sedimentary record to reconstruct paleo-temperatures (Prahl and Wakeham, 1987.

2. OBJECTIVES AND STRUCTURES OF THE PROJECT

There are four general scientific objectives:

1. To obtain an improved knowledge of physical processes controlling the gyre and the related mesoscale circulation through observations and nested circulation models. The information on the physical environment in the region will be an important basis for the studies of biogeochemical cycles and of carbon and particle flux

2. To study of the in the pelagic system in oligotrophic and productive waters in the area and to estimate the carbon flow through and from the pelagic system to deep waters in the oceanic area.

3. To determine, quantitatively, the influence of coastal upwelling and Saharan dust on the magnitude and composition of in the Canary region, and to investigate how this influence changed through the last glacial and interglacial period.

4. To quantify, understand and model the water mass exchange system through the Strait of Gibraltar, the processes of formation, evolution and fate of the Mediterranean Outflow, including the associated submesoscale eddies, and to measure the biogeochemical fluxes (in terms of carbon, nitrogen, trace metals and metalloids) accompanying these water exchanges.

The scientific objectives are reflected in the scientific organisation of the project. The scientific work is distributed in 4 subprojects, each subproject is co-ordinated by a chair- and vice-chairperson:

1. Circulation and dynamics of transport through the Eastern Boundary Current system.
2. The contribution of the pelagic system to the carbon flow.
3. Particle flux and paleoceanography in the Eastern Boundary Current system.
4. Fluxes and outflow from the Mediterranean, including the associated submesoscale eddies.

Methods of the research include in situ observations (cruises, moorings), remote sensing and modelling, and an important data set will be generated. For these reasons four subcommittees have been organised: a Ship Subcommittee, to achieve optimal use of shiptime; a Data Management Subcommittee, to ensure an appropriate interface between scientists and data managers; a Remote Sensing Subcommittee, to co-ordinate identification, acquisition and processing for remote sensing data; and a Modelling Subcommittee, to ensure the compatibility between models and encourage interaction between models and observations.

The responsibility for the scientific guidance and managerial aspects of the project, and the ensuring of the scientific quality rest on a Steering Committee. It is composed of: the Co-ordinator, the chairs and co-chairs of the subprojects, the chair of the Modelling Subcommittee and the chair of the Remote Sensing Subcommittee. The Steering Committee also assesses the quality of deliverables on the level of workpackages and decides on the continuation and possibly the adjustment of the workplan in consultation with the European Commission.

3. FIRST RESULTS

The first half of the project has been mainly dedicated to sample and data collecting and to the implementation of models (numerical, analytical and laboratory ones). The ship time in CANIGO adds up to more than 1 year, distributed in some 40 cruises of diverse variation (from 1 week to 1 month) beside the ship of opportunity sections. Practically all of the shiptime has been allocated and to this date more than 50% of cruises have been carried out. The field work, which is progressing as planned, consists mainly of CTD/Rosette surveys, float and drifter launchings and moorings. The shipborne measurements are complemented by

satellite observations of sea surface temperature, altimetry and pigment observations from the recently launched satellite SeaWifs.

The Azores Front and Current was studied on several CTD/ADCP sections in summer and fall 1997. The analysis of the tracks from drogued buoys and ALACE floats showed northern and southern recirculation cells adjacent to the Azores Current with length scales of up to 1000 km. At 200 m depth maximum speeds of 50 cm/s were observed in the Azores Current and of 40 cm/s in the adjacent counter flows.

During a cruise with NO Thalassa in summer 1997 in the central Canary Basin four moorings were deployed with current meters and tomographic instruments. Closed hydrographic boxes were obtained by CTD/ADCP-sections including geochemical sampling. Twenty RAFOS floats with a mission time of 1-1.5 years were deployed in the Azores Current. Ship observations showed a good agreement with a quasigeostrophic circulation model with altimeter data assimilation.

During cruises of FS Meteor in January 1997 and FS Poseidon in September 1997 CTD/ADCP-sections including biological and chemical sampling were carried out forming a closed hydrographic box between Africa, Madeira and the Canary Islands. A comparison of both cruises concerning the water mass distribution and the geostrophic transports was carried out. As expected with prevailing wind field changes the upwelling was stronger during September. The influence of fresh and nutrient-rich Antartic Intermediate Water, which moves northward along the African shelf, was stronger and the southward extension of Mediterranean Water was less during September. Across the zonal sections a southward transport of about 2-4 Sv was observed in the upper 800 m. The meridional section showed a westward transport within the North Atlantic Central Water of about 1 Sv. Along the African shelf a poleward undercurrent was observed. Seasonal variability within the Eastern Canary Basin is also studied by using XBT data collected from ships of opportunity between the Iberian peninsula, Madeira and the Canary Islands. These measurements, which are made approximately every three months, started in December 1996 and will continue until 1999.

To study the current system near the African continent an array with four moorings was deployed in December 1996 between the Canary Islands and the African shelf and exchanged in October 1997. The current meters showed a poleward undercurrent of high variability below 500 m. The strongest undercurrent, reaching to the surface, was observed in summer and fall 1997 with velocities of more than 20 cm/s. To study the effect of the Canary Islands on the Canary Current bimonthly XBT-sections are carried out since November 1996 between Tenerife and Gran Canaria and between the Canary Islands and the African shelf. Furthermore, two moorings equipped with current meters and thermistor chains were deployed in May 1997 south of Gran Canaria. They will be operating for one year and will be recovered in May 1998.

The data for estimating the carbon exchange between the air and the sea has been collected mainly around the Canary Islands region and in the East Boundary. After an intercalibration exercise on board the FRS Meteor the exchange has been estimated and the CO_2 of antropogenic origin determined. The total organic carbon has been suggested as one of the more efficient mechanisms of carbon subduction in the mixing period of the year.

Primary production have been measured in several cruises on board of the RV Ross Clark, during the project Atlantic Meridional Transit, in the Azores area. In spite of the primary production been very low, it presents a statistically significative seasonal variability.

The zooplancton abundance and composition have been determined. This is a very useful information for estimating the carbon export from the photic zone downwards.

Results from a cruise Southwest of the Canary Islands in June allowed us to estimate the nutrients there as well as the light extinction. This last parameter has been used, as a different method, for localising the eddies south of the Tenerife and La Gomera as well as the Eastern Boundary region.

Different biooptics methods have been developed. Profiles at different wavelengths have been obtained for determining triptophane, gelstaf and chlorophyll by different methods of fluorescence. The inverse relation between the profiles of gelstaf and chlorophyll suggests that both components are related by mineralization in depth. It has been also developed a method of plankton density determination, based on photoacoustic techniques, which gives a clearer responses to plankton density and is more sensible than the methods used currently. A booklet on optical methods has been produced and disseminated among the partners.

Two cruises has been programmed to take place next August and in April 99 in the Azores area on board of the BIO Hesperides. Another BIO Hesperides cruise as well as shorter cruises will be carried out in the Canaries. The sampling, included in the MAT cruises, in the Azores area will continue during the next year.

Three moorings with particle traps and current meters, one north of La Palma (LP), one north of Gran Canaria (at the time-series station ESTOC (European Station for Time Series in the Canary Islands)) and east of the islands Fuerteventura and Lanzarote (EBC) were deployed and re-deployed twice during the past year on German research vessels (FS "Meteor" and FS "Poseidon"). Paleoceanographically important organisms, such as coccolithophores, diatoms and planktonic foraminifera were sampled so far on three seasonal cruises. Planktonic foraminifera were also sampled in the Azores Frontal Zone (AFZ) region, an open ocean high productivity region. Samples of suspended particulate and dissolved trace metals were taken in the vicinity of the sediment trap positions at EBC3, ESTOC and LP. In addition, dust concentrations in the air have been measured daily since December 1996 on Gran Canaria Island. Results showed the highest variability during the spring due to the penetration of episodic air masses from African Continent, and the lowest values were registered between December and February 1997.

Sedimentological studies were conducted on selected surface samples and cores taken during the FS "Meteor" leg M37/1 (December 1996) in the Agadir Canyon and along the Moroccan coast. During this leg the shipboard acoustical systems Parasound and Hydrosweep were used to survey the uppermost sedimentary layers and the topographic features of the seafloor. These geophysical data were used onboard to select suitable locations for sediment-sampling. The subsequently analysis onshore using physical, isotopic, micropaleontological and sedimentological methods indicate changes of particle flux and deposition of atmospheric dust during the last glacial- and interglacial periods. Most of the surface samples from the FS "Meteor" leg M37/1 were analysed for TOC (total organic carbon), carbonate and microfossil content (planktonic and benthic foraminifera, diatoms, coccolithophorides). In addition, most

of the longer sediment cores were sampled and described. First down-core data (carbonate, foraminifera, TOC and coarse fraction data, other geochemical data) allow the establishment of a preliminary stratigraphic model. While sedimentation rates close to the coast in the upwelling areas were higher with 5 to 10 cm/1000 years, the offshore cores showed lower sedimentation rates with 2 to 5 cm/1000 years. The first data from the surface sediment analyses mirror the high biomass gradient from the coast to the open ocean, as seen for example by satellite images of ocean colour. The distribution of the planktonic foraminifera Globigerina bulloides as an upwelling-indicator reflects areas of strong filament production.

Work in the Mediterranean outflow and its source is structured in three main inter-related workpackages, namely the water exchanges through the Strait of Gibraltar, the organic and inorganic fluxes through the Strait of Gibraltar and the Mediterranean Outflow and associated meddies.

In what concerns the observations of the water exchanges through the Strait of Gibraltar, the monitoring of the water fluxes has been kept by using mooring arrays with current meters, thermistor chains and sea level gauges, bottom mounted Acoustic Doppler Current Profilers (ADCPs), and repeated transects across and along the Straits with shipborne CTD and ADCP. Acoustic methods show complicated flow structures in the sill and eastern entrance; ongoing work concentrates on optimal methods to merge the time series information from moorings with the spatial information from ship observations. In the eastern entrance tidal currents have a baroclinic nature, different to the clear barotropic behaviour they have in the sill. Subinertial variability seems to be mainly driven by local wind, i.e. westerly winds force an increase of the inflowing speed and, hence, of the net local flow. For the observations of the organic and inorganic fluxes across the Strait, three seasonal campaigns, in late spring (June 97), late summer (September 97) and winter (January 98), allowed the water sampling for determination of fluxes of organic and inorganic carbon and nitrogen, of trace metals and radionuclides, and of biomass and taxons. In September the Strait acted, on average, as a source of carbon dioxide.

In what respects the Mediterranean outflow in the Atlantic, the observations comprise current meter measurements at several sites along the main path of the Mediterranean undercurrent from the Strait of Gibraltar to the Southwest coast of Portugal, the regular deployment of RAFOS floats to follow the path of the upper (800 m) and lower (1200 m) cores of the Mediterranean Water, and two seasonal campaigns, in summer (September 97) and in winter (January 98), with CTD and water sampling for nutrients and sediment concentrations. Measurements have shown high velocities in the Mediterranean Undercurrent, up to 50 m/s at 800 m depth and occurrence of high temperatures episodes lasting between 4 and 6 days periods. There is some evidence of a offshore separation of the outflow or of a large parcel in the Gulf of Cádiz, which would eventually follow southwards.

CANIGO includes a set of modelling projects. The eastern North Atlantic model is complete and running. Surface forcing is from ECMWF winds and climatological temperature and salinity. Boundary forcing is from the OCCAM global ocean model. The results compare well with observations and include the Azores current, the spreading of Mediterranean water, coastal upwelling in the Canary current, coastal filaments along the African coast including Cape Ghir, undercurrents in the passages through the Canary Islands, and variability around Madeira.

