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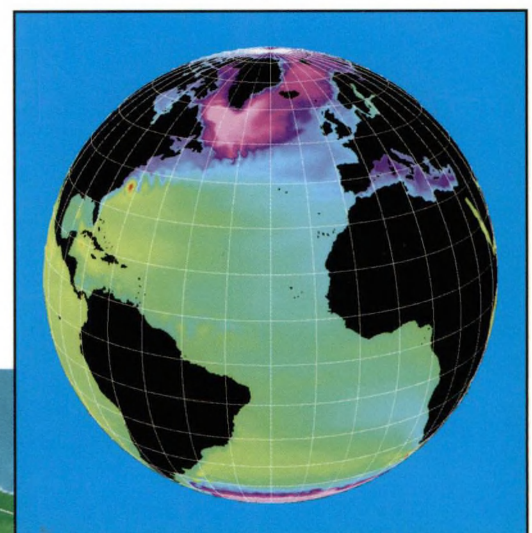
Operational Ocean Observations from Space



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Cover picture

Large image: "A water perspective of Europe", courtesy of Swedish Meteorological and Hydrological Institute. The white lines show the watershed boundaries between the different catchment areas flowing into the regional seas of Europe.

Inset image: Height of the sea surface in the north Atlantic and Arctic simulated by the OCCAM global ocean model, courtesy of David Webb, James Rennell Division, Southampton Oceanography Centre.

Operational Ocean Observations from Space

Report of the EuroGOOS Conference on Operational Ocean Observations from Space

organised by
the EuroGOOS Space Panel
in conjunction with and sponsored by
EUMETSAT and ESODAE

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Preface

by the EuroGOOS Space Panel

The Conference was held on 5/6 October 2000 at EUMETSAT HQ, Darmstadt, bringing together potential users of a European operational oceanographic satellite system to discuss the requirement for, and the means of creating, such a system. In strongly endorsing the need for the concept the Conference produced a number of recommendations for future action, including as a matter of priority, adopting JASON-2 as the first mission of the new system. The full set of recommendations is given in the Conference statement (see next section).

Since the 1970s a variety of oceanographic sensors have been flown in space (including infra red radiometers for SST, passive microwave radiometers for sea ice extent and concentration, microwave scatterometers for surface wind, radar altimeters for sea surface height and wave height, synthetic aperture radars for ocean wave spectrum and detailed sea ice conditions and motion, and instruments for measuring ocean colour). These have produced a wealth of scientific papers on the design and accuracy of such instruments and on their application in oceanographic research. By good fortune some of the data sets now extend for one or several decades. However, there has been no guarantee of continuity of missions and for some sensors there have large time gaps. Operational oceanography can no longer rely on this approach.

Oceanography lacks the equivalent of the World Weather Watch which is the backbone of the observing network used by weather forecasting centres. During the last decade plans have been developed for a Global Ocean Observing System; within this are several regional initiatives of which EuroGOOS is one. Representing some 30 member agencies in 16 European countries it has conducted a number of activities including the establishment of a scientific base to guide its plans, identifying the technological innovations required, and setting up task teams and pilot projects focused on specific regions of European interest. Both EuroGOOS and GOOS have identified remote sensing satellites as being a crucial component of the observing system both at global and regional scales.

For some years there has been concern over how the continuity of remote sensing satellites, which is necessary for operational oceanography and for research into decadal change, could be ensured given that NASA, ESA and other space agencies have remits which encourage development of new technology rather than repeating established measurement missions. Discussion between EUMETSAT and EuroGOOS in early 1999 raised the possibility of extending the role of EUMETSAT as an agency, building on the mechanism established for the highly successful operational meteorological satellites in the Meteosat programme. At the same time NASA and CNES were seeking partners to share and ultimately take over responsibility for the JASON-2 altimetric satellite. The OceanObs conference in October 1999, involving some 300 scientists, identified priorities for long term measurements and the actions needed to ensure that such data were available in a timely fashion; it was recognised that remote sensing satellites had a key role.

The important role of remote sensing is indeed also to be seen in the context of the Global Ocean Data Assimilation Experiment (GODAE) to be conducted in the 2003-2007 time frame. By a network of regional operational oceanography experiments a global system of observations, communications, modelling and assimilation will be demonstrated, that will deliver regular, comprehensive information on the state of the oceans, in a way that will promote and engender wide utility and availability of this resource for maximum benefit to the community

Within Europe, both EuroGOOS and EUMETSAT recognised the need to bring together key players from the operational agencies to consider in more detail the benefits to be gained from operational satellite systems and the means by which such a system could be initiated. One of the objectives was to give EUMETSAT Council information and guidance in planning a long term programme of operational missions to meet the needs of the agencies, industry as well as the operational oceanography user community. Using the networks within the EuroGOOS the most appropriate individuals in each country were identified and invited to the Conference.

The 1½ day programme consisted of assessments of the need as seen by EuroGOOS, reviews of planned space missions from both space agency and industry applications perspectives, and more detailed analyses of the opportunities for different user communities both by type and geographical region. This publication contains papers based on the presentations made. Of particular interest is the recurring theme that satellite remote sensing, almost without exception, is providing an increasingly important contribution to monitoring and forecasting. Although they are of considerable value on their own, the greatest benefit of remotely-sensed data comes from combining them with more conventional datasets, obtained *in situ*, and with models - both through initialisation and data assimilation. In this way, satellite data can significantly improve the information available at a given point and time even though no satellite data are actually obtained for that location in the appropriate time window. Most application sectors require different combinations of remotely-sensed parameters. However - and significantly, in the context of Conference's recommendations - altimeter data are those most frequently cited.

Taking into account statements by GOOS, GCOS and IGOS, considering the sensors currently planned by the space agencies and, in particular, recognising the opportunity afforded by the expanded remit of EUMETSAT, a number of recommendations were produced. The key recommendation concerns the JASON-2 satellite planned for launch in the first half of 2004, stating that the European part of this mission should be adopted by EUMETSAT as the initial component of an operational oceanographic satellite system for Europe. Other recommendations concerned the need for other sensors, the continuation of present missions which are already delivering products of use for operational oceanography, and the necessity of improving the representation of this community in international fora for satellite issues.

The conclusions of the Conference were brought to the attention of EUMETSAT's Policy Advisory Committee (PAC) in November 2000. Agreement on the concept and relevance of the JASON-2 mission was to be sought from the March 2001 meeting of PAC, with the intention of obtaining an-principle agreement at EUMETSAT Council in June to the effect that the mission be adopted as an optional programme. It was hoped that subscriptions would reach the threshold level by June 2002, compatible with an earliest launch date of June 2004.

The EuroGOOS Space Panel and Office will be providing support to member states in their national deliberations throughout this process. ESA have also established a Task Team to consider a strategy for their Earth Watch missions. EuroGOOS will maintain a dialogue with both ESA and EUMETSAT to ensure that the requirements of operational oceanography are incorporated to the fullest extent possible in what is to become a truly European Strategy for Space.

Conference Statement

Preamble

Noting

1. The necessity to combine satellite remote sensed marine data, *in situ* marine data and models into operational* information systems so as to enable signatories to the Framework Convention on Climate Change, the Kyoto Convention, the Convention on Biodiversity, and other international treaties and conventions, to fulfil their obligations to these treaties and conventions,

2. The requirements for remote sensed observation of the oceans and coastal waters published by UN Agencies and Programmes, the Intergovernmental Panel for Climate Change (IPCC), the Global Ocean Observing System (GOOS), and the Global Climate Observing System (GCOS),

3. That long term ocean observations and monitoring from space on a routine and operational basis are essential components of the global programme for forecasting, planetary management, response to climate change, maximisation of economic benefits from the sea, protection of public health and safety, and conservation of the environment,

* See Annex 1 for full definition of the term operational

Recognising

1. The importance of the published Conference Statement from the OceanObs Conference of 1999, and in particular the emphasis on satellite observation of sea surface temperature, wind speed, sea surface waves, sea surface topography, sea-ice extent and thickness, ocean colour, the precision gravity field and surface salinity,

2. The Integrated Global Observing Strategy (IGOS) Ocean Themes Report that sets out requirements for ocean observations in terms of research challenges and operational needs, and has been agreed by the IOC General assembly,

3. The existing programmes of research and operations conducted or co-ordinated by the regional and national space agencies such as ESA, EUMETSAT, CNES, NASA, NOAA, NASDA and their published priorities and policies,

4. That the planned global projects such as GODAE and its European components such as ESODAE, MERCATOR, FOAM, and DIADEM require real time and near real time data delivery,

5. The particular importance to Europe of developing techniques for integrating satellite observations into the marine information system for the adjacent shelf seas and the coastal zone,

Considering

1. The strong recommendations of the EuroGOOS Space Panel from the 1998 EuroGOOS Annual Meeting, leading to further plans endorsed by the 1999 EuroGOOS Annual Meeting, and stressing the importance of collaboration with EUMETSAT,

2. The importance given to satellite observations of the ocean by the publication of the EuroGOOS Technology Plan and the publication of the space data requirements by the EuroGOOS Science Plan and the EuroGOOS Regional Task Teams (Arctic, Baltic, North West Shelf Seas, Atlantic, and Mediterranean),

3. The significant economic and social and environmental benefits to Europe and globally, identified by EuroGOOS, which are dependent *inter alia* upon the assimilation of remote sensed data into models in order to enable routine ocean and coastal monitoring and forecasting,

4. The present value and increasing value of applications of remote sensed marine information to the industrial and commercial sectors of offshore oil and gas, fisheries, shipping, civil engineering, and to the

services of coastal defences, control of flooding and pollution, safety, and public health.

Recalling

1. The new convention of EUMETSAT, which expands its remit into operational services in support of climate and climate change understanding. This is articulated in the existing EUMETSAT strategy, established in 1996, which inter alia recognises that EUMETSAT may expand its operational remit by providing satellite data products and services to environment and climate issues, insofar as they drive, are driven by or interact with meteorology.

2. The importance of the ESA Earth Explorer satellite missions to investigate and test new observing capabilities for new variables such as ocean salinity, and sea ice thickness,

3. That the routine, repeated, consistent, and global coverage of the ocean by remote sensing can only be achieved by operational missions,

4. The strategic responsibility of Europe in sharing the task of providing the necessary suite of global observations, as a basis for gaining access to all global data sets. This will enable the European governments to undertake the necessary analysis as a basis for decisions that will protect their interests in the context of global environmental negotiations,

The EuroGOOS Conference on Operational Ocean Observations from Space hereby states and recommends, in the context of the European capabilities and heritage, and the existing international space agency plans

A. For the identification of priority operational missions

1. The continuation of European participation in the provision of precision altimetry through the JASON-2 Mission should have highest priority in the initial implementation of an operational oceanographic satellite system for Europe, capitalising on JASON-1, ENVISAT, and the approved ERS programme. As the recognised operational agency for European environmental missions it is recommended that EUMETSAT adopt the European part of the mission.

2. The need to continue to fly satellites to ensure long-term, continuous measurements of sea surface temperature, wind speed and direction from the existing research and operational satellites. The existing EUMETSAT meteorological programmes will with other international programmes provide the basic requirement for SST and wind. There is also a need to continue the operations of ERS-2 beyond its currently agreed end date to provide continuity of data until ENVISAT and METOP-1.

3. Support the concept of Earth Watch missions proposed by ESA to promote transition to operational missions, and recommends that continuation of relevant ENVISAT services be considered in the plans of on-going Earth Watch discussions, in close connection with EuroGOOS and EUMETSAT. In this context ocean colour could be considered as a candidate for subsequent EUMETSAT optional programmes.

4. Support for the initiatives taken by ESA in funding the Earth Explorer missions on the cryosphere, salinity and geoid.

5. Further recommends that studies be conducted to identify the mechanism for transitioning some of these ESA Explorer research missions to fully operational systems. In future R&D the development of new concepts such as, for example, wide swath altimetry, the use of reflected GPS signals, constellations of relatively cheap altimeters, and of new sensors for providing wave spectra needs to be given high priority.

6. In addition to the usual cal/val activities organised by space agencies special efforts be made by Europe to intercalibrate appropriate missions to enable long-term consistent datasets to be derived for operational purposes and climate studies.

B. On International Collaboration, Representation and Communication

7. EuroGOOS, EUMETSAT, ESA and national agencies should work together to ensure that long-term plans for operational ocean observing missions developed in consultation with international partners, reflect the needs of European users.

8. In the short term EuroGOOS, EUMETSAT, ESA and national agencies should collaborate to establish a regular procedure for communication and discussion to maintain progress in European operational ocean observing systems from space.

9. There should be consultation with the relevant committees of WMO and the IOC of UNESCO, including the Joint Committee for Oceanography and Marine Meteorology (JCOMM). Additional consultation should take place with the relevant committees of GCOS and GOOS.

C. On Funding

10. Member Agencies of EuroGOOS and Member States of EUMETSAT should seek to identify sources and procedures for funding ocean observing missions which are dedicated to the measurement of variables additional to those established products for meteorological purposes, and to support the collaboration referred to in (7) and (8).

Annex 1 - Definition of operational oceanography

Operational oceanography is the activity of routinely making, disseminating, and interpreting measurements of the seas and oceans and atmosphere so as to:

- Provide continuous forecasts of the future condition of the sea for as far ahead as possible.
- Provide the most usefully accurate description of the present state of the sea including living resources.
- Assemble climatic long term data set which will provide data for description of past states, and time series showing trends and changes.

Operational oceanography proceeds usually, but not always, by the rapid transmission of observational data to computerised data assembly centres, where the data are processed through numerical forecasting models. Some models are run in real time. The outputs from the models are used to generate secondary data products which have special applications, often at local or regional level. The final data products and forecasts must be distributed rapidly to industrial users, government agencies, and regulatory authorities.

Operational oceanography already exists at local levels, and for a limited number of factors. Forecasts regularly provided at present include: wind velocity and direction over the sea; wave height, direction and spectrum; surface currents, tides, storms surges, floating sea ice, and sea surface temperature. There are great advantages in making operational oceanography global so that all parts of the system can be analysed and forecast simultaneously with greater accuracy and further into the future.

There are many more products of value to industry and government agencies which can be made available, or for which the forecast periods and accuracies can be increased. These include indicators of marine pollution and contamination, movement of oil slicks, prediction of water quality, concentrations of nutrients, primary productivity, sub-surface currents, temperature and salinity profiles, sediment transport, and erosion.

Scientific and technological research which has already been funded in Europe leads logically to greatly improved forecasts through operational oceanography, and substantial benefits to a vast range of industries, services, and regulatory authorities.

Ultimately, new systems based on new technology and new understanding of the sea will permit long range forecasts which will be of great benefit in managing the seas and oceans, and in predicting changes and variability of climate.

From the EuroGOOS Strategy, 1996, p10.
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Conference papers presented

1. EuroGOOS Assessments

EuroGOOS analysis of the need for operational remote sensing

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Abstract

The justification for expenditure on European operational ocean observations from space depends upon the integration of the resulting data into a wide range of models and data processing channels, generating information products which have an enormous range of applications in time and space. EuroGOOS has been involved in many surveys, studies, and projects related to this chain of processing and use of data. Operational remote sensing of the ocean is a necessary component of long term climate monitoring and forecasting, medium term and seasonal analysis of marine and coastal conditions, and a host of short term operational services and products with economic and environmental benefits. The applications range in nature from public good global benefits, to regional and local environmental management benefits, from support for policy to commercial and profit-based activities on all scales. They include every aspect of marine physics and biology. An identified need, even an urgent need, may not be subject to evaluation in direct financial terms. Whenever possible this should be the first line of analysis, but there are many uncertainties regarding risk, the low probability of colossally serious disasters, and the unknown value of irreversible losses or events, which raise questions in the public good domain, and where the risk of taking no action, or being totally ignorant of the risk, is unacceptable. This paper does not seek to itemise the detailed applications and the related products required, which are presented in other papers in this conference, but gives an overview of the EuroGOOS position. Operational ocean observations from space are essential for the coming decades, and Europe needs the capacity to control its own destiny by having direct control of a portion of the world data from this source.

Introduction

Operational ocean observations can be justified by many different techniques (Flemming, 2000). Broad socio-economic and environmental objectives have been identified by the GOOS project over the last 6-8 years (OECD 1994; Woods *et al.* 1996; IOC, GOOS 1998; Flemming 1999; Sassone and Weiher 1997; Adams *et al.*, 2000). While accurate cost-benefit analysis (CBA) is applicable to commercial or governmental projects which have an obvious cash-based flow of inputs and outputs, combined with a well-documented flow of financial information and identification of customers, component suppliers, etc., the technique is not useful when the information base is limited, the products are uncertain, the risks are uncertain but are thought to be very large, and there is no way to collect the financial information needed before a decision must be made. Standing back, and saying in effect "Since cost benefit analysis cannot be applied in the time available, we will do nothing" is not an option.

Benefits and motives will first be identified in qualitative terms, distinguishing between manifestly different types of objective which cannot be analysed together. These objectives can then be further quantified or graded by various estimates of public demand, political priorities, national security, public health, treaty obligations, and long term estimates of risks. It may be possible to obtain broad financial implications, or an upper and lower bound, at least in some cases.

A general argument developed in the USA considers the large cost of certainly being totally wrong about climate variability and climate change. Most courses of possible action at present are the topic of strong lobbying by conflicting interest groups in addition to the official recommendations of IPCC. Responding directly to any one of these lobby groups is almost certainly very wrong. Doing nothing is probably wrong. Reacting in a purely responsive mode to successive negative events is almost certainly wrong. Since the stakes are very high, any knowledge which reduces uncertainty has a high value. Peck and Teisberg (1993) calculate a present value of $50bn for resolving specific uncertainties about climate change now rather than in 40 years time.

For over two decades it has been apparent that remote sensing of the ocean is vital if we are to understand the processes at work, and build up adequate time series and geographical cover. The remote sensed data are part of the data stream for models which also includes *in situ* surface and sub-surface data. For ocean observations as such, observing missions in the last 20 years have been conducted almost exclusively as science research projects, with the exception of military operations, and those observations needed for meteorology, namely sea surface temperature and wind fields.

Since the inception of GOOS in the early 1990's (OECD 1994, IOC 1998) it has been assumed that a point would be reached when the chance sequence of science missions observing the ocean would have to be superseded by an operational programme of dedicated satellites designed to produce data for a continuously functioning ground segment, feeding data to operational models, and then to users. Reviews of missions planned up to the mid-1990's are given by the regular CEOS Dossiers of those dates. A summary is provided by IOC (1998, p.53-56). The GOOS Prospectus (IOC 1998, p.57) concludes that the assemblage of science oriented missions will provide the necessary flow of data for SST, wind speed and direction, ocean topography, wave spectra, visible imagery, and SAR coverage of ice up to the year 2005. After that..."GOOS will require access on an operational basis to missions that provide (a list of parameters follows)".

It is now time to start making the decisions which will ensure operational missions to provide the data after 2005 for models and forecasting systems which already exist, or are in the trials and pilot phase.

In this paper I will summarise the needs and justification for the products of operational oceanography, the role of operational remote sensing in generating those products, and link the analysis to the other papers in this Conference. In the present context the term "operational" is used to mean all missions which are planned using established and proven technology to produce a data stream for which there is a planned and identified continuous routine need. The data may be used immediately in real time, or they may be managed off-line and used in applications such as seasonal or multi-annual monitoring and forecasting. Finally, I will refer to the Conference Statement, and the need for a consistent and steady focus on the development of operational ocean observing missions based in Europe.

Estimation of value, and contribution from remote sensing

A cost-effective Global Ocean Observing System (GOOS) is impossible without remote sensed observations by satellite. EuroGOOS has made this statement in its strategy paper submitted to the European Commission (EuroGOOS, 2000). In the present paper I am not going to try and assess the proportionate value of the data obtained by satellites and by *in situ* methods. Both are essential. To justify the whole system therefore we have first to evaluate the benefits (financial or otherwise) generated from all types of ocean observations, after which the role of different technologies can be considered in more detail, as in the OceanObs Conference (1999).

I do not necessarily believe in the reliability of all the methodologies which have been developed for deriving values from environmental information, but let us consider qualitatively four different systems of evaluation:

Commercial, Economic and Social Value

Many activities which we pursue at sea and on the coast would be much more efficient, or would do less damage, if we had better information on a daily basis. Accidents could be avoided; catastrophic spills could be reduced or managed; scientists could do better research; biological stocks could be protected better;

coastal erosion could be controlled at lower cost; ships' voyages would be more efficient; oil and gas would be produced more efficiently; public health could be improved, etc. On the same basis, though with a longer timescale, improved knowledge and forecastablity of the ocean climate, and the coupled ocean-atmosphere climate, provides benefits to the management of agriculture, fresh water, and power generation. In this category it should be possible to evaluate fairly accurately the value of the industries and services, and the benefits of having better marine forecasts (e.g. WHOI 1993; Sassone and Weiher 1997; Adams *et al.*, 2000). The benefits may accrue to producers, customers, or the community at large. Many of the applications of this kind are being considered by other papers at the Darmstadt Conference.

"True Environmental Value"

On this assumption (Costanza *et al.*, 1997, 2000) the natural environment, the air, forests, rivers, ocean, soil, etc., represent Capital, and are performing valuable functions such as keeping drinking water clean, providing the right balance of oxygen and CO2 in the atmosphere, etc., which we would have to pay for if nature did not do it for us (The Total Natural Capital). If the value of these services were properly appreciated, and if it were included in everyday financial calculations, we would arrive at quite a different way of treating the environment, and would take much more care of it. We need to understand the sea better in order to protect its true value. This argument can be applied to the marine environment as much as to the land.

Sustainable Development

The Framework Climate Convention, the Biodiversity Convention, and other agreements make it obligatory for states to try and manage and control the exploitation of the marine and coastal environment in such a way that the conservation and productivity of the ocean are preserved. On this assumption, some means has to be found to measure and compare costs, benefits, losses, and damage. Although the methods are not well proven, the objective is to convert all values to financial cash equivalent, and to discount for time to net present value, with allowance for the probability of occurrence of various future events.

"Saving the Planet"

The case assumes that the risk of damage to the environment of Planet Earth in the next few decades from loss of biodiversity, global warming, melting glaciers, rising sea levels, thermohaline circulation shut-down, etc., is so high that a Global Ocean Observing System (and presumably a Global Climate Observing System and a Global Terrestrial Observing System) is essential to protect the future of the human race on this planet, to detect and warn of adverse change, and to prevent or avoid it if possible. Given the high stakes on this assumption, there is little point in arguing about the cost of GOOS. On this basis GOOS is a moral imperative. There are however serious questions about uncertainty, risk probability, magnitude of risk, and time horizons. This argument has a political dimension in that it motivates public attitudes, but it is not susceptible even to the approximate quantification which is possible with types (ii) and (iii) above.

Most of the socio-economic justification for GOOS and GCOS has been concerned with arguments of type (i) above. Arguments of type (ii) and (iii) will be developed steadily by environmental research organisations and regulatory authorities in the next few years, and are likely to be very influential within a decade. The sum total of benefits estimated by EuroGOOS for the European region (Woods *et al.*, 1996, p.5, p.21) is of the order of 2-5 bn Euro per year. This figure is obtained by considering mostly components of benefit in type (i) above, with a small component of type (iii).

Adams *et al.* (2000) present the most sophisticated analysis so far of type (i) benefits, presented in general terms, for the seasonal to inter-annual benefits arising from better marine observations and their effect upon weather and climate forecasting across the USA, as well as for marine exploitation and conservation. A combination of forecast techniques incorporating ENSO analysis, the Pacific Decadal Oscillation, and the North Atlantic Oscillation, would provide benefits measured in hundreds of millions of dollars per year for each of several management sectors related to fresh water reservoirs, agriculture, oil and gas storage, and agriculture. Medium term to multi-year forecasting in the European region does not have the advantage of a clearly dominant signal like the ENSO cycle, but analysis of Atlantic and Arctic processes is beginning to yield several potential mechanisms and cycles in addition to the NAO, which may permit valuable forecasts. If this is the case, the improved boundary conditions for shelf seas models, and the climate forecasts for the whole continent. could have user values of the same order of magnitude as those derived for the USA.

The largest potential benefits from long-term integrated ocean observations are those which accrue 5-10 years into the future, or beyond, and the largest figures are also those shrouded in the greatest uncertainty given present knowledge. It is therefore prudent to use the observing system as intensively as possible in the short term to generate truly operational products with economic and social benefits. By this tactic the total cumulative discounted cash flow, including expenditure and computed value of benefits, is prevented from dipping too far into deficit (Flemming, 1999), and will show a total net benefit as quickly as possible.

The GOOS framework and regional policy: Nested modelling

EuroGOOS was established in 1994, a year after the formation of GOOS itself. GOOS is one of the three global observing systems linked through the Integrated Global Observing Strategy (IGOS). EuroGOOS has 31 Members in 16 countries, and its Members are all government agencies concerned with ocean measurements, forecasting, and management. We maintain close links with the European Ocean Industries Association (EOIA) and the Marine Board of the European Science Foundation, and with other GOOS Regions. There is routine correspondence and discussion of plans with the US national equivalent, the Integrated Ocean Observing System (ISOOS).

Computing power limits operational services to a restricted resolution in time and space for each geographical scale of model. There is no option to increase the time of computing run, since the product has to be generated in real time. Thus there is a natural series of scales and resolutions, with nested models within the larger geographical scales. Very roughly, the scales which have proved useful in recent years are Global, Ocean Basin, Shelf Sea, and Estuary/Coastal. EuroGOOS projects such as Baltic Operational Oceanographic System (BOOS) and the Mediterranean Forecasting System Pilot Project (MFSPP) rely upon multiple models interfaced at these nested scales.

Within the EuroGOOS organisation the contrasting oceanographic conditions and economic needs of the different regional seas provide a natural scale, both for modelling, and for administration. EuroGOOS has established Regional Task Teams for the Baltic, North West Shelf Seas, and the Mediterranean. Additionally we have Task Teams working on the observations and modelling required in the adjacent Oceans, the Atlantic and Arctic. Collectively this results in a pattern of organisations and groups working at the scales needed for nested modelling.

Reports by the various Task Teams (Le Provost 1997; MFSPP 1999; Buch and Dahlin 2000) and projects in hand (European Shelf Seas Ocean Data Assimilation Experiment (ESODAE), to be completed in 2001) have identified the data types and observations needed in each region. In every case satellite remote sensing is defined as essential at the regional sea level, while the large scale fields for meteorology and marine boundary conditions and fluxes are also needed, again depending upon remote sensing.

The oceanography of the different sea areas could hardly be more contrasted. The shallow Baltic Sea is dominated by fresh water input, winter sea ice in the northern sector, occasional bottom water renewal by inflows of oxygen-rich water from the North Atlantic via the North Sea, and a very large industrialised population on its shores and within its drainage basin. At the opposite extreme the Mediterranean is of full oceanic depth with a maximum trench depth of over 4000m, experiences an excess of evaporation over precipitation, has a higher than usual salinity, has a very small continental shelf, and is half surrounded by very dry countries with low industrialisation. The North West Shelf Seas are dominated by intensive industrialisation, massive exploitation of both fisheries and offshore oil and gas, and the shallow seas are mixed by strong tidal currents, combined with local storminess and steep waves. It follows that each sea area has to develop its own models oriented towards its own customers, but embedded in larger European and Atlantic models. At every scale, and for every purpose, ocean observations from space have a role to play. EuroGOOS Member agencies have already developed some operational models which can utilise remote sensed data from space, and the range of options and demand for data are continuously increasing.

Large scale experiments and trials

EuroGOOS projects are taking place against a background of Atlantic scale and global scale experiments and prototype ocean observing systems, within the context of the existing international meteorological data and service system. The Global Ocean Data Assimilation Experiment (GODAE) is designed to test and develop the techniques for gathering a global data set for the upper ocean in real time and provide a quality-controlled data stream for assimilation in real time into numerical models. GODAE includes real time data streams from both *in situ* and orbiting satellite observing platforms. Within GODAE a special project is being developed known as Argo, which will utilise up to 3000 automated profiling floats to measure the temperature and salinity profile of the upper 2000m of the ocean on a global scale. EuroGOOS Member agencies are active in conducting trials of the floats for Argo, and are participating with the USA in a North Atlantic pilot project with several hundred floats, as well as participating in the EU supported GYROSCOPE project to deploy 80 floats in the Atlantic as part of Argo during the next 3 years.

The development of EuroGOOS projects on all scales, taken within the context of the global and Atlantic projects run by UN bodies and international science programmes such as CLIVAR, demonstrates that oceanography by observations from space is ready to move into a fully operational phase, at least for those parameters which are already best understood.

Requirements surveys

The EuroGOOS Data Requirements Survey (Fischer and Flemming 1999) was conducted in six European countries and shows that most organisations and ocean data users require data products which have a spatial horizontal resolution of the order of 1km, temporal resolution of the order of 6hr, data variable accuracy of the order of 1%, with an almost equal interest at all geographical scales from estuarine to oceanic. This is a very brief summary of a complex report, which gives much more detail about the complex relations between these different categories. Products which give the user this degree of resolution are of course the results of high resolution modelling based on the original data.

About 15% of respondents identify remote sensing as a major application of their own work, and the 9 most commonly requested variables by all respondents are characteristics of the surface fields of currents, waves, temperature, wind, and salinity in that order. Not only are these most commonly requested variables all measurable from space, but many of the other commonly requested variables related to sub-surface conditions require at least a component of space observations.

The EuroGOOS Technology Plan (Tziavos, 1999) and the EuroGOOS Technology Requirements Survey (Bosman, 1997) both identify remote sensing from space as essential components of an ocean observing systems, and a source of data which is already important and in demand.

The EuroGOOS Regional plans (Atlantic, BOOS, MFSPP, ESODAE) all include frequent reference to the need for space based ocean data. The variables and technical details are provided in the publications, and are spelled out by other papers in this Conference.

European infrastructure

During the last 10 years many marine research projects have been funded during the EC Framework research programmes, FP3, 4, and 5. Many of these projects have recently been directly targeted at the development of operational oceanographic capabilities.

Examples are the Mediterranean Forecasting System Pilot Project funded under FP4, and the GYROSCOPE profiling float project in the Atlantic funded under FP5. As EuroGOOS projects become more directly related to fully operational services, the funding must either come from the Member agencies as part of their normal budgets at national level, or some activities may be considered as European operational services, meeting European policy objectives. Additionally, because of the novel and exceptional level of increased co-ordination and integration needed between many agencies to achieve the goals of operational oceanography, some components of a European system might be considered as European Infrastructure.

In May 2000 EuroGOOS submitted a proposal to DG XII, Directorate for Research, proposing that, as a component of European Infrastructure within the new policy of a European Research Area, the Commission should support a three-pronged investment in ocean remote sensing, investment in the development of a petaflops computer system for operational ocean modelling, and investment in an extensive array of *in situ* observing instruments. The proposal document can be obtained from EuroGOOS.

In summary, EuroGOOS has already proposed at a high level the concept that operational oceanography in Europe should proceed through rapid development of ocean observations from space, super-computers, and advanced *in situ* systems. High speed interconnectivity between the components is integral within the proposal.

Conclusions

Europe will benefit to the extent of many hundreds of millions of Euros per year from the application of information based on operational oceanography, both at sea, in the coastal zone; if the landward benefits from medium and long term climate forecasting are added, the potential benefit is of the order of 2-5 bn Euro per year. Regional and international negotiations and regulations concerned with environmental management, response to seasonal and multi-annual climate forecasts, and calculations regarding water quality, public health, and possible anthropogenic climate change, will become increasingly expensive. The cost of compliance with agreed treaties or directives will become increasingly high, while the possible damage resulting from non-compliance, or non-enforcement will be equally costly. Thus Europe must control an independent component of the global ocean observing system in order to form policy. This will give Europe a stake in the global system; provide entitlement to access to all the data and decision-making processes; and guarantee that we can replicate independently all types of models and forecasts upon which political agreements may be based. To fail in this respect would place Europe at a permanent and serious disadvantage. Europe needs a consistent and steady focus on the development of operational ocean observing missions, consistent with its global role and regional requirements. The purpose of the Draft Conference Statement (p.4-8, this volume) is to start this process formally.

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Developing a European oceanographic satellite system

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Introduction

This paper describes some of the issues to be faced in ensuring long-term continuity of satellite remote sensing programmes, reviews the progress made so far towards establishing a European oceanographic satellite observing system, and makes specific proposals concerning future developments involving EuroGOOS and EUMETSAT.

Satellite remote sensing has been identified as of vital importance to EuroGOOS by the Science Advisory Working Group (Prandle & Flemming, 1998), the Technology Plan Working Group (Tziavos & Flemming, 1998), the Marine Technology Survey (Bosman *et al.*, 1998) and all of the Regional Task Teams. Indeed, such data are already being used in the Mediterranean Forecasting System Pilot Project (Pinardi *et al.*, p.95-102 these proceedings) funded by the EU's 5th Framework programme. On the wider front the Ocean Obs meeting in St Raphael last year, attended by 300 researcher scientists and representatives of operational agencies, clearly articulated the need for satellite remote sensing as a major contribution to a long-term observing system, and identified priority measurements. These statements are consistent with those developed by IGOS and GODAE.

At present, a number of satellite sensors are orbiting the Earth which are capable of providing some of the required data. These include sea-state and topography measured by radar altimeters, scatterometer winds, infra-red and microwave sea surface temperature (SST), rainfall by both active and passive techniques, and sea-ice extent. Information derived from such datasets include: wind, wave and rainfall distributions in individual storms, global monthly sea surface temperatures, sea surface height anomalies associated with mesoscale eddies, positions of ice edge. For details of missions planned for the future see the paper by Ratier *et al.* in these proceedings (p.19-27). The status of these measurements varies from operational (e.g. IR SST) to research mode (altimeter topography) and lengths of data records obtained can be as long as 20 years (SST again) down to a couple of years (TRMM).

The limitations of existing satellite programmes

Continuity and consistency

Among the issues to be faced when considering long-term observations of the ocean are:

i) the need for continuity in measuring given parameters
ii) consistency across different missions

The first point implies that there is a spare platform or redundancy of sensors such that when a failure occurs there will be minimal loss of data. Research satellites do not guarantee supply of data and therefore there is a strong element of chance. Sometimes, the mission outlasts its original expectations – TOPEX/POSEIDON (T/P) is an excellent example having lasted from 1992 to the present, exceeding its design life of 5 years. However, other satellites have failed after a few months or less and with no replacement readily available long gaps can then result. In the case of ocean colour, even though a sensor operated successfully for 6 years the lack of an approved successor led to a gap in data which lasted from 1985 –1996. A further possible consequence, if careful coordination is not in place, is that several missions are then launched in the same time period to measure more or less the same parameter. Ocean colour again provides an example as in the next year or two it is possible that 4 sensors will be operating at the same time. Nor is it sufficient to wait until a satellite fails before launching another as this makes direct intercalibration impossible leading to difficulties in establishing consistency in data quality and accuracy between missions.

It is important to recognise the differences between building the *in situ* components of a global observing system and developing a spaceborne remote sensing component. One of the main ones is that *in situ* systems are more numerous, tend to use a variety of instruments to measure a particular parameter and have their costs shared across many organisations. The problem within the context of a global observing system is then to ensure that the sites are well-distributed geographically, that the data from each can be made available to users within the allotted (generally short) time, and that (for producing fields) measurement errors can be corrected for to produce meaningful syntheses of the datasets. By contrast, satellites offer coverage of large areas with a very small number of sensors (typically 1 - 3) which makes the problem of generating internally-consistent spatial fields much easier and, assuming a well thought-out calibration plan, the fields can be tied to an absolute reference level. The disadvantage is that all the eggs (sensors) are placed in a single, very expensive basket (the satellite platform) which concentrates risk and cost in one or two agencies. It also makes for a very inflexible system, unresponsive to individual user demands and with long lead times. This is especially true of large satellites such as ERS-1/2 and Envisat which were in vogue in the 1990s.

Responsibilities for developing operational satellite systems

As a result oceanographic satellites have been built by the space agencies with advice from, but not funded by, the big international research programmes, e.g. WCRP. T/P, for example, was so strongly associated with WOCE that the intensive observation phase of the latter was extended by 2 years to accommodate delays in the launch of the satellite. While this increased dialogue between the space technologists and environmental researchers is to be welcomed it is important to realise that such arrangements have worked for research-mode satellites but they are not suited to the requirements of long-term observations. One reason arises from the way missions are funded. TOPEX and ERS were funded by space agencies (national or European) within the R & D remit that such agencies have. The emphasis has been on development and evaluation of new sensors. By very good fortune it has turned out that for the last few years the oceanographic research community has been well served – as stated earlier, T/P has given 8 years of continuous altimeter data; ERS-1 and –2 have, together given 9 years of altimeter, alternating scatterometer/synthetic aperture radar, and IR SST data, supplementing routine SSTs from the NOAA AVHRR series; and, more recently, ocean colour and low latitude rainfall has been forthcoming from other research satellites.

However, while space agencies are happy to fly new sensors and (sometimes) repeat missions with minor modifications, it is not unreasonable for them to argue that if there is a user requirement for further, routine operation of identical sensors then the responsibility for funding those missions should pass from the space agency to other entities. This is not a hypothetical scenario; such a situation has already been reached in discussions over follow-ons to T/P. NASA and CNES have agreed to fund the first, JASON-1, but have said they will only partly fund the second. An altimeter forms part of ESA's Envisat payload and should operate over a similar period to that of JASON-1, providing an extension of ERS-type altimetry. There are no plans for a follow-on. This means that we face having no altimeter once JASON-1 and Envisat are terminated or fail.

It should also be noted that ESA have separated their future missions into two categories, Earth Explorer (one-off research-orientated missions) and Earth Watch (missions which are geared towards implementation of operational European EO capabilities lasting at least 12-15 years). Plans for the first Earth Watch Initiative are limited to high resolution visible and infrared sensors and synthetic aperture radars targeted on land applications. This also emphasises the urgency of developing plans for operational satellites for marine applications. The joint EUMETSAT-ESA polar orbiting mission programme is an example of the latter, in which operation of wind scatterometry and SST radiometry are secured for a period of 15 years; first on METOP-1 (confirmed launch delay until 2005) followed by METOP-2 and METOP-3 (see also below).

The role of EuroGOOS in developing the system

It is against this background that EuroGOOS has been considering what useful role it could play. Our intention from the outset has been to avoid duplicating the work of other agencies and organisations. Rather than re-inventing lists of parameters required we have been directing our attention at the particular needs of operational users and the specific situation in Europe. Among the issues we face are:

i) establishing a mechanism for funding and operating oceanographic satellites
ii) ensuring that satisfactory arrangements are made for intercalibration
iii) identifying research category measurements which should be transitioned to operational at earliest opportunity, e.g. salinity, time-varying gravity
iv) identification of the cheapest and most effective strategy of satellites and orbits
v) ensuring that regional needs of Europe are represented in international space agency discussions

Establishing a mechanism for funding and operating oceanographic satellites

It is clear that given the scale of the infrastructure required to launch and operate remote sensing satellites and to process the resulting data an organisation has to be dedicated to this responsibility. At first, some consideration was given to setting up the oceanographic equivalent of EUMETSAT. (EUMETSAT is the organisation responsible for operating meteorological satellites on behalf of European weather forecasting agencies. It has performed this role very successfully for many years, its main platform being the geostationary weather satellite, Meteosat, which provides visible and infrared images every few minutes of Europe and Africa and which are an integral part of TV weather presentations throughout Europe. In future, EUMETSAT will also take on responsibility for a new generation of polar-orbiting weather satellites (METOP).)

During the last few years EuroGOOS workshops and meetings have debated the best way to engage the European scale organisations (ESA, ECMWF, JRC-Ispra, EUMETSAT, etc) in the planning and funding of operational ocean satellites. We have consulted DGXII, ESA and EUMETSAT. We have repeatedly arrived at the same conclusions, that it is inconceivable that European governments or agencies would contemplate funding a new European agency (a sort of EUMARSAT) that would have the new responsibility as contractor to launch and operate ocean observing satellites.

The only other realistic option is for EUMETSAT to take on the responsibility, through a modification of its existing terms of reference. Discussions took place between EuroGOOS and EUMETSAT representatives during 1999, a period in which EUMETSAT were holding a series of meetings in member states to show what they could do for oceanography. It was recognised that EUMETSAT's considerable experience in running operational satellites missions and EuroGOOS's abilities in representing 30 major user agencies in 16 members states, was an extremely powerful combination. From these discussions, a clear view of the way ahead began to emerge and the present Conference is the next stage in the process.