The Mediterranean model is running at three different resolutions for both the 150 year simulation and the control experiment to check the consistency of the results for long term changes in the Mediterranean Outflow. A regional model of the Gulf of Cadiz and western Alboran Sea has been implemented with a variable grid size to analyse the processes controlling the exchange through the Straits of Gibraltar.

The streamtube models have been tested for parameters typical of the Mediterranean Outflow and show that only a limited parameter range is stable. Laboratory models to simulate the outflow plume in the Gulf of Cadiz have investigated effects of sill slope and water stratification, and produce cyclonic and anticyclonic eddy pairs.

Experiments have been conducted on the Grenoble rotating platform to study the influence of a cape on an underwater current. When the upstream current is unstable, the cape appears as a privileged place for meddy production. The physical properties of the meddies in the experiment are consistent with meddies at Cape St Vincent. The core of the anticylonic water in the meddy is surrounded by a cyclonic ring. The results of numerical simulations of the dynamical structures in the rotating tank experiments have been very enlightening and have generated some interesting three dimensional pictures of meddies in motion.

4. DATA MANAGEMENT

A communications infrastructure has been set up to facilitate easy exchange of data and information within the project. This infrastructure consists of e-mail distribution lists, ftp sites and a CANIGO WWW page which has open and restricted access depending on whether the information or data is public domain or project confidential. Two CANIGO WWW applications have been developed which are also accessed from the secure area of the page.

All data management-related information is documented in a CANIGO Project Data Handbook. This includes information on cruise reports, data documentation, data exchange, data quality, data formats, data policy and software applications. The handbook can now be viewed on-line (html version) from the CANIGO WWW page and is also available for downloading. It also includes Quick Reference Guides (QRGs) summarising each of the main data management procedures.

To further facilitate the transfer of data and information between the project partners, an application called the Data Tracking System has been designed to allow cruise-based information to be viewed or downloaded over the secure area of the CANIGO WWW page. The system comprises a geographically referenced database of all cruise information giving details of the data generated by each cruise. It has been designed to help CANIGO scientists find out what data has been collected at the various sampling stations during the project cruises and to download that data if it has been submitted to the Data Centre.

As part of the data submission procedure, a WWW Data Submission Form (DSF) has been developed which runs from the secure area of the BENGAL page and will allow on-line completion. This DSF is designed to ensure that the data are properly and consistently described as outlined in the MAST Guidelines on Data Documentation and the IMDC data management guidelines. This form is also available as MS Word and other electronic formats.

Data from the CANIGO cruises are entered into the WWW Data Tracking System on an ongoing basis. Processing and quality control procedures are documented in the data handbook and are updated as CANIGO data is submitted to the Data Centre.

The design of the CANIGO 'End-Product' has the purpose of ensuring that enough information is gathered from the CANIGO scientists to define the design and functionality of a database system or 'End product' customised for CANIGO project data. For this, a data classification form has been designed. The template aims to classify the data being generated from the research programmes into the disciplines, types, volumes, mode of collection (e.g. time series, stations, model output, remote sensing, etc.), functionality (mapping, graphing, searching), export formats, etc. This information is currently being gathered from the CANIGO scientists and will be used to input into the design of the end product.

On the basis of the above, a prototype system already developed will be adapted to form the basis of the CANIGO 'end-product'. It is comprised of a series of interactive modules including an upper 'information' level and a lower 'data' level. The upper level comprises an Inventory, Cruises, Methodologies, Scientists and Publications Modules while the lower level comprises of Stations, Underway, Moored Time Series, Images, Animation and Video Modules.

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I.3.4. The north-eastern Atlantic continental margin

TITLE: Ocean Margin EXchange II - Phase I (OMEX II-I)

CONTRACT NUMBER: MAS3-CT96-0056

CO-ORDINATOR:

Roland Wollast/Lei Chou
Université Libre de Bruxelles
Laboratoire d'Océanographie Chimique
Campus de la Plaine CP-208
Boulevard de Triomphe
B-1050 Bruxelles, Belgium
tel: (32)2.650.5212/5237
fax: (32)2.646.3492
email: rwollast@ulb.ac.be
lchou@ulb.ac.be

PARTNERS:

John Huthnance
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead, Merseyside
United Kingdom L43 7RA
tel: (44)151 653 8633
fax: (44)151 653 6269
email: JMH@wpo.nerc.ac.uk

Tjeerd van Weering
Netherlands Institute for Sea Research
P. O. Box 59
1790 AB Den Burg
Texel
The Netherlands
tel: (31)222 369 395
fax: (31)222 319 674
email: haas@nioz.nl

Paul Wassmann
Norwegian College of Fishery Science
University of Tromsø
N-9037 Tromsø
Norway
tel: (47)776 44459
fax: (47)776 46020
email: paulw@nfh.uit.no

Fauzi Mantoura
Plymouth Marine Laboratory
Prospect Place, West Hoe
Plymouth
United Kingdom PL1 3DH
tel: (44)1752 633 422
fax: (44)1752 633 101
email: RFCM@WPO.NERC.AC.UK

Soren E Larsen
Wind Energy & Atmospheric Physics Depart
VEA-125, Riso National Laboratory
P.O.Box 49, DK-4000 Roskilde, Denmark
tel: (45)4 677 5012
fax: (45)4 677 5970
Email: soeren.larsen@risoe.dk

ASSOCIATED PARTNERS

Pr Wolfgang Balzer
FB2 - Meereschemie
Universitaet Bremen
Postfach 33 04 40
28334 Bremen
GERMANY

Pr Tomasz Boski
UCTRA
Universidade do Algarve
Campus de Gambelas
8000 Faro
PORTUGAL

Pr J.-M. Bouquegneau
c/o Dr Patrick Dauby
Laboratoire d'Océanologie
Université de Liège
B6 - Sart Tilman
B-4000 Liège
BELGIUM

Dr Peter Bowyer
c/o Dr Martin White
Department of Oceanography
University College Galway
Galway
IRELAND

Dr Uwe Brockmann
Institut für Biochemie und
Lebensmittelchemie
Universität Hamburg
Martin-Luther King Platz 6
20146 Hamburg
GERMANY

Dr Peter H. Burkill
Plymouth Marine Laboratory
Prospect Place
West Hoe, Plymouth PL1 3DH
UNITED KINGDOM

Dr Pierre Chardy
Départemente Environnement Littoral
IFREMER
Centre de Brest
B.P. 70
F-29280 Plouzane
FRANCE

Pr Frank Dehairs
Dienst Analytische Scheikunde
Vrije Universiteit Brussel
Pleinlaan 2
B-1050 Brussels
BELGIUM

Pr Joan Manuel Alveirinho Dias
UCTRA
Universidade do Algarve
Campus de Gambelas
8000 Faro
PORTUGAL

Pr G. Graf
c/o Dr Laurenz Thomsen
GEOMAR
Wischhofstraβe 1-3
D-24148 Kiel
GERMANY

Mr Steve Groom
NERC Remote Sensing Data Analysis Service
c/o Plymouth Marine Laboratory
Prospect Place
West Hoe, Plymouth PL1 3DH
UNITED KINGDOM

Pr Carlo Heip
Centre for Estuarine and Coastal Ecology
Netherlands Institute of Ecology
P.O. Box 140
4400 AC Yerseke
THE NETHERLANDS

Dr Willem Helder
NIOZ
P.O. Box 59
1790 AB Den Burg
Texel
THE NETHERLANDS

Dr Peter Herman
Centre for Estuarine and Coastal Ecology
Netherlands Institute of Ecology
P.O. Box 140
4400 AC Yerseke
THE NETHERLANDS

Pr Frank Hodnett
Department of Mathematics and Statistics
University of Limerick
Plassey Technological Park
Limerick
IRELAND

Dr David J. Hydes
Southampton Oceanography Centre
Empress Dock
Southampton SO14 3ZH
UNITED KINGDOM

Dr Ian Joint
Plymouth Marine Laboratory
Prospect Place
West Hoe, Plymouth PL1 3DH
UNITED KINGDOM

Dr Jean-Marie Jouanneau
Département de Géologie et
d'Océanographie
Université de Bordeaux I
Avenue des Facultés
F-33405 Talence Cedex
FRANCE

Dr Alexis Khripounoff /
Dr Annick Vangriesheim
Département Environnement Profond
IFREMER
Centre de Brest B.P. 70
F-29280 Plouzane
FRANCE

Dr Richard Lampitt
Southampton Oceanography Centre
Empress Dock
Southampton SO14 3ZH
UNITED KINGDOM

Dr Søren Larsen
Department of Meteorology and Wind Energy
RISØ National Laboratory
4000 Roskilde
DENMARK

Dr Geritt de Leeuw
TNO Physics and Electronics Laboratory
Oude Waalzdorperweg 63
2597 AK The Hague
P.O. Box 96864
2509 JG The Hague
THE NETHERLANDS

Dr Marie Loye-Pilot
Institut de Biogéochimie Marine
Ecole Normale Supérieure
1 rue Maurice Arnoux
F-92120 Montrouge
FRANCE

Dr Jean-Marie Martin
Director
Environment Institute
Joint Research Centre
I-21020 Ispra
ITALY

Pr I. Nick McCave
Department of Earth Sciences
University of Cambridge
Downing Street
Cambridge CB2 3EQ
UNITED KINGDOM

Pr Ramiro Neves
Department of Mechanical Engineering
Instituto Superior Técnico
Avenida Rovisco Pais, 1
1096 Lisboa Codex
PORTUGAL

Dr Ba Cuong Nguyen
Laboratoire de Modélisation du Climat et de l'Environnement
CE Saclay, Bâtiment 709
Orme des Merisiers
F-91191 Gif-sur-Yvette
FRANCE

Dr Rolf Peinert
Institut für Meereskunde
Universität Kiel
Olshausenstraβe 40
D-24118 Kiel 1
GERMANY

Dr Olaf Pfannkuche
GEOMAR
Wischhofstraβe 1-3
D-24148 Kiel
GERMANY

Dr Robin Pingree
Plymouth Marine Laboratory
Citadel Hill
Plymouth PL1 2PB
UNITED KINGDOM

Dr Spyridon Rapsomanikis
Abteilund Biogeochemie
Max-Planck-Institut für Chemie
POB 3060, Saarstr. 23
D-55020 Mainz
GERMANY

Dr Chris Reid
c/o Dr Sonia Batten
Sir Alister Hardy Foundation for Ocean Science c/o Plymouth Marine Laboratory
Citadel Hill
Plymouth PL1 2PB
UNITED KINGDOM

Ms Aurora Rodrigues
Marinha-Instituto Hidrográfico
rua das Trinas 49
1296 Lisboa codex
PORTUGAL

Dr Toby Sherwin
Marine Science Laboratories
Uniersity College of Wales, Bangor
Menai Bridge
Anglesey LL59 5EY
UNITED KINGDOM

Pr Erwin Suess
c/o Dr Robin Keir
GEOMAR
Wischhofstraβe 1-3
D-24148 Kiel
GERMANY

Pr Kurt Tande
Norwegian College of Fishery Science
University of Tromsø
N-9037 Tromsø
NORWAY

Dr Paul Tett
Department of Biological Sciences
Napier University
10 Colinton Road
Edinburgh EH10 5DT
UNITED KINGDOM

Pr Peter A. W. J. de Wilde
NIOZ
P.O. Box 59
1790 AB Den Burg
Texel
THE NETHERLANDS

Ocean Margin EXchange II – Phase I

Roland WOLLAST[1], Lei CHOU[1], John HUTHNANCE[3], Søren LARSEN[5], Fauzi MANTOURA[2], Paul WASSMANN[4] and Tjeerd van WEERING[6]

[1]Université Libre de Bruxelles
[2]Plymouth Marine Laboratory
[3]Proudman Oceanographic Laboratory
[4]University of Tromsø
[5]RISØ National Laboratory
[6]Netherlands Institute for Sea Research

SUMMARY

The overall aim of the Ocean Margin EXchange (OMEX) project was to acquire a better understanding of the physical, chemical, biological and sedimentological processes occurring at the ocean margin in order to quantify fluxes of energy and matter across this boundary. Through improved knowledge of the biogeochemical interactions between the shelf seas and the open ocean, OMEX partners have developed predictive models to evaluate the response of the shelf and slope area to global environmental changes. During the one-year OMEX II-I project, efforts were devoted to the synthesis and integration of obtained results. The evaluation of physical structures, advection and mixing processes along the Goban Spur has shown that cross-slope flow induced by oceanic forcing can be controlled by friction and by the constraint on depth-integrated, on-shelf flow. Hydrodynamic conditions on shelves do have a major role in enhancing the import of nutrients from deep waters and the export of organic matter from the shelf. Evidence from the study of biological processes along the north Norwegian shelf suggest that export is strongly influenced by mesozooplankton grazing and *in situ* recycling. Comparison of nutrient profiles and hydrographical data from the Celtic Sea shelf break indicates intensive vertical mixing in this area. This phenomenon is responsible for supplying cold, nutrient-rich deep water to the surface which enhances primary production and possibly increases sedimentation of organic matter. Analyses of the role of benthic biota in exchange processes through the Benthic Boundary Layer of the Goban Spur area suggest that the main transport of particles is occurring close to the sea bed, within the bottom nepheloid layer. Examination of biogas exchange processes provides quantitative data concerning fluxes at the air-sea interface. The results clearly indicate that the continental margin plays a significant role in the exchange of gases between the air and the sea through biological activity. Research has also been conducted to develop ecological models that characterise cross-shelf and benthic-pelagic exchange processes.

INTRODUCTION

The Ocean Margin Exchange Project (OMEX) was established within the European Commission's Marine Science and Technology Programme to address specific problems associated with understanding the biological, chemical and physical processes occurring along the European shelf break facing the North Atlantic Ocean. Research has focused on vertical mixing and its role in importing nutrients and oligo-elements to surface waters resulting in enhanced productivity at the ocean margin. The OMEX Project also aims to characterise the fluxes of organic carbon, nutrients and other trace elements which may be exported to the open ocean or deposited and buried along the continental shelf. Given the complexity of the processes occurring along the ocean margin, efforts have been made to provide data concerning the local factors affecting horizontal and vertical transport of material in relation to general circulation. Special attention has been given to evaluating the role of eddies and filaments in the exchange between coastal zones and the open ocean.

Taking into account the priority goals formulated by the International Geosphere-Biosphere Programme, the OMEX project has focused on specific features of European marine environments, while attempting to provide an overall picture of the processes governing exchange at the ocean margin. The project itself was subdivided into five subprojects, each of which was co-ordinated by a subproject leader. While the overall aim of each group has been to provide a more accurate picture of the biogeochemical interactions between the coastal zone and the open ocean, each subproject has had specific objectives concerning the physical, biogeochemical, biological, benthic and air-sea interaction aspects of the exchange processes occurring along the continental shelf.

The physics subproject has focused on assessing the advective and diffusive transports acting to control fluxes in varied shelf-edge contexts. Efforts have been made to evaluate the relative role of various physical processes in circulation and exchange of water masses at the ocean margin. The ultimate goal of this group was to devise an adequate representation of the ocean and shelf boundary conditions for prognostic modelling.

The main task of OMEX biogeochemists has been to investigate the spatial and temporal distribution of nutrients and primary production along the continental shelf. By tracking the inventories and flows of carbon, research has focused on quantifying the flux of carbon, and of related elements, between dissolved and particulate phases in both living and non-living reservoirs. Experimentation has also been undertaken to develop biogeochemical mass balance models describing long term flows of carbon, nutrients, trace elements and their exchange fluxes between the open ocean and the shelf seas.

The focus of the biological processes subproject has been on the biologically-mediated cross-slope exchanges that characterise the ocean margin. Research has been oriented towards understanding the complex interaction of distinct pelagic and benthic communities, by investigating the effect of shelf edge discontinuities in seasonal microbial and grazing food webs. Efforts to quantify vertical flux of biogenic matter and to determine the extent of benthic-pelagic coupling, have led to the development of numerical ecological models of slope systems and resulting fluxes.

Partners participating in the benthic subproject have been concerned with establishing transport pathways and processes, settling accumulation and burial fluxes of particles along the European ocean margin. Attempts have been made to evaluate the role of benthic biota in the respiration and preservation of organic matter in shelf sediments. The overall objective of the group has been to study the diagenetic processes occurring in recent sedimentary deposits

and to quantify the fluxes of organic and inorganic carbon, as well as associated elements.

The objective of the fifth subproject (carbon cycling and biogases) has been to model the coupling and exchange of gases between the ocean and the atmosphere for the European marginal seas. While emphasis has been placed on exchange processes for elements, such as carbon dioxide, methane and sulphur components, that are important for understanding global climatic changes, methods and techniques have been developed to study the physical parameters that underline the mechanisms controlling gaseous fluxes in the marine atmospheric layer.

Co-ordinated by a sixth group from the Université Libre de Bruxelles, OMEX scientists have been directing their efforts towards estimating the importance of different carbon species and associated elements to the overall carbon budget at the shelf edge. Collaborating with scientists from more than 10 European countries, the OMEX group has concentrated on modelling the way in which carbon fixation and the intense, highly variable biological activity occurring at the ocean margin combine with climatic conditions and complex ocean processes to imprint, modify and ultimately control the transfer of material between the open ocean, the continental shelf and the land.

PHYSICS

The OMEX II-I physics subproject included data processing, analysis and interpretation (including remote sensing) and several lines of model development.

Data Processing, Analysis and Interpretation

All recovered OMEX current meter mooring and drogued buoy data have been calibrated and sent to BODC. One particular drogued buoy was tracked from the Celtic Sea along the slope west of Britain and into the North Sea. Analyses have been carried out for physical structures, advection and mixing in the region of Goban Spur, using observations adjacent to, prior to and during OMEX.

The results indicate that the along-slope flow, typically O(0.05m s^{-1}), is reduced or even reversed in spring; sometimes "overshooting" rather than following the depth contours around Goban Spur. Tidal currents on the adjacent shelf are O(0.2m s^{-1}), decreasing to O(0.1m s^{-1}) or less over most of Goban Spur and increasing to to the south. These currents are important in the total current variance, turbulence and mixing. Other currents (wind- and eddy-forced) are typically 0.1m s^{-1} or less, except on the shelf, and decrease with increasing depth. The stratification is intermittent until early June, shoaling during June and deepening by September. One storm on 5-8 September 1995 roughly doubled the upper mixed layer depth. These wind-, tide- and wave-forced currents are likely to be the most consistent agents of cross-slope exchange O(1m s^{-1}). While mixing is intermittent and dominated by surface inputs, towards the south east, internal waves of tidal origin are increasingly important for mixing across the thermocline.

West of Ireland, 40 years of data show a poleward slope current, 5-10 cms^{-1}. Maximum values are in November-January. A previously documented reversal along the Biscay - Porcupine Seabight margin in March-April shows a weakening of the slope current along the western Porcupine Bank shelf edge and north Porcupine Seabight. Records from the shelf indicate seasonality with poleward winter-spring and equatorward summer-autumn flows. Steadiness of the flow is least in February to May. The summer distribution of phytoplankton of sub-tropical water origin follows closely the distribution of warmer water

masses. Distributions are bounded by the Irish shelf front and sharply decrease north of Porcupine Bank. The typical phytoplankton indicator species are absent over the shallower portion of Porcupine Bank; water there is relatively isolated. Increased abundance along the Irish shelf edge suggests advection from Goban Spur along the eastern Porcupine Seabight into Rockall Trough.

At the Iberian margin, coastal upwelling is caused by predominantly northerly winds in summer; then filaments of upwelled water are persistent features. Variable wind forcing affects the local density field; internal wave packets at a moored thermistor chain site arrived earlier when the northerly wind was weak and stratification was enhanced. Surprisingly, the amplitude of the non-linear internal waves does not appear to be related to the tidal range.

Analysis and simple models now show that cross-slope flow induced by oceanic forcing can be controlled by friction and the constraint on depth-integrated on-shelf flow, even if stratification is reasonably strong. A prognostic model has shown that the presence (and proximity) of a land boundary can strongly affect cross-slope flow above the Bottom Boundary Layer and block that layer over the steepest slope in the absence of along-slope forcing.

3-D Semi-Analytical Wave Model and Slope Current Stability

An existing 3-D semi-analytic model, for waves propagating along a continental shelf and slope, has been extended to include a depth-uniform along-slope current. Thus instability has been found for sufficiently strong currents with particular cross-slope profiles. The range of stable flow was biased in favour of flow in a cyclonic sense around the deep ocean.

Ocean Circulation Model

The zonally-uniform work of OMEX I has been extended by testing effects of surface temperature forcing that varies in both latitude and longitude, using thermocline equations with thermal diffusion only in the vertical. The surface temperature distribution represents that in the North Atlantic, with isotherms shoaling eastwards in the equatorial-subtropical ocean and trending downwards towards the east in the subpolar ocean. However, the resulting meridional and vertical flow components differ from the zonally-uniform result only in the equatorial region. The zonal flow is affected more extensively; nevertheless, its sub-tropical and sub-polar forms for zonally-uniform temperature are correct at the western ocean margin and show the main structural features at the eastern margin.

Cross-Slope Diffusion Model

A model of diffusion and settling (only) in the cross-slope section has been used to investigate steady-state distributions of SPM. It is found that the strongest influences on distributions are effective diffusivities, settling velocity and "sources" including sea-bed resuspension. Resuspension is suggested as the usual reason for increased deposition recorded by sediment traps near the bottom. Over Goban Spur, observed intermediate nepheloid layers imply small vertical diffusivity and settling velocity.

3-D Prognostic Model

An existing north-east Atlantic physics model was run for the four seasons forced by climatological density, with some cases of wind forcing. Results explain features of the flow: poleward flow along the slope; stronger along-slope flow in autumn than spring, associated

with the oceanic density field; cyclonic flow in the south-east corner of Biscay; adjacent gyres and associated on- or off-slope flow; off-shelf bottom flow on the Armorican and Celtic slopes.

In order to couple physics and biology, the evolution equations were split into transport (advection-diffusion) and source/sink terms. To allow study of the fates of water masses, a Lagrangian advection-diffusion module was developed based on a particle-tracking model. Pelagic and benthic systems were coupled by including a module for the transport of suspended matter.

Remote Sensing

A system "Panorama" has been developed for processing large quantities of raw data from the Advanced Very High Resolution Radiometer (AVHRR) and Coastal Zone Colour Scanner (CZCS) instruments into calibrated ocean temperature and colour products. The processing includes improved cloud masking and SST or colour calculation with reduced "noise" from atmospheric variations. Weekly and monthly composites have been formed. Panorama has been used to process all AVHRR passes over NW Europe since June 1993, to compile a complete four-year data set of approximately 10,000 high-resolution SST images. Image data are available via World Wide Web.