It is our view that a European operational oceanographic satellite system should be initiated by focusing on the JASON-2 altimeter mission. There are several reasons:

i) large number of researchers in Europe using altimetry, varied range of applications (sea-sate, mesoscale currents, large-scale circulation, propagating features, sea level change, rain, sea-ice), well-matured capability which is logical follow-on/complement for SST and winds
ii) high possibility of gap in altimeter coverage in 4 or 5 years time.
iii) opportunity afforded by JASON-2 – relatively low cost and risk, better than starting from scratch.
iv) promising opportunity to improve and expand the use of altimetry in combination with advanced and new knowledge of the Earth gravity field and its geoid obtained from GRACE and GOCE within 2005.
v) need to complement the full demonstration of GODAE from 2003-2005, in which Argo is a vital in-situ observing system,

with altimetry as the spaceborne counterpart.

vi) bridge between meteorological and oceanographic communities (paving the way for other more oceanographic missions such as ocean colour, salinity).

Following discussions with EUMETSAT on the available mechanisms for initiating such a system our suggestion is that JASON-2 should be considered for adoption as an optional programme in EUMETSAT.

This raises the question of who should pay for such a system. At present EUMETSAT receives funds from each member agency (usually the national meteorological service). Although these agencies would have some interest in quantities to be measured by JASON-2 it is unreasonable to suppose that the extra costs in flying JASON-2 could be met by diversion of the existing contributions from these sources. However, the number of user agencies which are potential beneficiaries of JASON-2 data is large, so it is realistic to contemplate that extra funds can be found from such entities. Indeed, some of the larger countries may have several such organisations. One of our major tasks is therefore to convince the fund holders in these agencies of the benefits to be derived by contributing to the JASON-2 programme. This is therefore the motivation and main aim of the Conference. It will also be necessary to decide on a suitable mechanism for routeing funds to EUMETSAT; one possibility is for the present member agencies of EUMETSAT to act as conduits but the feasibility of doing this needs to be explored within each country.

Ensuring satisfactory calibration/ validation arrangements

Calibration of satellite sensors is a vital part of remote sensing missions if the data obtained are to be used widely. This is generally the responsibility of the space agencies and is one of the issues addressed by CEOS. Geophysical validation, e.g. assessing the accuracy of wave height measured by an altimeter, usually requires comparison with *in situ* observations and it is here that the operational agencies, who gather data on a routine basis, can provide valuable assistance. Past experience shows that involvement in this process is also a useful way of increasing the confidence of users in the spaceborne measurement because they are able to relate them to their own, more familiar data.

The above activities have been a standard part of one-off research satellite missions. However, there is an important additional requirement when considering the succession of missions necessary to achieve long-term records. This is to intercalibrate the sensors so that consistency across missions can be achieved allowing real long-term changes to be identified. To some extent this can be done via vicarious calibration. Ideally, one should aim for an overlap of missions that is long enough to quantify and correct for calibration differences between missions.

Identifying future candidate missions to be flown in an operational framework

Some ocean measurements already fall within approved EUMETSAT programmes. These are IR SSTs and scatterometer winds. The Space Panel is strongly of the view that such measurements be continued.

Ocean colour data have attracted widespread interest and have considerable potential for use in operational oceanography for example, through assimilation of Chlorophyll data into ecosystem models which could then be used to forecast phytoplankton blooms. In 1998, one of the first indications of the abrupt end of the El Niño was in the ocean colour measurements made by SeaWiFS. Biological information can sometimes help in the interpretation of ocean dynamics because of the way that the biology is influenced by the physics. There are, however, problems to be overcome with the quantitative estimation of Chlorophyll in coastal regions where other constituents in the water column such as sediments may contaminate the retrievals. The next generation of sensors with more channels and greater spectral resolution, together with continued improvement of algorithms holds out the promise of being able to obtain useful data on several biogeochemical parameters of interest, for both the global ocean and coastal/shelf seas. In our view, consideration should be given now to the prospect of an ocean colour mission as a possible candidate for an optional programme within EUMETSAT.

Several other types of measurement from space are planned by the research community for launch in the next 5 years and which are of relevance to EuroGOOS. These are: ocean salinity (e.g. SMOS), precipitation, time-varying gravity and sea-ice thickness. An overview of these mission concepts, with the exception of precipitation, is given in the paper by Johannessen *et al.*, in the St. Rafael Conference Proceedings. Studies should be conducted to identify the mechanism for effecting the transition of these missions from research mode to fully operational systems. The development of new altimetric concepts such as wide swath altimetry, high resolution (10 km) passive microwave system for SST, the use of reflected GPS signals, and of new sensors for providing wave spectra, also needs to be given high priority.

Identification of the cheapest and most effective strategy of satellites and orbits

In the case of a single satellite sensor flown to satisfy the requirements of only a few applications it is often not obvious what is the optimum orbit given the differing requirements for space/time sampling, geographical coverage and the need, perhaps, to avoid aliasing the measurements into certain frequency bands. The situation becomes more complex if one considers an increased number of applications with more than one sensor operating at any one time, e.g. a combination of two altimeters, one characterised by a high accuracy/coarse repeat track mesh and the other by medium accuracy and fine mesh. Issues of cost and the potential benefits of assimilating data into operational ocean models also enter the discussion. In this respect, the suggestion that constellations of relatively inexpensive satellites geared to specific applications could form an alternative that merits serious consideration.

For some purposes the exact choice of orbit may also be influenced by previous knowledge, e.g. repeating TOPEX/POSEIDON and ERS tracks would allow time-varying signals to be monitored over a long period. Account should be taken of new *in situ* datasets. For instance, the international Argo profiling float programme plans to provide, for the first time, synoptic subsurface data from 3000 locations, which will be a valuable complement to the satellite datasets.

Ensuring that regional needs of Europe are represented in international space agency discussions

Mechanisms exist for the space agencies to discuss their future plans with one another and with representatives of large international research programmes. In this way, rationalisation is possible so the most efficient ways of meeting the requirements can be explored within the framework of political, financial and other constraints. The danger with such an approach is that national/regional interests may not receive much attention, yet it is from such sources that funds for new missions are likely to emerge. This is particularly true for operational missions.

Building on the partnership which has developed in recent months in preparing for this Conference EuroGOOS and EUMETSAT can establish a regular procedure for communication and discussion to maintain progress in developing European operational ocean observing systems from space. Specifically, using such a mechanism, EuroGOOS and EUMETSAT can help to ensure that long-term plans for operational ocean observing missions developed in consultation with international partners (including the CEOS mechanism), reflect the needs of European users.

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Space-based observations in the Global Ocean Observing System: Status, plans and operational perspective

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Abstract

The ocean-related space programmes currently implemented and planned over the next decade are briefly reviewed. Critical data gaps and opportunities for transitioning from research to operational missions are analysed in the light of past experience and requirements formulated by the GODAE International Science Team, the OCEANOBS99 conference and other European groups including ECMWF. Capitalising on the heritage of past and current oceanographic space missions like ERS and TOPEX-POSEIDON, the incremental implementation of the space component of the Global Ocean Observing System seems now to be achievable. Altimeter and scatterometer missions are the first immediate candidates for operational transition due to their demonstrated "pre-operational" maturity, in terms of end-to-end performances, value to users and affordability. Further efforts are needed on the user side to assess and demonstrate the potential value of operational ocean colour missions and to justify systematic allocation of resources from multi-purpose SAR missions to observations of ocean wave spectra. Such missions could become operational in a second step based on convincing demonstration. In parallel new promising techniques will be demonstrated, e.g. to measure surface salinity.

With the successful transition from the ERS to the EPS/METOP Programme, Europe has already committed to an operational service for ocean surface wind vector data, and is expecting similar commitments from its international partners. Additional decisions are required in the short and medium term to secure continuity of operational altimeter services initiated by TOPEX-POSEIDON/JASON-1 and ERS/ENVISAT in which Europe has also a leading role. Ultimately, the framework of post-EPS co-operation between EUMETSAT and NOAA is expected to cover such services.

As demonstrated by the long gap between SEASAT and ERS, and between CZCS and SEASTAR, any transition towards sustainable and permanent operational systems cannot take place without timely, convergent and co-ordinated initiatives from space agencies and operational user entities. Significant investments will be necessary on all sides, as one must not only acquire and operate operational systems, but also prepare for their future evolution.

Keywords: Operational oceanography, Earth observation from space, space policy, space programmes, operational observing systems, Global Ocean Observing System

Introduction

Some 10 years after the SEASAT proof of concept mission, ERS and TOPEX-POSEIDON have become cornerstones of the integrated observing strategy of the World Ocean Circulation Experiment, along with the necessary *in situ* observations. Their payloads are providing a consistent series of global measurements of ocean surface wind and topography that complement the sea surface temperature maps already available from operational meteorological and other satellites. Their long lifetime has stimulated the steady development of global ocean models with data assimilation capabilities and, thus, the transition from "space oceanography" to operational oceanography. Continuation of space-based measurements will be critical to experiments like GODAE that will keep this momentum into the next five years.

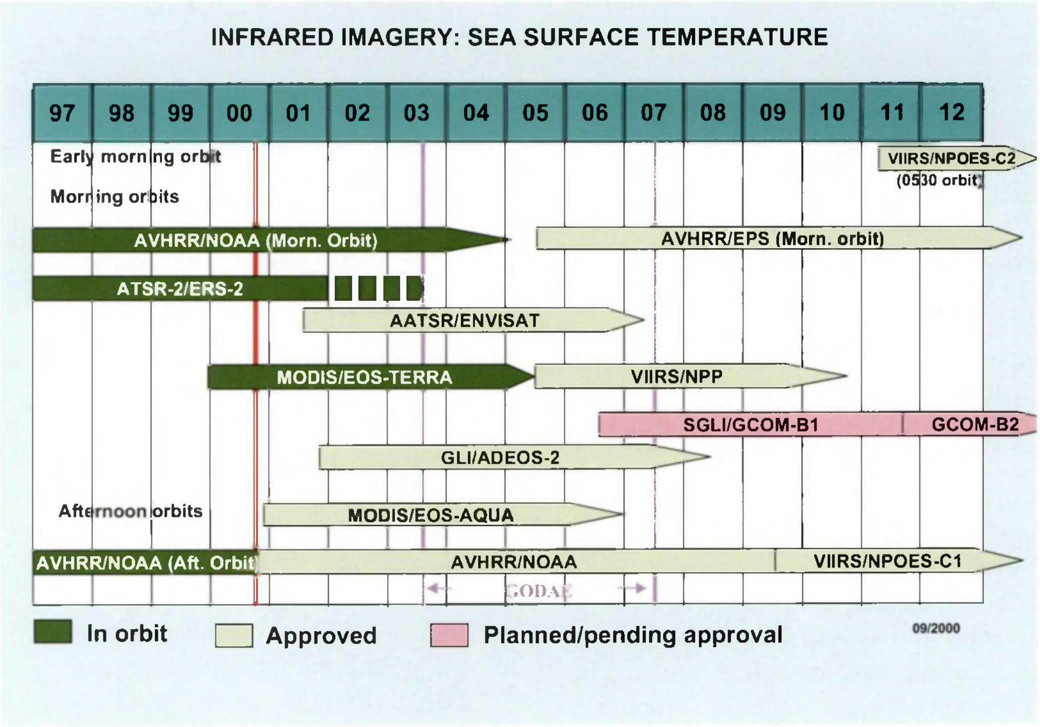

Figure 1: *Current and planned infrared imagery missions providing SST measurements (important contributions from geostationary missions, i.e. GOES and MSG are not represented).*

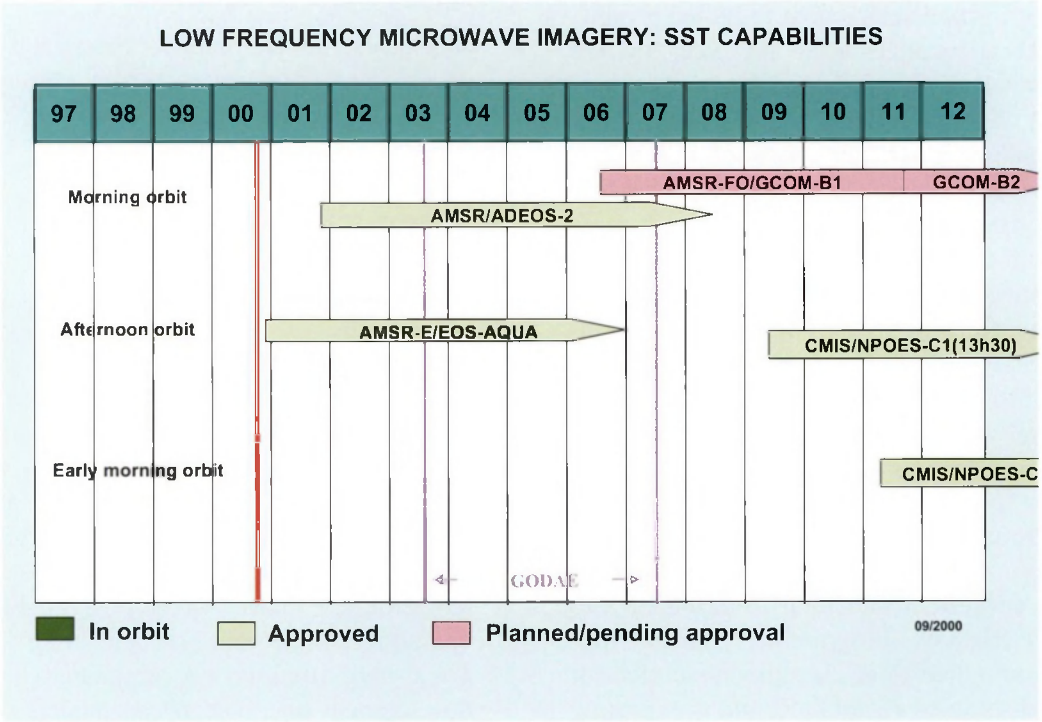

Figure 2: *Planned low frequency microwave radiometry missions with SST capabilities.*

In this context, the transition towards fully operational observing systems appears to be feasible and desirable but requires significant and long-term investments on the part of user entities. These need to be justified by societal or economic stakes and by the availability of sustained operational services.

This paper analyses the status and perspectives of relevant space programmes with focus on opportunities for European contributions to incremental transition towards operational ocean observing systems. This analysis is proposed in the light of requirements expressed in various international user fora. The "GODAE window" is used as a reference/proxy for the short-term period during which first decisions are necessary to support the development of large-scale operational oceanographic applications. In light of past history, conditions for the steady development of operational space-based ocean systems are briefly discussed.

Sea surface temperature measurements from space

(See Figs 1 and 2). Sea surface temperature (SST) measurements have been available operationally since the late seventies from the AVHRR imagers flown on the NOAA/TIROS meteorological satellites. Although AVHRR was not tailored to this mission, it is still providing valuable data, even if global observations cannot be available at full resolution from the TIROS spacecraft. Performance improvements were brought in the early nineties by ATSR on ERS, and more recently by MODIS on EOS-TERRA.

The requirements formulated in the GOOS, IGOS and GODAE framework call for "continuation of the geostationary and low-earth-orbit meteorological satellites that produce merged sea-surface temperature data products" (Ref 1) and for "continuity of the higher accuracy ATSR-class measurements" (Ref 2).

Continuity and enhancement of measurements is in fact secured in the medium term by research or pre-operational missions from NASA (MODIS on EOS-TERRA/AQUA, VIIRS on NPOESS Preparatory Project), ESA (AATSR on ENVISAT) or NASDA (GLI on ADEOS-2, SGLI on GCOM-B satellites), and operational missions from EUMETSAT (EPS/METOP) and NOAA (POESS). The solid state recorders on board METOP-1 will enable collection and centralisation of global data sets at full spatial resolution. Split window observations are also becoming available from operational meteorological geostationary satellites like GOES and Meteosat Second Generation (MSG, to be launched in 2002). These more frequent observations will document diurnal variations, provide more representative measurements in regions frequently obscured by clouds and deliver the additional number of independent measurement samples necessary to reduce the random errors affecting averaged values.

In the long run operational continuity is also secured with at least EPS and NPOESS. The challenge is rather to improve existing capabilities based on the heritage of research sensors like ATSR. Operational low frequency microwave radiometers (CMIS on NPOESS) will also follow experimental precursors, i.e. AMSR on EOS-AQUA and ADEOS-2.

From a European perspective the possible challenges are (i) continuation of ATSR missions beyond ENVISAT and (ii) the definition of the imager to be flown on post-METOP satellites if the latter is not provided by the USA. These are mid and long term issues.

Altimetry and ocean topography

(See Fig. 3). The development of altimetry has been steady and the benefits outstanding. There has been a quasi-continuous series of missions, starting with GEOSAT (1985), and then ERS-1/2 (1991 and 1995) and TOPEX-POSEIDON (1992). These will continue into the next century with JASON-1 and ENVISAT, both of which are scheduled for launch in 2001.

At present only altimeter systems can measure sea level on global scale. Increasing system performances have cut the error budget on sea surface height by several orders of magnitude, down to the centimetre level. The consequent reduction in the correlated part of the error now means that large-scale ocean circulation patterns can be extracted. Altimeter systems also provide co-located measurements of significant wave height and wind speed, at nadir.

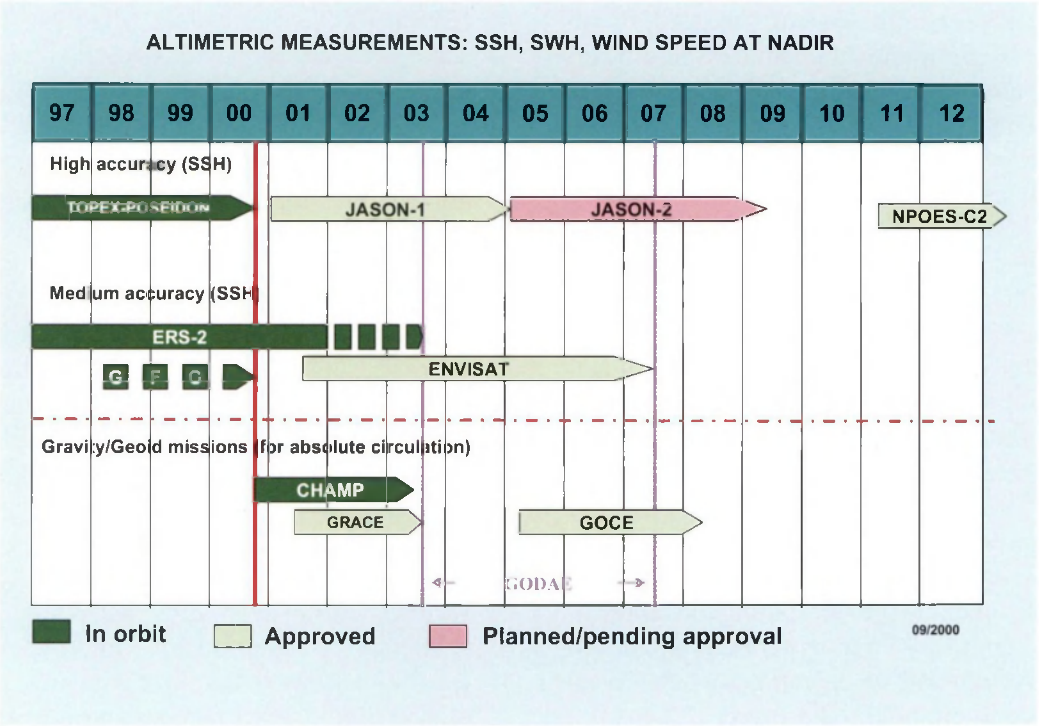

Figure 3: *Current and planned altimeter observations of sea surface height (SSH), significant wave height (SWH) and wind speed at nadir*

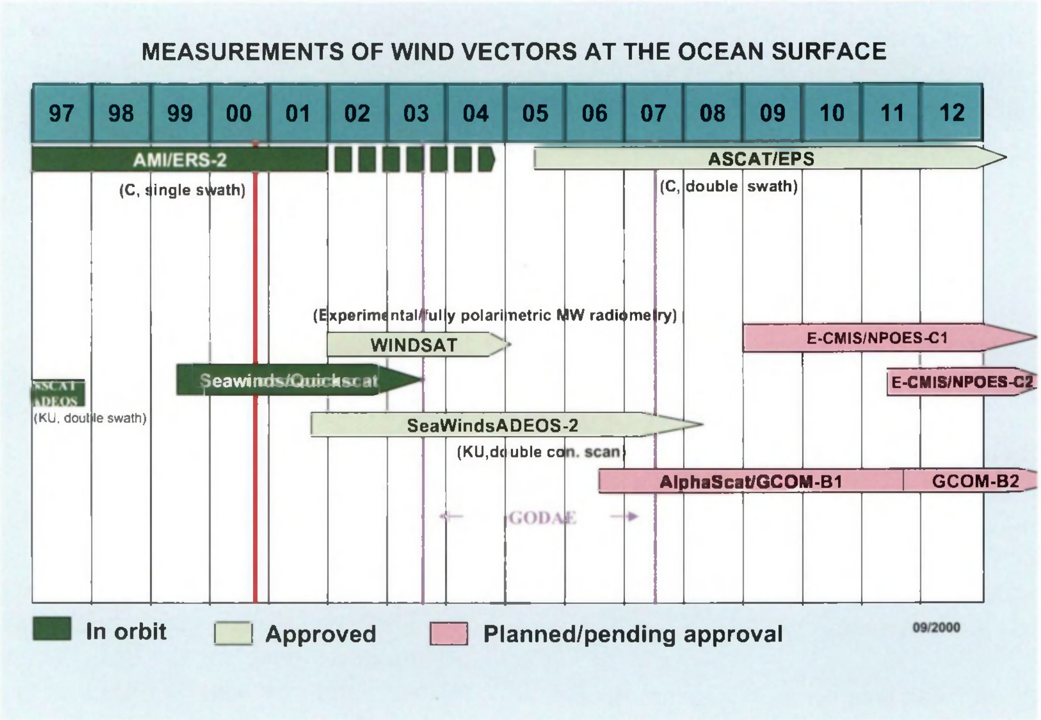

Figure 4: *Current and planned observations of wind vectors at the ocean surface*

With TOPEX-POSEIDON and ERS, the user community has had access to a two-satellite system with unprecedented space-time sampling and coverage of the global ocean, including the Polar Regions, and pre-operational near real time data services.

On the user side, GODAE (Ref 3) "requires global, near real-time, high accuracy and high resolution observations of sea surface topography" from "at least two (and preferably three) altimeter missions with one very accurate long term altimeter system. The latter is mandatory for climate applications and as a reference for the other missions". This means (Ref 1) "continuation of a TOPEX/Poseidon-class high-precision satellite (i.e. JASON-1) and an ERS/ENVISAT-class altimeter". As an additional requirement, the OceanOBS99 conference (Ref 2) "confirmed the value of improved estimates of static (geoid) and time-dependent gravity field for oceanography, in particular for estimates of the ocean circulation (with altimetry)."

The final approval of the CHAMP (DLR), GRACE (NASA) and GOCE (ESA) missions meets the high quality Geoid requirement (see Figure 3). Concerning altimetry, the short-term future looks promising (Figure 3) with a two-satellite altimeter system being maintained for the next five years with JASON-1 and ENVISAT. GEOSAT-FO (GFO) could even become available as a third mission but with severe performance degradations. As noted by IGOS, the key issue is the future funding of Jason beyond JASON-1, for which firm decisions are needed in the very short term to secure continuity through JASON-2 measurements in the "GODAE window". Further decisions will be needed in the medium term (i) to bridge the gap from JASON-2 to the NPOESS altimeter mission and (ii) to maintain a multi-satellite system after the end of life of ENVISAT.

From a European perspective, possible challenges are (i) to secure its contribution to JASON-2 and to (ii) trade-off possible options for bridging the gap between JASON-2 and NPOESS and/or for a contribution to the high resolution and polar altimetry. This may require Earth Explorer demonstration missions, e.g. to evaluate wide swath altimeter systems, altimeter micro-satellite missions, GPS reflection systems.

Wind vector measurements at the ocean surface

(See Fig. 4). While altimeter and SSMI-class microwave imaging radiometers (SSMIS, AMSR on ADEOS-2, AMSR on EOS-PM, CMIS on NPOESS...) deliver observations of the wind speed at the ocean surface and important information on sea ice, scatterometry is currently the only proven technique for mapping ocean surface wind vectors.

ERS-1, despite the narrow swath of its AMI/Wind instrument, has had the considerable merit of providing the first real time data service ever. The ECMWF and The Met Office have used this to demonstrate a positive impact of scatterometer data on weather forecasting. As a result, EUMETSAT was able to commit to a series of three improved, double-swath instruments, over 14 years as part of its EPS Programme. In the meantime, ESA has agreed to continue to operate its ERS missions until the end of ENVISAT commissioning, and is considering bridging the gap to METOP-1, subject to availability of ERS satellite resources. In parallel, the NASA QuikSCAT small satellite has been delivering high-resolution KU-band measurements since end of 1999.

On the user side, the OceanOBS99 conference (Ref 2) strongly endorsed provision of two scatterometers, one in each of the morning and afternoon polar orbits, for sustained global daily coverage at around 25 km resolution. This view is supported by IGOS requirements for "a coverage equivalent to, or better than, a dual-sided scatterometer".

WINDSAT, to be launched in 2002, is a proof of concept mission for a fully polarimetric microwave radiometry technique to be proven in orbit. If the mission is successful, the CMIS instrument to be flown on NPOESS could be enhanced to measure wind vectors, but starting only in 2009. In this context, the risk of a 5-year gap is very significant. In parallel, the simultaneous flight of C-band and KU-band scatterometers based on different instrument concepts over a long period is a major opportunity to trade-off design options for future operational scatterometer missions.

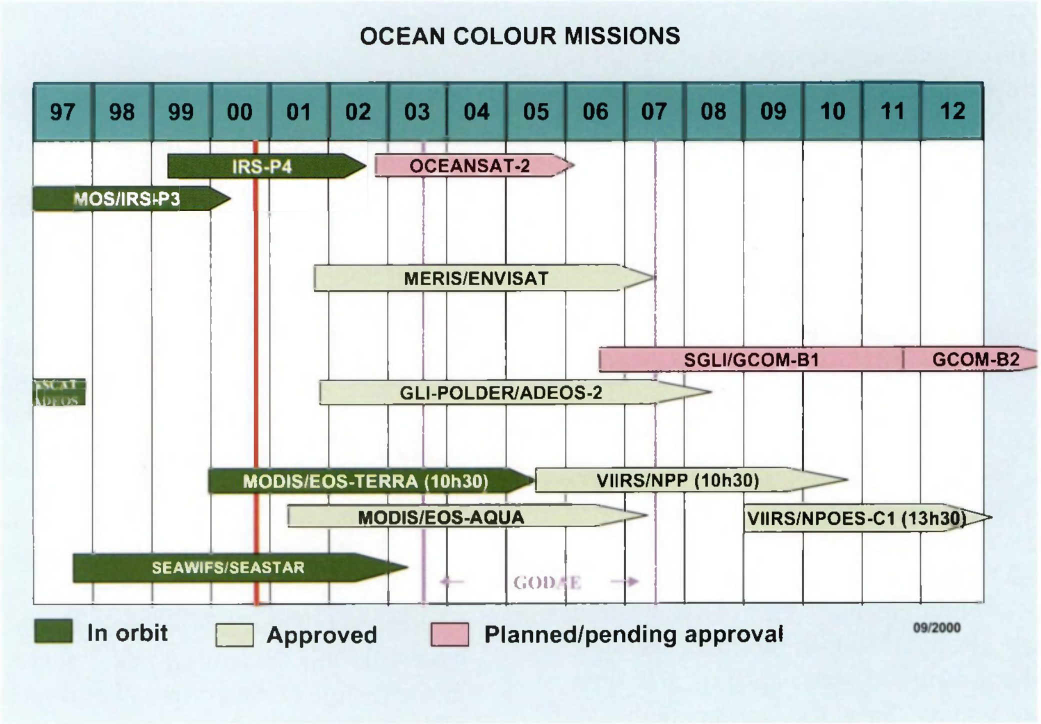

Figure 5: *Current and planned ocean colour missions*

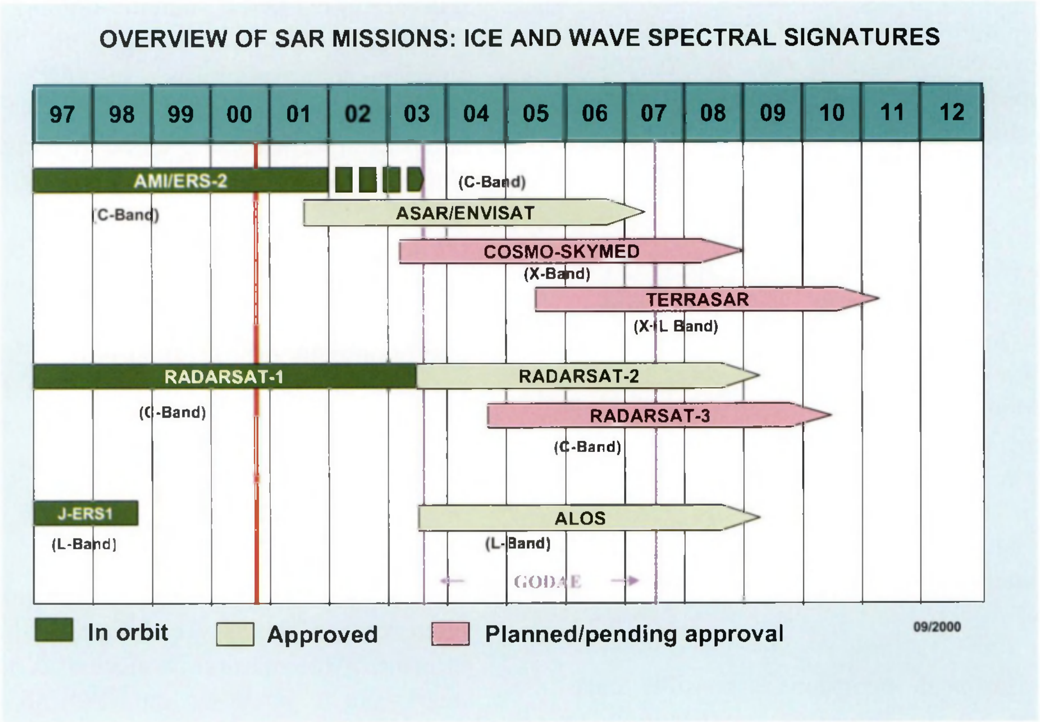

Figure 6: *Current and planned SAR missions*

From a European perspective, the possible challenges are (i) in the very short term, to prolong ERS-2 scatterometer operations until the start of EPS operations and (ii) to convince international partners to confirm their commitment to Alphascat/GCOM-B1. In the long run, an objective would be to study and trade off observing techniques and instrument concepts in order to support European decisions on the post-EPS system.

Ocean colour and ocean biology

(See Fig. 5). It took about 15 years to launch a successor to CZCS, but, paradoxically, a large number of overlapping missions have now been launched or are planned world-wide that will focus on ocean colour observations to serve climate research and coastal monitoring. SEASTAR, MOS, IRS-P4 and MODIS on TERRA are already in orbit and will overlap with the forthcoming MERIS on ENVISAT (2001), GLI on ADEOS-2 (2001), and MODIS on EOS-AQUA (2001).

In this context, the user requirement for "continuation of global satellite missions for ocean colour" (Ref 1) can only be long term as it is recognised (Ref 2) that "there remain significant scientific challenges and that long term continuity needs are not yet defined."

In practice even the long-term continuity and the operational transitions seem to be assured. Follow-on missions are approved or firmly planned in the US (VIIRS on NPOESS Preparatory Project and NPOESS), where the operational transition has already been approved, in India (IRS-P series) and in Japan (GCOM-B series).

From a European perspective, the main challenge is on the user side. This is to take the best advantage of data from the current and planned mission to assess the need for operational capabilities additional to those already approved in the USA (NPOESS).

SAR observations of sea ice and ocean waves

(See Fig. 6). Pre-operational and operational SAR missions have been developed or are planned by ESA (ERS-1, ERS-2 and ENVISAT), NASDA (J-ERS-1 and ALOS) and the Canadian Space Agency (RADARSAT-1 and RADARSAT-2), securing continuity of observations well into the next decade.

Like optical high-resolution imagery missions, SAR missions have targeted a multi-segment user community. This is because SAR systems have a broad range of capabilities and serve a great number of applications in various disciplines. They provide in particular operational sea ice monitoring services relevant to polar oceanography and navigation. A commercial approach has generally been adopted in order to develop the market, optimise the use of the limited coverage of these demanding payloads and generate revenues as a measure of success.

Concerning ocean waves, ESA took the pioneering initiative to develop and operate a pre-operational "wave mode" global service, providing 6 x 7 km "imagettes" every 200 to 300 km along the ERS and ENVISAT track. The objective was to deliver in real time a low bit rate product for use in wave models, together with altimeter and scatterometer observations. The current products are used to evaluate the outputs of global wave models, but further improvements are needed. Ongoing research has already achieved promising results to be evaluated with ENVISAT.

The OceanOBS99 conference "noted the utility of SAR data for wave applications and ice studies" and considered "enhanced availability" as an additional requirement, recognising that cost could be a limiting factor.

Considering the firm plans of ESA (ENVISAT, 2001), CSA (RADARSAT-2, as a follow-up to RADARSAT-1, and RADARSAT-3) and NASDA (ALOS, 2003), adequate SAR capabilities will continue to be available, well into the next decade, for sea ice and ocean wave monitoring (see Figure 6). From a Global Ocean Observing System perspective, a good case could be presented to all SAR operators for such a low bit rate "wave mode" service, if a consortium or federation of user entities can finance such a service. In the same vein, adequate SAR resources need to be allocated to sea ice monitoring at high latitudes, in combination with passive microwave observations (see Figure 7). Beyond ENVISAT, European opportunities exist in the context of ESA Earth Watch studies or similar initiatives like TERRASAR/INFOTERRA, COSMO-SKYMED or PLEIADES.

From a European perspective, possible challenges would be to (i) demonstrate operational value of improved SAR imagette products from ENVISAT for wave forecasting, (ii) secure availability of SAR resources from the planned post-ENVISAT Earth Watch SAR missions for wave forecasting and sea ice monitoring, and (iii) analyse the potential value of lower cost observing techniques e.g. conical scan scatterometers like Quickscat.

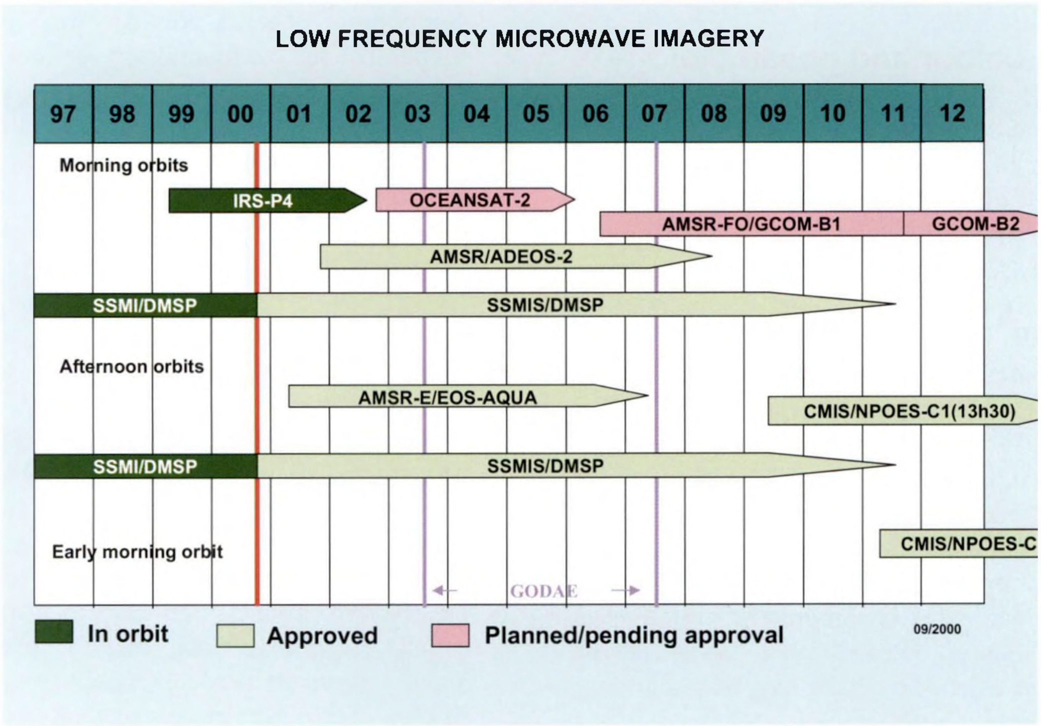

Figure 7: *Overview of current and planned low frequency microwave imagery missions.*

Affordability and other conditions for successful operational transition

Although it is clear that satellites will remain a critical component of any global ocean information system, one cannot address the operational transition issue without considering costs and benefits. The cost of small satellites is significantly decreasing as a result of continuous R & D investments. Although actual costs depend on the complexity of payloads, the typical cost of a full small satellite mission now lies in the 100 M$ range, including satellite, payload, launch services, commissioning and 4 years of operations. Annualised, the costs represent about 25 M$ per year of operation, and significantly less if the lifetime exceeds four years. This is a small fraction of the cost per year of the current global operational meteorological satellite systems of the World Weather Watch. Also, as in meteorology, international co-operations can share the financial burden and avoid duplication of efforts, whilst preserving the minimum redundancy required by operational services.

As demonstrated by JASON and QuikSCAT, operational continuity of space-based measurements of ocean topography, sea surface wind has become affordable but this still represents a significant additional investment from responsible user entities. The investment can only be justified by the integration of requirements from and benefits to various user communities and applications. In this respect, it is fortunate that most measurements of ocean surface parameters, if available in real time, are now at the crossroads of oceanography, marine meteorology, seasonal forecasting and climate monitoring. This convergence of interests presents a key opportunity.

Another condition for a successful and sustainable operational transition is explicit, convergent and balanced articulation of research and operational space programmes. This is needed for two basic reasons. First, operational transition cannot be successful without timely, convergent and co-ordinated initiatives from the development and operational agencies. Second, adequate resources need to remain available within development agencies to demonstrate promising new observing techniques expected to improve and expand operational capabilities in the future. As demonstrated by the long gap between SEASAT and ERS operational oceanography may well fall between two stools, if development and operational agencies do not balance their respective investments, or if they fail to agree on appropriate transition scenarios.

References

1. IGOS Ocean Theme Paper
2. OceanOBS99: final conference statement
3. GODAE Strategic Plan (draft)

Climate modelling and forecasting, medium to long term, methods and benefits

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Summary of presentation

Numerical models and observing systems presently under development will provide the capability to produce the following information and products:

- Long term climate simulations
- Models of climate variability
- Seasonal climate prediction
- Monthly ocean current predictions
- Weekly meteorological predictions
- Coastal current predictions a few days ahead

These products depend upon observing systems, communications, data assimilation, numerical models, and information product distribution. The forecasts themselves will be of benefit to a wide range of commercial and governmental users, as reported by other papers at this Conference. They are also important in providing the information needed to respond to the advice issued by the Intergovernmental Panel for Climate Change, and for their future research.

The global observing system includes space-borne sensors and *in situ* sensors. The design of the measuring system requires that special attention is paid to the following criteria:

- The choice of parameters which are required as priority
- The signal to noise ratio of the measurements
- Calibration-validation of the observing technology
- The design of the spatial and temporal sampling frequency
- Procedures for assimilation of data into dynamical models
- Technological aspects of data processing
- Capital costs and operational costs

Models already in operation can assimilate remote sensed satellite altimetry and SST data, as well as *in situ* data. For the design and implementation of the Argo project this complementarity between sub-surface *in situ* data and remote sensed data is fundamental. In addition, models require adequate information of the forcing fluxes at the boundaries, and biogeochemical fluxes.

The design of operational observing and forecasting systems depends critically upon the economics. Therefore we need to estimate both the probable total annual cost of such a system, and the best balance of technologies which will provide the optimum data flow at the most efficient cost. Since the observing system will be run for many years, it is important to consider the total long-term cost.