Algorithms to retrieve phytoplankton production and new production have been tested and improved using data obtained prior to and during OMEX. For primary production, a simple empirical relation between depth-integrated production and satellite radiances accounted for a high degree of variance. This algorithm has been applied to archived CZCS images to estimate seasonal production for the months of reliable satellite data over Goban Spur. Results are comparable with *in situ* estimates. For new production (supported by nitrate from outside the mixed layer) empirical, site-specific algorithms between temperature and nitrate, and the f-ratio and nitrate, enable the f-ratio to be retrieved from satellite SST data. OMEX data were analysed to generate these algorithms for the Celtic Sea; they were applied to satellite SST data during OMEX. Results suggest high nitrate levels and hence enhanced estimates of production along the shelf break, corresponding to higher phytoplankton pigment estimates obtained *in situ* and from archived CZCS data. These results have been compiled and presented in the *OMEX Hydrographic and Nutrient Atlas* which can be accessed via the World Wide Web.

BIOGEOCHEMISTRY

The main objectives of the Biogeochemistry subgroup were 1) to determine the spatial and temporal distribution of nutrients and primary production along the continental shelf; 2) to quantify the fluxes of carbon and related elements (N, P, Si and trace elements) between dissolved and particulate phases in living and non-living reservoirs; and 3) to develop biogeochemical mass balance models describing long term flows of carbon, nutrients, trace metals and their exchange fluxes between the open ocean and the shelf seas, with the aim of predicting the impact of human activities on land-ocean exchange processes.

Nutrient Dynamics and Pelagic Production

Satellite images of the Celtic Sea frequently show a region of cooler water at the shelf break as soon as stratification is established. Comparison of nutrient profiles and hydrographical data indicates a more intensive vertical mixing at the shelf break, which is responsible for

supplying cold, nutrient-rich deep water to the surface and, in turn, enhancing primary production. This may have implications for production available for other organisms, possibly resulting in increased sedimentation of organic matter.

Photosynthetic pigment analyses indicate that Prymnesiophytes are present throughout the year, often dominating assemblages in summer, fall and winter. Diatoms measuring greater than 5μm in diameter abound in spring, resulting in a significant spring bloom. Annual phytoplankton production is estimated to be *ca* 160g C $m^{-2}y^{-1}$.

The mean annual f-ratio at Goban Spur is close to 0.5. In summer and autumn, the ratio was relatively low (<0.3), with phytoplankton production occurring as a result of ammonia utilisation. During the spring bloom, the f-ratio increased to 0.8 when nitrate was the major nitrogen source for phytoplankton.

Microzooplankton were found to be abundant in surface waters, their biomass varied seasonally by over an order of magnitude and was lowest in winter. Community composition also varied seasonally with tintinnids and heterotrophic dinoflagellates forming a greater proportion of total biomass in the summer and other ciliate taxa being more important in winter. It was found that in spring, microzooplankton grazed between 10 and 30% of the primary production but in summer this rose to between 30 and 100% of the daily primary production.

In contrast to carbon uptake, size-fractionated assimilation of phosphorus indicates that this element is largely confined to fractions smaller than 2μm, for all seasons. This emphasises the importance of bacterial activity in phosphorus cycling. Results obtained from the use of inhibitors, such as antibiotics and sodium azide, demonstrate that phosphorus uptake due to photosynthesis represents only a proportion of the total assimilation rate. Incorporation of phosphorous due to microbial activity reaches as much as 15% of this total.

Data from satellite remote sensing and other studies were used to extend the seasonal coverage of the observations made in OMEX I, in order to estimate the cycling of organic matter in surface water and the potential export of carbon and nitrogen through the process of sedimentation. Primary production estimates were compared with estimates based on underway chlorophyll measurements, the archive of the Coastal Zone Colour Scanner (CZCS), other published data and models. New production values were estimated from sea surface temperature data from the AVHRR satellite sensors by developing temperature/nitrate relationships and nitrate/f-ratio relationships; estimates of new production provided an indication of the potential export to sediments. These data were used to estimate the likely losses of organic carbon by heterotrophic (respiratory) processes and the potential carbon export by sedimentation. The results demonstrate that microzooplankton have a major role in carbon cycling at the ocean margin.

Dissolved Organic Carbon and Phytoplankton Pigment Biomarker Fluxes

Dissolved organic matter (DOM) pools, and the quantification of biogeochemically-mediated changes therein, occurring over the continental shelf in the region of the Goban Spur (Celtic Sea) show a clear decrease (in winter) with fixed depth. Depth-integrated DOC concentrations were observed across the shelf, from coastal waters towards the open sea, representing removal of terrestrially-derived, and *in situ* produced, DOM across the shelf. Comparison of DOM concentrations for different seasons illustrates the summertime accumulation of DOM over the shelf and the subsequent sub-surface mixing under winter conditions. There is significant re-suspension/dissolution of material associated with bottom nepheloid layers, as demonstrated by the enhanced abyssal water DOM concentrations .

Seasonal distribution of phytoplankton pigments at the OMEX reference station revealed the characteristic chlorophyll sub-surface maximum at 30-50m in the summer, with concentrations ranging from 600-1000 ngm^{-3}, and deep mixing of the phytoplankton to below 200m in the winter. Most of the chlorophyll *a* was more evenly distributed in the upper 50m during spring and autumn. Integrated concentrations over 200m showed the highest levels in the spring, with a second less-pronounced maximum in the fall. The chlorophyll *a* levels in the 200m water column in the winter were similar to those estimated for the summer. Surface transect studies in July 1995 showed low chlorophyll *a* levels over deep water and elevated concentrations at the ocean margin, with sharp increases at particular localities on the shelf in the vicinity of 9.5-10.5°W and at 3°W.

Composition of Suspended Matter

Compositions of major components in suspended matter, collected by centrifugation, *in situ* pumping and sediment traps, showed a strong and rapid decrease in the biogenic fraction in the upper 200m of the water column, suggesting a preferential removal of this fraction due to production faecal pellet production and marine snow formation. Concurrent decrease in the content of organic and inorganic carbon, with increasing depth, demonstrates the importance of organic matter respiration and of calcium carbonate dissolution. Lithogenic and carbonate fluxes across the continental slope in the Goban Spur area were evaluated on the basis of sediment trap records. The production rate of calcium carbonate in surface waters (100g $CaCO_3$ $m^{-2}y^{-1}$), as deduced from primary production measurements, is much higher than (1) the rate of exchange of this component as determined from sediment traps observations (5-21g $CaCO_3$ $m^{-2}y^{-1}$) and (2) the estimated rate of burial (9-31g $CaCO_3$ $m^{-2}y^{-1}$). This strongly suggests the occurrence of carbonate dissolution in the water column that is likely to be associated with the respiration of organic matter at the surface of biogenic calcite or aragonite.

The concentration of trace elements in particulate matter collected from surface water is strongly affected by the dilution of suspended matter by phytoplankton which tend to remove the dissolved trace metals from surface water. However, all trace elements are enriched by the input of terrestrial material, when normalised with respect to aluminium. This enrichment is significantly higher in spring than in fall, and may be related to the fluctuation of the surrounding concentration of dissolved metals in the euphotic zone. The removal of many trace elements by plankton, thus contributes significantly to the biogeochemical cycling of these constituents. A notable exception to this behavioural trend of oceanic trace metals is particulate manganese. This element shows a depletion in surface water which has been attributed to photo-reduction processes. The most striking observation is the very rapid release of trace elements during settling which are remineralised mainly within the upper 500m of the water column. Nevertheless, there is a slight enrichment of trace elements in suspended matter collected at greater depths (below 1000 m) with respect to their mean composition in sediments derived from continental soils.

BIOLOGY

Zooplankton and Aggregates at the Goban Spur

Biomass and abundance are fundamental variables in the estimation of zooplankton production. Being closely linked to a great variety of elemental and energy processing rates, it is vital that both absolute biomass values and their variabilities are quantified. The Continuous Plankton Recorder (CPR) and the Longhurst-Hardy Plankton Recorder have been

deployed in the Celtic Sea to measure zooplankton biomass and abundance. The collected data were subsequently combined into a model which describes the vertical distribution of mesozooplankton biomass at the Celtic Sea shelf-edge through an annual cycle.

Research has concentrated on the estimation of mesozooplankton biomass and grazing pressures with variable horizontal and spatial resolution. This has been a major step forward in the use of CPR data in multidisciplinary studies. While long-term trends in biomass are not apparent in the Goban Spur area, a clear seasonal cycle of biomass does exist between shelf, slope and oceanic waters. The CPR data have been incorporated into models and used in estimates of carbon flux.

ADCP/SeaSoar survey data resolve mesoscale variability of complex patterns distributions for both biology and physics. Biomass measurements for meso-zooplankton, macro-zooplankton and micro-nekton show a marked decline, in an inshore direction, since April-May 1994. This pattern is likely to be the result of a weak migration signal being overshadowed by environmental patchiness and visual avoidance of nets. At the two deepest sites investigated in the OMEX study area, pteropods contributed about 50% of the estimated diel migration of carbon into the upper 200m.

Results from the benthic subproject concerning the slope show that well-developed bottom nepheloid layers are always present and intermediate nepheloid layers are present only intermittently. A seasonal variability in the concentration at the clear water minimum is thought to be related to the seasonal vertical flux and the aggregate break-up in transit during summer months. A budget of material constructed with additional information from trapping and *in situ* lander samples indicates that the mass arrival flux at the bed comprises a significant amount that is not measured by either traps or optical profiles of the nepheloid layer over 5m above the bed.

Vertical Flux Across the Goban Spur

The link between surface processes and particle fluxes at the slope are close in time and space at the Goban Spur. The prime determinant in the eventual fate of material at the continental margin is the importance of re-suspension and lateral advection below the depth of seasonal mixing. Physical conditions are crucial in distinguishing between along-slope (no exchange) or cross-slope (exchange) transport of dissolved and particulate matter. Perturbations in surface forcing are rapidly and directly reflected in changes in the flux of specific compounds. The continental margin functions differently for the exchange of different elements across this boundary zone, that is related to the mode of their transport.

Modelling of Pelagic-Benthic Coupling at the Goban Spur

Simulated seasonal cycles of chlorophyll and nutrients, and estimates of annual net primary production, run by one-dimensional models for a shelf break site on the Goban Spur, agree with OMEX (and CPR green colour) observations. The models with two microplankton boxes simulate the seasonal change from a spring microplankton, dominated by diatoms, to a nutrient-recycling summer microplankton, dominated by smaller organisms. Unlike observations of marine snow, a well-defined seasonal cycle in phytodetritus is predicted.

A coupled pelagic-benthic model, embedded in a turbulence-closure formulation to try to reproduce observations performed in the OMEX shelf break area revealed that the best results were obtained when herbivore consumption mimics micro-zooplankton grazing. In summer intermittent mixing events generate short-term nutrient injections which substantially increase euphotic zone production. A tentative nitrogen budget for the shelf break area

indicates that the sediment accounts for about 8% of organic nitrogen respiration; about 44% occurs in the euphotic zone; and the remaining 48% takes place in the water column below the euphotic zone. Over the year, only 56% of euphotic zone nitrogen assimilation is based on *in situ* regenerated inorganic nitrogen, the remainder is supplied from external sources, either in the form of nitrate (72%) or ammonium (28%).

A benthic diagenetic model has been used to fit the observed benthic pore water and solid phase profiles obtained along the Goban Spur transect with the sediment trap organic flux as external forcing. A methodological analysis of the process of inverse modelling has shown that the simultaneous use of pore water profiles of oxygen, nitrate and ammonium, combined with organic carbon profiles in the solid phase, constrains estimates of total mineralisation rate in the benthos to ± 25% or better. Fitted parameters were chosen to represent the significant off-slope transport of organic matter, which could subsequently be deposited in the margin or deep-sea sediments. The high degradability of the arriving organic matter and the consistency of the mass fluxes at the different stations provide the necessary constraints for hypotheses put forward.

Whether organic matter degradability, mixing activity, and total sediment mineralisation can be estimated by inversion of a coupled non-linear numerical diagenetic model was tested. Based on an extensive sensitivity analysis, it appears that the total mineralisation rates can be determined with reasonable precision. Total mineralisation rates can be assessed on the basis of nitrate and oxygen profiles only. The degradability of organic carbon prior to its incorporation in the sediment is of the order of 10-30 yr^{-1}, indicating that mineralisation at this slope station of the Goban Spur area is fuelled mainly by freshly deposited organic matter.

Trophodynamics and Vertical Fluxes on the North Norwegian Shelf

Seasonal variations in the supply of nutrients, the abundance and biomass of plankton and the intensity of vertical mixing along the north Norwegian shelf have revealed that bottom topography plays an important role in the formation of currents. In particular, at the shelf edge, the velocity of the current running across the shelf is high. Although the consumption of nutrients in this area is also high, nutrients were rarely depleted. The phytoplankton biomass consisted entirely of pico- and nano-plankton flagellates and monads. While microzooplankton do not appear to have an important role, the advection of mesozooplankton along and across the shelf was substantial and the vertical export of biogenic matter, such as detritus and faecal pellets, was high. The total biomass of planktonic organisms in the upper layers ranged from 3 to16g Cm^{-2}. The biomass of phytoplankton and protozoa ranged from 1 to 5g C $m^{-2}$and from 15 to 400mg Cm^{-2}, respectively.

Despite the significant consumption of nitrate and silicate, giving a new production rate of >75g C m^{-2}, large-celled organisms such as diatoms and dinoflagellates did not play an important role on the shelf. Large phytoplankton and protozoa were not present in the water column because of intensive mesozooplankton grazing. The north Norwegian shelf is thus characterised by high productivity and by low chlorophyll, which is typical for systems subjected to extensive grazing. This part of the European continental margin shares similarities with several large regions of the global ocean

The traditional concept of plankton dynamics in sub-arctic environments, which have short food-chains involving large organisms, seems inadequate for explaining pelagic cycling of biogenic matter on the north Norwegian shelf. The proposed prevalence of short food webs over the microbial loop under the influence of hydrodynamic singularities, such as fronts,

eddies and upwelling areas, is not necessarily the controlling factor in shelf systems. The advection and the over-wintering of mesozooplankton may be of significance for pelagic carbon cycling. The hydrodynamic conditions on shelves do have a major role in enhancing the export of organic matter, but this export is strongly influenced by both mesozooplankton grazing and *in situ* recycling. The assessment of resource availability and predation together offers a new conceptual framework within which the apparent regulation of the pelagic trophic structure on the north Norwegian shelf can be explained.

BENTHICS

The aim of the Benthic Processes subproject was to establish the transport pathways and processes and quantify the amounts involved in exchange of matter and energy from the continental shelf, over the slope to the deep sea. The ultimate goal was to determine the influence of the European continental margin for the global carbon cycle. The benthic processes studies were concentrated on the NE Biscay Margin (Goban Spur and Meriadzek Terrace), while a few small-scale and local studies were carried out off Galicia and off SW Portugal.

Nepheloid Layer Dynamics

Across the Goban Spur, surface nepheloid layers (SNL) of variable intensity and thickness were recognised at all stations and during all seasons. Intermediate nepheloid layers (INL), however, were rare, appearing to have an intermittent, temporary character. At all stations and during all seasons well developed bottom nepheloid layers (BNL) were present and found to range in thickness and intensity. The BNL's are downslope increasingly thick with a decreasing particle concentration, suggesting gradual settling of particles over the lower part of the slope. Concentrations of SPM range from 50-130$\mu g\ l^{-1}$ in nepheloid layers and from 12-25$\mu g\ l^{-1}$ in clear water. The composition of the particles within the BNL changes from diatom-dominated populations at the shelf and on the upper slope, to coccolithophore-dominated populations deeper down the margin, with a minor admixture of diatoms.

A budget of material based on trapping and in-situ lander samples shows that mass sediment arrival at the seabed comprises a significant amount of material not measured by traps or in the INL, suggesting that the main transport of particles is close to the seabed within the BNL.

This observation is supported by long and short term current velocity measurements in the lower 100cm above the seabed near mid-slope station OMEX II, where near bed current velocities (measured by Lander BOBO) have a semidiurnal tidal component and reach maximum velocities of up to 20 cms^{-1} for some 15-20% of the time. These currents are dominantly directed off slope. Similar magnitude peak velocities (15-25 cms^{-1}) were measured at the Meriadzek Terrace. These velocities are sufficiently high to periodically re-suspend, transport and prevent the settling of particles, causing either formation of a local INL or prolonged persistence of the BNL. Currents are stronger in autumn than during summer and both the long and short term records suggest interannual variability.

Short term flow velocity determination in the lower 40cm above the seabed shows that currents increase from the shelf to the mid slope and indeed are higher in autumn and winter. Decreasing values over the lower slope and lowest values at the continental rise support the mechanism of along and downslope transport of particles and organic matter in the BNL.

At the mid slope, high numbers of aggregates and small aggregate sizes occur associated with highest flow conditions (around 1400m water depth, station OMEX II/BOBO). Highest flow conditions here may cause re-suspension events and intermittent INL formation at the continental slope between 1000 and 1400m water depth. This interpretation is supported by the fact that the deeper sediment traps at OMEX II and III have highest C_{org} input, thus supporting the lateral input interpretation. Re-suspension and BNL transport at the upper slope and shelf is also evident from the freshwater and shelf diatoms found in the surface sediments along the transect.

It appears that aggregate formation is the main process controlling particle accumulation at the continental margin and lower slope, in line with the SEM observations on particle composition of the BNL. In the near bottom waters hydrodynamic sorting of the POC fraction occurs, and the main organic fraction has low settling velocities and high residence times in the benthic boundary layer (BBL). The degree to which carbon is made accessible to the benthic community therefore depends on aggregate formation, settling and/or biodeposition of the POC fraction.

Sedimentation and Accumulation Rates

Total organic carbon in the top two mm of the Goban Spur surface sediment increases from 0.1% (wt) at the upper shelf to 0.7% at the slope break, to decrease again with station depth to values between 0.3-0.4% at the continental rise. These values are much lower than those at the Tagus and Sado continental shelf off Portugal, where local maxima of 5% are found and at the shelf break where the organic matter content is still on average 1%. This is most likely the result of the proximity of the (estuarine) source and is governed by hydrodynamics rather than by remineralisation. The local mid slope high value of 0.7% does not coincide with more elevated benthic oxygen consumption rates. C/N ratios and carbon isotope determinations of the organic matter indicate that the C_{org} is mainly of marine origin.

^{210}Pb profiles of box-and multicores shows mixing of the surface sediments down to 5cm sediment depth, below that level the downcore organic carbon has low average background values of 0.3% and is largely of refractory origin. At Meriadzek Terrace these values are slightly higher, around 0.5-0.3%. Taking into account the trap-determined organic carbon flux to the seabed (at OMEX II 2.75g $m^{-2}y^{-1}$ C_{org}, at OMEX III 2.47g $m^{-2}y^{-1}$ C_{org}), the carbon mineralisation rates measured (at OMEX II 6.16g $m^{-2}y^{-1}$ C_{org} and at OMEX III 3.14g $m^{-2}y^{-1}$ C_{org}) and the carbon burial fluxes (0.05 - 0.10g $m^{-2}y^{-1}$ C_{org}), this again emphasises that lateral transport of organic matter is occurring, mainly in the BNL and that the burial fluxes at all stations are low and vary from 0.9-4.5% of the mineralisation flux. This is to a lesser extent the case at Meriadzek Terrace, where the organic carbon export flux is considered negligible. Late Holocene total sediment accumulation rates at Goban Spur and Meriadzek Terrace are slightly higher than sediment input at the lower continental margin and rise, but are considerably lower at the upper slope, compared with the trap data, again evidencing sediment transport over the slope, towards the deep sea, where mass accumulation fluxes are highest.

Oxygen is responsible for the major part (>90%) of the organic carbon mineralisation at the sediment-water interface and directly below the seabed, as indicated both by pore water modelling results and by direct oxygen measurements. Denitrification is only of minor importance (<5%) for the organic carbon mineralisation, and anoxic mineralisation plays but a small role, mainly in the shallowest stations. There is a decrease of sediment oxygen demand with water depth, contradicting the hypothesis of increased carbon deposition and accumulation at the slope.

Benthic-Pelagic Coupling

The NE Biscay Margin slope at Goban Spur is clearly no carbon depocenter. Long-term studies of carbon fluxes show that present day fluxes are lower than during the last glacial maximum and the deglaciation, when the input of terrigenous Corg to the continental slope was high; a switch to marine dominated carbon input was around 10,000 yr BP. The downcore ^{210}Pb profiles of annually repeated boxcore samples show a decrease of sediment mixing rates with increasing water depth, and a direct correlation between mixing coefficients with macro- and meio-faunal density. The macrofaunal densities and biomass decrease exponentially with depth and macrofauna is concentrated in the upper 1cm of the sediment, especially in the upper slope. Here also higher densities are found in May/June, suggesting dependence on the input of fresh phytodetritus (also observed on Meriadzek Terrace) and seasonal and possibly interannual variability of the organic matter input. Elevated pigment concentrations in May/June are consistent with the increased, pulsed input of fresh, labile organic matter in this period and with the high loads of phytodetritus observed in short term deployed lander traps.

An observed pulsed input of fresh labile organic matter at the lower continental rise and slope, comprised a carbon input exceeding the annual input measured from traps, however this pulse does not contribute to the Goban Spur carbon budget. This is especially clear in the different pigment and sterol composition of the upper slope stations. Meio-benthic communities are dominated by nematodes and densities, biomass and mean individual nematode weight decrease with increasing waterdepth. The total carbon demand of the fauna cannot be met by direct sedimentation and needs additional advective carbon sources. Respiration by the benthic community accounts for 50-60% of the benthic mineralisation at the slope but only for 10-20% in the deeper stations. Benthic metabolism here is dominated by very small organisms, mainly bacteriae and protozoans, and suggest a very rapid reaction of the benthic infauna to the episodic input of phyto detrital matter.

CARBON CYCLING AND BIOGASES

In trying to model the coupling and exchange of CO_2 and biogases between the ocean and the atmosphere for the European marginal seas, focus has been paid to how the process of carbon fixation combines with the intense and highly variable biological activity, the changing global atmospheric conditions and the complex ocean processes occurring at the ocean margin.

Sulphur Compounds

Volatile sulphur biogases, particularly DMS, COS and precursors, show a strong seasonality for both gases, and there is a strongly enhanced production of DMS at the shelf break zone. DMS shows a general flux from the ocean to the atmosphere, while COS shows less systematic geographical variation and appears to use the ocean not only as a sink, but also as a source.