In approximate terms the costs of the observing infrastructures are as follows:

Operational satellites, minisatellites

Initial investment 75 Million Euros, with a lifetime of 5 years, = 15 MEuro/yr
Operational recurrent running costs, 4.5- 6.0 MEuro/ yr.
Total annual running cost including amortisation = approx. 20 MEuro/yr
Three satellites required........................x 3, =...................60-63 MEuro/yr

Research Vessels

Initial capital investment, 75MEuros, with lifetime 25 years = 3MEuro/yr
Operating costs per vessel 4.5-6 MEuro/yr
Total annual running cost including amortisation of capital = approx. 8 MEuros/yr
Number of ships required is ....x 3 - 5, =...............24-45 MEuro/yr

***In situ* profiling floats** Initial investment in purchase of 3000 floats, 45 MEuro, lifetime 4 years, = 11 MEuro/yr Operating costs, deployment etc., = 5 MEuros/yr Total annual running costs including replacement costs = ...16 MEuro/yr
Computing and modelling centres Capital investment in installation, 15 M Euros, with lifetime 5 years, = 3 MEuro/yr Operating and running costs, 5 MEuros/yr. Total running costs including amortisation, 8 MEuros/yr. Three centres required.................x3 =...............24 MEuro/yr
TOTAL OBSERVING SYSTEM COST = 124- 150 MEuro/year

This cost is an order of magnitude less than the total value of global benefits of industry, government agencies, and socio-economic activities described in other papers presented to this Conference. It is also important to consider the proportion of the cost which would be born by Europe, and the extent to which the cost of open ocean operational oceanography would distort the conduct of research oceanography in Europe. If we assume, in approximate terms, that about 4000 professional oceanographers are working in Europe, each at a cost of 1 MF/yr for salary and laboratory costs, plus 1 MF for infrastructures and the running costs of infrastructures, we have a total cost of 8000 MF/yr. This is equivalent to about 1200 MEuros/yr.

From the calculations above, the cost of the operational oceanographic infrastructure in terms of initial investment and running costs is of the order of 200 MEuros/yr, to make a cautious or pessimistic estimate. To acquire and use the data from the operational system, to design systems, and interpret data, write and test new models, etc., there would be a need for science support teams, estimated at a further 200 M Euros/yr. This is a global estimate, at 400 MEuros/yr, of which Europe would have to support the cost of one third, that is 130 MEuros/yr. The total cost of Europe investing in and running its one third share of an operational open ocean observing system is of the order of 10% of the expenditure already allocated for oceanographic research in all aspects of marine science.

The hypothetical observing system described above includes 3 satellites which incur about 50% of the total cost of the system. In the case of JASON-2, which already has financial support from 3 agencies (NOAA, NASA, and CNES), the extra cost to a European agency would be one quarter of the total cost of 100 MEuro, that is only 25 M Euro, divided between several national agencies. This is an investment which would produce very substantial beneficial returns in the medium to short term, and contribute to long term climate study.

The private sector use of ocean remote sensing, industrial requirements and commercial services

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Abstract

The paper makes an assessment of the scale of the commercial market for marine satellite earth observations and provides some examples of present commercial operational data products based wholly or partially on satellite observations and measurements. The paper concludes with a review of sectors in which there is potential to generate increased use of satellite earth observation data to enhance existing commercial data products or generate entirely new products. Mechanisms to encourage greater commercial exploitation of marine satellite earth observations are also discussed.

Introduction

The development of satellite earth observation has provided powerful tools to observe the atmosphere, the land and the oceans with a level of spatial coverage that would be impossible to achieve by any other means.

However, despite the obvious power of these observational tools in helping to address strategic questions about the earth's environment and their key role in monitoring large-scale anthropogenic changes to the environment, estimates of the commercial market for satellite earth observations have invariably been excessively optimistic. This is because such estimates have frequently been derived with little or no real understanding of what customers might actually purchase, as opposed to what they might wish to have.

The British National Space Centre predicted that the world commercial market for earth observation information would reach £900 million (US$1,350 million) by 2000[1] (£100 million (US$150 million) for data and £800 million (US$1,200 million) for value added products). Latest figures from 1997 show UK earth observation revenue at £2.75 million (US$4.1 million) for data and £11 million (US$16.5 million) for value added products. These revenues are projected to grow to £4.9 million (US$7.3 million) and £20 million (US$30 million) respectively by 2002. The latest (2000) estimate for the accessible global earth observation market is £200 million (US$300 million) projected to increase to £1,000 million (US$ 1,500 million) by 2010[1].

Even these most recent projections disguise the very small value of the true commercial market for data and data products as they include 'sales' from government agencies to other government departments and international agencies. The UK House of Commons Select Committee on Trade and Industry recently reported [1] that the remote sensing value added industry is still struggling to develop a sustainable long term market'. Lord Sainsbury, the UK Science Minister, attributed this lack of growth to the fact that the main user is the public sector, stating "Government is the body that wants to know about the monitoring of the environment, and it expects to get this information, essentially from its own branches of Government, free, not to buy it commercially in the market".

In contrast to the market for satellite based earth observation products the commercial market for aircraft based earth observations is now a relatively mature sector. However, even this more mature commercial market has a comparatively small total size at an estimated US$70-100 million (£47-67 million) per annum[2].

The consistent overstatement of the value of the commercial market has served to inhibit the development of commercial satellite earth observation data products since the prevailing expectation of large commercial market opportunities has, in Europe at least, resulted in excessive pricing of data. For example, the European Space Agency prices for commercial access to SAR data[3] are currently two to five times the cost of access for research usage.

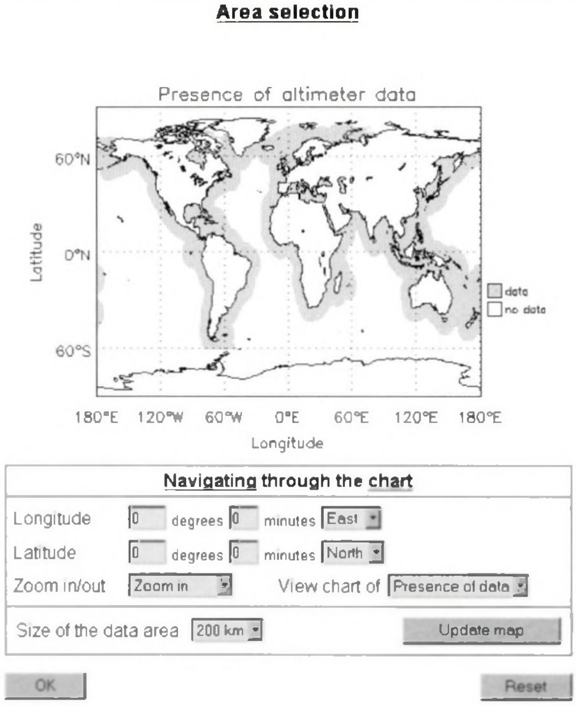


Figure 1: *Interactive selection of sea area for analysis of altimeter data*

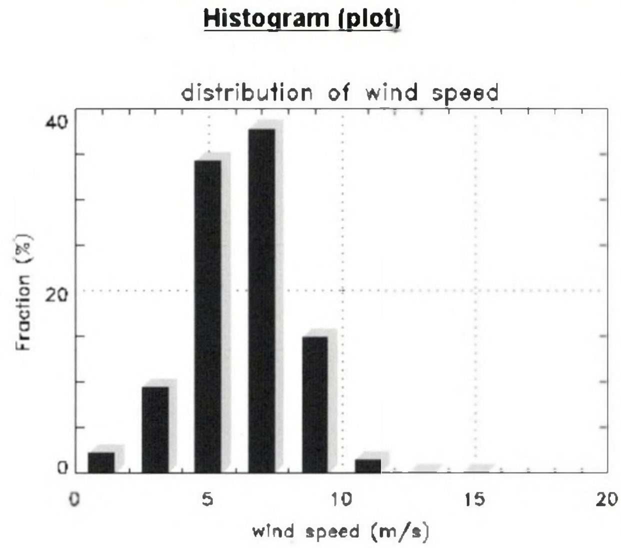
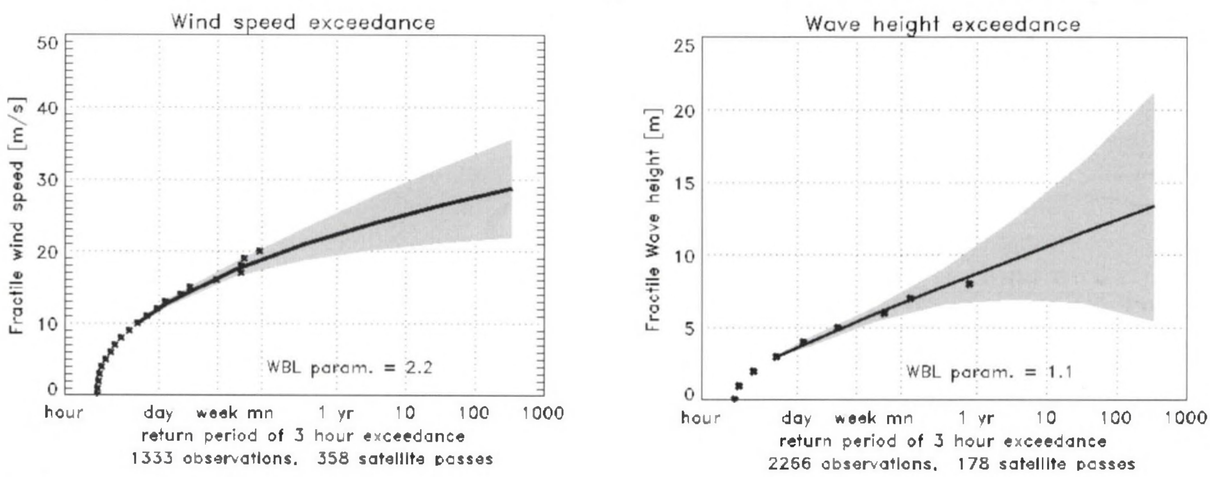


Figure 2: *An example wind data statistical analysis*

Exceedance plot

Exceedance plots show the wind speed or significant wave height versus the fraction of time that it is exceeded. The crosses give the fractile wind speed or wave height as derived directly from the data, the line is an extrapolation based on a fit of a Weibull distribution to the observations. The shaded area indicates the 90% confidence interval of the exceedance value.



The left plot above shows that the wind exceeds 28 m/s during 3 hours per 100 years. This estimate is based on a sample of about 1300 winds speed measurements made by the ERS scatterometer during 358 passes over our region of interest. The maximum wind speed actually observed by the satellite is about 20 m/s. The extrapolation to the frequency of occurrence of even higher wind speeds is made by extrapolating a fit to the observed wind speed distribution.

Analogous to the left plot, the figure on the right shows that the significant wave height exceeds 12 m during 3 hours per 100 years. This estimate is based on over 2000 wave height measurements by the ERS altimeters made during 178 passes.

Figure 3: *Example exceedance plots for wind and wave data*

The erroneous expectation that commercial customers will be both abundant, and willing to pay high prices for data from satellite earth observation programmes, has created an environment where the price of access to publicly funded data resources frequently renders their potential commercial use uneconomic.

Estimates of the commercial market for marine applications of satellite earth observation data are very difficult to obtain. However, given that terrestrial earth observation data and data products dominate present commercial sales the marine market is certainly very small, with much of the 'commercial' activity confined to research and development and 'technology demonstrator' projects rather than delivery of true operational products.

Nevertheless there are a number of small niche markets where value added marine data products which make use of satellite earth observation data are currently being successfully sold to customers on a viable commercial basis. There is also considerable scope for greater future use of satellite earth observation data to enhance a variety of existing marine value added data products and there are emerging opportunities for creation of new data products.

This paper discusses the market value of present use of marine earth observation data in support of commercial data products and provides examples of some operational products being provided by European companies. It concludes with comments on some areas of commercial use that may be expected to develop in the future and makes some recommendations on how development of these applications might be stimulated.

The market for marine earth observation data and data products

Before estimating the scale of existing commercial provision of marine earth observation data and data products it is first necessary to define the 'commercial' market. In the context of this paper, this market is defined as provision of operational data products to genuine third party customers under the terms of arms length contracts. This definition excludes sales between national government agencies and government departments within a given country, a source of much confusion in estimating real market size since these sales are effectively use of tax funds in one part of government to fund the activities of another part of government that would otherwise have had to be funded directly from the public purse. In these types of transaction there is no genuine wealth creation, tax funds having simply been re-routed. This definition also excludes research and pre-operational activities under government funded programmes such as the European Framework programme and the various research and development funding activities of national and international agencies since these also effectively re-route tax revenue.

The value of the world-wide commercial market for marine data collection services, marine data and marine data products has been estimated at £2.7 billion (US$4.0 billion) by the Marine Information Task Force of the UK Marine Foresight panel[4]. A large proportion of this sum represents the value of commercial data collection (especially marine geophysical data) commissioned to support the marine data requirements of the offshore oil and gas industry.

Probably the most significant current use of earth observation data within this market is the provision of commercial weather and seastate forecasting and the production of hindcasts and climatological information. In this market earth observation data is used both directly and indirectly. Commercial organisations make direct use of satellite earth observation data to create specific data products, and indirect use, in that satellite earth observations are used in the generation of intermediate public data products from which the commercial products may be partially or wholly derived. For example, a variety of satellite earth observation data is used in the creation of global weather and seastate models run by government agencies the output from which are sometimes used by commercial providers to create value added products to service niche commercial markets.

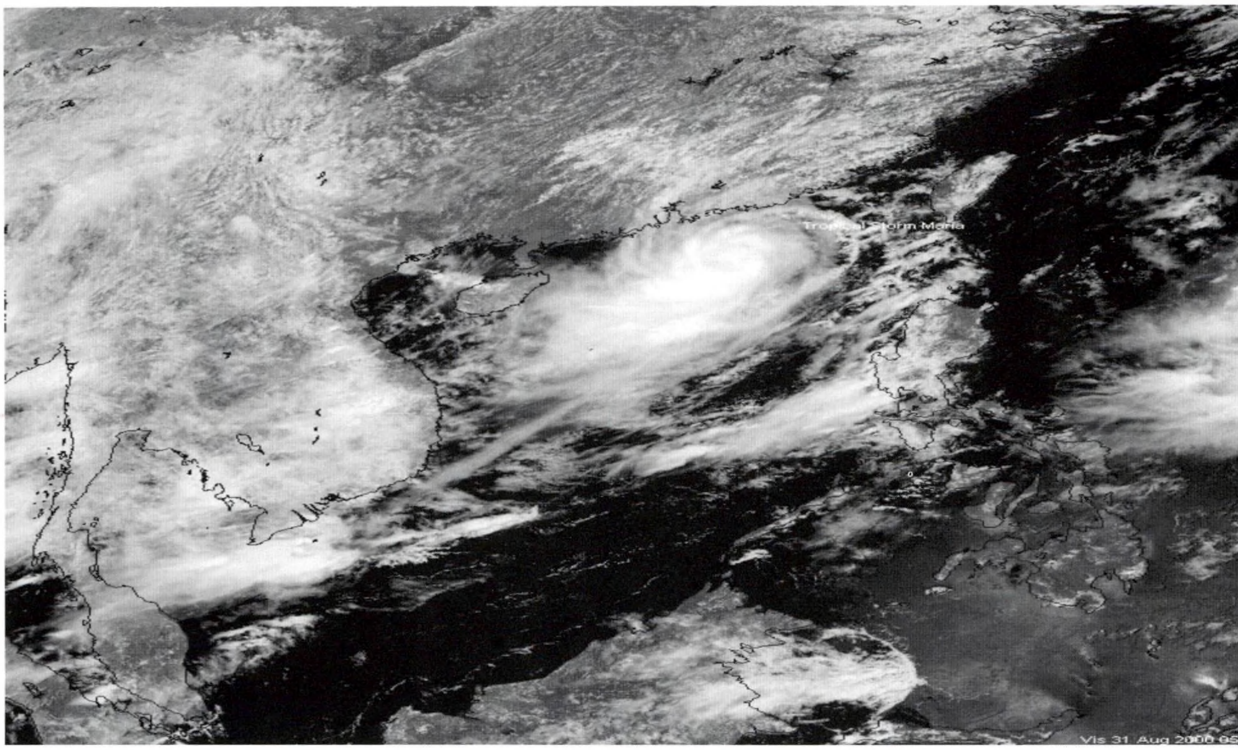


Figure 4: *Example Visible imagery of the South East Asia region*

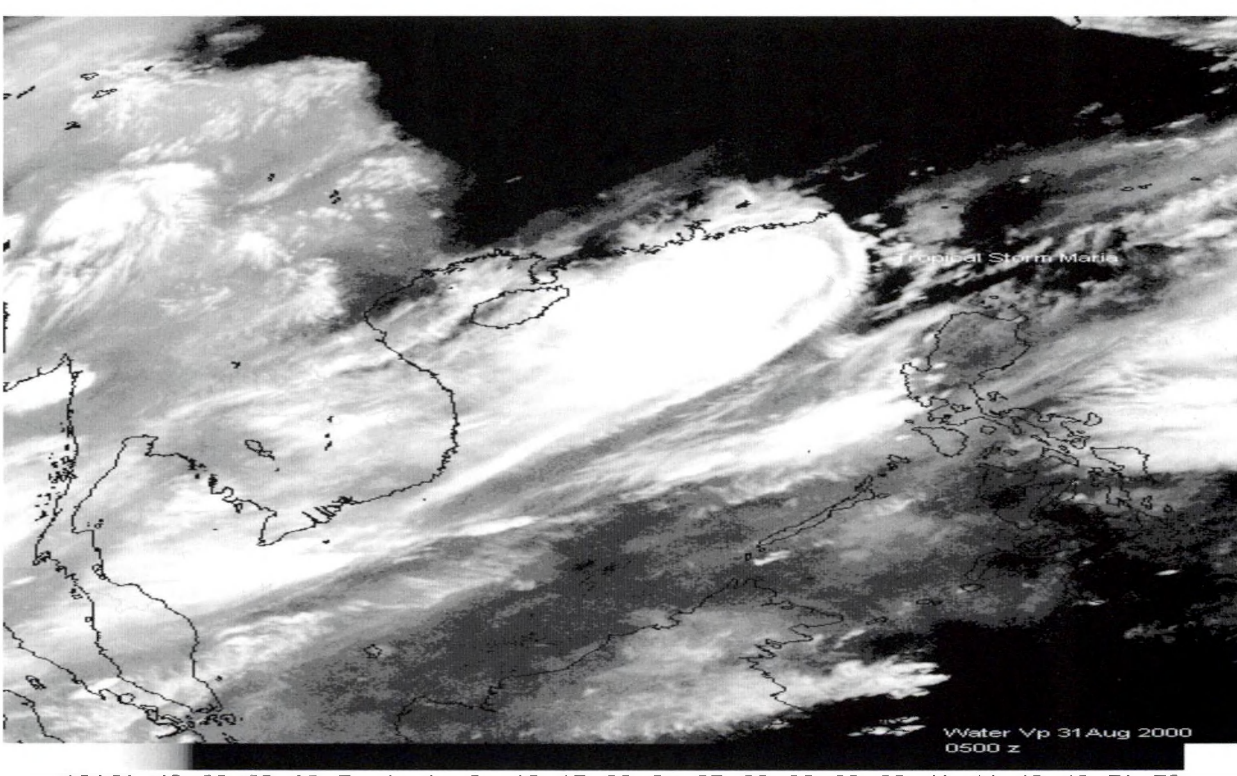


Figure 5: *Example water vapour imagery of the South East Asia region*

Commercial forecasting and provision of climatological products is dominated by terrestrial applications. For example, commercial forecasting activity represents a market estimated at US$400 million (£267 million) per annum[5] in the United States, with the majority of services being into terrestrial, rather than marine applications.

The principal customers for the marine component of this world-wide market are the offshore oil and gas and merchant shipping industries. Principal data products are high accuracy site-specific forecasts (in support of sensitive offshore operations such as deepwater drilling, heavy lifts, submarine cable installation etc), ship routeing services and climatological products to support operational planning, design and environmental protection. The majority of service provision to these client groups is by commercial companies.

Estimates of the total value of commercial service provision (i.e. total revenue inclusive of any marine earth observation data or data products used in production of the end deliverables) are hard to obtain since there is little or no published market data. Based on unpublished market assessments the total value of this market is estimated at £22-27 million (US$33-40 million) per annum[6]. Accurately quantifying the contribution of satellite earth observation inputs to these data products is impossible to achieve as, in almost all cases, satellite earth observation data is only one of many data sources used to generate the data products supplied to customers.

Even more difficult to quantify are the commercial opportunities for data products wholly or partially derived from satellite earth observation in support of maritime civil engineering, fisheries and coastal management. The total commercial market for marine measurements and data products currently provided to these markets is estimated at £160-200m[4] (US$240-300 million) per annum. No data exists on the contribution of marine earth observations to this sum but present usage of satellite earth observations in the sector is low and accounts for only a tiny proportion of this annual revenue.

Another commercial market for data products that may draw on marine earth observation data is that associated with environmental protection and the detection of, and response to, environmental incidents such as oil and chemical spills. Much work is currently being undertaken to develop operational satellite earth observation tools for this sector (for example a recent contract awarded to the UK's Defence Evaluation and Research Agency to develop an operational oil spill monitoring capability for the UK Maritime & Coastguard Agency[7]). This type of research and development activity may lead to fully operational services in due course.

The above analysis of current commercial operational use of earth observation data in marine applications does not permit an accurate quantitative evaluation of the present market but it would be reasonable to estimate this at a figure of the order of £10 million (US$15 million) per annum.

This estimate can be corroborated through knowledge of the number of individuals engaged in commercial consultancy in the marine data product field who have a professional interest in marine remote sensing. A recent analysis of the membership of the Alliance for Marine Remote Sensing Associations (AMRS)[8] identified that approximately 90 of the association's 670 members were engaged in commercial consultancy activities.

If we make some simple assumptions about this number we can get a good indication of the scale of activities in provision of marine satellite earth observation data products.

The revenue generated per employee in a typical specialist marine consultancy firm is in the range £50,000-£100,000 (US$ 75,000- US$ 150,000) per annum. If we assume that the 90 consulting members of the AMRS represent 25% of the total number active in the field and assume that 50% of the activity of these staff is associated directly with satellite marine earth observations then we arrive at a total level of revenue generation in the range £9.0-18.0 million (US$13-27 million).

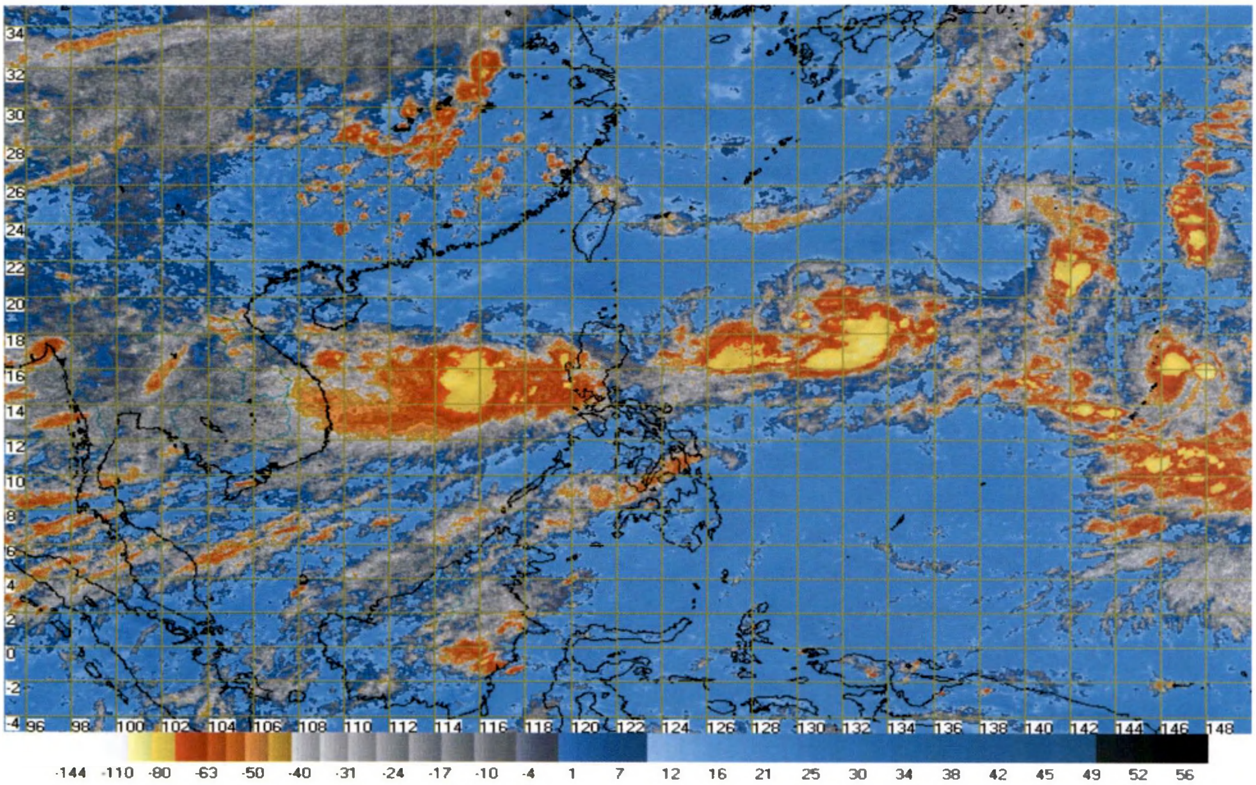


Figure 6: *Example Infrared imagery of the Pacific Ocean region*

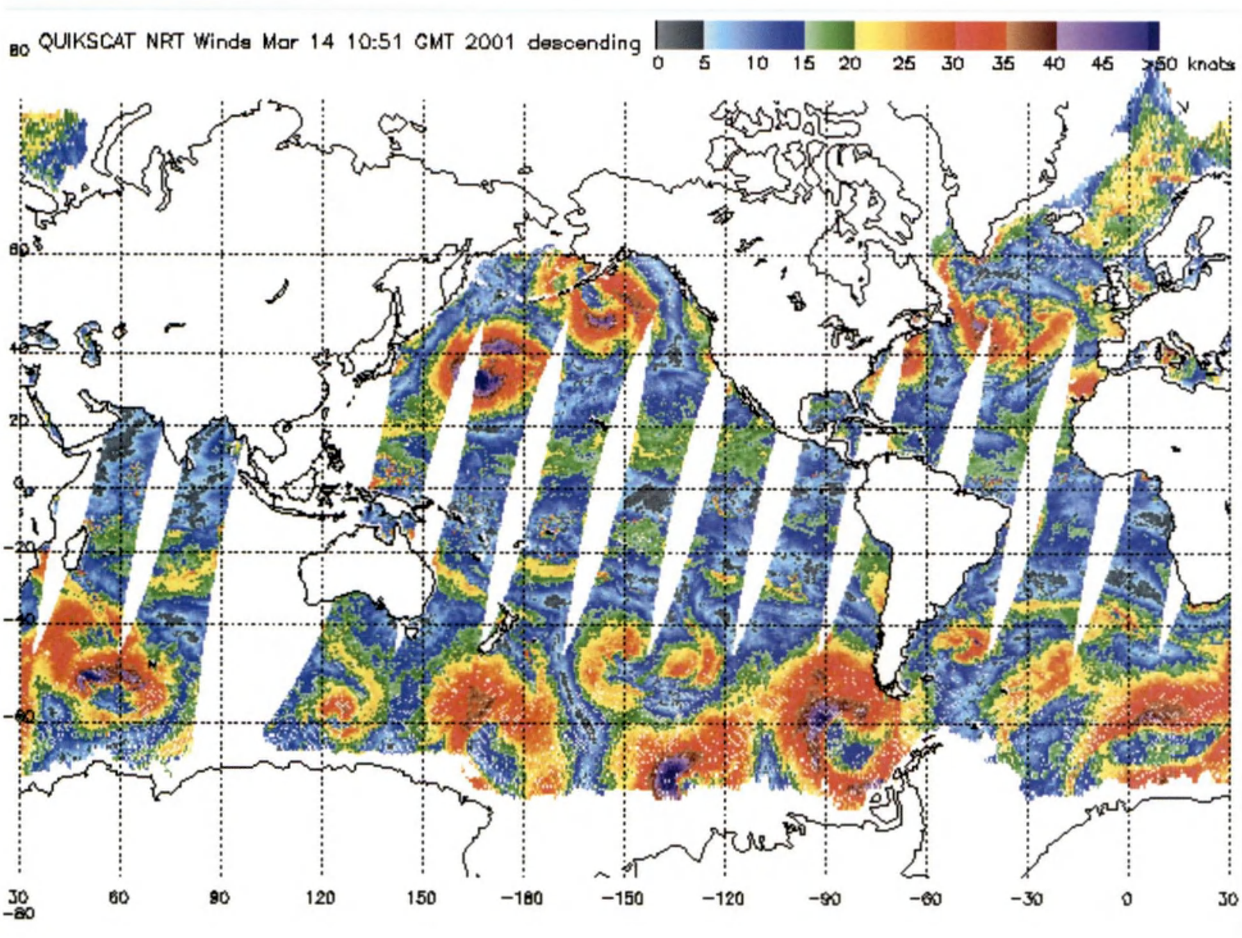


Figure 7: *Example Scatterometer data*

Some examples of operational data products incorporating satellite earth observation data

Commercial uses of satellite earth observations range from production of environmental statistics based on collation and analysis of long term observed data to complex data products and operational forecasts. This section of the paper provides some examples of this range of commercial activities.

The first example is the use of long term satellite altimeter data to derive wind and wave climatologies. A number of organisations, both institutional and commercial, provide data products of this type. One example is the web-based service provided by Argoss[9].

This service is based on analysis of over fifteen years of data and includes spectral wave observations acquired by the ERS-1/2 Synthetic Aperture Radar (SAR) and altimeter wave height data from Geosat, ERS-1/2 and Topex/Poseidon. Wind statistics are based on ERS-1/2 scatterometer data.

From a web-based interface the user is able to select a sea area from an interactive map *(see Figure 1)* or a dialogue box. A variety of seasonal or whole year wind and wave statistics, including extreme value estimates, can then be derived for the selected area *(see Figs 2 and 3).*

The service is subscription based with a current charge of Euro 5000 per annum.

An example of direct use of satellite earth observations is the site specific offshore forecasting service provided by Fugro GEOS.

This service makes use of direct reception of data from GMS-5 for infrared imagery, visible imagery and water vapour imagery; use of Meteosat for infrared imagery; and use of NOAA 12 and 14 polar orbiting satellites for infrared and visible imagery *(see Figures 4 – 6).* Use is also made of web distributed Quickscat scatterometer data *(see Figure 7).*

These data, together with numerical model predictions and surface observations, are used in the preparation of highly site-specific forecasts of weather and seastate tailored to offshore operations. For particularly sensitive offshore operations, such as float-overs and heavy lifts an experienced forecaster works with the rest of the offshore engineering team providing direct input to planning on a continuous basis.

Services are provided on a term contract basis with data distribution by fax, email or internet over Inmarsat channels.

An example of an indirect use of satellite earth observations is the maritime weather and sea-state forecast service provided by Chartco[10]. Chartco uses the Inmarsat point-to-multi-point facility to broadcast a mix of high accuracy positioning, digital notices to mariners, tracings and weather and seastate data to vessels world-wide.

This service makes indirect use of satellite earth observations in that the weather and seastate forecasts broadcast by the company are derived from the global atmospheric and seastate forecast models operated by the UK Meteorological Office. These models assimilate satellite earth observations. Model output is packaged and compressed for broadcast and is displayed on-board the receiving vessel in a number of forms specifically tailored to aid vessel passage planning.

The Chartco services are sold on a subscription basis through Admiralty Chart agents world-wide.

An example of a more complex direct use of satellite earth observation data is the use of SAR imagery to derive bathymetric information. The Bathymetry Assessment System developed by Argoss[11] utilises the fact that under favourable meteorological and hydrodynamic conditions SAR imagery shows features of the bottom bathymetry in shallow waters *(see Figure 8).* By using a suite of numerical models the depths of coastal waters may be inferred. This technique provides a rapid tool for assessment of coastal bathymetry *(see Figure 9).*

An example of a hybrid product that employs both satellite earth observations and the use of conventional in-situ observations is the Trinidad Rings Advisory Co-Operation (TRAC) service operated by Fugro GEOS.

Original resolution of image was 12.5m x 12.5m

Figure 8: *A typical SAR scene illustrating the surface expression of bathymetric features (supplied by ARGOSS)*

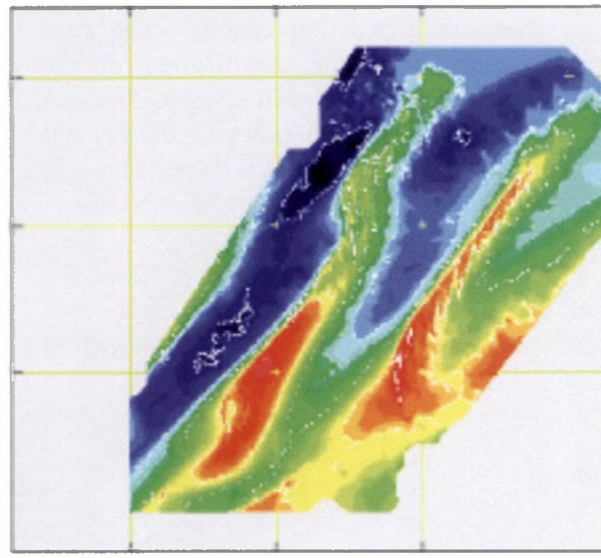


Figure 9: *An example of bathymetric information derived from SAR imagery (supplied by ARGOSS)*

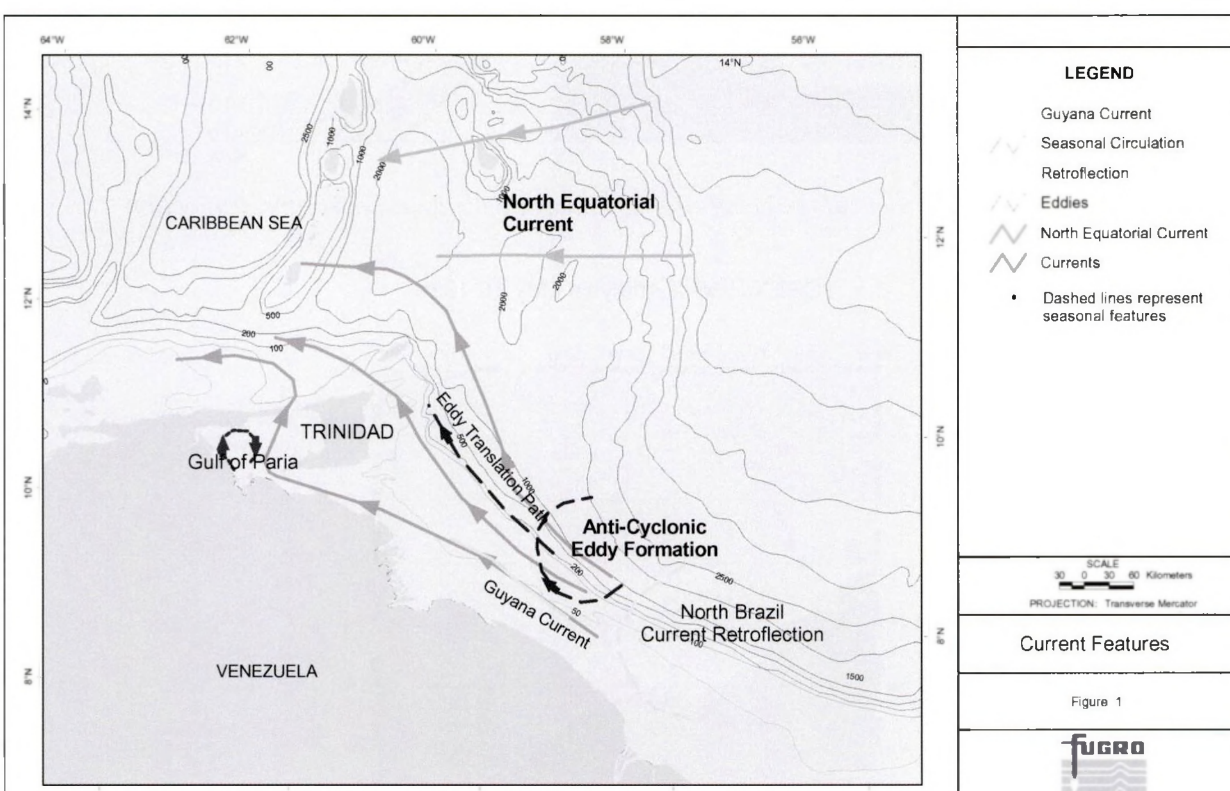


Figure 10: *Features of the currents off Venezuela and Trinidad*

This service provides offshore drilling operators with operational forecasts of the features of high energy eddies. High energy warm core eddies detach from the retroflection of the North Brazil Current and drift towards Trinidad and the Caribbean[12] *(see Figures 10 and 11)* and if such eddies pass an active drill site they can disrupt station keeping and subsea operations.

The generation of eddy forecasts involves the use of Topex/Poseidon altimeter data *(see Figure 12)* and conventional drifter tracks *(see Figure 13)* to support numerical simulation of eddy structure and propagation *(see Figs 14-16)*. Forecasts of eddies are provided to offshore operators on a subscription basis.

These examples are typical of the type and scale of commercial use of satellite earth observations to service small niche markets either by providing an entirely new way of addressing an information need or by supplementing *in situ* measurements to provide an enhanced product.