Correlations between DMS, DMSP and DMSO distributions as well as temperature, pigments and chlorophyll, were examined to provide a clearer picture of this source-sink cycle. The results clearly indicate that continental margin has a significant role in the exchange of gases between the air and the sea through the activities of biological organisms in this area. The new methods developed to determine during OMEX I and refined during OMEX II-I have yielded useful data concerning the concentrations of dimethylsulphoxide

(DMSO) and concentrations and fluxes of DMS. This research has further enabled OMEX partners to successfully establish semi-automatic systems to measure DMS and COS.

Carbon Compounds

Vertical profiles of carbon isotopes, CO_2 and CH_4 show great horizontal variability, confirming the increasing complexity of on-going activities at the margin. The along-slope currents at different depths can advect concentration patterns originating from vertical exchanges occurring in entirely different source areas. Underway measurements of pCO_2 in surface waters along the continental margin in the Gulf of Biscay show large fluctuations which deviate significantly from those pertaining to the atmosphere. These fluctuations are attributed in part to the high biological activity occurring at the margin, particularly during upwelling events, that acts to lower the concentration of pCO_2. In contrast, vertical mixing of deep cold water with surface water increases the concentration of pCO_2, thereby contributing to the marked fluctuations exhibited by this compound.

Exchange at the Air-Sea Interface

Assessing the origin and evolution of bubbles, in water and in air, has been facilitated by the development of a new measuring system which documents the frequency of bubbles in seawater from buoys. Air CO_2 fluctuations have now been successfully tested in conjunction with measurements of CO_2 fluxes using the exchange coefficient method and a variety of fixed platform experiments. Comparison between the CO_2 flux estimated by different groups using different methods shows good agreement. Results from onboard experiments with the bubble measuring buoy have been reasonably successful and it is now expected that facilities for measuring bubble formation and CO_2 flux will be available to OMEX partners.

Using data from equilibrators, it has now become possible to determine the partial pressure of CO_2 and CH_4. Using the micrometeorological and the exchange coefficient methods we can now establish the CO2 fluxes by two independent methods and also study in more detail those situations where the two methods disagree. The main highlights of the subproject have so far been 1) a contribution to the mapping of source and sink regions within the European margins for atmospheric sulphur and carbon gases and 2) a successful application of a number of new techniques for estimating gas concentrations and fluxes. Tentative estimates of air-sea exchanges of several gases, such as CO_2, DMS, COS , are now available. This information of special importance for the role of the ocean, and here with focus on the ocean margin, as source and sink for atmospheric trace gases.

ACKNOWLEDGEMENTS

This work was supported by the EU MAST III Programme (Contract Number MAS3-CT96-0056). All OMEX II-I partners are acknowledged for their contributions to the progress achieved. We also thank Andrea Bullock for the preparation of this document.

TITLE: Ocean Margin EXchange II - Phase II (OMEX II-II)

CONTRACT NUMBER: MAS3-CT97-0076

CO-ORDINATOR:

Roland Wollast/Lei Chou
Université Libre de Bruxelles
Laboratoire d'Océanographie Chimique
Campus de la Plaine CP-208
Boulevard de Triomphe
B-1050 Brussels, Belgium
tel: (32)2.650.5212/5237
fax: (32)2.646.3492
email: rwollast@ulb.ac.be
lchou@ulb.ac.be

PARTNERS:

John Huthnance
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead, Merseyside
United Kingdom L43 7RA
tel: (44)151 653 8633
fax: (44)151 653 6269
email: JMH@wpo.nerc.ac.uk

Tjeerd van Weering
Netherlands Institute for Sea Research
P. O. Box 59
1790 AB Den Burg
Texel
The Netherlands
tel: (31)222 369 395
fax: (31)222 319 674
email: haas@nioz.nl

Paul Wassmann
Norwegian College of Fishery Science
University of Tromsø
N-9037 Tromsø
Norway
tel: (47)776 44459
fax: (47)776 46020
email: paulw@nfh.uit.no

Peter Burkill
Plymouth Marine Laboratory
Prospect Place, West Hoe
Plymouth
United Kingdom PL1 3DH
tel: (44)1752 633 422
fax: (44)1752 633 101
email: PHB@WPO.NERC.AC.UK

ASSOCIATED PARTNERS

Dr Hans van Aken
Netherlands Institute for Sea Research
P.O. Box 59
1790 AB Den Burg
Texel
THE NETHERLANDS

Dr Ricardo Anadón
Laboratorio de Ecología
Departamento de Biología de Organismos y Sistemas
Universidad de Oviedo
C/ Catedrático Rodrigo Uría, (S/N)
E-33071 Oviedo
SPAIN

Dr Des Barton
School of Ocean Sciences
University of Wales Bangor
Menai Bridge
Anglesey LL59 5EY
UNITED KINGDOM

Dr Sonia Batten
Sir Alister Hardy Foundation for Ocean Science
c/o Plymouth Marine Laboratory
Citadel Hill
Plymouth PL1 2PB
UNITED KINGDOM

Dr Antonio Bode
Instituto Espanol de Oceanografia
Apdo. 130.
E-15080 La Coruna
SPAIN

Dr Peter Bowyer/Dr Martin White
Department of Oceanography
University College Galway
Galway
IRELAND

Pr Joan Manuel Alveirinho Dias
UCTRA
Universidade do Algarve
Campus de Gambelas
8000 Faro
PORTUGAL

Dr Gerard Duineveld/Pr Peter de Wilde
Netherlands Institute for Sea Research
P.O. Box 59
1790 AB Den Burg
Texel
THE NETHERLANDS

Pr Emilio Fernández
Facultad de Ciencias del Mar
Universidad de Vigo
Campus Lagoas-Marcosende
E-36200 Vigo
SPAIN

Dr F.G. Figueiras/Dr X.A. Alvarez Salgado
Instituto de Investigaciones Marinas
Consejo Superior de Investigaciones Científicas (CSIC)
Eduardo Cabello, 6
E-36208 Vigo
SPAIN

Dr Michel Frankignoulle
Mécanique des Fluides Géophysiques
Université de Liège
Unité d'Océanographie Chimique (B5)
B 4000 Sart Tilman
BELGIUM

Dr Helena M. Galvão
UCTRA
Universidade do Algarve
Gambelas
P - 8000 Faro
PORTUGAL

Pr F. Dehairs/Ir M. Elskens
Dienst Analytische Scheikunde
Vrije-Universiteit Brussel
Pleinlaan 2
B-1050 Brussels
BELGIUM

Mr. Steve Groom
NERC
Remote Sensing Data Analysis Service
c/o Plymouth Marine Laboratory
Prospect Place
West Hoe, Plymouth PL1 3DH
UNITED KINGDOM

Pr Carlo Heip
Centre for Estuarine and Coastal Ecology
Netherlands Institute of Ecology
P.O. Box 140
4400 AC Yerseke
THE NETHERLANDS

Dr Willem Helder
NIOZ
P.O. Box 59
1790 AB Den Burg
Texel
THE NETHERLANDS

Dr Peter Herman/Dr Jack Middelburg/Dr Karline Soetaert
Centre for Estuarine and Coastal Ecology
Netherlands Institute of Ecology
P.O. Box 140
4400 AC Yerseke
THE NETHERLANDS

Dr Alan M. Davies
Bidston Observatory
Proudman Oceanographic Laboratory
Birkenhead, Merseyside L43 7RA
UNITED KINGDOM

Dr Ian Joint
Plymouth Marine Laboratory
Prospect Place
West Hoe, Plymouth PL1 3DH
UNITED KINGDOM

Dr Meirion Jones
British Oceanographic Data Centre
Bidston Observatory
Birkenhead, Merseyside
L43 7RA
UNITED KINGDOM

Dr Jean-Marie Jouanneau
Département de Géologie et
d'Océanographie
Université de Bordeaux I
Avenue des Facultés
F-33405 Talence Cedex
FRANCE

Dr Robin Keir
GEOMAR
Wischhofstrasse 1-3
D-24148 Kiel
GERMANY

Dr Richard Lampitt
Southampton Oceanography Centre
Empress Dock
Southampton SO14 3ZH
UNITED KINGDOM

Dr Søren Larsen/Dr Lise-Lotte Geernaert
Department of Meteorology and Wind Energy
RISØ National Laboratory
4000 Roskilde
DENMARK

Pr I. Nick McCave/Dr Ian R. Hall
Department of Earth Sciences
University of Cambridge
Downing Street
Cambridge CB2 3EQ
UNITED KINGDOM

Dr Axel E.J. Miller/Dr Stuart Gibb/
Plymouth Marine Laboratory
Prospect Place
West Hoe, Plymouth PL1 3DH
UNITED KINGDOM

Pr Ramiro Neves
Department of Mechanical Engineering
Instituto Superior Técnico
Avenida Rovisco Pais, 1
1096 Lisboa Codex
PORTUGAL

Dr Rolf Peinert/Dr Avan N. Antia
Institut für Meereskunde
Universität Kiel
Olshausenstrasse 40
D-24118 Kiel 1
GERMANY

Dr Jean-Louis Reyss
Centre des Faibles Radioactivités
Domaine du CNRS
Avenue de la Terrasse
F-91198 Gif sur Yvette Cedex
FRANCE

Ms Aurora Rodrigues
Marinha-Instituto Hidrográfico
rua das Trinas 49
1296 Lisboa codex
PORTUGAL

Dr Toby Sherwin
Marine Science Laboratories
Uniersity College of Wales, Bangor
Menai Bridge, Anglesey LL59 5EY
UNITED KINGDOM

Dr Dag Slagstad
SINTEF Electronics and Cybernetics
Automatic Control
N-7034 Trondheim
NORWAY

Pr Kurt Tande
Norwegian College of Fishery Science
University of Tromsø
N-9037 Tromsø
NORWAY

Dr Laurenz Thomsen/Dr Gerhard Graf
GEOMAR
Wischhofstrasse 1-3
D-24148 Kiel
GERMANY

Dr Carlos Vale
Instituto de Investigacao das
Pescas e do Mar
Avenida Brasilia
1400 Lisboa
PORTUGAL

Dr João Vitorino/ Dr Emanuel
Ferreira Coelho
Marinha-Instituto Hidrográfico
rua das Trinas 49
1296 Lisboa codex
PORTUGAL

Ocean Margin EXchange II - Phase II

Roland WOLLAST[1], Lei CHOU[1], Peter BURKILL[2], John HUTHNANCE[3], Paul WASSMANN[4] and Tjeerd van WEERING[5]

[1]Université Libre de Bruxelles
[2]Plymouth Marine Laboratory
[3]Proudman Oceanographic Laboratory
[4]University of Tromsø
[5]Netherlands Institute for Sea Research

SUMMARY

The main objectives of Ocean Margin EXchange II - Phase II (OMEX II-II) are to construct and to understand the carbon cycle and its associated elements along the Iberian margin. This area is dominated by wind driven upwelling events during the summer, and by river inputs and downwelling during the winter. Coastal upwelling areas are among the most productive biological systems in the ocean and therefore of particular economical interest. They are also characterised by large fluxes of organic carbon, nutrients and other trace elements which may be exported to the open ocean or rapidly deposited and buried at geological time scales. The coastal upwelling regions are thus playing an essential role in the marine biogeochemical cycle of many elements. The study of the physical processes should provide knowledge of the local factors (wind and topography) affecting horizontal and vertical transport in relation to the general circulation. Special attention will be devoted to the role of filaments and eddies in the exchange of material between the coastal zone and the open ocean. Short time scale measurements of flows of carbon and nutrients through the food web will be performed during upwelling events and occasionally in the winter during periods of downwelling. On the other hand, spatial and seasonal variations of the inventories and fluxes of the carbon and associated elements will be investigated to obtain a mass balance of organic matter in the water column in the area of study. A large part of the primary production in the coastal upwelling zones is rapidly deposited. Therefore, a special attention will be brought to the understanding, quantification and modelling of the benthic processes related to biological activity and early diagenesis. A better knowledge of the carbon fluxes and budgets will improve our evaluation of the role of upwelling in organic carbon production and fate in the marine system. This study may refine our understanding of the effect of coastal upwelling on the global climate control and vice versa of potential effects of global warming on the upwelling processes.

INTRODUCTION

The coastal zone represents the main interface between the land and the open ocean. It is an area of enhanced productivity under the strong influence of continental input, and is an important source of dissolved and particulate matter for the open ocean. On the other hand, deep ocean waters, nutrient-rich and with high concentration of trace elements, are transferred across the shelf edge and help to sustain the high productivity of biota in the coastal zone and shelf seas. The quantification of fluxes across the ocean margin is thus a fundamental requirement for the evaluation of the carbon budget and nutrients between the continents, the coastal zone and the open ocean.

It has been widely recognised today that there is a lack of knowledge and understanding of the processes occurring at the ocean margin which is critical for the evaluation of global biogeochemical cycles (Walsh, 1988; Mantoura *et al.*, 1991; Wollast *et al.*, 1993). A comprehensive understanding of the distinctive and often enhanced processes occurring at this boundary is, however, a prerequisite for the prediction of the consequence of climatic change and of other anthropogenic perturbations.

The Ocean Margin EXchange project is designed to meet the priority goals of the International Geosphere-Biosphere Programme (IGBP), taking into account the specific features of the European marine environments and settings, and the expertise of the European oceanographic community. The project focuses essentially on the study of fluxes and processes occurring along European shelf break facing the North Atlantic Ocean. Its aim is to measure and to model exchange processes at this margin to provide a basis for the development of global models that predict the impact of environmental changes on the oceanic system in general and, more specifically, on the coastal zone.

During the first phase of OMEX, efforts have been concentrated on the Goban Spur area in the northern part of the Gulf of Biscay. This zone is characterised by a very broad continental shelf with a typical shelf edge front which encourages the vertical mixing of nutrient-rich deep ocean water with surface water, thereby inducing an enhanced primary production along the margin.

The focus of OMEX II-II will be on the upwelling region of the Iberian coast. Coastal upwelling occurs extensively at eastern Atlantic and Pacific margins and these areas are some of the most productive marine systems. It is estimated that these areas supply nitrate for 11% of the global new production (Chavez & Toggweiler, 1995). A largely wind-driven phenomenon, upwelling is complex in both space and time, making it difficult to understand how physically driven biogeochemical systems are integrated. Knowledge of how upwelling systems function today is essential for predicting how they may change in the future, particularly in view of the possibility of a global climate change (Summerhayes *et al.*, 1995). Such understanding can only be achieved through an interdisciplinary approach.

The main objectives of OMEX II-II are to construct and to understand the carbon cycle and its associated elements along the Iberian Margin, dominated by variable upwelling processes. Major questions have been raised that need to be addressed if one is to improve the mechanistic understanding of the Iberian Margin system. In particular, it is necessary to gain a better knowledge of those processes that control fluxes associated with upwelling and downwelling, and this will require a well integrated multidisciplinary approach. Accordingly, OMEX II-II is organised into multidisciplinary Work Packages, listed below, each of which integrates physics, biology, chemistry and geology.

Work Package I:	Temporal Evolution of Surface Production and Fate of Organic Matter
Work Package II:	Spatial and Seasonal Fluxes and Biogeochemical Processes in the Water Column
Work Package III	Fluxes and Processes in the Nepheloid Layers and Surface Sediments
Work Package IV:	Integrated Margin-Exchange Product
Work Package V:	Project Management and Co-ordination

The WP I focuses upon understanding the mechanisms and processes involved in the temporal evolution of primary production and its fate during typical upwelling and downwelling events. This will be achieved using a quasi-Lagrangian approach. Since WP I addresses relatively localised space and time scales, WP II will focus on a broader space (Iberian margin from the coast to beyond the ocean front between 41°25'N and 43°N) and time (seasonal) scales within the pelagic zone. In addition, while WP I addresses the biological processes occurring during upwelling events, WP II is more oriented towards the study of biogeochemical processes, with emphasis on the spatial and seasonal variation of fluxes. The objective of Work Package III is to contribute to the understanding, quantification and modelling of the benthic processes involved

in exchange of carbon and associated elements along the Iberian ocean margin. Much of the research transcends different Work Packages: an example is that concerned with the trajectories of particles in the water column which involves WP I, II and III. To maximise the products of the individual partners, Work Package IV is responsible for integrating and, where necessary, synthesising measurements, to provide data for, and to calibrate models. Comparison and integration of OMEX II-II results with those obtained from other ocean margin studies will contribute to the final objective of OMEX which is to understand and to evaluate exchange of material at these boundaries, while providing a model to predict the impact of environmental change on the oceanic system at a global scale.

WORK PLAN

Work Package I: Temporal Evolution of Surface Production and Fate of Organic Matter

The short-term temporal evolution of surface production and fate of organic matter will be investigated on the shallow shelf (< 200m) and at the shelf edge during upwelling, relaxation and downwelling cycles off Galicia, north-western Iberian Peninsula. The overall goal is to understand and to model the dynamics of production, degradation and export of organic matter. The more specific objectives of WP I are to study the production and fate of organic carbon on the shallow shelf and along/across its margin, to approximate the flux of new nitrogen from oceanic deep water into the surface ocean and onto the shelf and analyse the temporal variability of primary and new production as well as recycling. In addition, this work package will also examine the role of a shallow shelf for the production and development of zooplankton, the microbial loop and vertical flux and to evaluate to what extent shelf production is exported to the ocean interior.

Short-term field investigations will be carried out with oceanographic vessels by WP I partners. Contingent upon ship time, two seasons will be selected: the upwelling season (July-August) and the downwelling season (autumn/winter). In order to achieve the aim, WP I will focus on the following tasks involving physical, biological and biogeochemical aspects.

- On-, off- and along-shelf transport of water, filament transport and turbulence
- Inorganic carbon biogeochemistry and atmospheric CO_2 uptake and release
- Nutrient dynamics, primary production, biomass and phytoplankton
- Zooplankton and microbial cycling
- Suspended matter, aggregation potential, faecal pellet production and vertical flux
- 2-way nested sub-model, Lagrangian particle-tracking and ecological model
- 3D nested model for the Galician shelf: ecological response and interannual variation in the carbon export

Work Package II: Spatial and Seasonal Fluxes and Biogeochemical Processes in the Water Column

The overall aim of WP II is to measure and model the mesoscale spatial and seasonal variability in the oceanic, coastal and terrestrial sources of water, particles, carbon and nutrient elements in shelf, upwelling and slope waters of the Iberian Margin. Broadly, methods will be based on strategic moorings of current meters, pumps, sediment traps combined with shipboard oceanographic mapping and profiles of CTD, turbulence, chemical, microbiological and geochemical rate measurements during summer upwelling and winter regimes.

A multidisciplinary task force of scientists will generate the essential hydrodynamic and biogeochemical data needed to quantify the mesoscale distributions of the summer upwelling and filament regime and the winter discharge and eddy regime along NW Iberian Margin. Our

aim is to construct budgets of the flows of water, carbon and nitrogen through an approximately 100 x 100 km box on the Iberian Margin. WP II strategy combines moorings fitted with current meters and sediment traps with on-shelf cruise tracks for hydrography, turbulence, nutrients, carbon, plankton, and satellite remote sensing. Partners will deploy advanced hydrographical techniques, tracers for water masses, turbulence probes, and high resolution chemical methods that measure all forms of nitrogen, carbon and plankton biomass in the seawater. The resulting biogeochemical and hydrodynamical data fields will make it possible to complete a regional mass balances for carbon and nitrogen in the water column, to 'seatruth' and develop mapped products from satellite sensed images. An important aim of the WP II is to validate 3-D numerical circulation models of the Iberian Margin. WP II studies will address (1) the balance of terrestrial versus marine sources of nutrients, (2) whether upwelling systems are net ventilators of supersaturated CO_2 or biological pumps for drawdown of atmospheric CO_2, (3) the coupling between climate (winds, temperature), upwelling and ocean margin fertility, and (4) the quantitative role of upwelling, longshelf, longslope and filaments in the export of organic matter to the ocean, and (5) whether the slopes act as 'depocentres' for the burial of carbon on the Iberian Margin. The WP II activity concentrates on the following investigations involving all disciplines:

- Moorings, currents, circulation, flow fields
- Water mass analyses by conservative and transient tracers
- Spatial distribution of turbulence and mixing
- Nutrient distribution, speciation, upwelling and fluxes
- Source markers of particulate matter
- Dissolved organic carbon
- CO_2 drawdown and ventilation
- Primary, new and size-fractionated production
- Microbial populations as pelagic sinks
- Mesozooplankton distribution and production processes
- Suspended and sedimenting marine organic and terrestrial matter
- Remote Sensing and Biogeochemical algorithms

Work Package III: Fluxes and Processes in the Nepheloid Layers and Surface Sediments

The main objective of WP III is to contribute to the understanding, quantification and modelling of the benthic processes involved in the exchange of carbon, elements and energy at the Iberian ocean margin. Results obtained and models developed will be compared and integrated with those attained for other well studied European and other continental margins such as the Biscay and Mediterranean margin (Gulf of Lions) and the Middle Atlantic Bight. WP III will contribute to the main objective of OMEX II-II "to measure and model exchange processes at the ocean margins as a basis for the development of global models to predict the impact of environmental changes on the oceanic system, and more specifically, on the coastal zone".

To meet these objectives WP III studies will be carried out by conducting field measurements and subsequent laboratory analysis, interpretation and data integration. The results obtained will then be used for integration with those of WP I, II and IV, and for verification and validation of physical, diagenetic and ecological models of shelf-slope-margin exchange processes and fluxes. By comparison and integration of the results and models obtained with data and results from other well studied European and other continental margins, WP III will eventually contribute to the evaluation of budgets of carbon exchange between the ocean and the coastal zone in response to environmental change. The following investigations will be the major foci of WP III:

- To establish and to quantify particle transport, settling, accumulation, mixing and burial fluxes: temporal and spatial variability
- To study and to assess sediment/water exchange processes and early diagenesis
- To evaluate the role and importance of the benthic community

Work Package IV: Integrated Margin-Exchange Product

OMEX aims to measure and understand the fluxes contributing to ocean margin exchange of water, carbon, nutrients, lithogenic and biogenic particulate matter. Corresponding objectives of WP IV integration are: to synthesise the measurements obtained on complementary cruises in WP I, II, III, forming consistent flux and budget estimates from these data; to integrate models to form these budgets and thereby test understanding of these fluxes; to study sensitivity to global climate change, particularly that brought about by human activities.

The principal means of integration are:

- the extrapolation of relationships established from detailed process-related measurements in WP I, to derive values of additional variables from the spatially-extensive measurements in WP II, along with the inter-calibration (of essentially the same measurement by different partners) and the inter-comparison between the different approaches for compatible flux estimates;
- the determination of ocean margin flux and budget estimates (differing "cross-cutting" views according to constituent and aspect, for example 2-D cross-slope section, "summer", "winter") combining information of varied dimensionality, resolution and extent, pre-OMEX data and models; and
- the development of integrated margin exchange models.