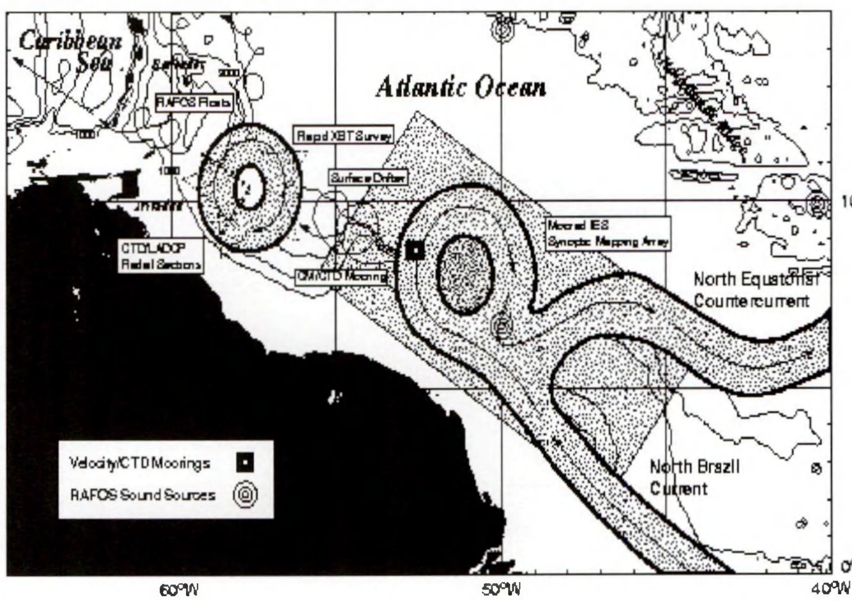


Figure 11: *Diagrammatic view of the generation of eddies by the Brazil current retroflection*

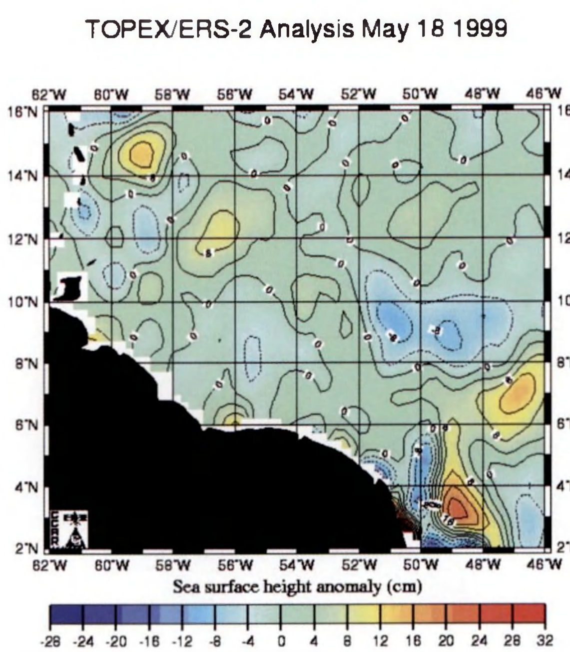


Figure 12: *Topex Poseidon/ERS-2 altimetry data*

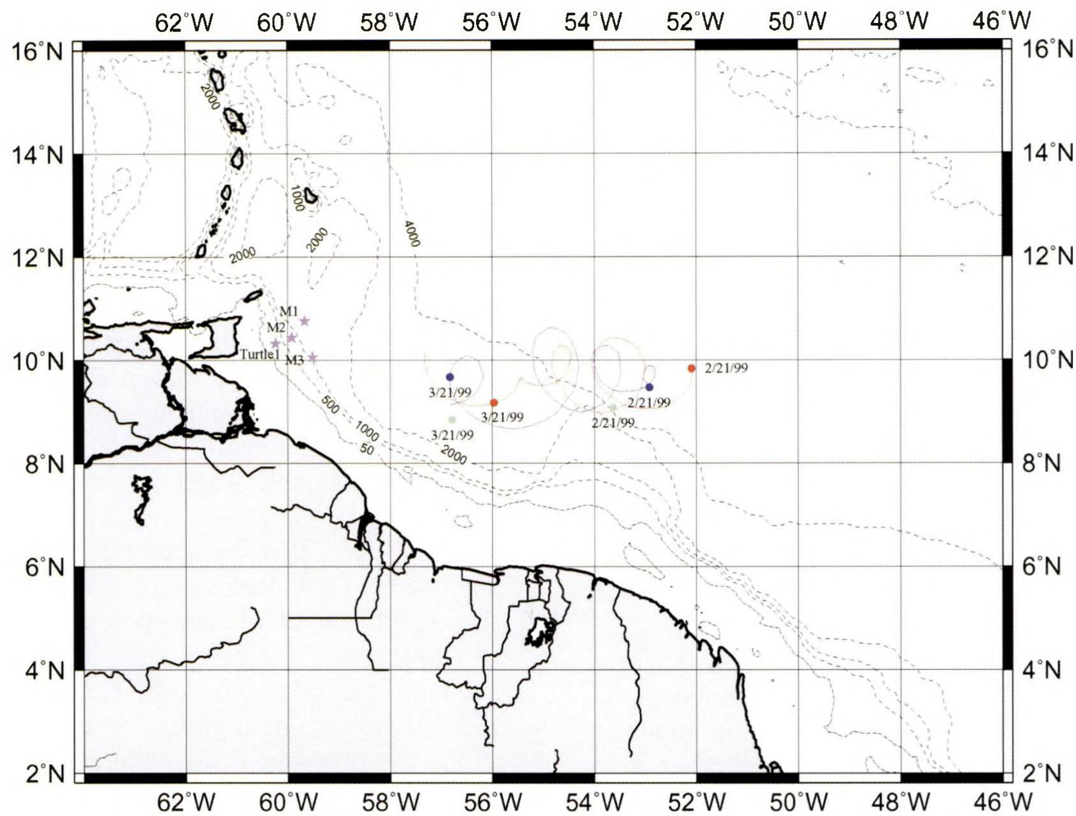


Figure 13: *Typical drifter tracks*

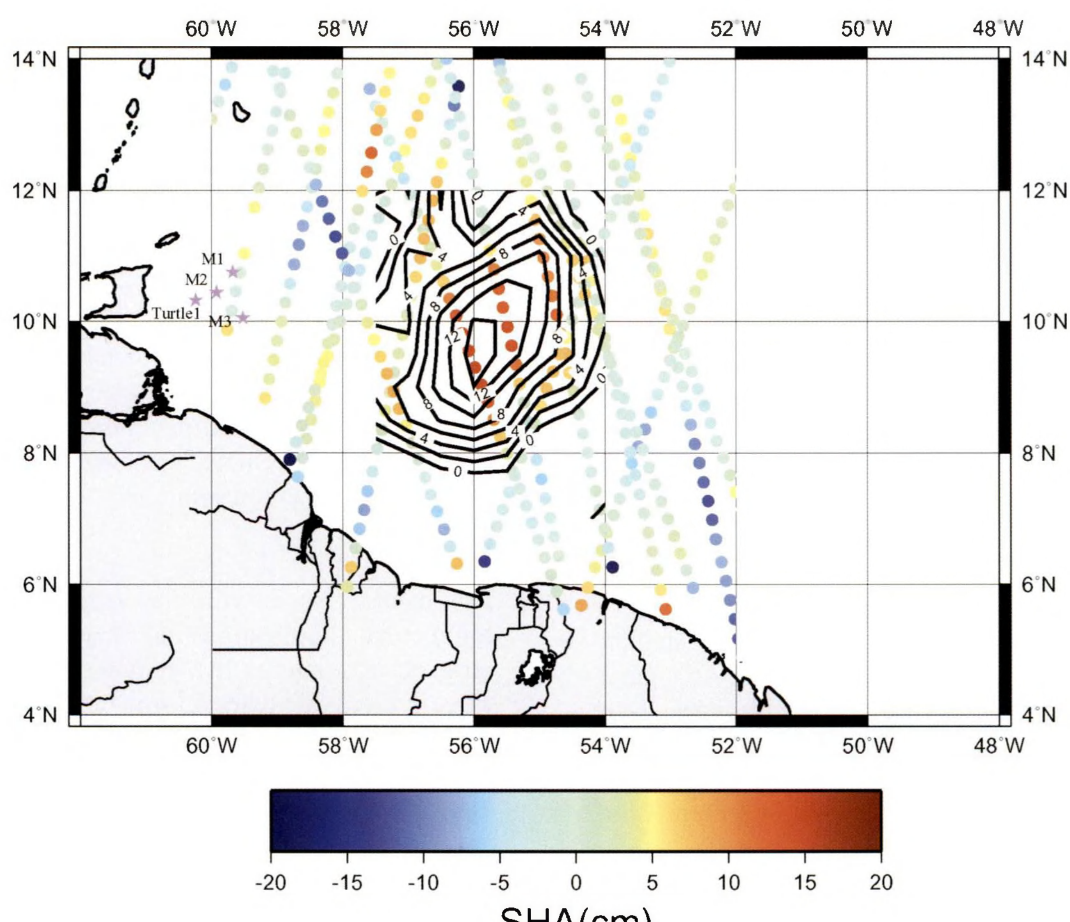


Figure 14: *Surface height anomalies over a typical eddy*

Conclusions

The above analysis of the market and the examples of products illustrate that satellite earth observational data makes a small but significant contribution to the enhancement of existing commercial value added data products and the creation of completely new products.

Overall, the assumption that commercial sales of value added products derived wholly or partially from satellite earth observations will increase is realistic. Growth will be fuelled by increased pressure on the coastal zone, increased level of maritime trade and the demands generated as oil and gas exploration and production moves into ever deeper and more hostile waters.

Developments will not always increase the value of the total market, as new data products will sometimes replace existing services at a lower selling price. Indeed, this is one of the key ways that new techniques for addressing information needs already serviced by other means achieve market penetration. If the new data product is of equal, or better quality, but is lower priced than a pre-existing means of serving a customer need then it will, if properly promoted, supplant the existing data product.

An example is the provision of wind/wave climatology products based on satellite earth observation data. This type of data product is already sold at prices substantially below that of existing services based on other means of observation and, given sufficient utility in the product, will eventually supplant the pre-existing services. Unless the lower price then attracts a wider customer base, then the total value of the market for this type of product diminishes.

The commercial market for marine data and data products is expected to grow by a significant proportion in the coming decades - the Marine Information Task Force of the UK Foresight Programme[4] projects a doubling of the market size in twenty years in present value terms.

Satellite earth observations will undoubtedly play a role in this growth, but their contribution is likely to be modest and there is no obvious reason to expect the sort of step changes that have been assumed in many market studies. Such projections often seem to be based on the assumption that because a new data source can be created there will automatically be a commercial market waiting to purchase it.

The role of another branch of satellite use, satellite data communication, will probably play a far greater role in stimulating sale of certain marine data products by lowering communication costs and providing increased bandwidth making a wider range of marine data products commercially viable.

It seems likely that the largest commercial use for satellite earth observations will remain their direct and indirect use to support the production of specialist forecast and climatological products for sale into relatively small niche markets where the forecast or climatological product is very specifically tailored to the needs of each customer group.

The emergence of operational ocean forecast models which assimilate satellite earth observations and *in-situ* measurements will create a range of new and enhanced commercial data products as the cost of the telecommunications and computing costs of running such models falls to levels where they become commercially viable tools.

New and enhanced products are also likely to be derived from increasingly high-resolution satellite observations of coastal regions although the largest contribution to this market will probably come from increased use of aircraft based remote sensing given the inevitably higher resolutions that can be achieved.

The central issue with the majority of the commercial applications of marine satellite earth observations is that remote sensing from space can provide extra information, but seldom provides information that completely replaces traditional survey and *in situ* measurements. The benefits are therefore mostly incremental rather than revolutionary. Given that the majority of the potential commercial markets for these incremental improvements are discretionary, the ability to generate large revenues or high margins is very limited.

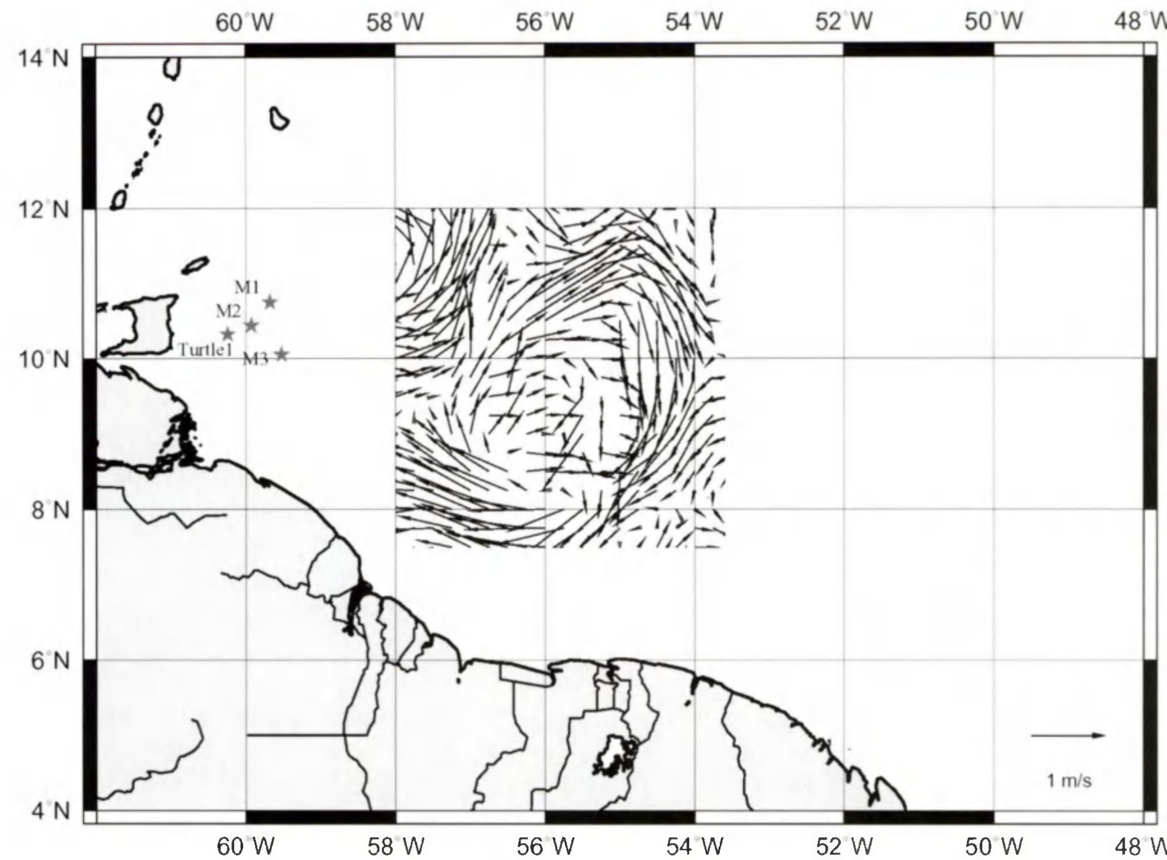


Figure 15: *Modelled eddy current structure*

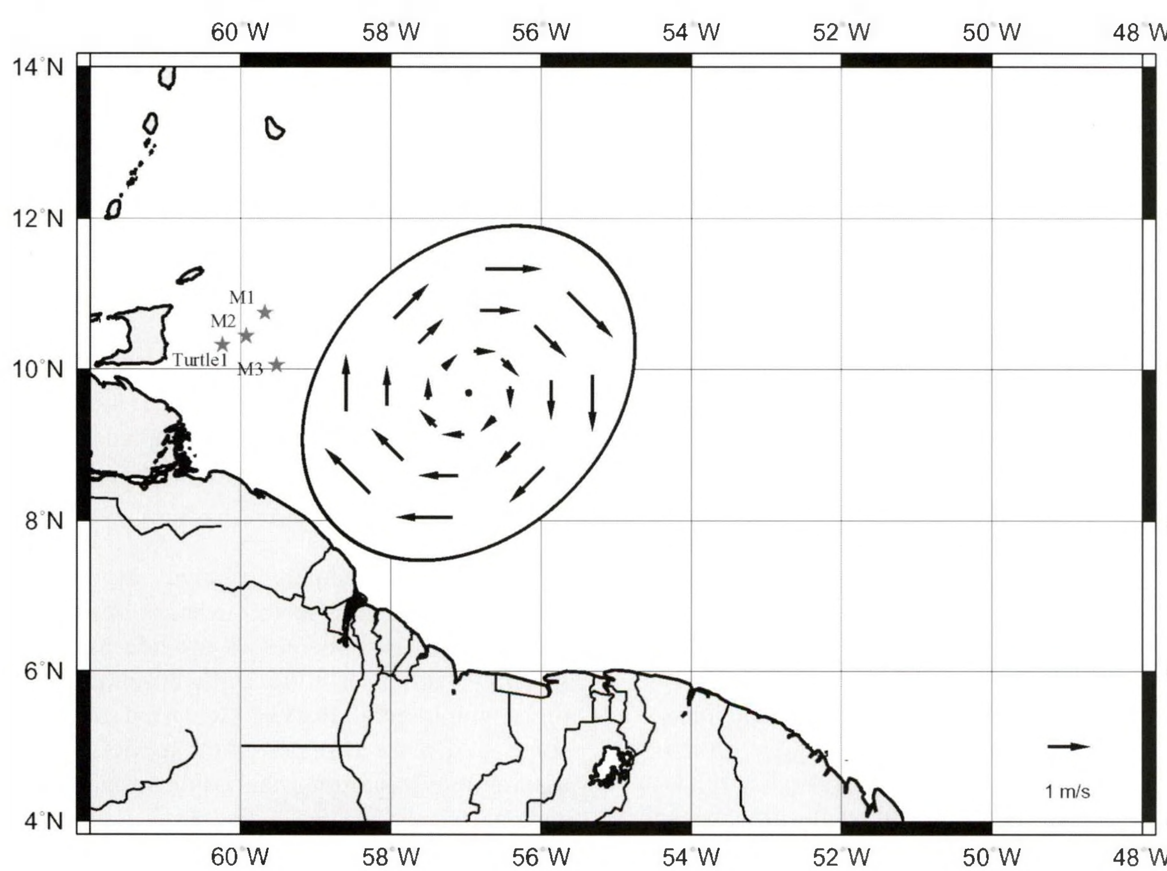


Figure 16: *Forecast output*

In a discretionary market, take up of a given data resource is determined by the balance between the cost of the data and the value of the information derived. For example, there is little doubt that future improvements in satellite observations will permit small incremental improvements in the quality of site-specific marine weather and seastate forecasts. However, it is less certain whether a market already receiving good quality information from existing services will be prepared to pay a significant premium for these improvements.

Overall, the value of commercial use of marine earth observations is likely to remain small and will probably continue to represent only a tiny fraction of the costs of launching and operating the satellites from which the data are derived.

The primary justification for meeting these high costs from the public purse is therefore overwhelmingly one of 'public good' through the use of the resulting data in improving the understanding of large scale phenomena such as El Niño and global warming and better forecasting of global and oceanic conditions to satisfy defence and strategic needs of governments and international agencies.

The successful emergence of new commercial applications of satellite earth observations will only occur in a climate where government fosters and encourages the commercial use of data collected for public good. The present situation where government agencies and organisations, in Europe at least, seek to recover significant differential charges for the commercial use of satellite earth observational data is an effective block on the creation of novel and innovative commercial products. This, in turn, restricts the emergence of sustainable commercial ventures making effective further use of data beyond its originally intended public good purpose.

Novel niche market applications are unlikely to be effectively exploited by public bodies since they lack the international marketing structures and intimate knowledge of specialist end-customer requirements needs to develop such opportunities. Central to success in commercial exploitation of marine earth observation data is the effective linkage between data collected for strategic governmental needs and the commercial value added data industry's understanding of market needs and the development and promotion of commercial data products. A data pricing policy and framework that encourages and fosters this linkage is a necessity *(see Figure 17)*.

This inequitable European situation in which policy inhibits the development of genuinely profitable business ventures serving external customers and creating returns to the tax payer through personal and corporate taxation stands in marked contrast to the situation in the United States. In the US commercial exploitation is actively encouraged through public data being public, that is available for use by any person or organisation without copyright restriction and without charge (other than in some cases the cost of retrieval).

It is, therefore, not surprising to find that the largest providers of commercial products derived in whole or in part from satellite earth observational data are North America based. To quote a recent comment from the Technical Director of the US Office of Naval Research[13]: "Our primary mission is to perform research and development and acquire data and assimilate and apply the data for purposes of national security. So our *sine qua non* in this whole exercise is to make sure that we are getting the best research and development for the fleet. Subsequent to that it is research and development that's paid for by the US taxpayers and we're always going to make those data available to the commercial sector and in fact about 80% of our holdings are accessible to the public".

If we are to stimulate a small but vibrant European industry sector where commercial value added data businesses provide a conduit to apply marine satellite earth observations in niche commercial markets we need to revisit some of the underlying policies and assumptions regarding the commercial use of such data.

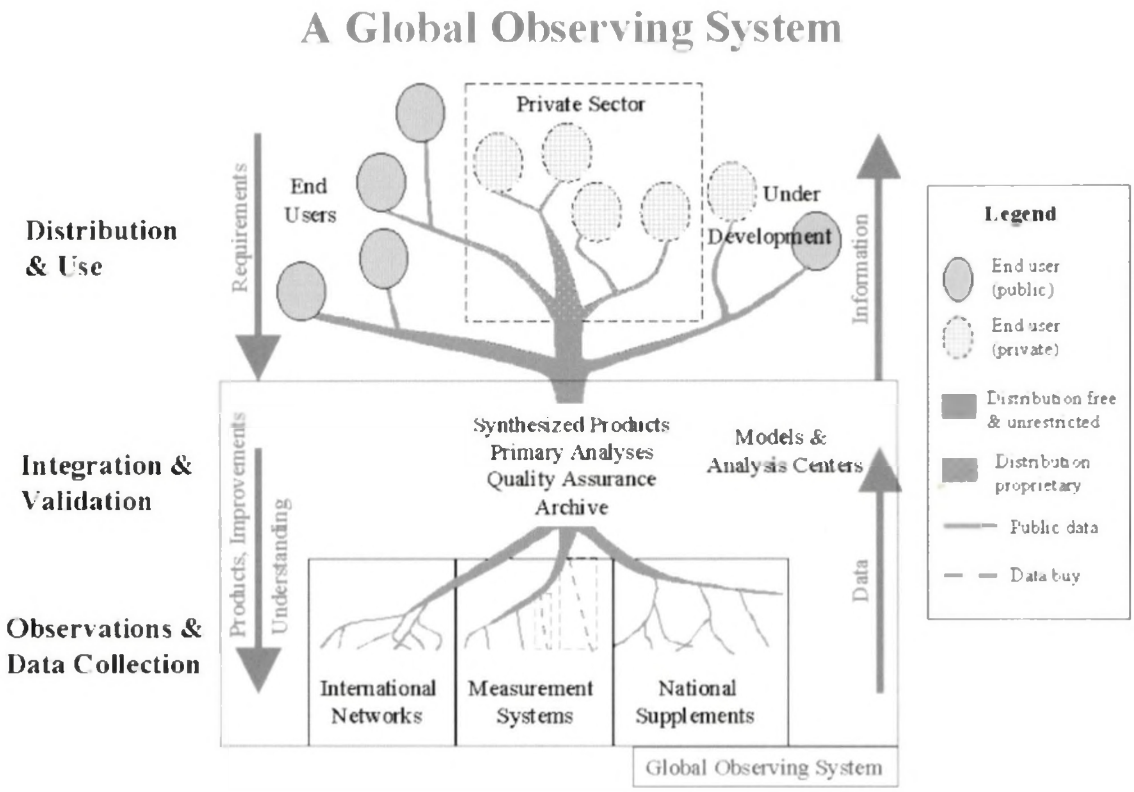


Figure 17: *A diagrammatic view of the relationship between freely available public data and the use of such data in the creation of commercial data products*

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Requirements for remotely-sensed data for operational ocean modelling: the European shelf seas and ESODAE

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Introduction – the status and scope of ESODAE

The European Shelf Seas Ocean Data Assimilation and Forecast Experiment (ESODAE) is aimed at a practical demonstration of the overall capabilities of ocean analysis and forecasting models for the North West European Shelf Seas in providing operational oceanographic products on time scales out to a few days. ESODAE is currently in its planning phase. This is being carried out through a European Commission-funded MAST III Concerted Action MAS3-CT98-0187. ESODAE is linked in concept to the Global Ocean Data Assimilation Experiment (GODAE) and indeed is intended to form a regional seas component of GODAE itself. As such ESODAE primarily concentrates on physical oceanography, in particular on prediction of the sea surface elevation and the temperature, salinity and current structure of the European shelf seas. ESODAE includes consideration of surface waves where these are relevant, for example, to mixing processes and potential over-topping of coastal defences during high storm surge events, but not more widely at this stage since wave products are well covered through other initiatives.

It is anticipated that the ESODAE experiment itself will be carried out with a series of nested models. These will include: shelf-wide models covering the shelf, shelf break and deeper waters with a typical resolution of 5km and forced from boundary conditions taken from the GODAE global or basin-scale models; higher resolution embedded models (e.g. for the shelf break, southern North Sea or Irish Sea) and other (e.g. coastal and estuarine) models embedded in these for local applications.

The key objectives of ESODAE are thus:

- to run participating model systems in a consistent framework;
- to assess the use of data assimilation in a North West European Shelf context;
- to contribute to networking in operational and pre-operational oceanography of the region;
- to exchange and assess products with involvement of users.

To further the last of these objectives, an ESODAE users Workshop was held in Aberdeen from 20-22 September 2000 with invitees from operational agencies and both 'intermediate' and 'end' users. Intermediate users included marine information system providers, commercial forecast service providers and those involved in the provision of data dissemination services. End users included those involved in oil and gas production, marine transportation, the construction industry, port management and ship pilotage, search and rescue, coastal defence, dredging, aquaculture and fisheries.

North West European Shelf Seas-characteristics

The North West European Shelf is an area of intensive industrialisation, including major fishery and offshore oil and gas exploitation, shipping and leisure activities. On the shelf itself, the seas are shallow and mixed by strong tidal currents. There are also marked coastal effects, including river inflows, estuarine exchanges and exchanges with the Baltic Sea. At their outer edge is a steep shelf break, a region of narrow boundary currents and marked internal wave activity. From a modelling perspective a particular complication is the presence of open boundaries with the Atlantic Basin to the north, south and west of the area.

These characteristics put clear demands on the resolution needed for numerical models of the region, observing system requirements in terms of *in situ* data and remote sensing (in particular the number of staggered satellites, repeat cycles and coverage) and the adequacy of existing techniques for data assimilation (Johannessen, 2001).

Remote-sensing contributions to meeting the needs for operational ocean modelling

For operational ocean modelling on the global ocean/basin scale, these include use of

- sea surface temperature data from AVHRR
  - for analysis for the sea surface temperature fields of numerical weather prediction (NWP) models, with impacts on the predicted surface fluxes used to drive operational ocean models
  - for assimilation into operational ocean models, for example the Met Office's Forecast ocean Atmosphere Model (FOAM) system (Bell *et al.*, 2000)
- scatterometer wind data
  - assimilated into NWP models to provide the best surface forcing data for shelf seas (and wave) models
- altimeter significant wave height data
  - assimilated into wave models to provide wave model initial conditions
- altimeter wind data
  - to partition between wave model wind sea and swell at the end of the data assimilation phase
- synthetic aperture radar data
  - to provide information of wave energy spectra for wave model validation
  - to provide detailed information on eddies, fronts and internal waves
- altimeter height data
  - for assimilation into ocean models, proving information on the sea surface height and inferred temperature structure at depth
  - for calibration of storm surge models (Philippart and Gebraad, 2001)

- remote sensing of sea ice via active and passive sensors (SSMI/SSMR, SAR)
  - for assimilation of ice concentration and ice edge data into models (see e.g. Bell *et al*, 2000)
  - for provision of bottom boundary conditions for NWP models with impact on the surface flux field

and for the future:

- surface salinity data from space
  - for assimilation into models
- ocean colour data
  - to provide information on the biological component, including harmful algal blooms
- use of remote sensing to provide sea ice thickness data

Remote-sensing data in the shelf seas context

Two key characteristics of shelf seas models are their relatively limited area and the need for provision of data at their open boundaries. Limited area provides a restriction on the usefulness of remotely sensed data from space because of the limited data density which orbital tracks provide. Thus, for example, significant wave height data over the European shelf seas are limited by having only one pass per day at 7 km along-track resolution and Synthetic Aperture Radar (SAR) wave spectral data from ERS-2 by their spacing of 200km (ENVISAT will bring this down to 100km spacing). Whilst this provides a limiting restriction, remotely-sensed data can be usefully employed in development and validation of shelf seas and limited area models, as illustrated in the examples below.

Use of altimeter sea surface height data for calibration of storm surge models

Altimeter sea surface height (SSH) data applied to shelf seas modelling are limited both by horizontal resolution and by the need to take account of the complex tidal motions of the shelf seas in their assimilation. Philippart and Gebraad (2001) have carried out experiments to examine the impact of assimilating sea surface height data from both coastal tide gauges and from satellite altimeters into the Dutch continental shelf model. They find the greatest impact to be from assimilation of the tide gauge data which with their proximity to the coast are located precisely in the areas where the sea surface height anomaly has its potentially highest value. By contrast, an isolated altimeter track may lie anywhere over the region with little impact on initialisation of sea surface height. Even so, they point to the potential usefulness of data from a collection of tracks over a period for calibration of sea surface height models in particular in shelf areas where no tide gauge data exist.

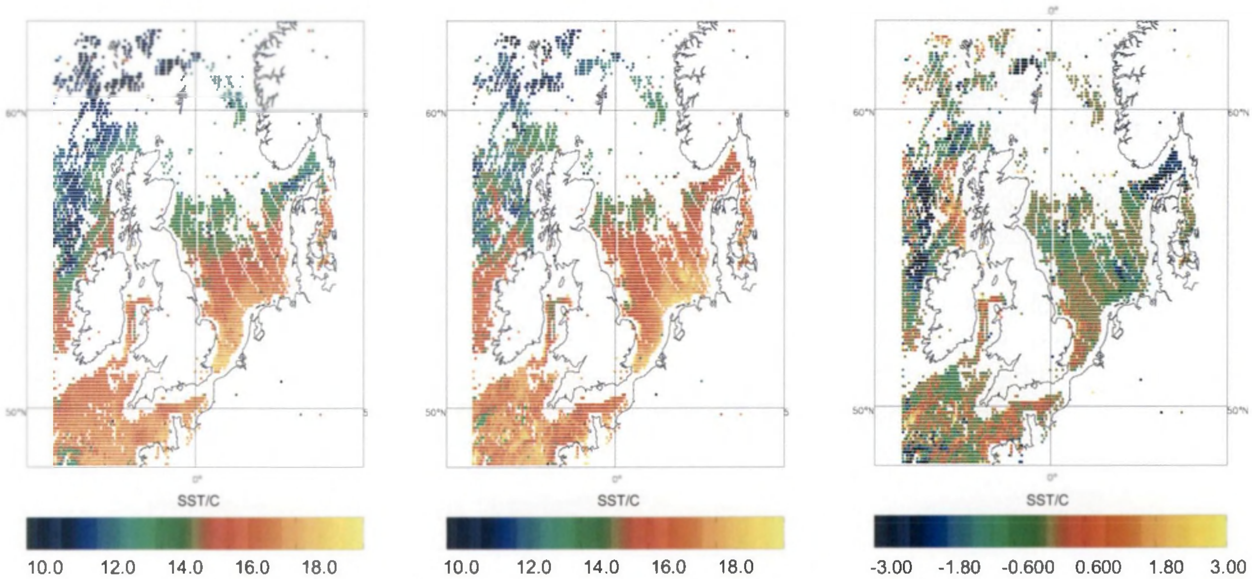

Figure 1: *Example of use of monthly composite AVHRR data for shelf seas model validation averaged over August 2000. Left: observed field. Centre: corresponding model field; the model data are extracted to the times and locations of the observations. Right difference (model - observed)*

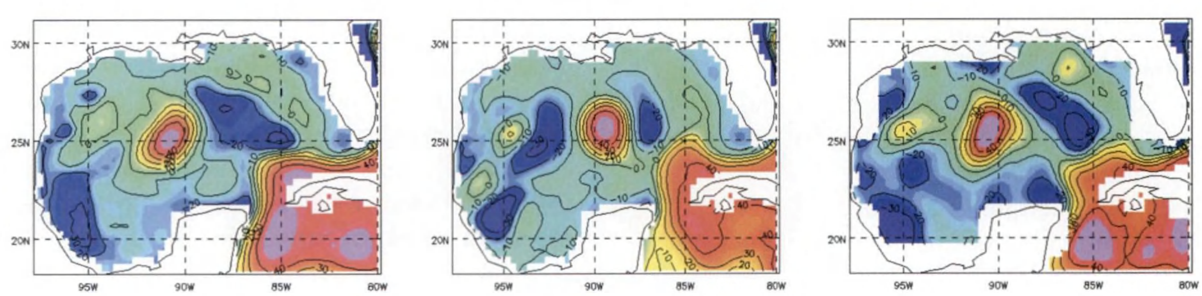

Figure 2: *Comparison of the CLS gridded observed sea surface height field over the Gulf of Mexico (left) compared with a run of a 1/9 degree version of the Met Office FOAM model without (centre) and with (right) inclusion of altimeter sea surface height data.*

Use of AVHRR data for shelf seas model validation

As is well known, sea surface temperatures from AVHRR are markedly cloud-limited. However, composites of these data have been found useful in validation of shelf seas model sea surface temperature fields (Figure 1).

Assimilation of altimeter data into a high resolution regional model

Trials of nested versions of the Met Office FOAM model presently being carried out include experiments to assimilate remotely-sensed and *in situ* sea surface temperature data, *in situ* temperature profiles and satellite altimeter data. These include runs of a limited area model at 1/9 degree resolution model of the Caribbean region nested into a 1/3 degree Atlantic basin model. These have demonstrated that the best representation of the mesoscale temperature structure is to be achieved with a combination of all three data types and high model resolution (Figure 2: M J Bell, personal communication).

Provision of boundary data for shelf seas and regional models

At the present time, a key, if indirect, use of remotely sensed data for shelf seas operational modelling is in their assimilation into large (basin) scale ocean models which then provide boundary data both for shelf seas and regional models. Provision of boundary data for trials of such systems is one of the objectives of GODAE and their use for experiments in real time modelling of the European shelf seas an objective of ESODAE. Care needs to be taken however to ensure consistency of treatment between modelling systems. Thus, for example, experiments with the Met Office FOAM system (M J Bell, personal communication) have demonstrated the need for care in the consistency of the bathymetric treatment across model boundaries to ensure correct propagation of features from one model to another. Other issues, which apply to both global/basin scale and more local models include the need for effective data quality control, the need for good knowledge of needed assimilation statistics and of the mean sea level state.

Concluding remarks

As noted above, a key way in which remotely sensed data can be expected to impact on shelf seas models in the future is by their assimilation into basin-scale models which then provide needed boundary data for operational running. Assimilation of altimeter sea surface height data into ocean models is already actively underway in some centres for operational oceanography (e.g. in the SOPRANE system of the French Navy and in models run by the US Navy). Its use is also under development in other centres (e.g. in the Met Office FOAM system in the UK, for the French MERCATOR system under active development and in other European Commission-sponsored projects such as that on 'development of advanced data assimilation systems for operational monitoring and forecasting of the North Atlantic and Nordic Seas' (DIADEM). Specification of boundary conditions for shelf seas models is also being tackled by the EC's project on 'global assimilation applied to modelling of European shelf seas' (GANES).

Data assimilation for the North West European Shelf Seas is in its infancy at present, but efforts are underway, exploring the direct use of altimeter sea surface height data and AVHRR data. This is a both a focus and a challenge for ESODAE. Issues for direct use of satellite remote sensing data on the shelf include those of repeat cycle and coverage. Other use of remotely-sensed data includes use of SAR data to give information on eddies, front and internal waves and, where appropriate in a wider shelf seas context, the use of remotely-sensed data to provide information on sea ice characteristics.

Operational centres are already using scatter-ometer wind and radar altimeter data on wind and waves for NWP and wave forecasting, and these are well established applications. Use of SAR data for validation of the wave spectrum is under active development at a number of centres and there is potential for assimilation of SAR spectral data into wave models in the future.

Finally, use of ocean colour data is also being explored at operational centres. For example work at the UK Environment Agency has shown the clear potential for this in terms of monitoring of the growth of algal blooms (D Palmer, personal communication). Use of such data will become increasingly important as operational models are developed to include ecological parameters.

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Pelagic fisheries and operational ocean services

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Introduction

The present analysis will be conducted in view of the potential support that operational ocean services can provide to pelagic fisheries sustainability and management. Examples with some tuna species and swordfish will be shown.

A few major needs and still open questions, may be defined as follows:

i) Stock assessment for large pelagic species is faced with a very significant lack of data independent from fisheries activities.

ii) Present stock assessment is based on fish catch discharged data. Thus, biased estimates of fish abundance are expected since fishing fleet space and time distribution is far from isotropic.

iii) Most of the large pelagic species of commercial interest do probably have migration behaviours, but these are still largely unknown and presently accepted migration patterns are still at the stage of working hypothesis.

iv) There are a few examples that clearly show a link between ocean mesoscale dynamics and thermodynamics and the large pelagic fish distribution and behaviour, but such results had never been used for stock assessment.

In order to make oceanographic data useful for reliable and accurate stock assessment, one would need:

i) To establish accurate ocean basin-wide patterns for the large pelagic fish migration pathways.

ii) To obtain accurate three-dimensional ocean mesoscale dynamics and thermodynamics at ocean basin-wide scales.

iii) To establish the ocean basin-wide correlation between oceanographic features and pelagic fish distribution with, at least, mesoscale resolution.

iv) To incorporate such correlation knowledge into a coupled modelling system of realistic ocean dynamics and population dynamics including natural and fishing mortality sources, reproduction rates, larvae dispersion, feeding grounds, migration pathways.

v) To use realistic model results with data calibration and assimilation, both of remote and *in situ* origin, for stock assessment.

In what follows we will show a few pragmatic examples of correlation between observed / calculated ocean dynamics and pelagic fish distribution. The present performance of some numerical model/data assimilation examples will be addressed in view to justify the need for, i) their extension to ocean basin-wide coverage, ii) maintaining mesoscale resolution capabilities and, iii) maintaining a regular ocean data gathering system (remote and *in situ*) for assimilation into numerical modelling. Finally, some discussion elements will be enhanced.

Some examples of correlation between ocean dynamics and pelagic fish distribution

Large scale correlations in the Atlantic

The Temperate and Tropical large-scale Atlantic circulation patterns are dominated by two subtropical gyres, one in the North Atlantic and another in the south. Each of these gyres has a circulation contour boundary, which is coincident with the most significant current systems that we can find in the Atlantic. In particular, the North Atlantic Subtropical Gyre has the Gulf Stream has its western and north-western boundary, the Azores Current at the north, the Canaries current in the east and the Cape Verde (or North Equatorial Current) in the southern boundary (Fig. 1). All these current systems are prone to mesoscale turbulence, which develops around its mean path.

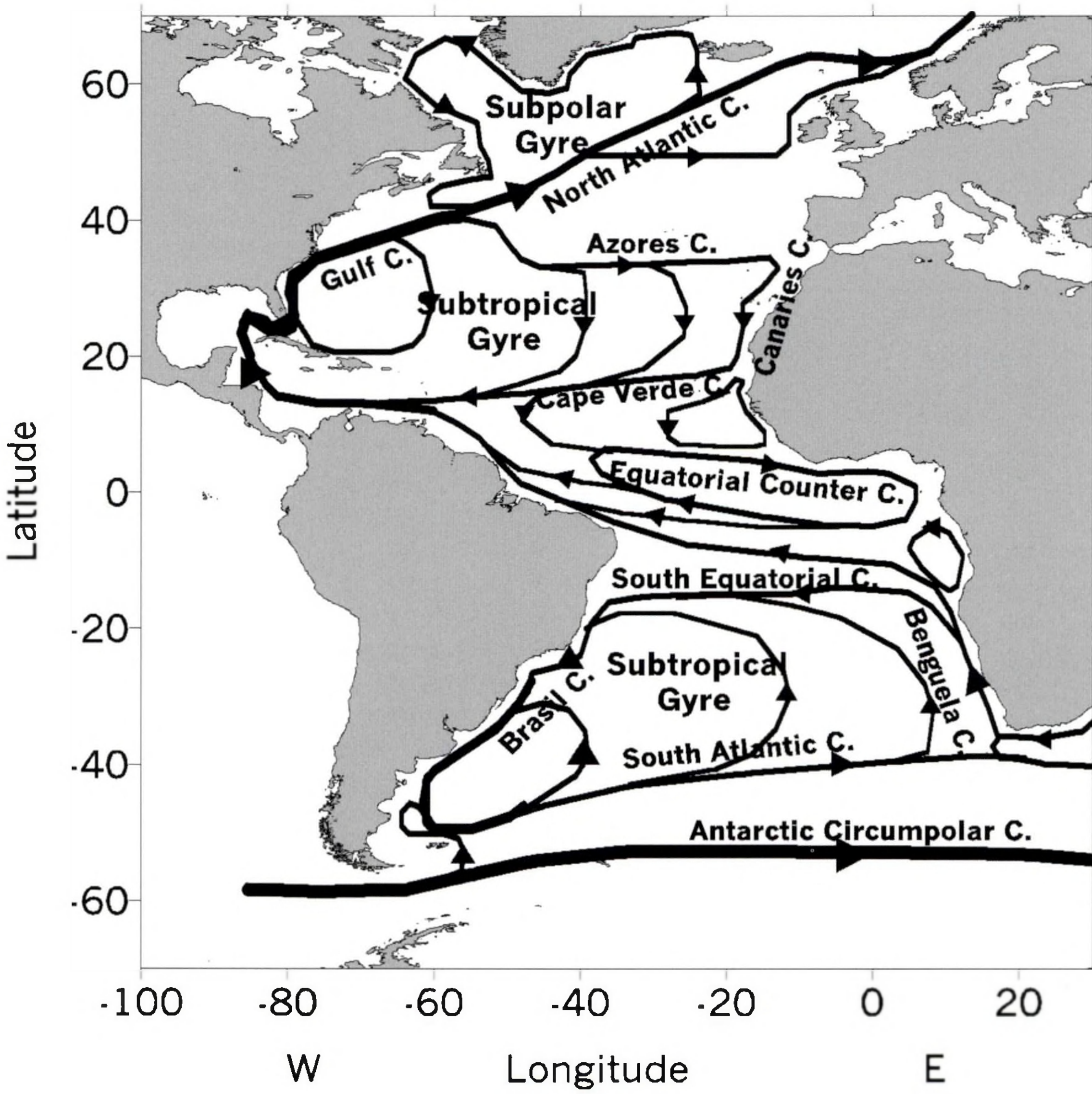

Figure 1: *Surface currents in the Atlantic*

Following Fonteneau (1998), we may compare this large scale circulation with the distribution of longline catches of swordfish (Fig. 2) or with the longline catches of different tuna species (Fig. 3), both for the period 1989-1993 (according to Fonteneau *et al*, 1998), it is clear that catches coincide with the mean current paths.

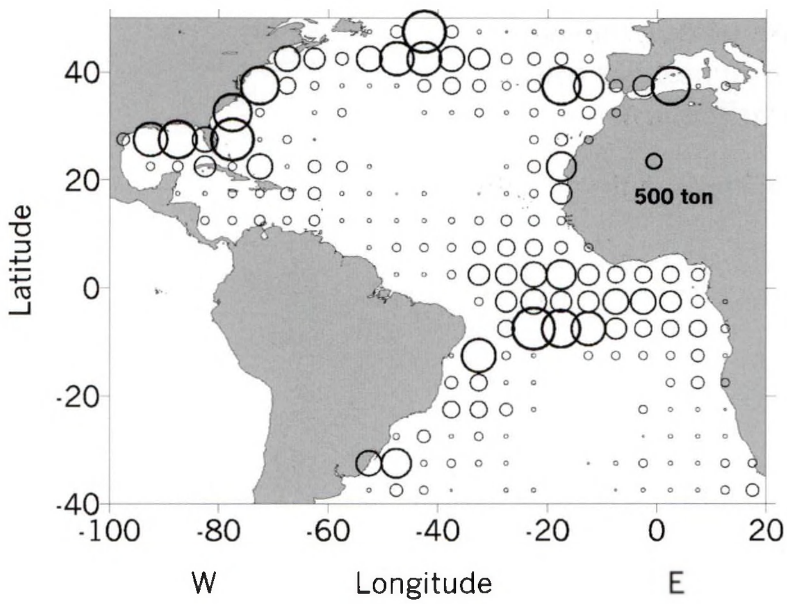

Figure 2: *Average longline catches of swordfish (1989-1993). The 5°N line is the accepted separation between southern and northern stocks (Fonteneau et al 1998).*

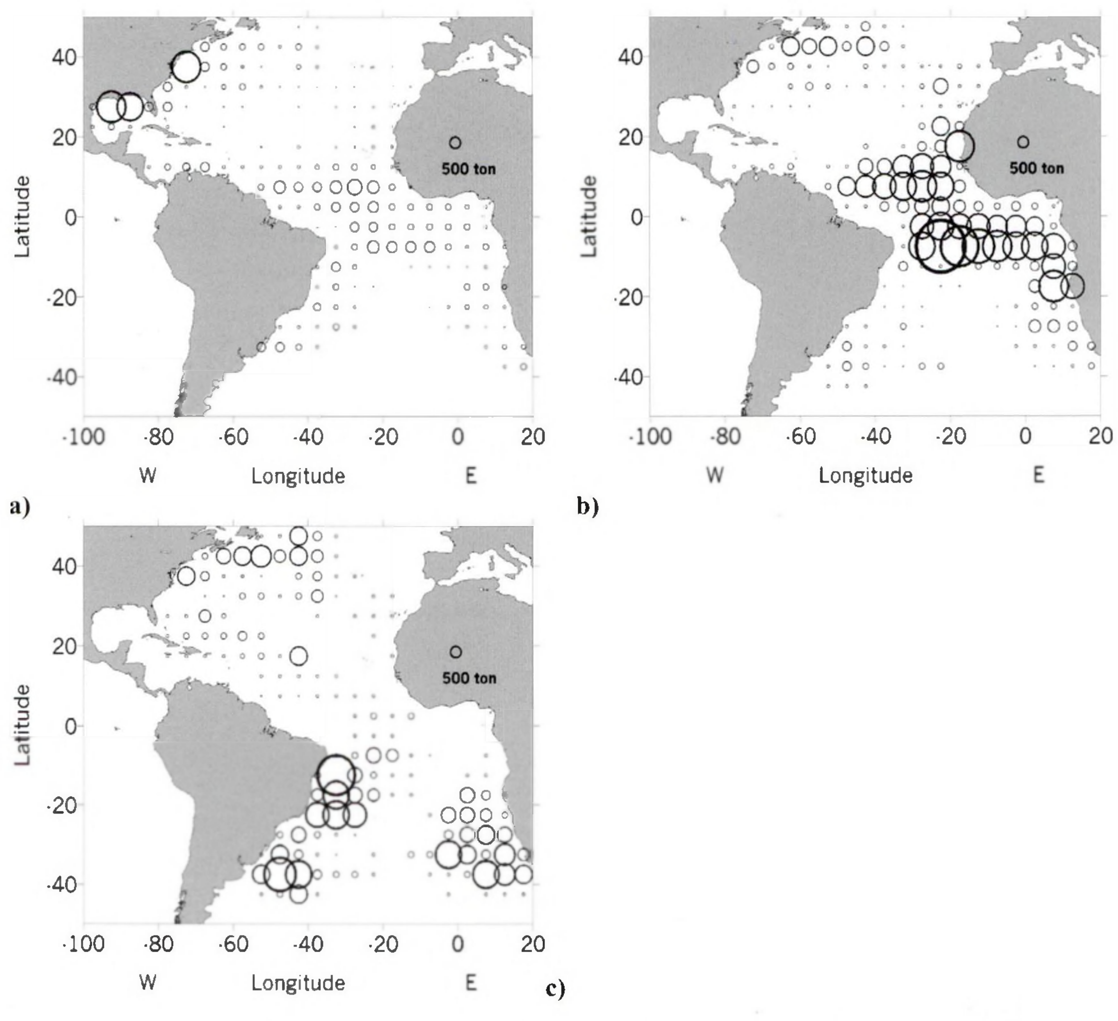

Figure 3: *Average longline catches by species (1989-1993), for (a) Yellowfin, (b) Bigeye and (c) Albacore (Fonteneau, 1998). Note scale of circles is shown by unit circles of 500 tons/yr plotted in West Africa. The catches are centred on 2° x 2° squares.*

Mesoscale Correlations

When we come to the synoptic details of a given mean current, it is immediately clear that there are meanders and eddies. It is, in fact, with the details of these oceanographic features that we can find the strongest correlations with the food-web distributions (from primary production up to the large predators). Fig. 4 is a selected example from Alves (1998) in which the acoustic scatter for large pelagic tuna appears clearly associated with the northern edge (shear zone) of the Azores Current - AzC (cruise FCA94C conducted by the Oceanography Group of Azores University during Summer 1994).

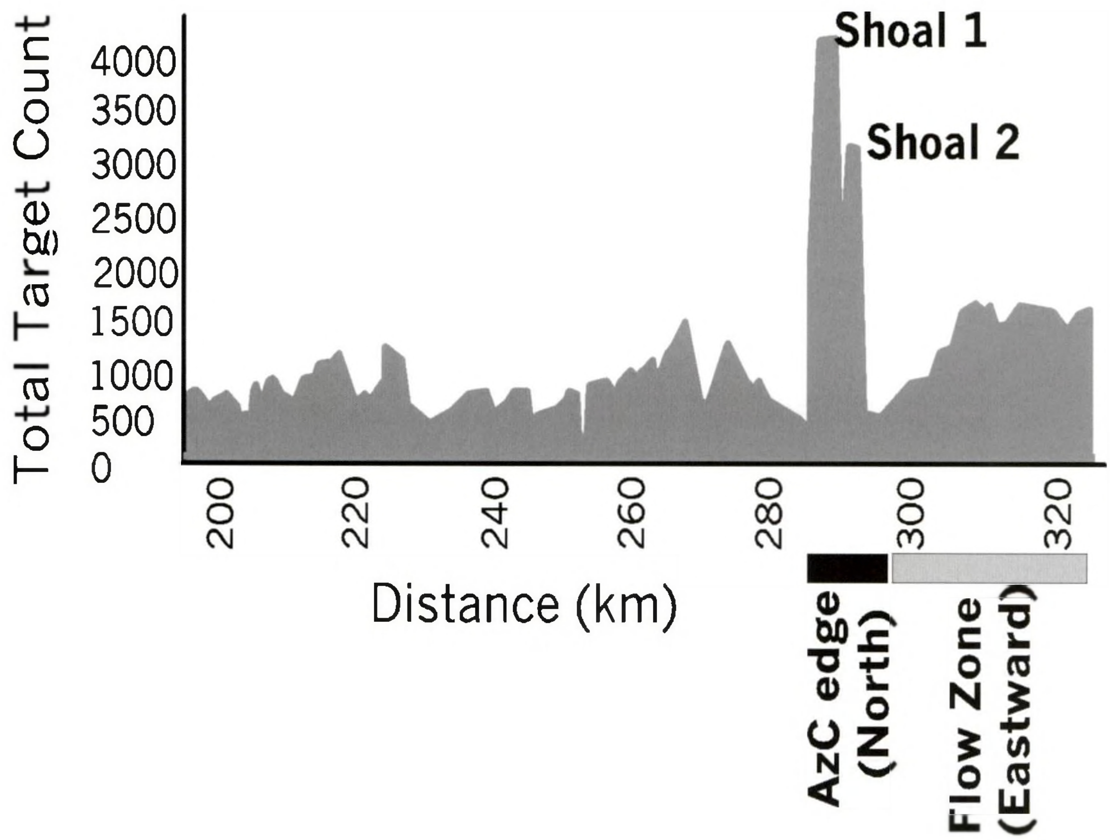

Figure 4: *38 kHz acoustic scatter, showing 2 fish schools in North-South transect across AzC shear zone (mean latitude of 34°N and longitude 28°W). Horizontal axis is N-S distance travelled and vertical axis is the total target count for bins with 500m(horizontal)*250m(vertical).*

Similarly, for the FCA97C summer cruise (Alves *et al* 1998), whose current patterns are presented in Fig. 5, the total acoustic echointegrated biomass has its maximum values well along some parts of the meandering current (where the strongest vertical movements take place) and almost no expression outside of it (Fig. 6).

Small scale correlations

Further reducing the observational scale to the order of 1 km, it is possible to get clearer insights about what is happening at the level of large pelagic fish behaviour strategies. In particular, during FCA94C cruise, if we get into the details of the vertical fish distribution (obtained by acoustic echointegration) associated with the maximum abundance (schools 1 and 2) presented in Fig. 4, it is clear that both schools were feeding on small pelagic fish (shadowed horizontal layers in Fig. 7), whose distribution was linked with the northern edge of Azores Current shear zone.

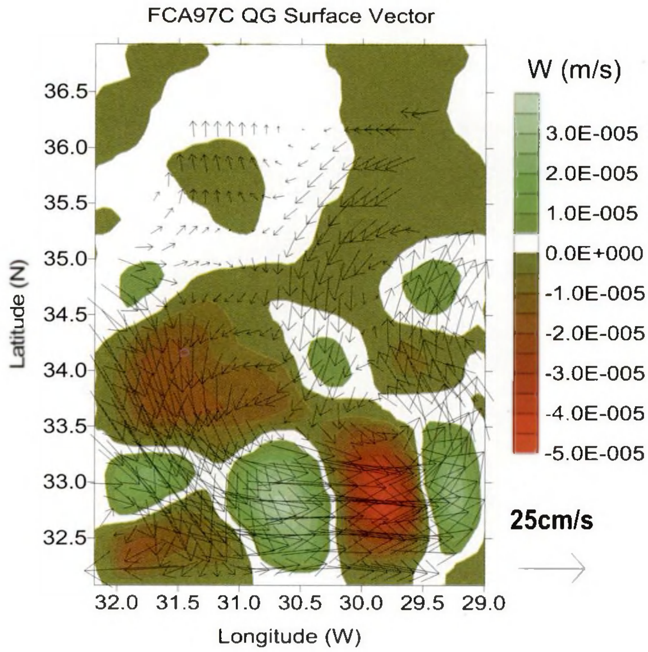

Figure 5: *Surface current distribution at the Azores Current area, south of Azores islands, during FCA97C (end of July 1997). Shaded patterns represent the areas of most intense vertical movement. Surface Azores Current flows, in the mean, from west to east.*

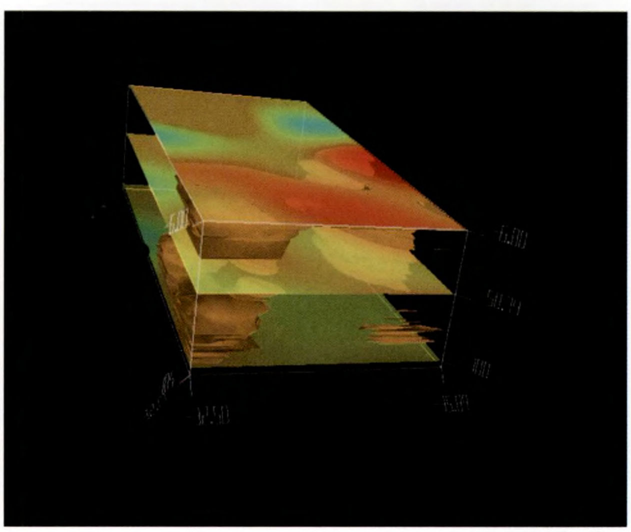

Figure 6: *Three-dimensional representation of the acoustic echo-integrated signal covering the whole FCA97C cruise area. Left is west and the closest horizontal limit is south. Vertical co-ordinate is in meter and extends from surface down to 100m. The most significant biological activity is concentrated along the Azores Current path, where the vertical movements are the most intense.*

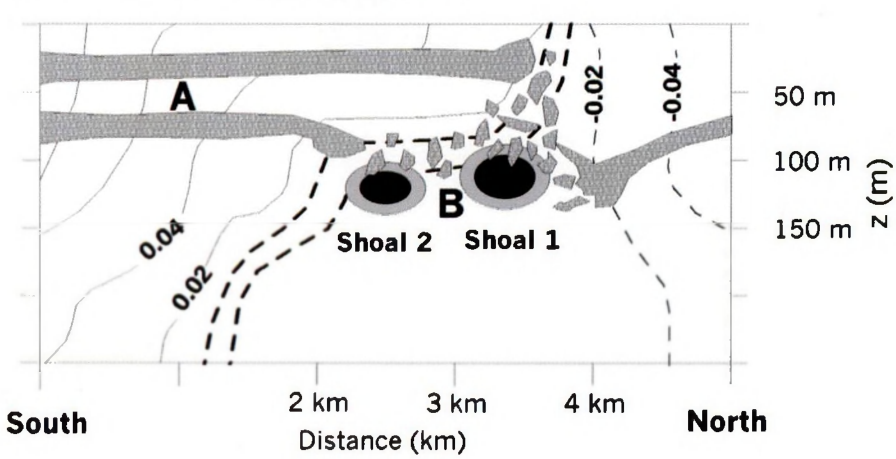

Figure 7: *Sketch of vertical distribution of biological activity as observed in relation to the oceanographic features of AzC. The features marked A are the two scattering layers detected by the 120kHz echointegrator and those marked B are schools detected by the 38kHz signal. B coincides with the disruption zone of the 120kHz signal and with the strongest AzC shear flank. Dashed (solid) lines represent measured (ADCP) current intensity, in m/s, to the west (east).*

The need for ocean mesoscale observations and numerical simulation of the real ocean dynamics

It is now obvious that accurate knowledge of ocean mesoscale circulation is of capital importance to establish any future methodology for pelagic fish stock assessment and, thus, avoiding the problems caused by a fisheries dependent and biased analysis. This is so not only because of the clear correlation between ocean dynamics and pelagic fish distribution, but also because ocean currents may play a crucial role in recruitment. During the early stage of pelagic ages, *larvae* distribution is strongly dependent on ocean currents and thermodynamical conditions. A pragmatic example was given by Alves *et al* (1998). An hypothetical initial *larvae* distribution released in the Azores Current is strongly advected downstream and stirred by the current dynamics and shapes. These results, bring us immediately to the need for reliable ocean simulations.

Accurate ocean mesoscale circulation estimates require not only adequate model formulations (e.g. Quasi-Geostrophic or Primitive Equations), but also a continuous data forcing / updating (through data assimilation) of the model dynamics. Remotely sensed data (mainly altimetric and surface wind), together with ocean interior *in situ* observations are of critical importance to tune ocean dynamics to simulate that of the real ocean.

We are now at the stage in which assimilation of satellite altimetric data and *in situ* observations into adequate numerical models will enable us to produce accurate ocean circulation dynamics. As an example, Fig. 8 (from Alves *et al* 2000) illustrates the achieved performance for the Azores Current system when satellite altimetric data is assimilated into a Quasi-Geostrophic - QG model (Dombrowsky and De Mey, 1992) and the interior thermohaline fields projected from the surface using thermohaline EOF representations (De Mey, 1997). The parallelism of such QG simulated currents (arrows in Fig. 8) with the simultaneous dynamic height estimates from FCA97C and CAMBIOS 97 cruises (conducted, respectively, by the Azores University and the IFREMER during the MAST III CANIGO project) clearly reveal an already acceptable realism for the simulations (despite the natural difference between the two approaches). To improve these results and keep them running regularly in time, will be a fundamental requirement for any future pelagic fish stock assessment system.

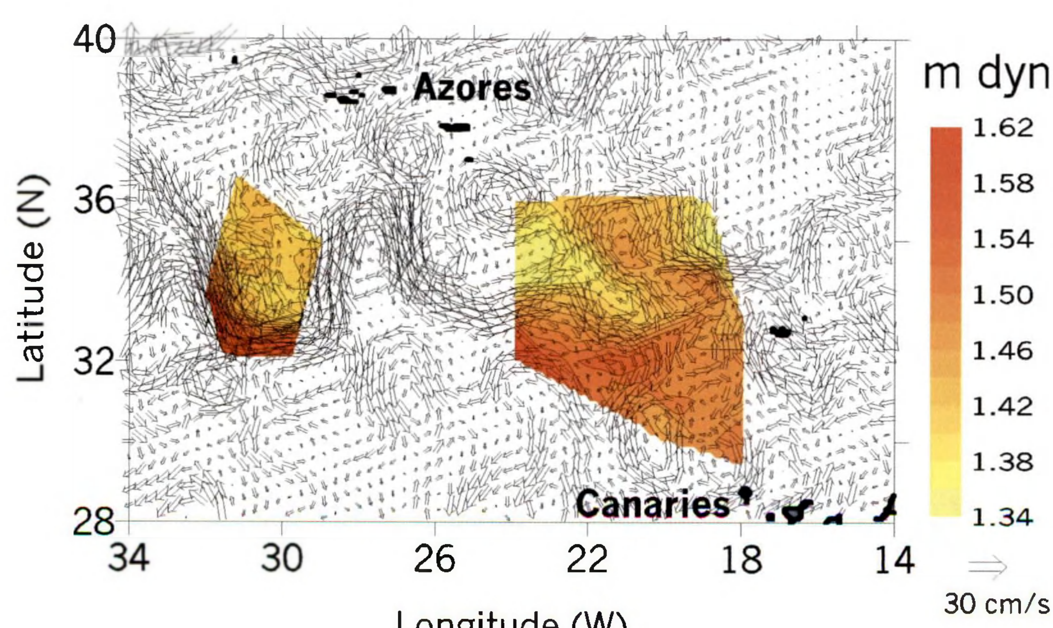

Figure 8: QG altimetric assimilating model result at day 30/07/1997 (arrows), superimposed with dynamic height lines, as obtained during FCA97C and CAMBIOS97 (Alves *et al* 2000).

Discussion

We may summarise the major requirements for the future pelagic fish stock assessment system as described next.

Continuous data flow for numerical model assimilation coming from:

- Satellite altimetry and surface wind (and also to some extent remotely sensed ocean colour)
- *In situ* 3D absolute dynamics and thermo-dynamics
- Acoustic echointegration of biomass and fish schools
- Fish catch location from fisheries activity

Adequate coupled model dynamics and reliable numerical simulations of:

- Primitive Equation/ Quasi-Geostrophic dynamics and thermodynamics
- Primary/secondary food-web chain dynamics
- Population Dynamics (multispecific VPAs)

Combining these we may expect to achieve:

- Accurate stock status quantification and assessment.
- Clear hints on how to define sustainable fisheries policies.

We certainly must evolve in the subject of fisheries sustainability. The "precautionary approach", often used in this context, should not transform itself into an excuse for our ignorance.

The presently proposed approach has its major concern focused on how to count and estimate better and accurately the number of existing individuals and how does such number change in response to the different factors that may affect it. Since it is almost a common place that large pelagic fish obey ocean basin-wide migration paths (for example, tropical tuna species are found in the whole Temperate and Tropical North Atlantic, but in different seasons of the year), whose geographical patterns do still have many uncertainties (Fonteneau, 1998) it becomes clear that the proposed coupled system of data collection/assimilation into adequate numerical models for pelagic stock assessment, should cover full ocean basin areas, but with mesoscale resolution.

This leads us naturally to the conclusion that the developing programs like DIADEM, FOAM, MERCATOR, SOPRANE, or integration programs like ISOOS, are of crucial importance as a base line for the stock assessment requirements on ocean dynamics and thermodynamics. A step forward must be done, however, by adding also acoustic remote sensing of the ocean interior biomass as a routine part of those systems.

Acknowledgements

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Operational oceanographic requirements in the offshore oil and gas industry

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Abstract

This paper examines the requirements by the offshore oil and gas industry for meteorological and oceanographic (metocean) data and the challenges the industry is faced with as the development moves farther into deeper waters. The data acquisition systems are described in general terms but as great progress has been made in utilising data received from remote-sensing satellites which have radar altimeters and scatterometers, the space observations have been discussed in more detail. The paper underlines some successful applications of satellite altimeter data to acquire ocean current information in deepwater areas.

Introduction

The offshore oil and gas industry has a long tradition to obtain and utilise meteorological and oceanographic (metocean) data, and these data are mainly used to establish design and operational criteria for field developments. The effort to improve weather and sea-state forecasts is another. Accurate data are of foremost importance because operations have to be performed in a safe and cost-effective manner. Already in the late sixties and early seventies it became clear that in the North Sea the wave and wind climatology were largely underestimated when they were produced from rather crude and inaccurate ocean atlases based on visual ship observations. This created a need to extend ongoing measurements and establish new locations for long-term *in situ* buoy measurements. With maturity of the area, these programmes have been exchanged with a network of platform-based monitoring stations. Over the past years, the industry has managed to utilise data obtained by remote-sensing satellites to an ever-increasing rate. It is now common to make use of altimeter and scatterometer data on a routine basis. The instruments produce their best data sets in remote areas far from the coast and at high latitudes.

Technical Requirements and New Challenges

The engineering requirements for metocean information are linked to a variety of offshore needs, such as (i) design of new structures, facilities and pipelines, (ii) structural integrity assessment of existing structures, (iii) operational planning and (iv) day-to-day operations offshore. A typical, modern metocean station comprises the full spectrum of metocean parameters, which include:

- Waves, currents, tides, sea temperatures and salinity
- Winds, air temperature, barometric pressure
- Precipitation, humidity, visibility, clouds and cloud height

Waves are by far the most important variable but the increasing importance of ocean currents in deepwater areas is today's major challenge. For instance, loads from waves, winds and currents are of equal importance for particular types of deepwater floating structures. The industry is already producing at 1700 metres water depth and is aiming for developments at 3000 metres in the next few years. In the harsh environment area found at the Atlantic margin, drilling is performed at 1500 metres water depth in Norway and development is planned for Norway's first deepwater field – Ormen Lange at 900 metres.

It is not necessary in every case to collect field data at a new site of interest. The metocean variables are in many cases spatially homogeneous (nevertheless with great variations in relation to parameter and local condition), and then it is possible to extend the range of existing measured data sets into new areas by use of calibrated hindcast wind, wave and current models and/or data obtained from remote sensing. This is a very cost-effective way of increasing the value of existing measurements. Even for sites where say 2-3 years of measured data sets are available, properly verified hindcast models can provide a means of extending the data sets to say a 25 year period and thereby significantly improving an estimate of the extreme values. A recent example is the design criteria on winds and waves established for the deepwater field 'Ormen Lange' off the West Coast of Norway. A composite (measurements with an infill of calibrated hindcast data) wave data set from Haltenbanken for the period 1980 – 93 was extended to a deepwater area 240 km away with the use of hindcast and satellite altimeter data with good result. However, the spatial homogeneity for ocean currents can be completely lost in certain areas. Typical examples are found in the Norwegian Atlantic Current flowing northwards along continental slope off mid-Norway. Stations located only 1 km apart show very different current features in east-west direction.

For obvious safety reasons, the offshore industry will avoid under-designing an offshore installation, hence the price paid for not having the right design data available when it is needed is essentially the cost of over-designing facilities for the future. However, these arguments must be balanced by considering the use of design criteria which are deliberately conservative for today's solution but which will allow additional facilities to be added to the structure in the future without the need, and associated high costs, for major offshore structural modifications.

Developments in even deeper waters give rise to new metocean challenges and the acquisition of ocean current information is the most important task. Monitoring real time currents in water depths greater than 1000 metres - including surface currents - and obtaining reliable data from 3-D current modelling to be used for hindcasts and forecasts are the most critical issues to be dealt with. Other challenges are related to wave monitoring from floating structures and real time data assimilation.

Platform Operated Monitoring Systems and Metocean Networks

All offshore oil/gas platforms carry a variety of metocean sensors and wind, pressure and temperature sensors of some form or other are the minimum to meet statutory requirements and to assist with daily operations. The statutory requirements vary from one country to another but a platform, or a network of platforms, in the North Sea will include the full range of metocean parameters. Most operators are satisfied with a good balance of regulations, which enable 'fit-for-purpose' structures to be installed, and hence adequate metocean data to be collected. Some of these systems are described below:

- In the Norwegian sector of the North Sea, the Norwegian Petroleum Directorate initiated in the mid 1970s a statutory monitoring system from fixed offshore platforms. Today there are some 10 offshore platforms operating between 56°30'N and 66°30'N transmitting data in true time to the authorities and to the companies for internal use. Further, the data are stored and reprocessed for statistical purposes. Several more platforms are making the same measurements on a voluntary basis. Actually, there are no differences between company and regulatory requirements. This metocean data collection - statutory or not - is regulated by a NORSOK standard (Ref. 1). One of the platforms in the system is the Shell platform 'Draugen' which is located at Haltenbanken offshore mid-Norway. Data in true time is transmitted to DNMI, the national weather forecast agency (and further fed into GTS for world-wide exchange of meteorological data), to the local weather forecast agency and to the internal Web-site for operational use.
- MetNet is the name of a network connecting some 20 Shell platforms in the UK sector (Ref. 2), covering the northern, central and southern parts of the North Sea. Also here the data are sent to the national weather forecast agency, UK Met Office for further use. Two of the platforms in MetNet are linked to the Dutch governmental sea level surveillance system Meetnet Noordzee (Ref. 3).
- SeaNet Data Interface (SNDI) will be a network in the North Sea to combine traditional oil industry networks with other data monitoring networks (Ref. 4). SNDI will be an agency to exchange data between the monitoring networks in Norway,

Sweden, Denmark, The Netherlands, Germany and Belgium.

- Similar to the North Sea networks of platforms, several networks are set up in other parts of the world. Shell operates systems offshore East Malaysia (Ref. 5) and Brunei in the South China Sea, and a system of deployed directional wave buoys off the coast of north-western Australia for tropical cyclone swell warnings (Ref. 6).

Regional studies

The offshore metocean industry has been successfully generating joint industry projects for many years and the main incentive behind this collaborative effort is to unite the strength of the companies, and to share the costs and risks. The co-operation in Norway has a long tradition and the first joint data gathering programmes go back to the late 1970s. There is also a tradition to exchange metocean data and make them available to the scientific community. Most regional studies have been established in the International Association of Oil and Gas Producers (Ref. 7) but others are formed and based on national needs. Examples of regional co-operative projects in the Atlantic margin are:

- North European Storm Study (NESS)
- North West Approaches Group (NWAG)
- Norwegian Deepwater Programme (NDP)
- Faeroes GEM (Geotechnical, Environment, Metocean)

It is also a practice to establish co-operation with national and international research programmes (EUROMAR, MAST, VEINS and many others) in the form of financial support, organising fieldwork and measurement planning. Most research programmes need industrial support and, with the right focus from the industry, these projects have pushed the metocean technology ahead.

Application of Altimeter Data and Imagery to Determine Ocean Currents, Fronts and Eddies

The development of microwave radar techniques has made it possible to observe and quantify several processes and phenomena at the sea surface such as waves, winds, fronts, eddies and currents. The industry is now using - some may say rather late – this opportunity to enhance and accommodate the metocean database.

The ability to process radar altimeter data with regard to sea surface height anomalies and velocity anomalies is showing promising results. Recent studies of the Norwegian Atlantic Current – initiated by the Norwegian Deepwater Programme (NDP) - have shown both mesoscale variability and spatial distribution that is advantageous in understanding the current regime of the area. The main purpose of the NDP Metocean Project (Ref. 8) was to obtain the best possible information on ocean currents in the deepwater areas off Norway, and a series of activities on data acquisition, modelling, remote sensing and studies were performed during the period 1996 - 2000. The idea to link ocean current information derived from satellite altimeter data with specific measurements and ocean current model data was initiated from the needs to have simultaneous current information over a large area of eight degrees (60^oN to 68^oN). It was impossible to have measurements in more than one cross-section at the same time because of cost and capacity restrictions.

The OPERALT project (Refs. 9, 10 and 11) was built upon the promising NDP results and the selection of the OPERALT study area and the validation of results were two issues with apparent relevance to NDP. The study area was selected to extend from 60^oN to 66^oN and 10^oW to 10^oE. The northerly extension was chosen to match the Topex/Poseidon boundary but little information was lost due to this. More important, however, was that the study area included the waters between the Faeroes and Shetland. This area is the entrance of warm Atlantic water to the Norwegian Sea and the Norwegian Atlantic Current following the north bound continental slope. The temporal and spatial variations of this region are important for conditions further to the north.

The specific objectives of the OPERALT project were outlined in five points:

1. To produce an accurate high-resolution local altimetric mean sea level.

2. To produce merged ERS-1/2 and Topex/Poseidon data sets.
3. To validate altimeter-derived current estimates against *in situ* measurements.
4. To develop appropriate altimeter data products.
5. To assess the benefits and cost-effectiveness of Near Real Time (NRT) as well as off-line altimeter data products.

In addition, the evaluation of general results was seen in light of the extreme environmental conditions found in the exposed area of the north-eastern Atlantic margin. This means that altimeter products developed in this project could be more advantageous in areas with milder wind and wave climate and less baroclinic effects. The slope areas off West Africa and Brazil should be examples of such regions.

Methods to observe surface winds, ocean fronts and eddies from SAR have been developed and applied in a number of studies and an outline to use satellite data in operational oceanography within EuroGOOS has been analysed and published earlier (Ref. 12). Radar altimeter data, as shown above, have been used to map the kinetic energy in the Norwegian Sea to study the variability of the inflow of Atlantic water. A study to combine SAR and altimeter data was also carried out (Ref. 11) and the results are promising.

Other Applications of Remote Sensing in the Offshore Industry

Wind and wave conditions

Far-reaching work is presently performed to utilise radar altimeter data, and results are positive and encouraging. For instance, spatial variations of the wave field are now extensively resolved by altimeter data and applications at remote locations have proved its success. Even in areas were the data coverage is good, the altimeter database (Geosat, ERS-1/2, Topex/Poseidon) has proved its value. At Ormen Lange it was possible to utilise long time series of measured wave data obtained 240 km away by applying the spatial variability between the two locations. These results were also compared with hindcasts with good results.

The spatial resolution is much better than grids based on numerical models and especially close to islands and shorelines are the data of better quality. However, validations against reference buoy data are strongly needed to remove systematic bias. This is because storm conditions are of utmost importance and good extreme wave, wind and ocean current data are needed. Attempts to combine corrected altimeter data and *in situ* measurements by filling gaps in the measured time series has so far not been successful.

Operations in ice-infested areas

Ice-infested areas put special requirements on the operation and design of structures, and remote sensing has played an important role to improve the data basis on ice. Information on the sea ice extent is used on a routine basis along with weather forecasts. In addition, information on first year and multi-year ice, and the size of floes are of vital interest. SAR images provide useful information on these conditions where it is needed. Iceberg detection and drift is another very important topic and a lot of research work has been dedicated to the problem. RADARSAT has overcome some of the earlier problems encountered with ERS-1. Extensive use of satellite data was utilised on the Siberian Shelf where many components of oil and gas transport have been evaluated (terminal at Kolguev, pipelines from Yamal).

Weather forecasting

Reliable weather forecasts get increasingly more important as offshore operations become more complex and the industry moves into deeper waters and harsher environment. Assimilation of the scatterometer and altimeter data will be the main application to drive the quality of forecasts forward. It is a fact that forecasts based on assimilated ERS-1 data have proved a higher skill than forecasts that do not utilise ERS-1 data. An assimilation method for spectral wave observations has been tested in the North Sea wave model over a one-year period. It is found that the assimilation improves the model estimate of the seastate up to at least 24 hours in forecast, especially under swell conditions.

The endeavour to make use of ERS-1 wave data in nowcast systems has proved its usefulness. A challenge for ocean-wave modellers will still be to assimilate continuously the large stream of SAR wave-mode data in operational wave models in a cost-effective manner. Many national meteorological centres run numerical wave models operationally side by side with numerical weather prediction models (UK Met. Office, KNMI in the Netherlands and DNMI in Norway).

Seismic and facilities planning

Satellite imagery (Landsat TM and SPOT Pan) provides a powerful visualisation tool, especially combined with terrain height data. This technique can be adopted in many key stages in the E&P lifecycle process. Geological interpretation and engineering are two of the most utilised areas. Route planning is widely applied throughout the business and it benefits greatly from what is called Digital Elevation Models (DEM). In pipeline or seismic planning, DEM and other appropriate software will provide calculations of slope vectors, long-itudinal profiles and various statistics. Although these methods are mostly used in onshore applications, they can be extended to nearshore areas in shallow water depths (landfall of pipe-lines, terminal/harbour construction, navigation channels, sand movement).

Geological interpretation and hydrocarbon seepage

Satellite imagery provides a relatively low cost method of gaining knowledge about potential acreage at the stage when investment is being kept at a minimum. This applies to new acreage both off- and onshore. It is especially useful in sensitive areas where political or environmental matters make other means difficult to achieve. Another important issue is that there is no restriction on areas for which satellite images can be purchased. In offshore locations, satellite images (radar data in particular) are used to give an indication of the presence of hydrocarbon charge. The technique – although still subjective - is well proven for oil seepage and it is widely used in new acreage or 'green field' areas. In well-developed areas such as the North Sea, it is a challenge to distinguish natural seep from seeps from platforms and ship traffic. For gas, this technique is unproven and currently being researched.

Environmental assessment

Satellite imagery provides a quantitative method to detect changes to the ground cover, and such base-line studies are important for documentation purposes. Oil pollution in offshore and coastal areas can be easily detected as long as it is related to platforms. Ship pollution is more difficult to detect but the satellite information can narrow down areas of particular concern for further surveillance.

Data Management

Enormous quantities of data are produced today (either directly from instruments or from numerical models) and the task of managing the metocean data must not be underestimated. Data management includes not only storing but also being able to access it quickly and efficiently once it has been collected. In addition, efficient analysis tools must be available. An effective storage and access to data is also a necessary form of safeguarding the investment so that further value can be extracted in the future. Although the power of computer hardware is increasing substantially, building and maintain-ing the appropriate software is still a significant cost item. This item is often neglected in relation to the cost of acquiring the data.

Conclusions

Over the past decades, and despite periods of uncertainties in the oil and gas industry, we have seen a more or less steady continuation of interest in collecting metocean data and in continuing development of metocean tech-nology. The backbone of metocean information is still *in situ* measurements but simulated results from numerical models and remotely sensed data are now playing an even more important role in providing data for the industry. With the development of microwave radar techniques it is possible to observe and quantify several processes and phenomena at the sea surface such as waves, winds, fronts, eddies and current features. Based on the good results obtained over the past years, some opinions suggest that satellite altimeter data will dramatically change our way of obtaining ocean wave and wind information. Certainly the funds presently available are smaller and timescales to get projects off the ground are longer, but it is still recognised that metocean technology can be a key contributor to cost-effective offshore field developments, while visibly maintaining safety standards.

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Operational ocean observations and ship routing

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The basics of ship routing

Ship routing is the process of optimising a vessel's route across the ocean to conform to a specific limitation of one kind or another on the overall performance of the vessel or on the conditions to be encountered. In the vast majority of cases this is a matter of time and fuel but may be for a scheduled arrival at a port to match a fixed berth reservation. Much less frequently it will be governed by the specific avoidance of certain sea or wind conditions but this will usually only be the case for specialised craft, tows or damaged vessels. Whatever the constraints on the voyage the routing process is performed by bringing together the weather conditions (wind fields, tropical storm tracks etc), the oceanographic conditions (wave fields, currents etc) and the ships' characteristics (speed-down and vessel motions, wind effects etc.) Drawing data from all these sources and the overall constraints which may be imposed on the voyage, the routing algorithms determine the optimum route. A whole range of services is then offered to the ship starting with pre-voyage route planning then regular route advice and forecasts updated throughout the voyage and ending up with an end of voyage report summarising the actual weather encountered, ship's performance and fuel consumption.

In the present context it is vital to note the form of this service which most of the time is based on the premise that a vessel at sea should be able to take whatever conditions are likely on the high sea. The optimum route will avoid the heaviest weather simply because the speed loss such conditions cause will preclude that route from being the optimum but the route will often not avoid storm conditions per se. The reason for this is quite simply that on winter passages in the North Pacific and North Atlantic a storm free route simply does not exist from Oakland to Yokohama or Port Talbot to Seven Islands. An optimum track does however exist and in such winter conditions, the difference between it and the master's choice is often marked.

Routing and satellite data

Previous work – The ERS1 Study

In 1992 Oceanroutes took part in a study for the British National Space Centre.[1] This was carried out for essentially the same reasons as are being considered here: the advantages of satellite data for ship routing. The method used was to assimilate the ERS-1 wind and wave data into the wave model and general routing process. The wind data was incorporated into the fields driving the wave model. The wave data was incorporated as edits to the initial value wave fields of the wave model. As the wave model works with spectral information giving the energy of the sea in terms of frequency and direction it is difficult to perform these edits if only sea height information is available.(as it was from ERS-1). There is no absolutely correct way to perform this adjustment but a reasonable compromise was employed whereby the wind speed was compared to the phase speed of the seas and various options were then selected which directed the energy difference implied by the measured wave height either to the sea wave or the swell wave components or between the two. A more basic limitation in assimilating satellite data is the simple one of its extent in space and time. A wave model works with fields covering entire oceans in fixed time steps on a grid point basis whereas the satellite data is available for limited swaths at varying times which do not often match the time steps of the wave model. Again there are various schemes available for incorporating the data, none of which are ideal. These matters are discussed further below.

The main conclusions from this 1992 work may be summarised as follows:-

1. The entire program of comparisons was significantly curtailed by data quality problems at the time.

2. The assimilation of the ERS 1 data into the wave model produced improvements on all

occasions which were significant at times. The more spectacular cases of improvement were at least partially thought to have been caused by a rather wide grid spacing of 2.5 degrees by 2.5 degrees in the wave model. This has subsequently been reduced to a 1 degree grid globally with local nested models where appropriate.

3. The use of the ERS-1 data in the wave model made no significant difference to the choice of route chosen for any voyages in the study.

These conclusions are still broadly valid and the reasons for them are explored further below.

The effects on the routing process – initial recommendation

The last result of the previous paragraph shows that the routing process itself does not directly benefit from the satellite data. It should be noted that this does not mean that the routing process does not benefit from the input of general (atmospheric data as well as surface winds) satellite data to the main meteorological model behind the whole process but that it is not sensitive to wind and wave input to the wave model. The benefit of this general assimilation of satellite derived information is implicit in the model products used in the routing process and its possible future expansion is the province of other speakers at this conference. In the specific case of ship routing however the reasons for this insensitivity are to be sought in two main causes.

The first is the tendency for the improvement signal in the wave fields injected by the incorporation of the satellite surface data to be lost in a relatively short time. This problem would be eased with more extensive coverage. This case however reduces to the problem of initial conditions in a chaotic system. Even with extensive coverage, the *improvement* signal afforded by the satellite in the already relatively well known wave field, would soon be lost in the errors growing from the remaining initial errors of wave field and the more general ones in the forecast wind fields which drive the wave model.