WP I focuses on time-evolution in a small drogued patch of water, minimising complexities of spatial variation. WP II provides a context of systematic spatial coverage, in both horizontal dimensions and through the water column, on larger scales in space and time. Remote sensing provides in-filling temporal and spatial coverage of surface features between the in situ measurements. WP III studies benthic conditions at all time scales. Following this approach, WP IV aims to form compatible estimates of fluxes at the Iberian margin, testing consistency and understanding by forming budgets. The final WP IV objective and thus that of OMEX II-II is to form an integrated margin exchange model.

Water budget and circulation

Compatible estimates of circulation and fluxes of water at the Iberian margin will first involve water mass analysis, to quantify biogeochemical water mass modification due to cross-margin exchanges and mineralisation of organic matter. Tracers will determine observed waters as combinations of source water types, derived from WP I and WP II CTD and pre-OMEX data. Description of the flow field will be made, on the basis of analysis and mapping of OMEX and previous current measurements. WP II moorings in three cross-slope sections will show spatial and temporal variability, with interpolation and extrapolation over cruise tracks by ship-borne profiler.

Consistency will be tested and understanding gained by forming budgets, in particular for lateral exchange between two cross-slope sections using a characteristic tracer, for example enhanced salinity. Fluxes in filaments and eddies will be estimated using WP I and locally detailed WP II survey measurements as "sea truth" for satellite data showing these features' statistics and form.

Finally models will be developed to identify water masses, residence times and trajectories and to calculate fluxes, budgets and effective diffusivities on a coarser grid. 3-D simulations of the OMEX period will be forced by a meteorological model of the actual weather and guided by OMEX data.

Carbon sources, cycling and fates

Dissolved and particulate carbon sources, cycling (fluxes) and fates will be quantified, and integrated to form a budget. The research will involve horizontal exchange: riverine and oceanic sources, advection, filament transport; it also deals with air-sea import & export (exchange) of CO_2. The pelagic cycling, pelagic-benthic coupling, and benthic cycling and burial will also be investigated. Finally long-term record will be studied using transect cores, stratigraphy and proxies.

Nutrients, trophodynamics and fertility

Compatible estimates of nutrient and organic matter concentrations and fluxes (nutrient supply, sources, speciation, assimilation, remineralisation) will be assured by intercalibrating measurements of nutrient concentration, dissolved organic matter, pigments, primary production, nutrient uptake, nutrient regeneration and grazing. Different methods of estimating fluxes will be compared.

In situ determinations of nitrate concentration and its relationship to f-ratio and sea surface temperature (SST) will enable estimates of f-ratio from satellite SST images. Models will evaluate phytoplankton production from remote-sensed chlorophyll. Hence both primary and new production, and the influence of wind-driven upwelling and filaments, may be assessed.

WP I will enable temporal changes following upwelling to be fully described; nutrient flux through phytoplankton and zooplankton will be estimated, eg. microzooplankton grazing as a function of independent variables. WP II measurements will be used to quantify variability in nutrient flux and production on a time-scale of months. Modelling and remote sensing will interpolate between cruises and extrapolate to longer time scales.

Particle dynamics, scavenging and trapping

Estimates of particulate fluxes will involve their dynamics, scavenging, trapping, characterisation in the bottom boundary layer of the processes of re-suspension, particle aggregation, settling, disaggregation and sediment accumulation - all in relation to hydrodynamic conditions - and microbial processes. These processes' role in ocean-margin carbon flux will be estimated, assessing the importance of the benthic boundary layer for ocean margin exchange by comparison with sedimentation as recorded by traps. Vertical, lateral and resuspended particle contributions will be discerned, with the aid of analyses to distinguish biogenic and lithogenic material.

Sensitivity of upwelling systems to environmental changes

Consequences of global changes at the NW Iberian margin, and the capacity for anthropogenic inputs, will be estimated. The sedimentary (past) record from cores will be used to

- quantify enhanced productivity during the late glacial;
- determine if productivity and carbon storage values were lower in the warm climate (6000y bp);
- determine if a filament indicator is present under a recurrent filament more than nearby;
- examine the seasonal and on/off-shore spatial extent of past upwelling systems.

Sensitivities will be investigated via the past record and by modelled scenarios using the Iberian OMEX-validated 3-D hydrodynamic model. It will be re-run using stepped changes in climate forcing (wind, heat flux, river export, sea level) appropriate to a "Greenhouse" scenario. The model with embedded biology will also be run; it will track climate change consequences for the flow of water, production, particulate and dissolved carbon. For effects on the capacity of the Iberian margin to trap or disperse pollutants, constituent parameters (partition coefficients, specific degradation rates) will represent transformation processes.

Integrated margin exchange model

Various components of the integrated model components are to be developed. The first one concerns a general circulation model for interaction between the NW Iberian study area and the NE Atlantic. It will apply "real" meteorological forcing, an explicit turbulence scheme using specific measurements, variable-size vertical and horizontal grids and best bathymetry in the NW Iberian area, to provide the data necessary to run the local nested model.

A nested model of grid size (1 km will also be developed. It will give detail of the local flow (eg. mechanisms of filament formation and development), its interaction with fine-scale local bathymetry, and advective and diffusive transport for the water column ecological model.

A water column ecological model will be established wherein state variables include nutrients, phytoplankton, zooplankton and their role in the formation of particles. Formulation and validation will be iterative, short-scale process rates and rate-determining parameters being constrained by the WP I Lagrangian experiment. They will form a basis for simplified versions whose sensitivity and representation of successions and seasonal cycles will be evaluated.

Ecological formulations for benthic processes will be made. They include the activity of benthic organisms, possibly more detailed biogeochemistry and a sub-model for the benthic boundary layer. Fluxes of matter at the sediment/water interface will be coupled with the water-column ecology.

A model of the Bottom Boundary Layer physics controlling exchanges between the water column and the bottom (deposition and erosion conditions) will be constructed. The hydrodynamic model will supply the actual geometry, flow rates between model cells, turbulence properties, bottom shear stresses, temperature, salinity and density. A transport module calculates the modifications of properties due to advection and diffusion. Non-conservative properties will be modified by sources and sinks (e.g. by the ecological module). Validation will use analytical, laboratory, archived, climatological and OMEX data.

Work Package V: Project Management and Co-ordination

A large multidisciplinary project such as OMEX II-II demands sound and efficient project management and co-ordination to ensure its integration to the greatest extent. One of the main objectives of WP V is to provide harmonised management of the field data collected within OMEX II-II, both for the benefit of the scientists involved in the project and to ensure that OMEX II-II leaves a legacy of safely archived, fully documented data for comparative studies in years to come. The project office also organises the general project planning, the co-ordination between the Work Packages co-ordinators and between individual scientists on specific topics, the exchange of information among partners, as well as the administrative and financial aspects of the project.

WORK IN PROGRESS

Planning meeting was first conducted during the 3rd EU workshop on *Exchange Processes at the Continent/Ocean Margins in the North Atlantic* which took place in Vigo in May 1997. A major decision was agreed that the research area for the slope surveys should be between 42° and 43°N. Three priority transect lines have been identified (line N at 43°00'N, line P at 42°40'N and line Sat 42°09'N) that should be visited by every OMEX cruise.

Significant progress has been achieved during the first 9 months of the OMEX II-II project. Four major cruises have been conducted: Charles Darwin CD105 (29/05/97 - 22/06/97), Belgica BG9714 (18/06/97 - 08/07/97), Pelagia PE64/108 & 109 (23/06/97 - 05/08/97), and Charles Darwin CD110 (23/12/97 - 19/01/98). Real-time remote sensing images were provided to chief scientists by the partner located at the Plymouth Marine Laboratory (NERC Remote Sensing Data Analysis Service, **(http://www.npm.ac.uk/rsdas/omex/)** during each cruise. The two Charles Darwin cruises and the Belgica cruise were devoted mainly to WP II slope surveys of spatial and seasonal variations of biogeochemical parameters. The Pelagia cruise was focused on the benthic studies including physical, biological, chemical and sedimentological aspects. OMEX II-II cruise inventory has been established by the OMEX Data Centre (British Oceanographic Data Centre, BODC) and as of 1 December 1997 contains information on the 123 data sets collected which can be consulted by OMEX partners at the web site **(http://www.nbi.ac.uk/bodc/omex)**. Banking of data obtained during OMEX II-II has commenced. Analyses of samples collected by partners during various cruises are underway.

During the first OMEX II cruise on board the Charles Darwin CD105, swath bathymetry and 3.5 kHz sounding were performed. Multibeam echo-sounding data collected in the OMEX II study area were worked up and processed at BODC. The original data set comprises over five million echo-soundings and these were gridded onto a five seconds of latitude by five seconds of longitude grid. A special smoothing algorithm was used to minimise the effect of spikes and the data was then contoured at 50m intervals within an area bounded by the limits 41°43' to 43°5'N; 9°25' to 10°5'W. The following bathymetric data products, which provide valuable information on the choice of moorings locations to be deployed during subsequent cruises, were made available to the OMEX II community:

- 5-second grid file in flat ASCII format;
- 50m interval contours in DXF and flat ASCII formats;
- scale and A4 size colour contour (50m intervals) plot files in postscript format; and
- 3D view in postscript format.

Four moorings (current meters, ADCP and sediment traps) have been deployed so far during OMEX II-II (Table 1).These moorings are scheduled to be recovered and re-deployed at 6- to 10- month intervals.

One of the tasks of WP IV is to conduct intercomparison exercises as early as possible on various measurements made using the different approaches of WP I, II and III to ensure comparable estimates of fluxes. Such intercalibration activities were carried out on the CD105 and BG9714 cruises for CTD, nutrients and pigments. The results are partially available, showing good agreements in general among various laboratories, although there were abnormalities concerning certain nutrients. Additional samples for the intercomparison of nutrients were taken on CD110.

Table 1. Locations and specifications of OMEX II-II mooring deployed along the Iberian margin.

Mooring	deployed by	location	water depth (m)	Mooring type	equipped with
1	UCG	42°40.10' N 09° 34.40' W	686	sub-surface	current meters serial no. 11217 at 666m serial no.1 1218 at 586m serial no. 10727 at 386m serial no. 11213 at 236m
2 (IM2)	IfM	42°38.75' N 09°41.86' W	1453		sediment trap at 600m RCM+transm at 620m sediment trap at 1050m RCM+transm at 1070m
3 (IM3)	IfM	42°37.72' N 10°01.67' W	2238		sediment trap at 600m RCM+transm at 620m sediment trap at 1080m RCM+transm at 1100m sediment trap at 1720m RCM+transm at 1740m
4	UCG	42°40.94' N 09° 28°58' W	156	bottom-mounted ADCP	surface-oriented apparatus, measures currents at 4 min. intervals, from 6m above the seabed to 100-120m above the seabed

UCG: University College Galway; IfM: Institut für Meereskunde

ACKNOWLEDGEMENTS

This work is supported by the EU MAST III Programme (Contract N° MAS3-CT97-0076). All OMEX II-II partners are acknowledged for their contributions to the progress achieved to date. We also thank Andrea Bullock for the preparation of this document.

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EUR 18220 — Third European Marine Science and Technology Conference — Project Synopses — Volume I: Marine Systems

Luxembourg: Office for Official Publications of the European Communities

1998 — xxx, 482 pp. — 17.6 x 25 cm

ISBN 92-828-2896-4 (Volumes I to VI)
ISBN 92-828-2898-0 (Volume I)

Price (excluding VAT) in Luxembourg (Volumes I to VI): ECU 78

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3 14 15 CG-60-98-001-EN-C

Price (excluding VAT) in Luxembourg (Volumes I to VI): ECU 78

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