The second reason is a simpler one. When selecting optimum routing for a vessel, the route chosen depends on the major atmospheric systems and their relative dispositions. These routes tend to be a choice from two very different alternatives. A route must be chosen on forecast data and therefore knowing that the seas are 7m and not 5m in an area which the vessel is not going to reach for several days is of very little relevance. More importantly, satellite surface data will not cause revision of the surface analysis above the level of mostly minor adjustments: it will leave all the major synoptic features in place and therefore the route choice, except possibly in highly marginal situations, remains the same. The only way in which satellite surface winds can influence the basic route choice is by incorporation into, and improvement of the atmospheric model. Now this is being done and involves satellite derived data other than that we are presently considering. We leave the discussion of improvements in the atmospheric model to other speakers. We would however suggest that these improvements are not often going to attain the scale of major synoptic revisions except in the relatively long range and are therefore still unlikely to alter the basic track choice. This is supported by the fact that only around 8% of routed voyages have had to have their basic routing advice changed to a radical alternative at some point during the voyage as a result of major changes in the forecast. All routes have continual adjustments made by routine supplementary messages during the voyage. However such is the insensitivity of the basic route choice to anything but major changes in the forecast distribution of weather systems that the basic recommendation remains good for over 90% of routes albeit continually updated by minor adjustment. It is in the realm of routine adjustments to route selection that satellite derived data is perhaps more useful.

The effects on the routing process – route adjustments and forecasts

Vessels are routinely given further routing advice and forecasts as they progress on their tracks. These are composed in the light of the latest forecasts and evaluations of the nature of the weather ahead of vessel. At present the QuikSCAT winds are being assimilated and plotted on the 3 hourly charts whose time of validity is closest to the orbit timing. The analysis which is drawn taking advantage of the information contained in the satellite winds is then used as guidance for the adjustment of the surface pressure analysis in the Forecast Productions Assistant (FPA) which is the Environment Canada forecasts' workstation in use within WNI/Oceanroutes. This allows complex editing and re-sampling to be performed on basic model data. The surface pressure field is edited subjectively in response to the latest winds and by this means the implications for surface patterns outside the swath of satellite data can be accommodated. These edited patterns are then fed on a continuous basis to the wave model and therefore all the initial fields of winds driving the wave model have the advantage of satellite derived wind information. For global routing there is not at present any attempt to incorporate any wave heights data as it is felt that using the editing method described allows the wave model to have advantage of the satellite data and still correctly apportion the energy spectrally. We are shortly to use the above technology to share local wind edits and run global and nested wave models to produce one world wide database of winds and seas which fully reflects local short term ideas via the editing ability.

The process above generates the wave fields which are used to base the ongoing route corrections which accompany a vessel throughout its voyage. It is through these adjustments that the satellite derived data will be of advantage. However there are several limitations even in this form of usage. These divide into two very broad typical circumstances:-

1) The vast majority of occasions when strong winds and high sea are encountered *without being forecast* involve rapidly developing temperate latitude low pressure centres. Often these systems are simply not forecast or are forecast with a lesser central pressure anomaly and hence lighter wind fields. Satellite data will give early warning of such events but it will mostly be too late for many vessels unfavourably positioned and possibly already performing at an (anticipated) reduced speed to take any realistic avoiding action.

2) In other circumstances a vessel may be positioned on the edge of an area of strong winds and high seas. Such positions are often implicated in optimum routes around bad weather. Now in anticipation of possible forecast errors the route analyst will position the ship as far from the strong winds as possible without overly compromising the optimised route and prolonging the voyage. Should the band of very strong winds show themselves to be nearer the vessel than anticipated through the use of satellite data, again it is often the case, that the vessel will be unable to actually avoid the bad weather through again simply not being fast enough.

Thus satellite data will improve the routine updating of advice to a vessel and again this form of advice benefits as much if not more from the benefits which come via the improvements in the atmospheric model. There are however classic rapidly developing situations which broadly fit into the two forms described above, when the forecast is in error and the satellite data is of little help.

Handling aspects of ships in high sea

We have covered above the various aspects of satellite derived data on winds and seas and how it can aid the routing process. It can be seen that many of the uses of what would be termed a nowcasting service on land are often nullified by the lack of ability of a ship to respond in time. Completely apart from any questions of vessel routing however is the subject of vessel handling in a heavy sea. This covers all aspects of speed reductions, course alterations and the ultimate decision to heave-to completely. All these will be progressive responses by the prudent master to increasingly severe sea states and are measures taken in their more moderate forms in predicted high seas which are part of the planned route. Although not strictly part of the routing process the utility of accurate sea height measurements from satellite sources in such circumstances is of interest. This question is probably best left to the seafaring world to answer but in our experience these decisions are based upon ship motion responses to the sea and are almost entirely a matter for the master's judgement possibly aided by an on-board vessel motion monitoring system. Accurate wave height information even with wave period information would therefore be of limited value in such a situation.

Satellite data in hindcasting

The performance of vessels is often a source of discord, typically between owners and charterer which may escalate through various degrees of acrimony and at times ends up with arbitration or court proceedings. In the preparation of the various forms of reports appropriate to the level of dispute, increasing use is made of archive satellite data on wave heights and, to a lesser extent, wind speeds. Such data is mostly accepted in shipping and law circles although not universally. It is not unknown for legal opinion to favour the master's description of winds and sea when they are coincident with a contradictory satellite pass. (This sometimes is also the case when the log weather is completely against the statistical records for some part of the world).

Ships' logs constitute a source of definitive information on waves and winds which provides a finer structure of detail than archive fields of winds and seas which are the usual source of such work. Unfortunately coverage at present is not nearly great enough to ensure that suitable data in time and space is available. By the nature of such work the match must be fairly exact in time and location as any deficiency is used by the legal opposition to dismiss evidence.

Marine forecasting

Much of what has been said for the routing process is equally valid for marine forecasting. There are however certain differences of emphasis which makes the satellite data perhaps more useful.

In the short term, on many occasions of rapidly developing weather systems, the nowcasting advantage of satellite winds and wave heights is regained. This results from the fact that, although the forecast is for a fixed location or a stationary vessel, some weather sensitive activity that can be suspended at short notice will be the current focus of activity. Where the activity is not subject to suspension at short notice however, a short term response to satellite data may be impossible and a forecast for the entire period below the critical level coupled with a corresponding low probability forecast of exceedence of that level may be what is required.

The ingestion of satellite winds and waves to the wave model is by FPA but includes the second stage whereby the waves are included also in a separate FPA field which represents the wave heights for starting the wave model. Edits to this field include not only satellite information but also any additional surface observations which may not perfectly match the "hot start" stating values of the wave model. Edits are kept simple for the forecaster and consist of changes to wave height only with the spectral distribution being taken care of automatically by a version of the algorithm already mentioned above. For use in coastal waters the North Atlantic must be edited and also the nested model in use in UK waters.

Currents

At present the currents used in the routing process are derived from a variety of sources. In general background ocean currents used are taken from a wide variety of climatological sources, mainly from NOAA and US Navy sources. This is applied monthly. For the more active areas of the world's currents, account is taken of data on the actual positions of these systems. This is used for the main areas of strong and eddy prone currents around the world. These include the Gulf Stream, Kuroshio etc. Data on these currents is added in to the climatological background data around twice per week. This is done based on information supplied by the U S Navy . No attempt to include forecast positions is at present made although this is the projected next step and various options including the Princeton Ocean Model (POM) are being considered for both limited area and also general current modelling. Where these narrow but strong currents are concerned however, the choice of route for a vessel does not really have any great dependency on forecast conditions in that the route may be adjusted in the short term purely on a broad knowledge of the current's present position. This can be done without any very great effect on overall time en-route as the average position of these current systems is known and in terms of positioning a vessel for entry or avoidance of the core of the current only minor changes of the route are sufficient and there is minimal advantage to be had from knowing the forecast structure of a current system long before a vessel reaches it.

The general fields of ocean currents apart from the specific ones dealt with above are at present considered only in a statistical way. Real time knowledge of actual current fields would be of limited use as it is forecast currents which are of importance. However their importance is considerably reduced as the vast majority of routes will spend a considerable time in any given current system and therefore any inhomogeneity in its structure will largely balance out and the overall effects will be close to monthly current climatology anyway. Indeed such mean currents may prove better than forecasts which are prone to error. As mentioned above, these are matters which are being considered at the moment.

Summary

As an overall conclusion the benefits to the ship routing process to be obtained over and above the present situation may be simply summarised.

1) There is no present outstanding need for other than greater coverage of basic physical measurements wind speed and direction and wave height and surface elevation/currents. The geographical region of interest would be predominantly between 60N and 40S.

2) Full spectral measurement of sea state would also be desirable.

3) Some of the potential improvement in the ship routing process is via the atmospheric model used and this is mostly to be gained through satellites other than those being considered presently.

Reference

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Operational applications in North Sea coastal zone management

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Abstract

A brief overview will be given of opportunities of remote sensing from the perspective of coastal zone management with a focus on the North Sea. The North Sea coastal zone is relatively well covered by conventional observations and monitoring programs. This existing information-infrastructure can and should be fully exploited for an integrated observation approach including in-situ observations, numerical models and remote sensing. This makes the North Sea region ideal for testing and validating purposes. High standards apply for the necessary surplus value of remote sensing data compared to other sources of information. Coastal zone management authorities will consider operational use of remote sensing data only when it will contribute to operational demands e.g. faster response time, lower false alarm rate, increased spatial resolution, increased area covered (overview and view in neighbouring countries), increased reliability in the prediction of the water/bottom system, more flexible fleet operation etc. A few examples will be used to sketch the realistic ideal of a satellite mission that fulfils (a number of) the operational demands. Key factors for successful application of remote sensing are: real time availability, reliable data-link, long term availability, transparent data and cost policy, potential for integration with numerical models being developed, possibility to generate easy to interpret end-products for both operational and management use.

Coastal zone management in the Netherlands

In the Netherlands the importance of coastal zone management is beyond discussion. The budget for water-management and the coastal zone is well established but relatively small compared to transport and traffic infrastructure budgets. Pressure from politics is mainly based on efficiency and transformation of established governmental organisations to more flexible and dynamic groups based on a knowledge based network concept.

In the past decade the main focus was on coastline management. An intensive coastal monitoring program resulted in a 40 years historical database of coastal profiles that have been measured every year with high precision survey techniques. Based on the information gained from the annual coastal measurements and the knowledge built up over time it is possible to predict coastline developments in the coming decade. New technological advances such as aerial laser scanners, multi spectral scanners and satellite SAR images can be used to map large areas in the coastal zone for a wide variety of users.

To prevent coastline recession sand nourishment has been used for dynamic preservation since 1990. More recently sand nourishment programs have been re-designed. The sand that is obtained from depths greater than 20 m or at locations more than 20 km from the coast is added close to the coast, at depths of approximately 5 m. The dynamics of tidal currents, winds and waves distributes the sand eventually to the beach. This innovative and cost effective approach can only be applied successfully when the dynamics of the coastal zone are understood.

Obtaining sand from the deeper offshore areas is regarded as harmless to the ecosystem. There is a growing use for exploiting the geological potential of the North Sea bottom other than the existing oil industry and the sand nourishment programs. Large infrastructures in the sea (airport, industrial complex, wind energy etc.) increase the demand for sustainable use of geological resources, bringing the eco-system into the equation of costs.

Monitoring programs

Developments driven by politics

Multi-year monitoring programs are being upgraded to facilitate quantitative and qualitative changes in the necessary information used for a wide range of political needs. The conventional way to design a monitoring program is to collect information that enables specialists to investigate and improve their knowledge of the water system and processes. Recently politics demands information that is also suited for studying environmental effects resulting from human activities. The existing network for collecting data and information should be transformed into a flexible information infrastructure that can be used for a dedicated or dynamic monitoring within the long term program. A quick response to new situations (e.g. high river output) or new scientific theories should be incorporated in the existing networks, which practically means a modular approach with an open standard.

Operational oceanography is still gaining interest from the meteorological community. It is recognised that the air-sea interaction is a dominant factor in improving weather prediction. Progress in operational numerical models, both meteorological and oceanographical is limited by improved boundary conditions (meteorological parameters, sea level, sea state and bathymetry). Parts of the budgets available for the high density network of meteorological stations on land are being reallocated in favour of investing in the existing network of hydro-meteo observations on the North Sea.

Developments driven by technology

The conventional monitoring program mainly consists of a well-designed strategy in which survey ships sample periodically along tracks in the Netherlands part of the North Sea. A wide range of bio-chemical parameters such as oxygen, temperature and colour, are monitored periodically at high spatial resolution along track. Hydrographic surveys focus on bottom depth mainly for studying bottom dynamics at different spatial scales. The observation strategy with survey ships is combined with a network of fixed platforms that collect hydro-meteo parameters used for the prediction of water levels along the Dutch coast. The North Sea network of fixed stations takes part of a European initiative (SEANET) to create a combined network of the entire North Sea region.

Technological development has resulted in operational so-called smart buoys that can act as a multi sensor platform, competitive with a fixed monitoring platform. Automated underwater vehicles will in the near future act as relatively low cost sensor platforms, operated from land or from survey ships.

Airborne sensors (multi spectral, laser scanning, SAR interferometry) have developed into commercially available systems. Rijkswaterstaat (North Sea Directorate) operates a multi-spectral scanner from its Coastguard aeroplane. This scanner is used for inspection purposes, and can be used for detailed water quality surveys, both in the North Sea and for inland waters.

Resolution and data accuracy

Fixed monitoring networks are particularly suited to observe processes characterised by high variability in time and large spatial scales. Ship surveys are particularly suited for the investigation of processes with strong spatial variations. Remote sensing can provide data with relatively low spatial and temporal resolution. The power of remote sensing can be found in spatial coverage, and availability of data outside the direct location of interest.

Satellite remote sensing: examples

North Sea surface temperature

An operational system has been set up at the Royal Meteorological Institute of the Netherlands (KNMI) to process fully automatically and in real time locally received raw AVHRR data, and to generate Sea Surface Temperature (SST) images of the North Sea. Special attention has been put into the development of robust processing algorithms. The persistent cloud cover above the North

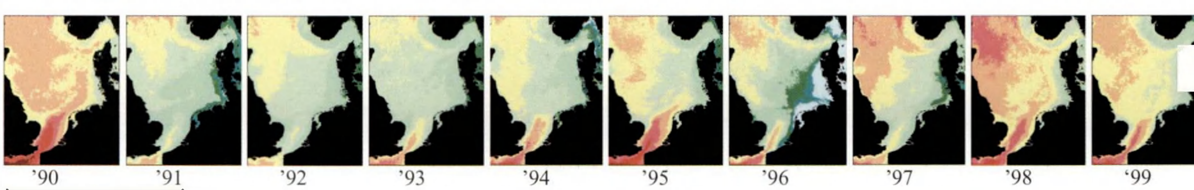
Sea compels the use of compositing techniques in order to obtain more complete SST-maps. Therefore, KNMI produces weekly SST composite maps using all SST-images of a period from Monday to Monday. All weekly SST maps are archived in digital form at KNMI and also the more cloud free instantaneous SST-images.

A complete 10-year archive of AVHRR SST maps of the North Sea is available at KNMI. During the 10 years of operation of the production system no major changes have been introduced. Therefore, the data set can be trusted to be consistent and continuous. The length of the archive period is approaching that which is relevant for climate studies. Time series of SST maps show the significant variability of the North Sea SSTs from year to year (Figures 2 and 3). The SST images in real time are used at KNMI for the following purpose:

- *Operational forecasting*: There is a strong relation between the Dutch weather and the temperature of the North Sea and the North Atlantic Ocean. Forecasters use the actual SST maps to evaluate the impact of anomalies in the SST patterns on the current weather.
- *SST assimilation in HIRLAM NWP model*: The current operational version of HIRLAM is run at KNMI at a resolution of 30 km. Actual SST measurements from ships and buoys are assimilated in HIRLAM. In the near future a high resolution (5 km) version will be implemented. This high resolution version will need high resolution SST data which can be provided by the NOAA-AVHRR SST maps.

Real time and archived SST images of KNMI are used on an ad-hoc basis for climate research, oceanographic research and research at fishery institutes.

Monthly mean SST maps of February:



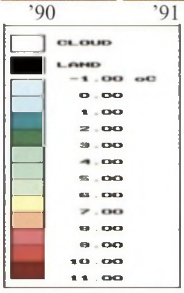
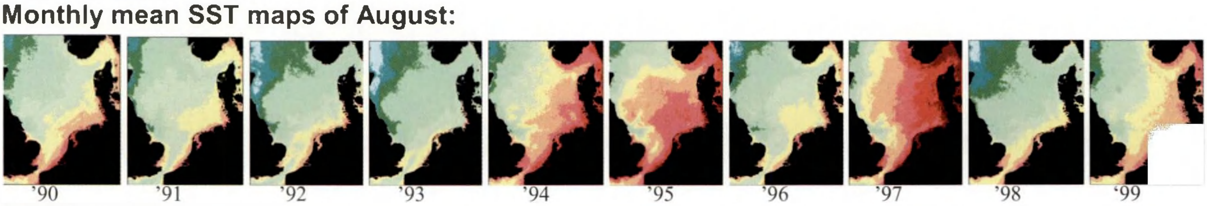


Figure 1: *Time series of monthly mean SST maps of February (coldest month in the year) in the period 1990-1999. In most February images the plume of 'warm' Gulf stream entering the southern North Sea is nicely visible. The shallow waters near the shores of the eastern North Sea are in general much colder than the deeper waters in the open sea. The winter of '96 was extremely cold in the German Bight and the Kattegat.*

Monthly mean SST maps of August:



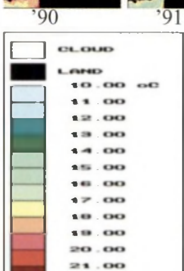


Figure 2: *Time series of monthly mean SST maps of August (warmest month in the year) in the period 1990-1999. In this month the shallow waters are the warmest due to the strong solar heating of the shallow water column. Cold ocean water is entering the North Sea from the north along the British coast. The years '95, '97 and to a less extent '94 and '99 had warm summers.*

Sea surface topography

Processed radar altimeter data can provide valuable information about the sea surface topography. Radar altimeter data from a range of altimeters (e.g. ERS and Topex/Poseidon) has proven to be a valuable data source of information about the variations in sea level delivered on a global scale. Shallow sea regions need dedicated tidal and atmospheric corrections. Operational models that are used for early warning of storm surges and extreme tidal conditions can be assimilated with altimeter data. So far, no added value has been achieved in this field. The system requirements combined with the strong existing network of fixed stations in the North Sea are the main reasons.

Bottom depth

SAR images contain valuable information about variations in bottom depth. Given a tidal flow and favourable wind conditions variations in bottom depth will clearly show in SAR images. A clever combination of SAR images with a first guess of the bottom topography e.g. an old bathymetric map and a limited number of more recent depth observations result in a better bathymetry. This approach has been proven to work for distant regions and bathymetry maps with limited accuracy specification (see Fig. 3).

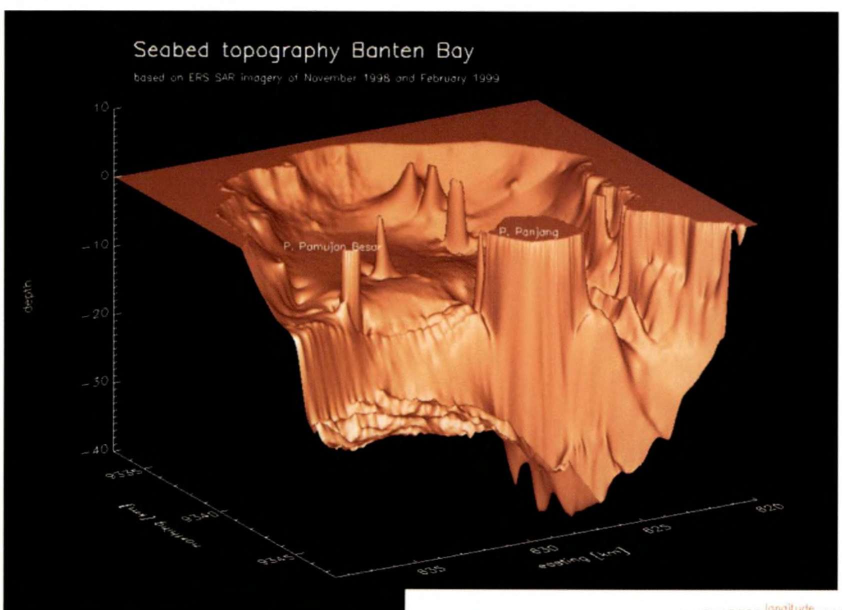
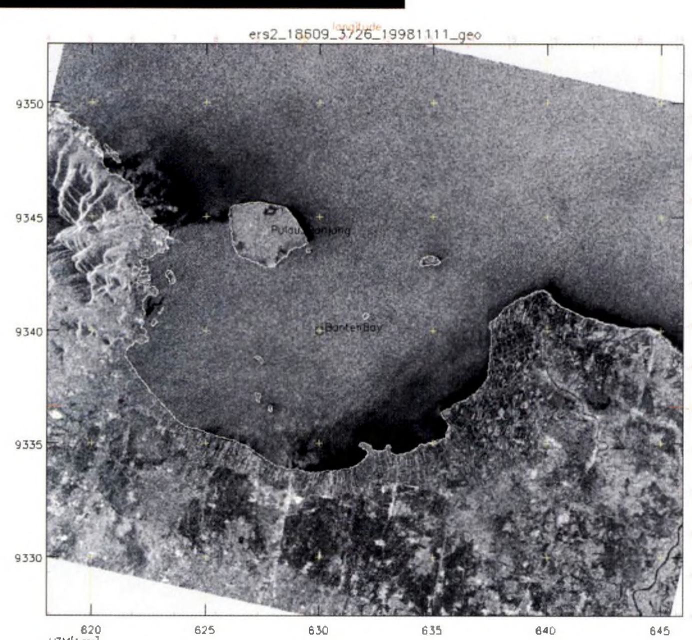


Figure 3

Depth map produced of Banten Bay, Indonesia



Geo-referenced ERS-2 SAR image of 11 November 1998 (orbit 18609, frame 3726)

Projecting this successful example onto the operational needs for the North Sea region it fits in a proposal to deliver a package of North Sea bathymetry grids for operational oceanography. There is a clear need for high-resolution bathymetry grids for 3D flow models that provide information for dedicated local applications e.g. port authorities. On a European scale the operational oceanographic models need consistent bathymetric grids of regions that can be nested in North Atlantic or Global models. This approach needs a procedure that combines several information sources to provide the most accurate and up-to-date version of the bathymetry used as boundary condition in operational models.

Laser scanning, airborne

Maybe the most successful example of remote sensing in coastal zone management is not from spaceborne remote sensing but from airborne laser altimetry. Airborne laser altimeter data can provide both the high spatial resolution and the high precision that is required to compete with existing survey techniques like photogrammetry. Consequently, the yearly monitoring program of beach profiles has been fully operational for several years, resulting in a better information product in less production time and for lower costs.

Wave climate

Using all the available altimeter, scatterometer and SAR data, and combining these data sources into a wind and wave climate database gives a valuable instrument for commercial use (engineering consultants, contractors, shipping and insurance companies). An operational system that enables quick access to this data using an internet-based interface clearly demonstrates successful use of satellite data on a commercial basis (www.waveclimate.com).

Open concept of information infrastructure

The vast majority of monitoring programs is still based on research ships, fixed platforms and smart buoys that deliver a wide range of information products. Remote sensing is adding several high potential information products to the existing ones. Numerical models will act as a natural integrating platform for different data sources, to be combined into one consistent information product. New operational remote sensing parameters should be integrated with existing information products. Operational models, suited for data-assimilation, will provide a platform or system for such an optimised information infrastructure (see Fig. 4).

Operational needs for near future missions

Satellite remote sensing could provide a suite of parameters that add value to existing long term monitoring programs. The operational oceanographic community searches for defined information products that supplement existing monitoring programs in such a manner that existing budgets can be used to further develop and operate a dynamic information system. This dynamic system should be able to adapt easily to changing demands. Operational remote sensing missions have a future in this strategy if they fit into such an optimised re-design of long-term monitoring programs. Existing observation capacity can be re-allocated for flexible environmental effect studies. Selected remote sensing parameters with their specific spatial and temporal sampling characteristics are perfectly suited for long term data collection. Successful examples of existing remote sensing illustrate that operational remote sensing missions for the coastal zone should aim at low-cost long term data collection combined with delivering real time boundary conditions for coupled ocean/atmosphere models. Parameters of use are water quality, sea surface height, sea state and bathymetry.

Near future satellite missions should be incorporated in an information strategy based on expected developments in operational oceanography (visionary). The existing meteorological information infrastructure could act as a successful example (learning form today). A major factor of success in such a development is the role of government and private companies including financing structures.

Numerical models have high potential for 1) getting forecasting within the coastal zone at the level it should be and 2) integrated information products and value adding. Any investment in a satellite mission should go hand in hand with

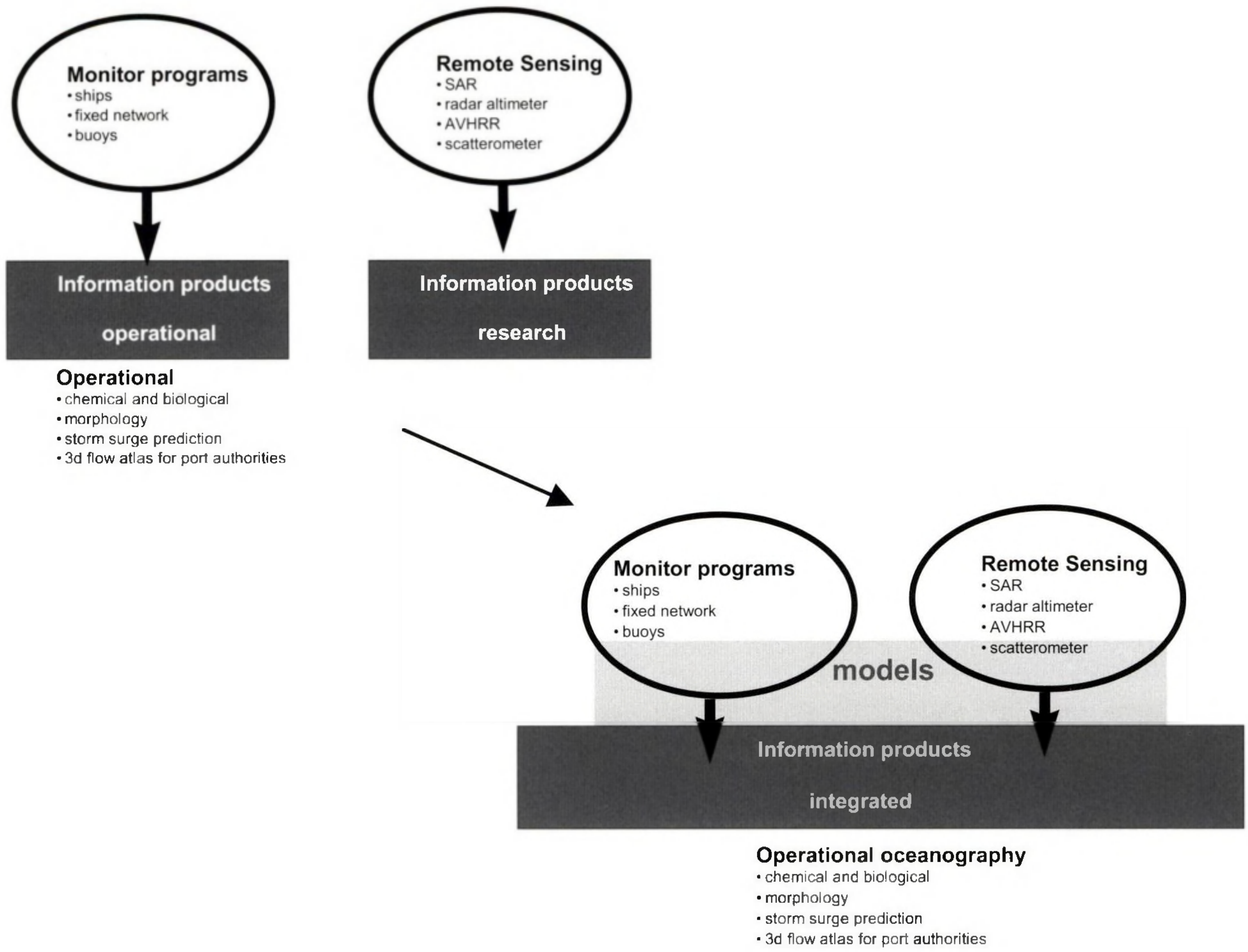


Figure 4: *Integration of in situ observations and remote sensed data through operational models*

investments in a value added production facility. Political consensus within Europe about priorities in coastal zone management, environmental actions, monitoring strategies, standards and data policy still needs a lot of time and discussion.

Acknowledgements

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The marine observing system of Puertos del Estado, Spain

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Abstract

This paper intends to give a synthesised perspective of the Marine Monitoring System, Data Banking and model forecasting activities developed by Puertos del Estado in order to support Port Planning and Operation. It also points out some of the plans and ongoing developments planned to integrate the different system components under the requirements of operational oceanography.

This paper presents a technical description of a wave forecasting system based on *in situ* instrumentation, and shows the constraints on the system in order to provide the information needed for port and ship management. At present, the system does not include remote sensed data, and any proposals to introduce remote sensed data would have to provide a demonstrable added value, and be compatible with the existing system, and provide improved products to end users.

Introduction

Puertos del Estado is the official institution in charge of the co-ordination of the state-ruled Spanish Ports System (SPS) constituted by twenty-seven Port Authorities (PAs), which are responsible of forty-five Ports. The technological development of the SPS is one of the tasks assigned by law to Puertos del Estado including activities related to Marine Climate Monitoring relevant to the Ports.

The origin of the first moored buoy network of the SPS in the late seventies was the urgent need to define design actions (mainly in terms of wave climate) for planning harbour facilities and operation conditions under the modern statistical-probabilistic techniques. Characterisation of coastal wave climate also required at this time the development of wave records Quality Control procedures, and a Data Bank to be used as a storage and management tool for this information.

This initial marine monitoring and data handling system has been expanded to a great extent following available improvements in measuring and communication technology and further needs of the Ports for a broader data coverage and measurements of other environmental parameters such as sea level, meteorology and currents. Numerical modelling both at deterministic and stochastic levels has been used as a complementary tool to the monitoring system since the start, allowing extrapolation of spatial data to areas without observations, together with the possibility of comparing forecast values with the observational data for validation/assimilation purposes. Important efforts have been made lately to improve those aspects of the system related to communications and process (data transmission from measuring devices, data analysis and forecasting and data transfer to users) having Puertos del Estado as a specific Centre dedicated to controlling all these activities.

In charge of the system Puertos del Estado has the Department of Marine Climate composed of 15 scientists and engineers that carry out the activities related with Planning and Administration of the monitoring system, Modelling and Forecasting, data Quality Control, Communication network, web Server and Data Bank. The operational fieldwork has been outsourced by Puertos del Estado, and has been carried out by private firms working under maintenance contracts supervised by the Marine Climate Department.

The Puertos del Estado Data Bank, fed with data coming from its own networks and other metocean sources such as numerical models (hindcast analysis), supplies on a paid basis reports of elaborated statistical or extreme event information to the industry: construction firms, navigation companies, fish farms, etc. The information included in the Data Bank and data analysis methodology also constitutes an important background for some of the "ROM" Maritime Works Recommendations (Wave

Climate, Design actions, Manoeuvring Areas) which are the official design guides issued by a Commission led by Puertos del Estado that settle best practice design criteria for such work. The ROM design guides depend strongly on original ocean measurements for their application to the safety and operationality of harbour infrastructures.

The actual status of the system based on the Data Bank, Monitoring Networks (Figure 1, Table 1) and Forecasting Models (Table 2) is in process of integration to enhance its usefulness for the SPS regarding supporting Port Operation and Construction Works. It will provide precise forecasts of environmental conditions and put real time metocean data together with other operational parameters into PAs Decision Making schemes (expert systems). In this last context work needs to be undertaken to co-ordinate data dissemination with other administrative bodies to provide availability of metocean real time data in tasks of vessel traffic, pollution fighting and rescue at sea.

Table 1: Monitoring Networks of Puertos del Estado

NETWORK	EQUIPMENT	MEASURED PARAMETERS	DATA TRANSMISSION
COASTAL	19 moored Buoys WaveRider (Datawell, Holland) 13 Spare buoys	Scalar Wave field in coastal waters (Port Authorities or Lighthouses)	Via radio to Shore station and then via telephone to Control Centre (Madrid).
	3 moored buoys Smart-820 GPS (Seatex, Norway)	Scalar and Directional Wave fields in coastal waters (Port Authorities)	Via radio to PAs main buildings Harbour Intranet
OFFSHORE	3 moored Buoys WaveScan (Seatex/Oceanor, Norway) 1 Spare buoy	Meteorology and Scalar and Directional Wave field at deep waters (Shelf Break)	Via Inmarsat-C satellite to Control Centre (Madrid). Via radio to Shore station and then via telephone to Control Centre (Madrid).
	9 moored Buoys SeaWatch (Oceanor, Norway) 3 Spare buoys	Meteorology, surface current, Scalar and Directional Wave field, CTD profiler at deep waters (Shelf Break)	Via Inmarsat-C satellite to Control Centre (Madrid).
	3 moored Currentmeter Strings RCM-7 (Aanderaa, Norway) 1 spare String	Current, temperature and salinity fields in the vicinity of Buoys (Shelf Break)	In-situ data recovery
REDMAR	14 Tidal Gauges Ultrasonic (Sonar, UK) 1 spare TG	Sea level at piers of Port Authorities	Via radio or telephone to PAs main buildings Harbour Intranet
REMPOR	20 Meteorological Stations Geonica (Spain) 1 spare station	Meteorology at piers of Port Authorities	Via radio or telephone to PAs main buildings Harbour Intranet
RADAR	5 Land Based Navigational Radars Furuno, JRC (Japan)	Scalar and Directional Wave field at coastal waters (PAs or Lighthouses)	Via telephone to Control Centre (Madrid).

Table 2: Daily Forecasting Models of Puertos del Estado

NUMERICAL MODEL	KIND OF MODEL VERIFICATION	INPUT DATA	FORECASTED VARIABLES HORIZONT	DISTRIBUTION TO PA'S AND OTHER USERS
WAM	Spectral generation and propagation Model Validation of forecast with real time Buoys data (Offshore and Coastal).	Wind fields every 6 hours supplied by Instituto Nacional de Meteorología (Spain)	Wave Spectra and derived integrated parameters. Horizont: 48 hours. Forecast at 0, 12 UTC	Instituto Nacional de Meteorología Web Server (www.inm.es) Harbour Intranet
HAMSOM	3-D Barotropic current Model. Data Assimilation with Tide gauge data (REDMAR)	Wind and pressure fields every 6 hours supplied by Instituto Nacional de Meteorología (Spain)	Sea Levels and Currents at coastal shelf Horizont: 48 hours. Forecast at 0, 12 UTC	Puertos del Estado Web Server (www.puertos.es) Harbour Intranet

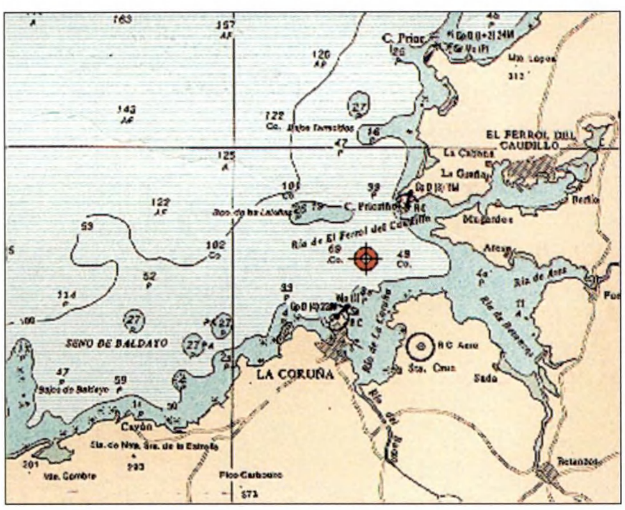
Figure 1: *Monitoring Networks of Puertos del Estado*

The expansion of the monitoring system outside the Port areas, mainly intended as a means to define far field conditions for wave models, has driven Puertos del Estado to initiate official contacts with other Spanish institutions (Met Office, Oceanographic Institute, etc) with responsibilities in marine environmental matters in order to convert the offshore Network into a shared multipurpose system. The future incorporation of these agencies into network management and financing, will allow network upgrading by adding new sensors and platforms for other physical and non-physical parameters which are of no direct interest to Puertos del Estado.

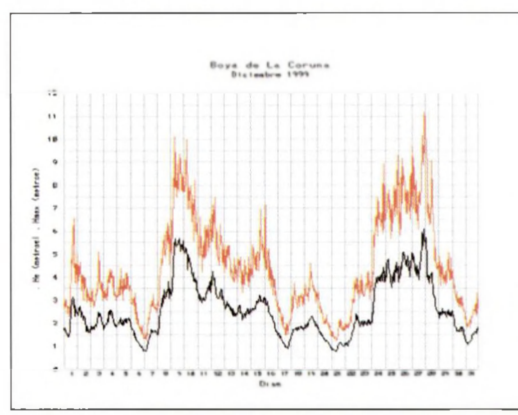
Following this co-ordination policy Puertos del Estado and the Spanish Met Office have signed an agreement so that Puertos del Estado receives from the Met Office meteorological fields to be used as input for wave models. Wave forecasts as well as offshore buoy real time data are included within the Met Office's official web page. In the short term this will allow the Met Office to take full charge of open sea wave forecast modelling, also incorporating into its legal forecast duties real time buoy data for assimilation purposes. This leaves Puertos del Estado to work at harbour level in order to fulfil its operational requirements. Puertos del Estado and the Oceanographic Institute have kept a common moored array off the North coast of Spain and are now planning several field tests of new CTD profilers and current meters which will be installed on offshore buoys as a way of defining common requirements for future network expansion.

The buoy networks

The Puertos del Estado's buoy networks are classified in two categories: coastal and offshore. The coastal network was the first one to be installed in the late seventies, being developed to get a characterisation of the wave climate in coastal waters. It constitutes the main source of wave data available for Spanish shallow waters (<100 m). The mooring positions are close to Port Authorities or lighthouses (Fig. 2) in order to allow easy transfer via radio of recorded data. The standard buoy sensor is the Datawell scalar Waverider (Holland) which is of well proven performance. This network has been very useful for the SPS during the last twenty years for planning new port facilities and maritime works. It has helped improve design specifications and construction works when real time data became available. The historical records provided by this network are the main source of information used for the ROM design guide "Wave Climate at Spanish coastal waters" which is applied within the SPS and by construction firms designing maritime works in Spain.



Coastal Buoy at La Coruña (NW Peninsula)



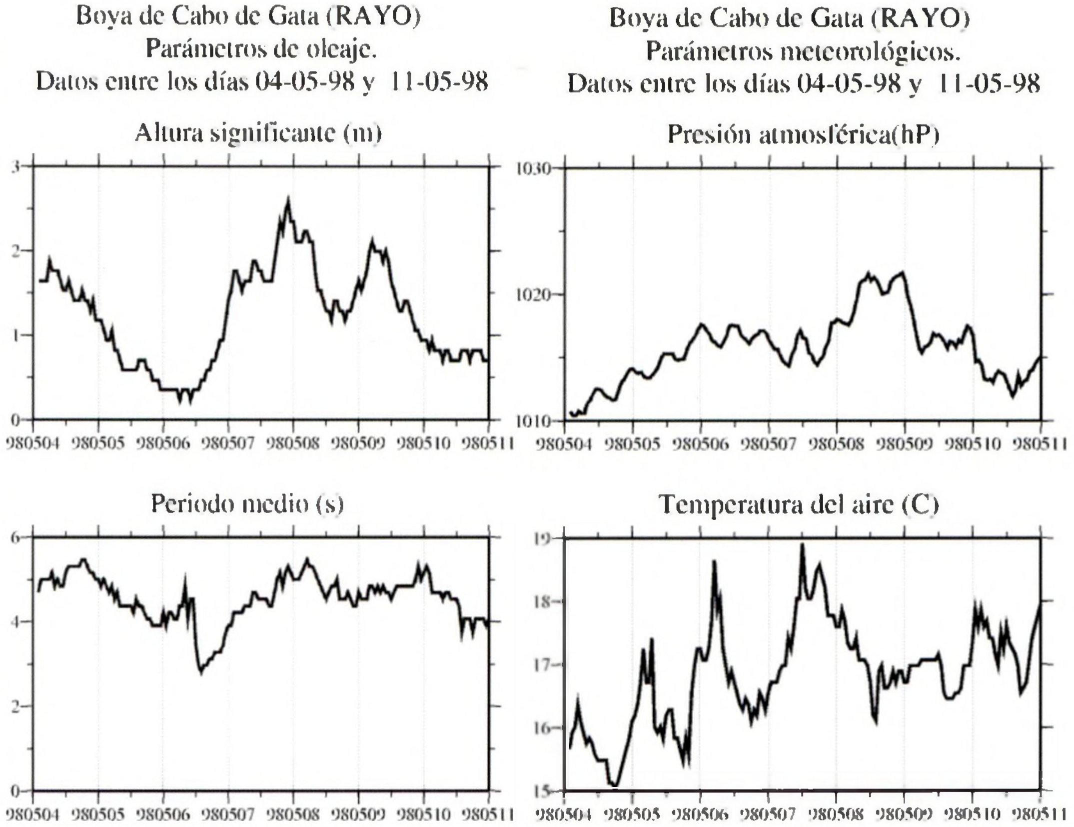
La Coruña significant and maximum wave height, December 1999

Figure 2: *Coastal Network*

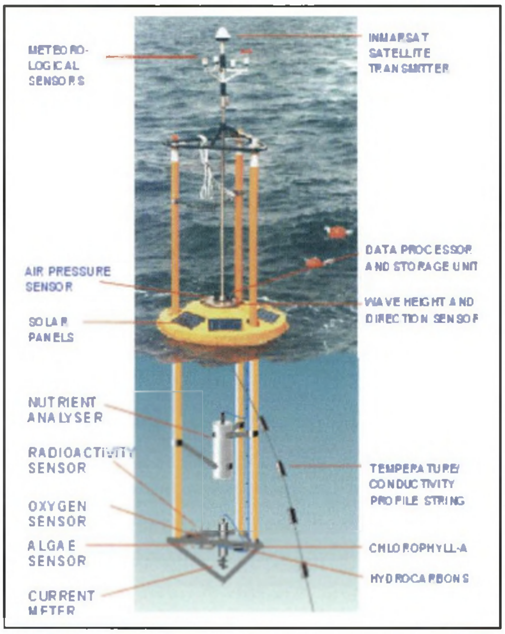
Since the mid eighties it was considered necessary in order to have a full picture of the coastal wave climate to incorporate measurements on the directional wave field. This allows fewer buoys to be used by mooring them in deep water and extrapolating records to the coast by means of wave propagation models. A first attempt in this direction was done using a few Seatex's WaveScan buoys (Norway), which have a wave directional Hippy sensor, which due to size and robustness were suitable to be moored in deep waters. Although promising results were reached the complexity of buoy maintenance logistics and its high cost together with the frequent number of driftings by accidents has restricted the number of continuously moored units to three.

In 1995 the RAYO (Red de Alerta Y Observación - Warning and Observation Network) project was launched. The main goals of this project of Puertos del Estado were to deploy a stable monitoring network capable of obtaining a broad descriptive picture of the surface physics of Spanish coastal waters. This is useful at both scientific and engineering levels. It incorporates process and communication systems which allows rapid dissemination to potential users of data. Forecasts are used in decision making schemes for alert purposes. This project has meant a great innovation regarding existing networks in Spain for several reasons: the variety of sensors in every buoy, their location in deep water and the real time transmission of measured data.

CABO DE GATA BUOY: Real time transmitted data (graphic presentation)



SEAWATCH BUOY



Estaca de Bares Buoy (NW Peninsula)

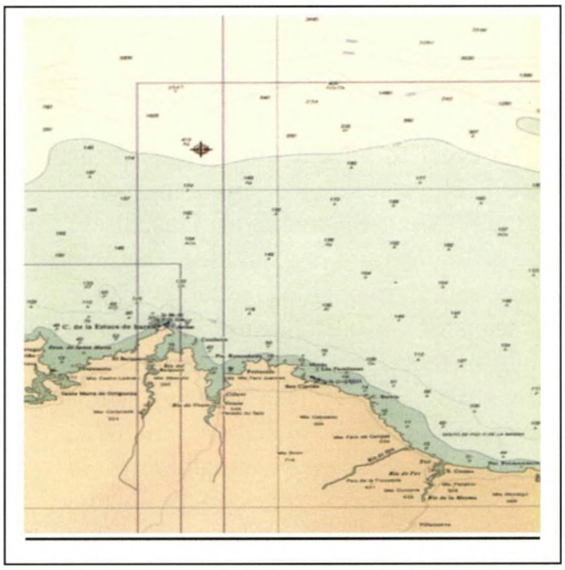


Figure 3: *Offshore Network*

The project was launched in 1996 and the set-up phase ended in December 1998 with all the planned instruments working properly in the assigned positions. The project set-up phase was co-funded by the European Community through EFTA resources (85%) and by Puertos del Estado (15%).

The Rayo system is composed of moored buoys and current meters plus land based radars. The main part of the system is the so called "deep water network", consisting of 9 multipurpose Seawatch buoys (Oceanor, Norway) measuring waves (Waverider sensors, three of them are directional), currents (UCM-60 sensor), wind (Aanderaa 2740 for speed and Aanderaa 3590 for direction), atmospheric pressure (Vaisala PTB200A (D)) and temperature (Aanderaa 3455), sea surface temperature and conductivity (Aanderaa 2994S). Additionally 3 of the moored buoys have a string of 3 CT/CTD cells (Seamos, Norway) fixed on the mooring line.

Besides the Seawatch buoys the Rayo Project has installed three current meter strings (each one based on three Aanderaa RCM-7), 3 directional Smart buoys (GPS based and linked by radio to the harbour) and 3 coastal Radars, both for shallow water directional wave measurements. These instruments provide further oceanographic information useful for understanding the measurements from the offshore buoys and the main processes taking place at the coasts under study.

From a harbour-engineering point of view, the measurement of sea state was one of the main goals of the RAYO project. This was one of the main reasons for Seawatch buoys to be located at points with depths greater than 300 meters, so wave measurements were not affected by local bathymetry and thus could represent large portions of the coastline. Increased spatial coverage was provided at the north-western corner of the Iberian Peninsula, a region which usually suffers severe storms, and there are many navigational hazards. Three of the Seawatch buoys with directional wave sensors are moored in this area in key positions to detect bimodal sea states with crossing seas coming from different directions. This is a situation very dangerous for navigation when north-westerly gales coming from the North Atlantic interact with the less frequent north-easterly gales developing in the Gulf of Biscay.

The Seawatch buoy (Fig. 3) measures information every hour which is transmitted in real time via Inmarsat-C satellite to Puertos del Estado's premises in Madrid. Information is processed and posted on the Internet for public access (http://www.puertos.es) and also sent to Port Authorities through the Harbour Intranet. The on-board-processed information is transmitted in real time via satellite and also together with the recorded raw data is saved on the hard disk inside the buoy. In this way, two sets of information are available which if there were no problems might be similar. However, sometimes, satellite transmission or the data reception station does not work correctly. On other occasions, the hard disk on the buoy is defective and information cannot be retrieved or for some reason dates from the two sets do not coincide. Usually the two sets are coincident with minor differences due to data codification for satellite transmission. For these reasons, the satellite transmitted information and the hard disk data are treated separately. Puertos del Estado's standard data quality control and analysis is applied to wave raw time series, when this information is recovered.

As a part of the RAYO project the 3 existing moored WaveScan buoys were upgraded to Inmarsat-C transmission facilitating integration of these buoys with the Seawatch in a common offshore network.

The transmission of the buoy wave spectral coordinates in real time via Inmarsat-C, allows that at its reception, an estimate of the propagated wave spectra can be computed at coastal points of special interest (for instance the harbour entrances). This is done (Fig. 4) by means of the PROPS wave propagation model (Rivero and Arcilla, 1993). The propagation calculation is based on the so called "one-point spectral propagation" (Alvarez Fanjul *et al*, 1997), developed at Puertos del Estado. The system is based around "wave transfer tables" computed with the model during a set-up or preprocessing operation. The main advantage of this system is the extremely low computational cost. This allows the computation of the spectral propagation to the coastal points of interest in literally dozens of places along the Spanish coast without a serious computational effort in addition to the operational system. In order to couple this system to the real time data from the offshore buoys, in November 1998 we started transmission of directional spectral information from the directional buoys. The transmission of the whole directional spectrum or the complete time series becomes very expensive, so, the transmitted directional information is limited to the scalar spectral density, the mean direction and the mean angular spreading for every frequency band. From this data, the directional spectrum is rebuilt fitting in every frequency band a Mitsuyasu directional distribution (Mitsuyasu *et al.*, 1975). The one-point propagation is based on linear theory and thus, should only be applied to areas where generation and nonlinear effects, such as bottom friction, are considered to be non-critical. Results obtained from this method are identical to those obtained with the linear version of PROPS at the points of interest. Due to the fact that the Spanish shelf is very narrow, these conditions are fulfilled along almost all the Spanish coast and propagated results have a very good statistical agreement with in-situ measurements (Fig. 4), showing that this propagation system is for practical purposes a very convenient way to estimate wave information in real time at harbour entrances or other positions near the coast line.

Once the full operationality of the Offshore network has been reached, Puertos del Estado will have re-defined the role for its coastal network as a network of specific harbour interest, leaving to the offshore one the characterisation of climatological wave climate. This will imply its conversion in the short term in a directional wave network of lesser number of permanent measuring points placed in the vicinity of harbours.

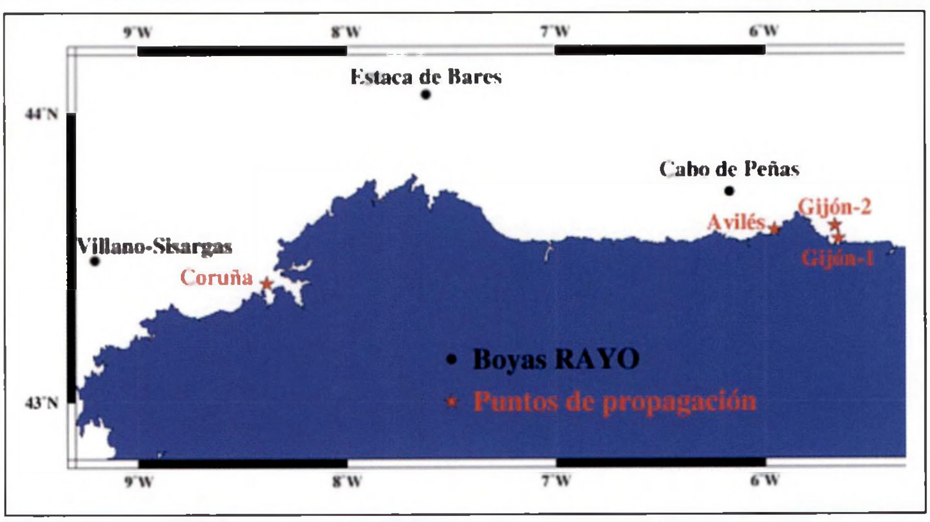
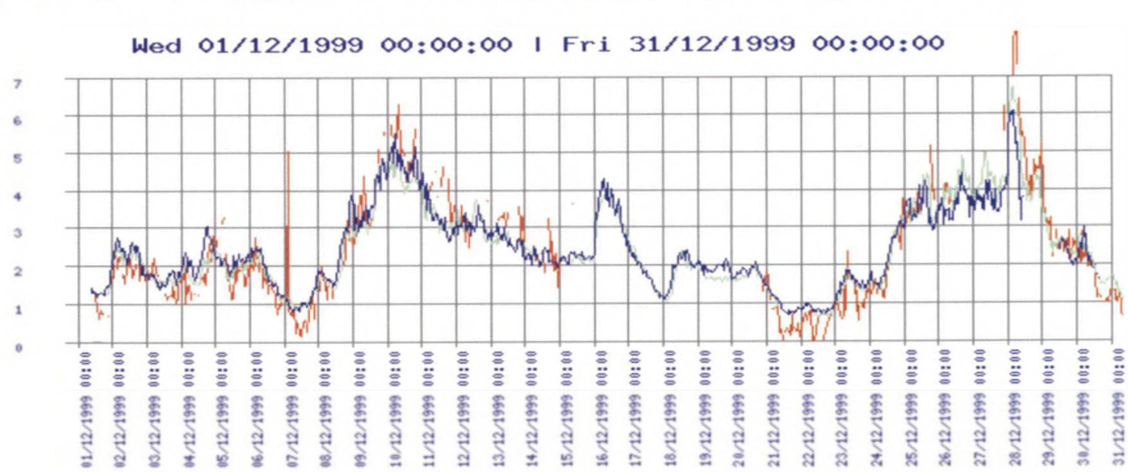


Figure 4: *Spectral Propagation to the coast (Gijón) from an Offshore buoy (Cabo Peñas)*



Comparison of significant Wave height propagated from offshore buoy with a coastal buoy

To do this, the wave recorded information of the coastal network needs to be linked to the positions of the offshore network, using the previously described spectral propagation technique. In addition the offshore network needs to be completed by filling gaps mainly on the Mediterranean coast which was left out of the RAYO project funding. Additionally, the whole network will need to incorporate directional wave sensors. Puertos del Estado's plans foresee these works to be finished by 2004.

In the meantime there is an ongoing process to select a convenient wave directional buoy for port operation that can fulfil the conditions of economy, measurement reliability and easiness of maintenance. It should also be able to include some other sensors for meteorology and currents. Although some harbour directional buoys were installed within the RAYO project, there is not yet been a final choice in this regard, with a requirement for further tests on available market buoys.

Besides the objective of obtaining a general picture of the surface circulation of Spanish waters, further oceanographic considerations were taken into account to fix buoy locations and current meter chains, to study the following oceanographic processes:

- The so called Navidad (Christmas) current: a poorly known warm water mass moving northward along the continental slope, usually in winter time, from Portugal to France.
- The upwelling phenomena in the Spanish northwestern coast (position of the Silleiro and Villano-Sisargas buoys), taking place in summer due to southerly prevailing winds. This is important from an economic point of view for fish farming.
- The inflow of Atlantic water into the Mediterranean, critical to understanding the physics in this sea.

After one year of pre-operational data acquisition, most of the well known oceanographic processes in these regions have already been detected and recorded (Alvarez *et al.*, 2000). This reinforces the value of the multipurpose measuring system, promising future long time series capable of producing a better understanding of those phenomena and their impact on economic activities. It is important to emphasise the added value that can be achieved by incorporating other kinds of sensors in stable monitoring positions intended for process study.

All the received and processed information is freely distributed on the Internet under the heading http://www.puertos.es/Rayo. Numerical values are posted as soon as they are received and graphical evolution of parameters is updated every 12 hours. The plots include the evolution of all the variables during the last measured week (Fig. 3). At this moment, the quality control for this real-time information is limited to the detection of spikes but, once more data has been gathered and analysed, dynamical characteristics of the measuring points can be precisely determined and a more sophisticated quality control will be developed. The Port Authorities have an additional way of accessing the data. A Motif and C based application, named XrayoMon, is running under Linux on the port's local computers, displaying in real-time the useful information that the buoys can provide. Information is sent to those machines via FrameRelay through the Harbour Intranet.

Every year, after detailed quality control of the measurements, several codes are employed to produce data reports containing representations of the measured parameters (i.e., progressive vectors of winds and currents) as well as the following analysis of the results:

- Statistical analysis, including wind and current roses, histograms, monthly evolution tables, etc.
- Power spectra of several magnitudes by means of Fourier transform smoothed in the frequency domain using a Parzen window (Jenkins and Watts, 1968).
- Decomposition of currents into tidal and residual components by means of the Foreman harmonic analysis program - (Foreman, 1977).
- Computation of the inertial component of currents using a filter in the frequency domain (Jenkins and Watts, 1968).
- Sub-inertial time-series computation through an A24A24A25 Godin filter (Godin, 1991).

The final reports obtained with this software can be freely found on the Internet under the heading http://www.puertos.es/Rayo/informes.html (in pdf format).

Real time buoy transmitted data is currently used for validating wave forecasts. Data recorded by land based networks (met stations, tidal gauges, wave radars) are used together with buoy data for assessing the quality of the whole set of measurements. In this regard for instance harmonic analysis of tide gauges provides a good basis to analyse the tidal component of current records. Availability and integration within this consistent analysis of simultaneous space derived sea surface data will contribute in the future to a better assessment of recorded data.

Land based networks

The meteorological and tide gauge networks are placed at the ports themselves, usually at piers, and transmit data via radio or telephone to PA's main building. They are very much involved in the operational aspects of harbour activity.

The real time meteorological data provide PA's with operational thresholds on:

- Loading and Unloading operations: Crane use.
- Navigation conditions at harbour entrance and inside the port: Trawlers use (vessel manoeuvres).

There are ongoing developments to enhance applications of real time meteorological data. In this regard the PA of Valencia and Puertos del Estado have implemented a monitoring system in this port for control and assessment of particle dispersion coming from handling operations at quays of dusty solid bulk materials. Several particle collectors have been installed at various sites of the port. The recorded data together with those of the meteorological stations are coupled to a dispersive model (Fig. 5) allowing operation control.

Besides operational aspects, the meteorological historical records provide methods of defining design actions (temperature and wind) for construction works and are used in statistical analysis to obtain the mean and extreme values of meteorological variables. Real time meteorological data are also used for validating high-resolution wave or current models near the harbour.

The tide gauge historical records are provided to the Spanish Hydrographic Office which computes the official Spanish Tide Tables. They are used by Puertos del Estado to analyse the trends in sea level in order to control the zero reference harbour level and detecting infrastructure subsidence or emergencies. The computation of the mean and extreme values of water levels for design purposes is another important application of these data.

Real time sea level records are used by PAs to settle berthing and navigation conditions within the harbour, for control of dredging works, etc.

An important use of tide gauge data is to validate sea level forecasting in the harbours (Fig. 6). Real time data are also used to improve the forecasting model capabilities by assimilating them into model runs. The NIVMAR forecasting system derives sea levels by adding the tidal component obtained from harmonic analysis of long time series to the meteorological component which is based on the results of a barotropic 3D hydrodynamical model forced by meteorological fields (pressure and wind stress). The meteorological component is very important in Mediterranean harbours due to the small amplitude of the tide there.

In order to explore alternative ways of wave monitoring Puertos del Estado started at the beginning of the nineties to install land based navigational radars to remote sense the full scalar and directional wave fields. The technique of deriving the wave field from images of sea surface roughness recorded by the radar inhibiting sea-clutter has lately experienced important advances, although further developments are required for full operationality of these systems. These systems will play an important role in the future in areas where buoy deployment is difficult because maintenance is less costly and there is the capability to measure the sea state spatially.

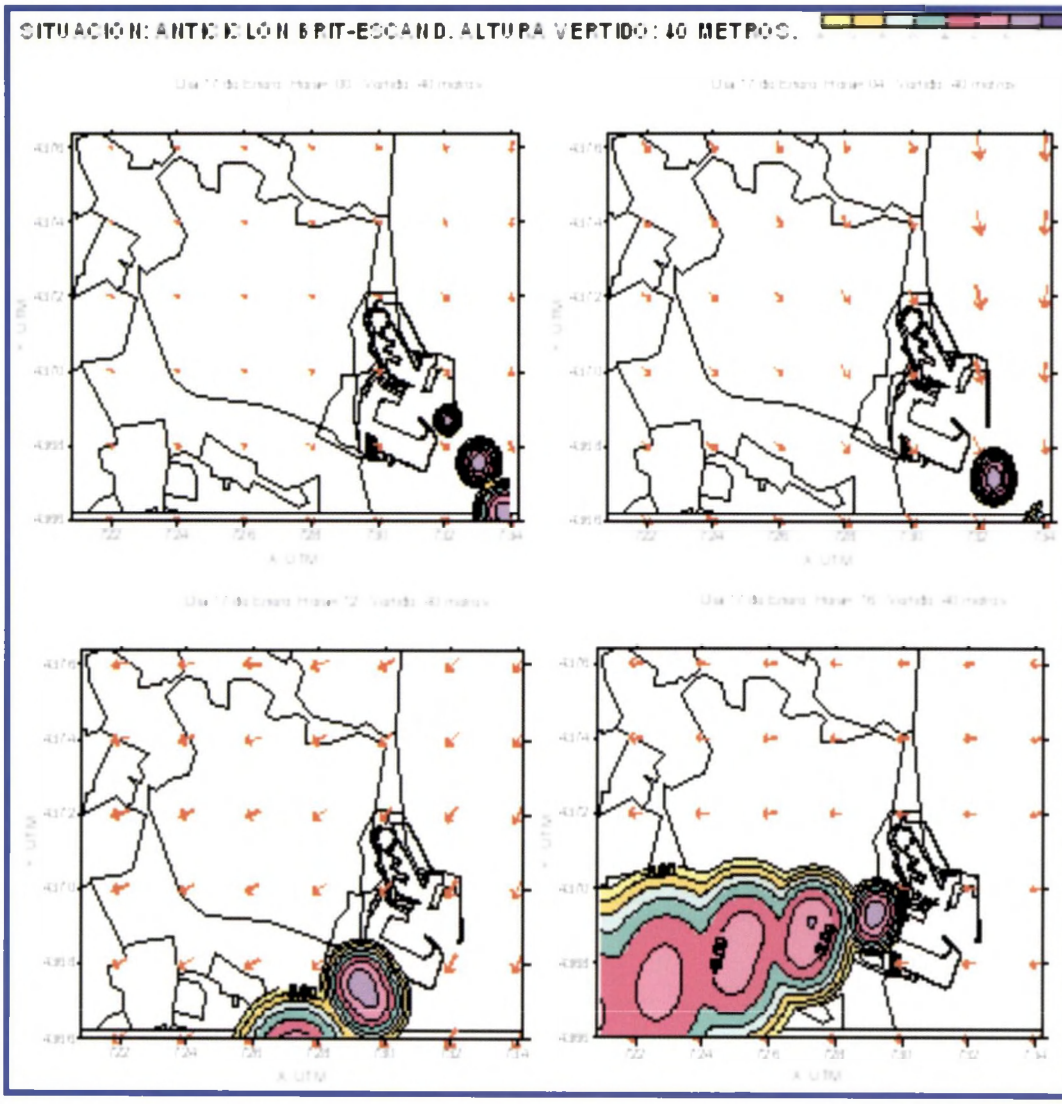


Figure 5: *Particle Dispersion model. Unloading at east quay PA Valencia*

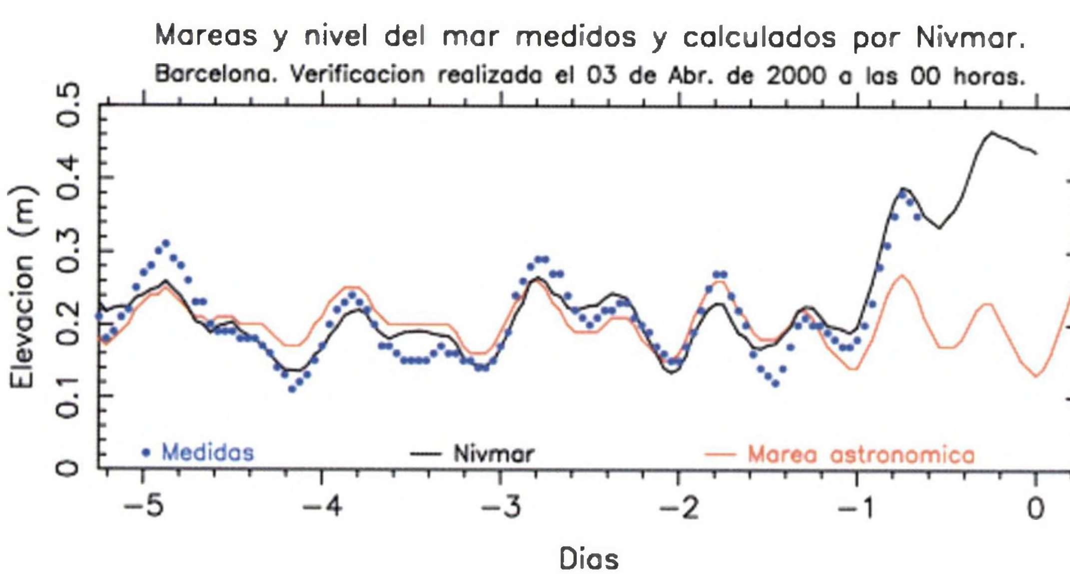


Figure 6: *Verification of sea level at PA Barcelona*

The data bank

Monitoring networks and forecasting models provide a huge amount of data that are stored and distributed through the Data Bank. In order to facilitate easy access to both data and elaborated information (statistics or mean/ extreme regimes), Puertos del Estado has developed a scheme for on-line consulting of the Data Bank. This is done through the web server (www.puertos.es). Figure 7 shows an example of this kind of access to the Data Bank. User select on a map showing positions with information, the point, and kind of data required.

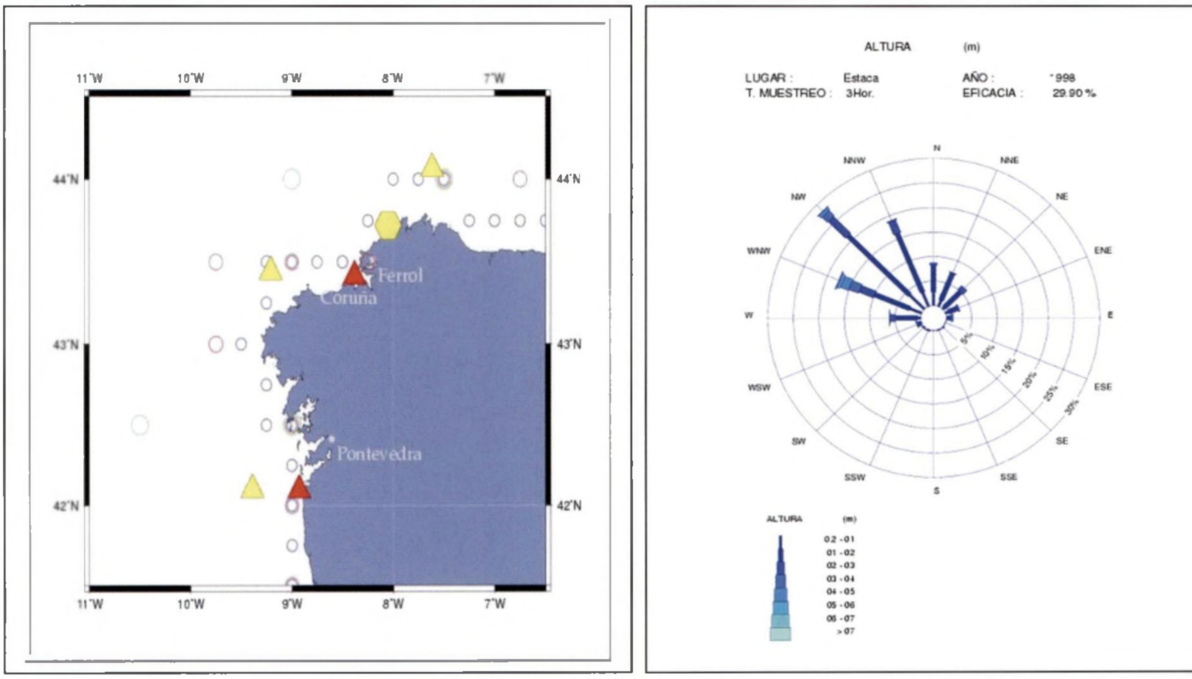


Figure 7. *Graphic Access to Data Bank (Internet). Wave Rose at Villano position*

Conclusions

This paper has shown the way in which *in situ* data can be processed to provide real time operational services and forecasts for port management and ship management. Observational data added to the system from remote sensed observations would have to meet the same criteria in providing a service to the end users.

The developed system has strong usefulness potential not only for the SPS but also for a broad spectrum of users. It is important now to reinforce the link between the system and the needs of the PAs in order to plan its development and to better disseminate data and by-products of the networks. The offshore network has capabilities beyond the interest of the SPS, being in this regard convenient to find an administrative framework at national Spanish level to combine and share both management and financing in order to reach full potential development in for operational oceanographic systems.

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BOOS and the use of operational ocean remote sensed observations

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Abstract

The Baltic Operational Oceanographic System - BOOS has the goal to:

"Establish an operational oceanographic service for the Baltic Sea area in order to provide the marine user groups with high quality information's and prognoses and to decrease production costs by sharing the workload."

Remote sensing is already an integrated part of the existing monitoring activities of the Baltic Sea and will be of increasing importance in the future. The existing activities include:

- Production of weekly maps of SST based on remotely sensed data, *in situ* observations and model results. Members of BOOS are in the process of implementing a system for production of a daily SST map.
- Production of ice charts during the winter months.
- Monitoring the presence and distribution of harmful algae blooms.

In the future BOOS expect to benefit from using remote sensing for observations of the following additional parameters:

- Waves
- Water level
- Oil on the sea surface
- Winds
- Chlorophyll-a
- Suspended solids
- Sea surface salinities

Data will be used for:

- providing the most usefully accurate description of the present state for the Baltic Sea
- initial conditions for operational models
- data assimilation

Introduction

The marine industry has always been an integrated and well-established part of business community in the countries surrounding the Baltic Sea, where fishing, shipping and ship building have been a feature of the history and livelihood of the coastal areas for hundreds of years. For natural reasons, contact with the sea has been, and still is, concentrated to marine areas close to the coast. It is also in such areas that pressure on the utilisation of marine resources and the threat to the marine environment is most noticeable.

Figure 1: *Baltic Sea area (Bottom topography, drainage basins, and political borders)*

Due to the importance of the Baltic Sea to the economic life of its bordering countries, marine research in the Baltic was initiated at a very early stage in the history of oceanography. Registration of water level and monitoring of the sea ice distribution were the first regular data collection activities that started already more than two centuries ago. In the middle of the previous century observations of temperature, salinity and current were initiated on Light Vessels. Regular research/monitoring cruises started a little more than one hundred years ago. These measuring programmes have generated some of the best oceanographic time series existing in the world.

In the present century and especially after World War II other monitoring programmes have started involving physical, chemical and biological oceanography, fisheries- and environmental assessment. Additionally numerous research projects with international co-operation have been carried out over the years, whereby a detailed knowledge of the complicated processes governing the Baltic Sea has been achieved.

In recent years several modelling activities focusing on the Baltic Sea have been initiated, most of them with the aim to study specific processes in the area while a few have the goal to be operated in an operational mode to provide the marine industry with required prognoses of the behaviour of the Baltic Sea.

The Baltic Sea is a natural entity not only in a hydrological sense but also for multilateral co-operation. Every subject related to the sea is of common interest to the bordering countries and co-operation between the countries has existed on a more or less voluntary basis for the last millennium. Much of the Baltic marine co-operation has been co-ordinated by international bodies such as International Commission for Exploration of the Sea (ICES), the Baltic Marine Environment Protection Commission (HELCOM) and the International Baltic Sea Fisheries Commission (IBSFS), but much work has also been initiated through institutional or personal collaboration.

Since the formation of EuroGOOS its Baltic Sea Task Team has started to discuss, plan and co-ordinate activities related to operational oceanography in the Baltic Sea with the purpose of creating a Baltic Operational Oceanographic System - BOOS, see BOOS Plan, 2000.

The most important marine related areas which require operational oceanography in the Baltic are:

- Shipping - all kinds
- Navigation in shallow areas and entrances to harbours
- Rescue operations, drift forecasting
- Military purposes
- Storm surge warnings
- Flood protection
- Coastal protection
- Transport calculations of water, substances and passive biological material, e.g. algae and fish eggs
- Bottom water renewal, oxygenation
- Environmental protection, impact assessment and management
- Ecosystem assessment
- Fisheries planning and management
- Recreation purposes
- Public warnings
- Research

The basic requirements of these and related industries are to a very high degree concentrated on information from the same few oceanographic parameters although the demands for resolution in time and space may be very different. An operational oceanographic service supporting these activities shall primarily focus on observations, analysis and model predictions of water level, waves, currents, temperature, salinity, sea ice, oxygen, nutrients, algae and chlorophyll.

BOOS will be based on past investments in marine scientific research, marine technological systems including existing operational observing and forecasting services as well as on the established international infrastructure. Scientific and technological investments on a national and Baltic level have made BOOS possible and a number of services do already exist providing local data and forecasts for marine operations such as storm surge warning, wave forecasts, oil drift, toxic algae blooms, the extent of sea ice etc. In order to establish an integrated operational forecast system for the Baltic with its special physical, chemical, biological and geological characteristics, there is, however, a great demand for additional investments in scientific research and technological development focusing on the special demands for rapid data delivery, optimal model performance, data exchange, user friendly product dissemination etc. that are required by an operational service.

Some of the extremely ambitious tasks that BOOS has to address are:

- development of a mesoscale data analysis system
- coupling of ocean and atmosphere models
- coupling of regional and local models
- development of ecological models taking into account the very special Baltic environment
- optimising the existing observation network
- introducing new observation technologies (remote sensing, radar) into an operational routine
- develop and establish a harmful algae bloom warning system
- establishing an efficient data exchange and product dissemination

In almost all of these tasks there will be a component of or related to remote sensing, because satellites offer the only way of systematically observing the entire Baltic Sea within a short time frame and with the ability to resolve down to small scales.

Existing activities

Several of the BOOS partners are already using satellite observations in their operational or semi-operational activities.

Sea surface temperatures

In a semi-enclosed sea area like the Baltic Sea sea surface temperatures (SST) may change considerably within a short time frame - hours to a few days - due to processes like up-welling, sea ice formation etc. Knowledge of such rapid changes will have a number of practical applications within an operational service, first of all through defining the initial boundary conditions in both atmospheric and oceanographic forecast models. Preliminary research has proven that short-range weather and ocean forecasting will improve by the introduction of real-time observations of SST (Gustafsson *et al.*, 1998).

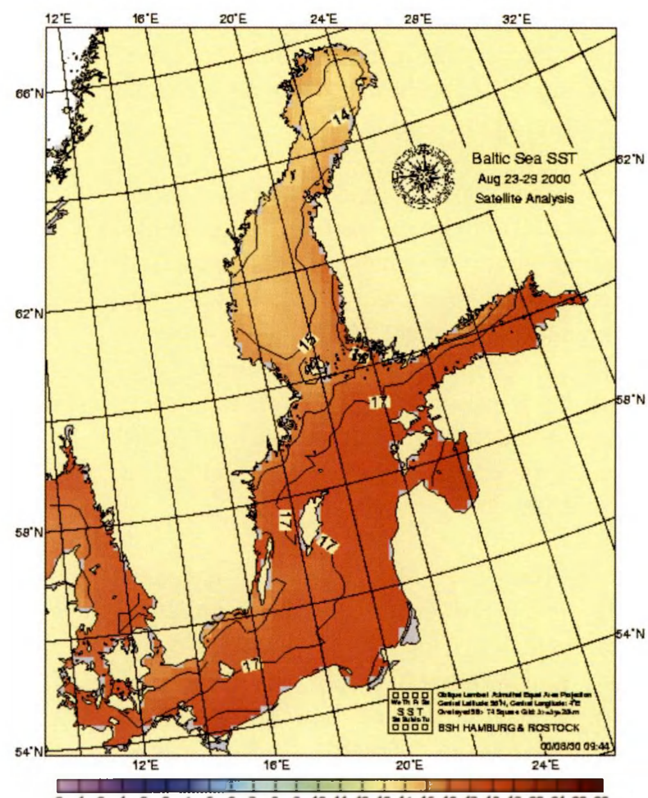

Figure 2: *Baltic Sea SST map produced by Bundesamt für Seeschiffarht und Hydrographie (BSH), Hamburg. The map is updated once a week.*

At present SST maps for the Baltic Sea are produced operationally once or twice a week at a couple of the BOOS member institutions using a combination satellite observations and in-situ measurements. It is, however, a clear goal of BOOS in the near future to be able to produce operationally daily SST maps for the Baltic Sea to the benefit of primarily the modelling activities.

Figure 3: *Cargo ship in sea ice*

The presence of sea ice is of large practical and economical importance in the Baltic Sea. In the Baltic Sea some 90% of foreign trade is marine transported and over 500 million tons are transported annually - 40% during winter months. The Baltic Sea ice season lasts up to seven months and the maximum ice cover ranges from 50,000 to 420,000 km².

National ice services are responsible of the ice monitoring. Around the Baltic Sea there are operational services in Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden. Sea ice data are collected, analysed and distributed by these services. The input data consists of (a) ground truth, such as data from observation stations, observations of vessels and icebreakers, etc., (b) visual and/or digital airborne data collected by aeroplanes and icebreaker-based helicopters and (c) space-borne data of various satellites. Especially since SAR images have become available in near real time satellite observations have become increasingly important.

The services are issuing on daily or twice-a-week basis ice charts, ice reports in national languages and in English and in the Baltic Sea Ice Code. Some services are also able to produce ice forecasts and transfer satellite images and SAR based classifications to the icebreakers and ships.

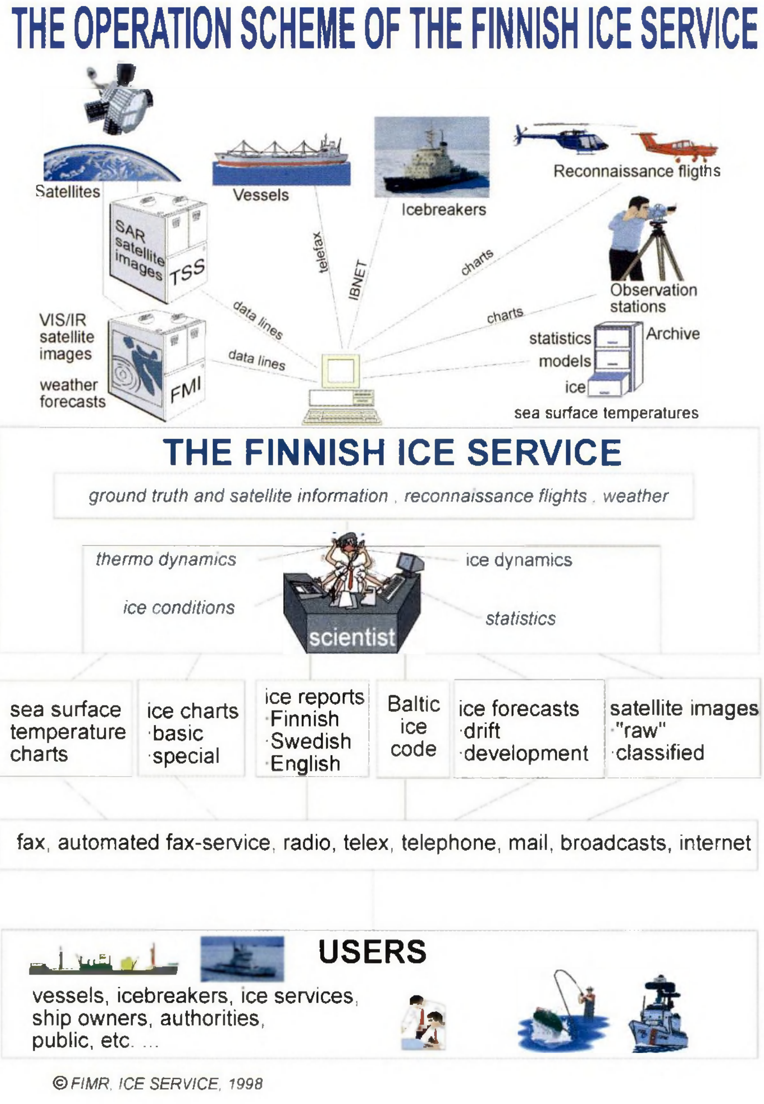

Figure 4: *The operation scheme of the Finnish Ice service*

Harmful algae blooms

In most of the countries around the Baltic Sea, specific programmes are carried out to monitor and inform the authorities and the public of potentially harmful algae blooms.

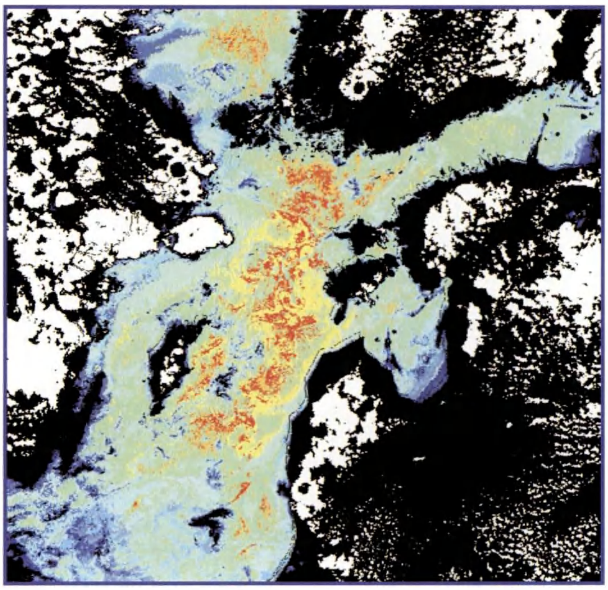

Figure 5: *Satellite image on surface accumulations of cyanobacteria in the Baltic Sea on 4.8.1999. Satellite image of surface water accumulations of cyanobacteria 4.8.1999. The red colour stands for very strong blooms, yellow and yellowish-green colours for moderate surface accumulations. (Picture received by Institute of Meteorology and evaluated by the Finnish Institute of Marine Research).*

Frequent coastal sampling using ships and helicopters, ship-of-opportunity lines, satellite imagery and visual observations by e.g. coast guard pilots are used for this purpose. It is however the goal to improve the data sampling procedures and to provide an early-warning information system.

Future activities and demands

In the future additional parameters observed by satellite will be integrated into the BOOS service activities. The most critical questions regarding the future utilisation of satellite data are:

- which parameters can be observed at a satisfactory high level of observation frequency and with the required quality level
- availability of data within the required time frame
- the BOOS partners ability to use the data operationally

The most important future parameters are foreseen to be:

- **Waves**. Wave forecasting is at a relatively advanced level in the Baltic region but only a few *in situ* observation points are available. There is therefore a great need for more wave observations to calibrate and validate the wave models and to be assimilated into the models. This task is believed to be best solved through satellite observations, since this method will allow for a basin wide real time display of the wave fields.

- **Water level.** The Baltic Sea has almost no tidal signal, but frequent passages of atmospheric pressure systems cause changes in air pressure and wind forcing that generate water level fluctuations within the Baltic Sea of up to $\pm$ 1 m, extremes up to $\pm$ 2m. Due to the risks for flooding in parts of the Baltic observations of water level is carried out in an intense network of water level recorders placed primarily in harbours along the Baltic shoreline. There exists almost no information on the water level and its variability in the open Baltic Sea and that kind of information constitutes a valuable input to ocean circulation models.

- **Oil on the sea surface.** There is a major ship-based transport of oil in and out of the Baltic Sea and prognoses indicate that this traffic will increase dramatically in the future, whereby also the risk for oil spill into the open sea increases. An early observation of the oil spill will secure that drift prognoses can be worked out and effective oil combating can be initiated to protect the environment in the best possible way.

- **Winds**. An important forcing parameter to ocean models is the wind, and although the meteorological models covering the Baltic Sea area generally have a very good performance only few off-shore wind observations exist to verify atmospheric model winds.

- **Chlorophyll-a.** Ecological modelling will be a very important task in future BOOS work and satellite observations of chlorophyll-a constitute an important contribution to this work.

- **Suspended solids.** Observation of the concentration and drift of suspended matter in connection with river outflows, coastal engineering projects etc. is an important component of local coastal environmental monitoring and protection programmes.

- **Sea surface salinities (SSS).** The SSS distribution is - like SST - a very important parameter in understanding the circulation in an ocean area, and thereby as input to ocean circulation models. In the Baltic Sea only very few observations of SSS are available in real time from moored buoy systems. Future satellite based observations of SSS will therefore constitute an important input to ocean models.

Conclusions

The implementation of an operational oceanographic system like BOOS will depend highly on satellite observations of high observation frequency, with good data quality and for most parameters availability in near real-time.

Satellite observations will together with in-situ observations from shore based stations off-shore buoys and from ships form the basis for a detailed description of the actual state of the Baltic Sea. They will additionally serve as a valuable input to models both as initial conditions as well as through assimilation into the models.

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The Atlantic Ocean Forecasting System's requirements for remote sensing data from space

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Introduction

Europe is influenced by marine conditions more than any other developed continent. It has the longest coastline per unit area, the mean distance of land from the ocean being only 340 km, and the European continental shelf adds 63% to its land surface. Natural fluctuations and human induced perturbations in its marine environment have thus a great impact on its economy: shelf-seas and deep ocean fisheries, offshore oil industry, transport and dispersion of pollutants, shipping, coastal management, tourism (Flemming, 1997, 1999). Also, the mild weather of Europe is a consequence of the Northward transport of heat by the surface current in the Atlantic. On the longer time scales, decadal to secular or larger, this transport of heat in the surface currents of the Atlantic depends upon the rate of formation of the cold bottom waters in the Norwegian Sea, the Irminger and Labrador seas. Hence the needs for developments to monitor and predict the northward transport of heat in the North Atlantic.

In accordance with this dependence upon the Atlantic Ocean and its shelf seas, most European coastal states have developed operational oceanographic data collection facilities and forecasting services, which provide monitoring and short term forecasts of conditions such as storm surges of sea level, wave spectra, icing conditions, coastal and estuarine pollutants, movement of oil slicks. These existing marine forecast systems, are however mostly of limited spatial extent. Prototypes of ocean forecasting systems are thus now under development at the scale of the Atlantic to respond to the more global demands. Their objective is to produce 1) estimates of the 3D thermodynamic state of the Atlantic ocean circulation at the large scale, and 2) one to two week ahead forecasts of the mesoscale structure of the upper ocean. They will respond to demands ranging from the short term applications (marine safety, military applications, oil exploitation, continental and coastal shelf applications, ecosystem modelling) to longer term seasonal and climate predictions.

These developments are in phase with the international effort aiming at the emergence of the operational oceanography, and in particular the Global Ocean Data Assimilation Experiment (GODAE) of which the objective is to provide a practical demonstration of the feasibility and practicality of real-time global data assimilation operational oceanography (Smith and Lefevre, 1997, Le Traon *et al*, 1999).

The components needed for implementing and running such systems involve the availability of a good initial state of the ocean thermodynamical parameters, ocean surface forcing field observations and short term forecasts, adequate observation networks transmitting data in real time and efficient real time data transmissions, a good thermodynamic model of the ocean, and efficient assimilation methods to merge observations in the model for further forecasts with good skill. The scientific and technical progress of the recent years in the field of oceanography suggest (GODAE Strategic Plan) that the period 2003-2005 appears optimal for the operational trial, in term of likely observational capacity, and scientific and technical capability. The Atlantic Ocean is the most observed and the best understood area of the world ocean. The developments focused on this basin thus appear as a unique opportunity to contribute to this demonstration of feasibility and to evaluate the performance, difficulties and weakness of such developments.

In situ and remote sensing data are a major component of these systems. These data are needed to define the forcing fields driving the models, to be included in the assimilation process and to contribute to the validation of the products. Satellite remote sensing is recognised to provide the key component of the observing system required to fulfil the requirements in

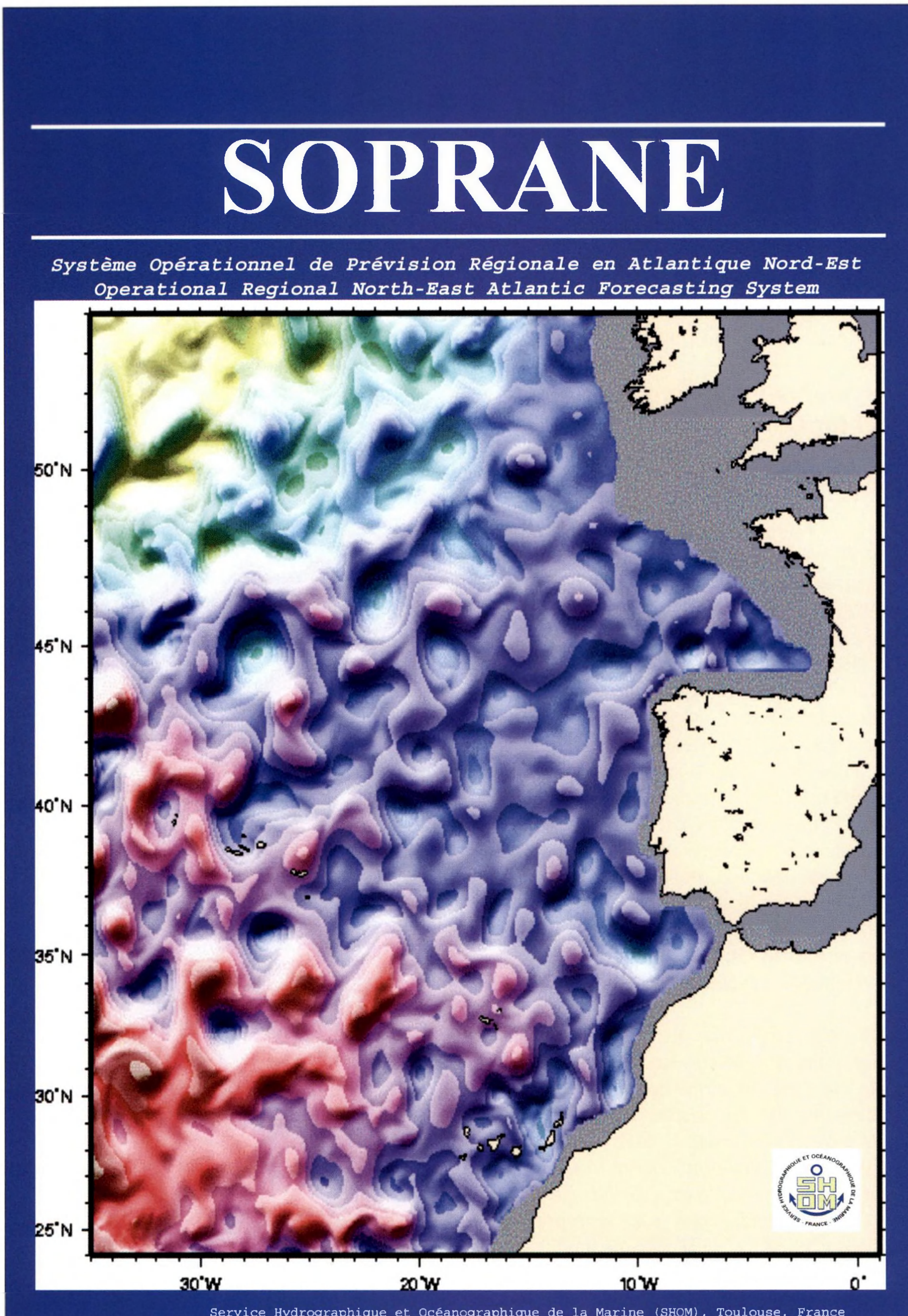

Figure 1: *Typical output forecast from the SOPRANE model for the stream function at level 1 for part of the east Atlantic*

terms of global coverage on space and time scales of interest, for the large variety of applications listed above. The aim of this presentation is to remind us of these needs and to illustrate on the basis of the Atlantic forecasting systems under development in Europe (DIADEM, FOAM, MERCATOR) the importance of the satellite data within these systems, how they are used in terms of forcing, assimilation and validation, and point out what are the specific requirements in relation to the physics of the ocean circulation in this basin. We will focus on satellite altimetry.

The systems in Europe operated in real time

The SOPRANE system

This system routinely run by the French Navy since 1998 is based on a QG model of the Northeast Atlantic, 1/10° horizontal resolution, assimilating altimeter data from ERS2 and T/P with the already above cited suboptimal linear filter SOFA. It delivers predictions of the 3D mesoscale structure of the ocean circulation over this area, up to 2 weeks ahead. The first demonstration of the system was done during two scientific cruises (ARCANE and CAMBIOS) during the summer 1997: forecast were sent to the research vessel in real time, and good agreement between the data and the forecasts were obtained, showing the efficiency of the system (Giraud *et al*, 1997). (Fig. 1)

The Forecasting Ocean Atmosphere Model (FOAM) System

The UK Met. Office has developed an ocean data assimilation system used for real time analysis and forecasts of the ocean structure out to 5 days ahead. The ocean model is built around a version of the Cox-Bryan-Semtner primitive equation numerical ocean model. This is a z-co-ordinate model which uses an Arakawa B grid. The bathymetry used is an appropriately smoothed version of DBDB5 or Smith and Sandwell (1997). An improved (3rd order upwind) advection scheme or the Gent-McWilliams parameterisation is applied to the tracer fields. A suite of parameterisation schemes, developed for a leading coupled ocean-atmosphere model, is used for vertical mixing of tracers and momentum and isopycnal mixing of tracers. A 1D thermodynamic and dynamic sea-ice model is coupled to the ocean model.

The data assimilation scheme is the filtered increment version of the analysis correction scheme (Lorenc, *et al.* 1991). Analysis increments are calculated and applied at each time step thus avoiding excitation of internal gravity waves. The following groups of data can be assimilated: sea surface temperature (SST), thermal profiles, salinity profiles and altimeter data. The surface temperature data is usually applied to the whole of the model's mixed layer. Geostrophic baroclinic current increments are applied to balance thermal and saline increments away from the equator. The scheme used for altimeter data currently uses a lifting/lowering method.

A one degree, 20 level, version of the system has been run daily in an NWP operational suite since August 1997. Bell *et al.* (2000) describe the system as it was when implemented. Driven by 6-hourly mean surface fluxes from the NWP system, it assimilates only thermal profile and SST observations. These are quality controlled using the previous day's model analysis and the Levitus (1994) climatology of standard deviation of observations from climatology and applied using forecast error correlation scales of 300 km (except close to the equator). Fields of sea ice concentration data from the Canadian Meteorological Centre (CMC) based on SSM/I data have been assimilated since July 1999.

Higher resolution models are now nested within this global model. These use the flow relaxation scheme of Davies (1983), which is a one-way nesting scheme. A 1/3 degree model covering the Atlantic and Arctic and assimilating altimeter data is due to be ready for use in the operational suite by March 2001. A 1/9 degree model of the Caribbean and Gulf of Mexico has been tested and a model of slightly higher resolution covering the North East Atlantic will be set up this year.

The MERCATOR system

The French MERCATOR System is built on a primitive equation ocean numerical model, based on the OPA-8.1 code of LODYC (Madec *et al*, 1998). It is a rigid lid model, with

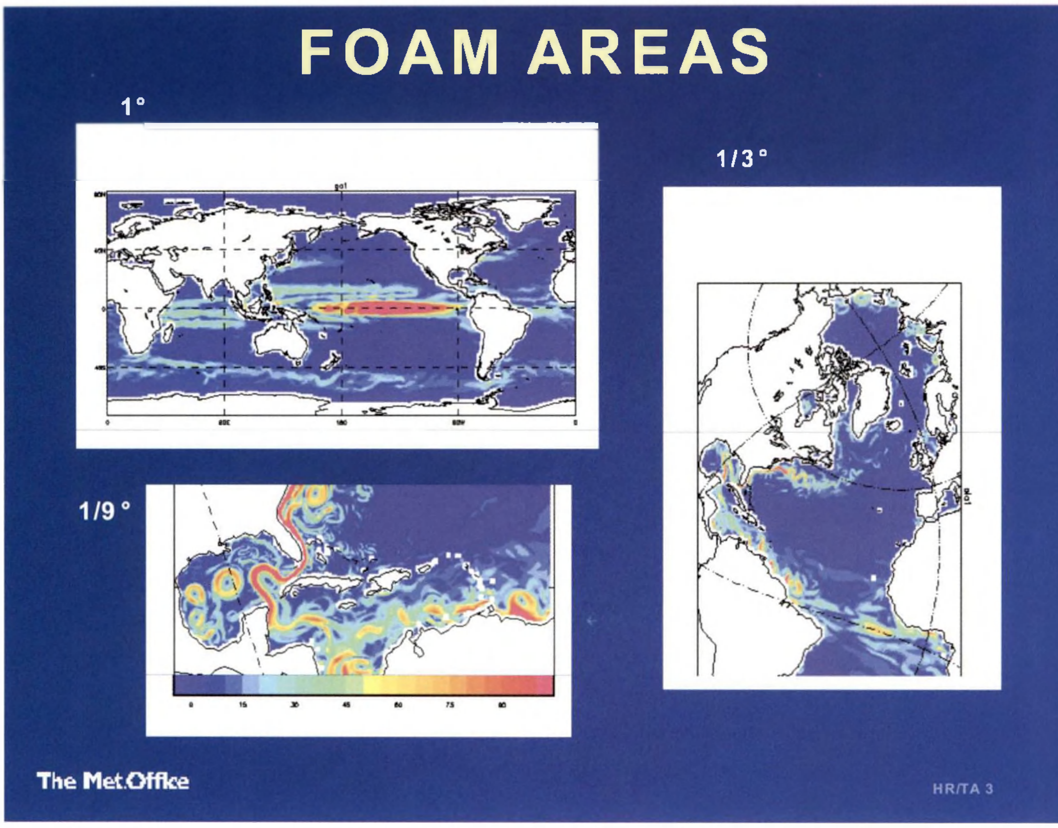

Figure 2: *The FOAM operational model is already in service, and is operating at multiple scales from 1° global to 1/9° at the regional sea level.*

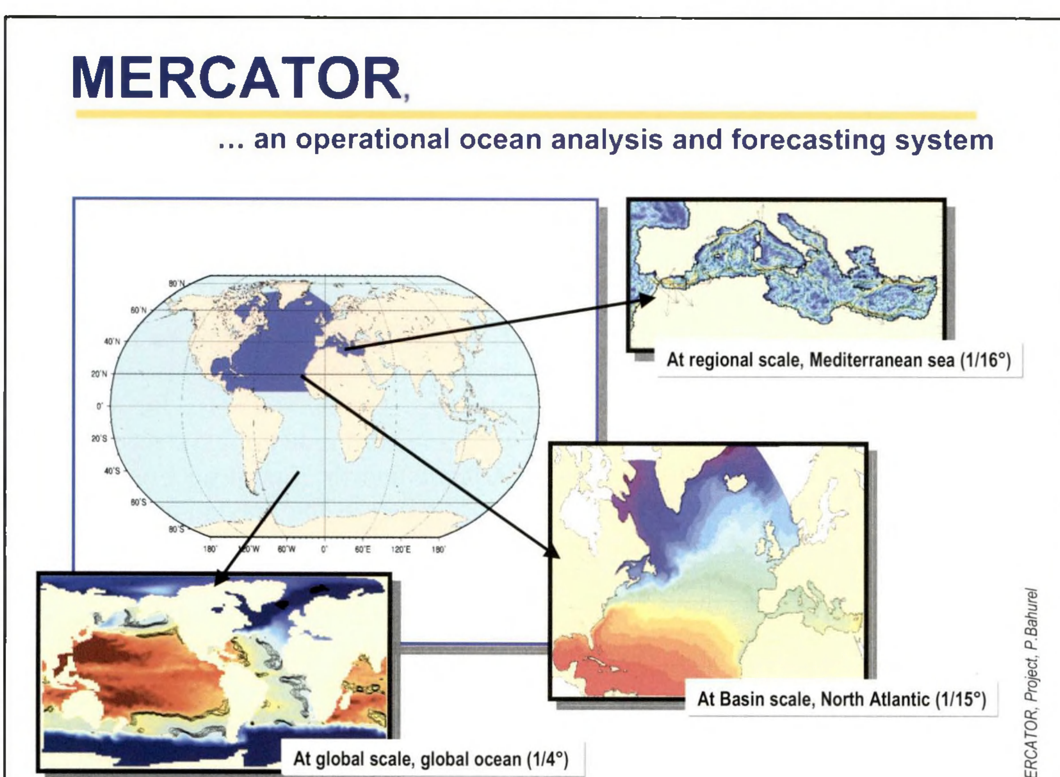

Figure 3: *The MERCATOR system is based on a series of models of different scales, from 1/4° global to 1/16° for regional seas.*

z-coordinate on the vertical, and an Arakawa C grid on the horizontal. The advection scheme is second order centred. Horizontal bilaplacian mixing is used for tracers and momentum, with a spatially variable coefficient. Vertical mixing is based on a turbulent closure scheme, with an enhancement of mixing coefficient in case of convection. The lateral boundary condition is free slip. There is a quadratic bottom friction coefficient using a variable background kinetic energy based on the energy of tidal currents. The system uses ECMWF momentum and heat fluxes as surface forcing. The surface temperature is relaxed to the Reynolds SST. The surface salinity is relaxed to the Reynaud *et al.* (1998) seasonal climatology. The bathymetry is based on the Smith and Sandwell (1997).

Two versions are implemented over the North Atlantic: one eddy permitting, and one eddy resolving. The eddy-permitting version covers the North and tropical Atlantic from 20°S to 70°N, with a Mercator grid 1/3° resolution at the equator, and 43 levels on the vertical (including 20 levels in the first 1000 meters, and a maximum of 200 meters between the deeper levels). Buffer zones are implemented on the northern and southern limits, based on climatological T and S fields. The exchanges with the Mediterranean sea are controlled by a buffer zone situated in the Alboran Sea.

The eddy-resolving version covers the North Atlantic from 9° N and 70° N and the Mediterranean Sea. Each basin has its own vertical grid of 43 levels, with the discretisation on the first 400 meters (the depth of the Gibraltar Strait). The horizontal discretisation is a 1/16° Mercator grid over the Mediterranean Sea and 1/15° Mercator 90° rotated grid on the Atlantic (with the pole on the equator at 30° E). This leads to a resolution varying between 5 and 7 km. Buffer zones are implemented along the northern and southern limits of the domain.

The assimilation is based on reduced-order optimal interpolation (Sub Optimal Filter Assimilation – SOFA, De Mey, 1998). The model error is projected onto a set of vertical modes defined empirically from the Reynaud *et al.* (1998) historical data set. The background error covariance matrix parameters are defined empirically.

The DIADEM system

The EC-funded MAST-III DIADEM and FP5 TOPAZ projects develop a pre-operational data assimilation system for the North Atlantic, Nordic Seas and the Arctic. The model grid extends from about 60°S and northwards including all of the Arctic. The resolution is focussed in the Gulf Stream extension and the Nordic Seas which are the major regions of interest.

In DIADEM, focus has been on the implementation of a multivariate data assimilation system for the North Atlantic and the Nordic Seas. The project involves partners from six European countries working with ocean and ecosystem modelling, data assimilation and processing of remotely sensed observations. The major objective of the project is to implement and demonstrate novel sophisticated data assimilation methods such as the Ensemble Kalman Filter and Smoother, and the Singular Evolutive Extended Kalman Filter, with the Miami Isopycnic Coordinate Ocean Model (MICOM) and a marine ecosystem model. The data which are assimilated are remotely sensed sea level anomalies, sea surface temperatures and ocean colour. The assimilation systems have now been completed and applied in hindcast experiments, and a real time operation of the system is about to start during October 2000, with predictions of marine parameters issued on the project web page (to be announced).

The data assimilation system developed in the DIADEM project will now be further improved and applied in the recently funded TOPAZ project. TOPAZ stands for "Towards an Operational Prediction system for the North Atlantic and the European Coastal Zones" and was funded in the previous round for the FP5. The TOPAZ project adds several new modules to the DIADEM system. First of all the isopycnic MICOM model is replaced by the Hybrid Coordinate Ocean Model (HYCOM) which improves the major weaknesses in MICOM, e.g. by introducing vertical resolution in the upper mixed layer and by using the KPP vertical mixing scheme. Further, the system now introduces a downscaling to the coastal zones by nesting of high resolution regional versions of the model. There will also be

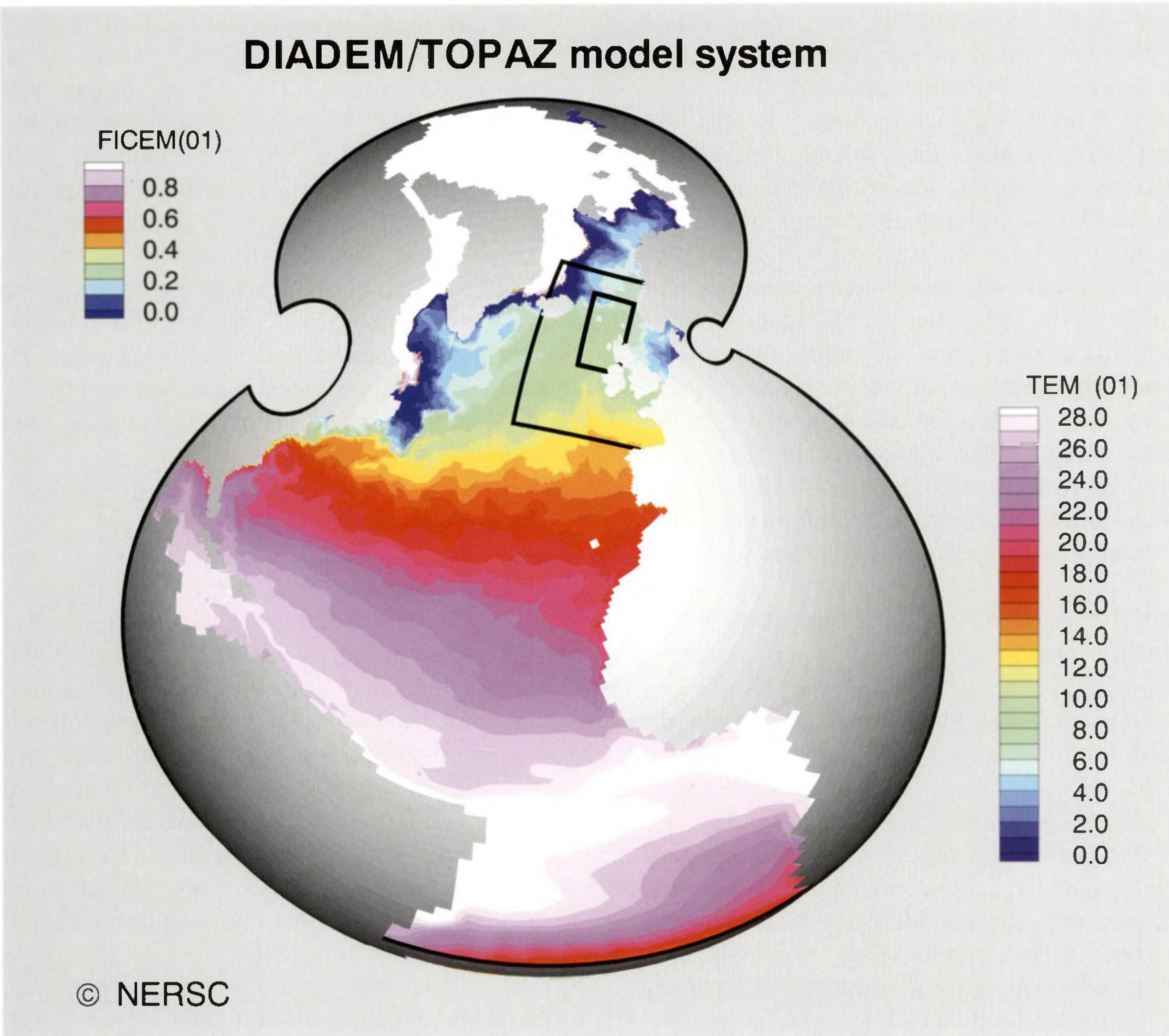

Figure 4: *Modelling grid for the DIADEM/TOPAZ model showing a surface temperature field, and the high resolution zones where nested models will be run with resolution of 7-8km and 2km*

several new data types assimilated, including the *in situ* data from the Argo floats and ice parameters from satellites. TOPAZ will lead to a fully operational monitoring and prediction system and will be tailored to meet the needs for marine forecasts from the off-shore oil industry operating in the harsh deep-water areas along the Atlantic Margin.

The remote sensing satellite data required

As noted in the introduction, remote sensing data are a major component of these ocean forecasting systems. The needs depend on the applications, in particular those requiring the resolution of the mesoscale by contrast to the large scale climate. The needs depend also on the model and assimilation methodologies. However, there is a common agreement on the final requirements leading to common specifications for a permanent, global and real time ocean observing system (see the conclusions of the International Conference on the Ocean Observing System for Climate – OCEANOBS 99- Saint Raphael- France). The needs for the Atlantic forecasting systems are not different from the ones for the other ocean basins and for the global ocean. We can thus refer to the specifications expressed in the GODAE strategic plan. The Ocean Theme from the Integrated Global Observing Strategy (IGOS, 2000) provide further detail and justification within the broader context of earth system monitoring.

Remote sensing from satellites is the only way to get detailed global coverage on the space and time scales of interest for the various applications listed in the introduction. These techniques can provide near real-time, long-term, synoptic, global estimates of the key parameters needed: they include sea surface topography, oceanic geoid estimation, ocean surface winds, sea surface temperature, surface radiation and precipitation, sea surface salinity, sea ice extent and sea ice concentration, ocean colour. In the following, we will focus on those techniques which are the more mature and which supply data readily or soon to be used to constrain the ocean forecasting systems. In this section, we will briefly recall the major GODAE requirements. In the following section, some justifications of these requirements will be illustrated on the case of the Atlantic basin.

Sea Surface Topography (altimetry and marine geoid)

GODAE strategic plan clearly points out the needs for:

- Global, near real-time, high accuracy and high resolution observations of sea surface topography, from at least two (and preferably three) altimeter missions with one very accurate long term altimeter system. The latter is mandatory for climate applications and as a reference for the other missions. The combined data of several altimeters is needed to constrain the ocean model mesoscale circulation and provide useful information on the surface velocity field. JASON-1 and ENVISAT will ensure the minimum to fulfil these requirements.

- Improvements in the geoid, necessary to extract from the satellite altimetric data the absolute dynamic topography and currents. With GOCE/GRACE, continued improvements may be anticipated (Le Provost *et al*, 1999).

- Complementary *in situ* data (Mitchum *et al.* 1999) to insure consistent inter-mission calibration and monitor altimeter performance.

Sea Surface Temperature

GODAE requires global high resolution sea surface temperature in near real-time for assimilation into ocean models. Indeed, the SST data provide a unique capability to determine finer scale features (e.g., oceanic fronts) and contribute to the controls for the thermal fields. GODAE needs global SST field at high resolution in time (at least daily) and space (at least 10 km). Present analyses are generally too coarse so the GODAE strategy embraces specific activities to develop higher-resolution products, merging different satellite products and *in situ* data. Remote sensing missions on-going and planned in the near future broadly meet the needs in term of sampling and accuracy.

Wind Vectors

GODAE requires wind vector measurements and scatterometery is likely to provide the best wind stress products. The IGOS (IGOS 2000) has concluded that the overall ongoing scientific and practical uses of ocean vector winds provide justification for two scatterometers, one in each of the morning and afternoon polar orbits. These two satellite systems are needed to provide the sampling and coverage required to capture critical weather patterns and to document the atmospheric forcing of the diurnal and inertial ocean response.

GODAE recognises that forcing fields for short-range ocean forecasts must come from NWP forecasts. However, at present, NWP assimilation filters out important spatial scales that are present in the original data. One option for operational oceanography will be to seek special real-time analyses that preserve these important scales. New wind products synthesising several types of remotely-sensed data may be required to provide the full-spectrum of information needed by the models. This will depend on the ability of NWP groups to enhance their product.

Other remote sensing inputs

Other important data sets that have a strong dependence on remote sensing include surface radiation, sea ice products (sea ice extent, sea ice concentration) and ocean colour (penetration of light). If remotely sensed salinity data become available during the GODAE time-frame, this will be a priority for assimilation.

The case of the Atlantic

As noted in the introduction, the Atlantic Ocean is the most observed and the best understood area of the world oceans, and many of the above requirements can indeed be justified by reference to the physical processes and associated typical scales / order of magnitude which need to be resolved by the Atlantic pre-operational systems. In the following, we will focus on the sea surface topography.

Satellite altimetry, and specially TOPEX / Poseidon (T/P) with its unprecedented accuracy, has provided a new picture of the ocean, from the high frequency ocean tides to the intra-seasonal, seasonal and inter-annual variability of the ocean circulation. In the field of ocean modelling, the availability of the altimetric data, coming from Geosat, T/P and ERS has contributed to very significant progress at several levels. These data have been used for diagnostic investigations on the realism of the simulations. They have also been introduced in assimilation procedures for improving the ocean circulation simulations and forecasting experiments.

Satellite altimetric data: A revolutionary source of information for ocean circulation model simulations

Until recently, even at the highest resolution affordable simulations of important features of the general ocean circulation in the Atlantic were absent or poorly represented, including Gulf Stream separation, recirculation regions, and regional statistics dependant upon dynamics and energetic of the mesoscale eddy field (poleward heat transport, mean and eddy kinetic energy distribution). The availability of altimetric data has highly contributed in guiding the modellers in their efforts to improving the realism of their simulation by offering global and high resolution in space and time observations of the ocean sea surface topography and surface velocity variability.

As explained before, numerical modelling of the Atlantic ocean has been intensively developed, in particular since the advent of the WOCE programme and the joint US-German CME (Community Model Experiment) effort (Böning and Bryan, 1996). For all these simulations, with resolution from 1/2 to 1/6 degree, the mesoscale variability was too low compared to observations including Geosat, in particular in the North East side of the basin (Treguier, 1992). This was attributed to the lack of resolution. Indeed Beckman *et al* (1994-a) showed that when doubling the resolution, the mesoscale turbulence was increased, although not at the right level, by referring to the statistics derived from altimetry. The availability of the altimetric data allowed to investigate not only global statistics but also the spectral characteristics of the eddy field (Stammer and Böning, 1994, Beckmann *et al*, 1994-b), showing that increasing the resolution improved the realism of the spectra.

It is only recently that the resolution barrier has been overcome with very high resolution simulations of the North Atlantic down to 0.1° (Bryan and Smith, 1998), in which, in particular, the amplitudes and spatial scales of the SSH variability in the vicinities of the North Atlantic current (50°N) and the Azores current (35°N) are in very good agreement with the altimetric data. Detailed comparisons of the SSH variability and eddy kinetic energy (EKE) fields have been carried recently by Ducet (PhD Thesis), based on new altimeter products merging T/P and ERS-1/2 altimeter measurements. It must be noted that these products lead to EKE levels 30 % higher than the maps of T/P alone (Ducet *et al*, 2000), in agreement with the conclusions of Le Traon and Dibarboure (1999) who show that T/P alone cannot observe the full spectrum of the sea level and ocean circulation variations. Indeed in this paper, Le Traon and Dibarboure also confirm the usually agreed upon main requirement for future satellite altimeter missions: at least two (preferably three) missions, with one very precise long term altimeter system to provide a reference for the other missions.

Satellite altimetric data: A basic observation dataset for assimilation in ocean forecasting systems

The feasibility and interest of the assimilation of the SSH variability observed from satellites in the context of operational oceanography has been clearly demonstrated by the SOPRANE system which routinely delivers since 1998 for the French Navy predictions of the 3D mesoscale structure of the ocean circulation over the North East Atlantic (Giraud *et al*, 1997).

The previously mentioned forecasting systems under development will, all of them, assimilate altimetric data. For MERCATOR and DIADEM, the assimilation of this dataset is indeed the priority, and will be soon operational. Dedicated investigations are presently carried out to evaluate the impact of the assimilation of the SSH variability on the improvement of the 3D structure of the ocean.

We can refer here to the preliminary investigations carried by Killworth *et al* (2000) in the context of the European DYNAMO project (1997), in a 1/3° resolution model of the North Atlantic, assimilating merged T/P and ERS-1 data on the period of one year (1992/1993), following the method developed by Oschlies and Willebrand (1996). The experiment succeeded in adjusting the route of the Gulf Stream to a somewhat more realistic position, energy levels were increased towards observed values, and wave propagation was enhanced. The effects of assimilation were confined to the top 1000 m, with the deeper structures almost unaffected. The conclusions of this study pointed towards two suggestions:

1. Only the temporal anomaly of SSH was assimilated, because of the uncertainty on the geoid at scales smaller than 2000 km. Hence the wrong mean circulation of the "free" Ocean model can only be corrected indirectly due to non-linear effects associated to the eddy field. While this does occur to some degree, it would obviously be more effective to assimilate a given mean SSH field. Hence the importance of the expected improvement of the marine geoid down to 200 km resolution expected from the GOCE mission.

2. The assimilation scheme used in this study was designed to leave water mass structure unaltered as far as possible. Hence the fact that the main ocean response to assimilation lies in its kinetic energy. The conclusion was then that the assimilation of altimetric data must be complemented by assimilation of *in situ* observations in order to impact also the temperature and salinity fields. Hence the importance of the Argo and SMOS programmes for improving the thermodynamical structure of the simulated fields and forecasts.

The ongoing tests carried within the MERCATOR, FOAM and DIADEM projects will soon bring new information to resolve these questions.

Conclusions

The very high resolution forecasting systems of the Atlantic Ocean under development in Europe will soon provide a new suite of products ranging from seasonal climate analyses and predictions to mesoscale open ocean and coastal-shelf applications. Remote sensing data are a major component of these systems for driving the models, for the control of the quality of the analysis and forecast and for the validation of the products. The few examples here presented on the case of the Atlantic basin intend to illustrate the key contribution of satellite remote sensing. Operational oceanography is a new era responding to the demand of the society, but also a chance for the scientific community to progress in the understanding of the ocean at the local and global scale.

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The Mediterranean Forecasting System Pilot Project: The initial forecasting phase

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Abstract

The first two years of the Mediterranean Forecasting System Pilot Project (1998-2001) are completed and every week a ten days forecast is released on the Web: (http://www.cineca.it/mfspp). This is realised with a networking of Near Real Time observing and modelling centres started within the project and working operationally from January 2000. The network consists of:

1) Three data centres that provide *in situ* and satellite data for initialisation of model forecasts. The observations are released with a time delay of one to three days through the internet;
2) A meteorological data centre for the collection and transmission of atmospheric forcing fields;
3) A central modelling and data assimilation centre which executes the forecasts.

The satellite data consist of sea level anomalies and sea surface temperatures while the *in situ* data are temperature profiles acquired on Voluntary Observing System ship tracks at biweekly frequency. All this data is assimilated to produce an initial condition for the forecast that is coupled asynchronously to the atmospheric forecast of surface fields. The system is briefly evaluated in terms of forecast skill scores.

Introduction

In the past five years, EuroGOOS (Woods *et al.*, 1996) has promoted the formation of a Mediterranean Test Case Task Team (MTCTT). This is composed of representatives of all European and non-European countries bordering the Mediterranean Sea, together with several other European and non-EU countries. The MTCTT involves scientists and operational agencies with an exchange of expertise in order to:

1) Build a cost-effective basin wide multi-platform, multi-parametric monitoring system;
2) Build capacity in local centres to model the shelf areas with state of the art hydrodynamic and ecosystem models;
3) Create a network between all the nations bordering the Mediterranean Sea and other European countries which will freely share observational data and model results in order to build an ocean forecasting local user community.

The MTCTT has elaborated a Mediterranean Forecasting System Science and Strategic Plan (Pinardi and Flemming, 1998) that describes the rationale and the strategy of implementation of a sector of marine environmental predictions in the Mediterranean Sea.

The overall Mediterranean ocean Forecasting System goal can be synthesised as follows:

Scientific

To explore, model and quantify the potential predictability of the ecosystem fluctuations at the level of primary producers from the overall basin scale to the coastal/shelf areas and for the time scales of weeks to months through the development and implementation of an automatic monitoring and a nowcasting/forecasting modelling system, the latter called the Mediterranean Forecasting System as a whole.

Pre-operational

The objective is to demonstrate the feasibility of a Mediterranean basin operational system for predictions of currents and biochemical parameters in the overall basin and coastal/shelf areas and to develop interfaces to user communities for dissemination of forecast results.

The first phase of implementation of the MFS is contained in the Mediterranean Forecasting System Pilot Project (MFSPP). In the following we will discuss the results and products of the first two years of the Project.

The multi-platform monitoring system

The elements of the monitoring system developed and implemented in MFSPP are a Voluntary Observing Ship (VOS) network, a multi-purpose moored buoy and satellite data analysis in near real time (Fig. 1).

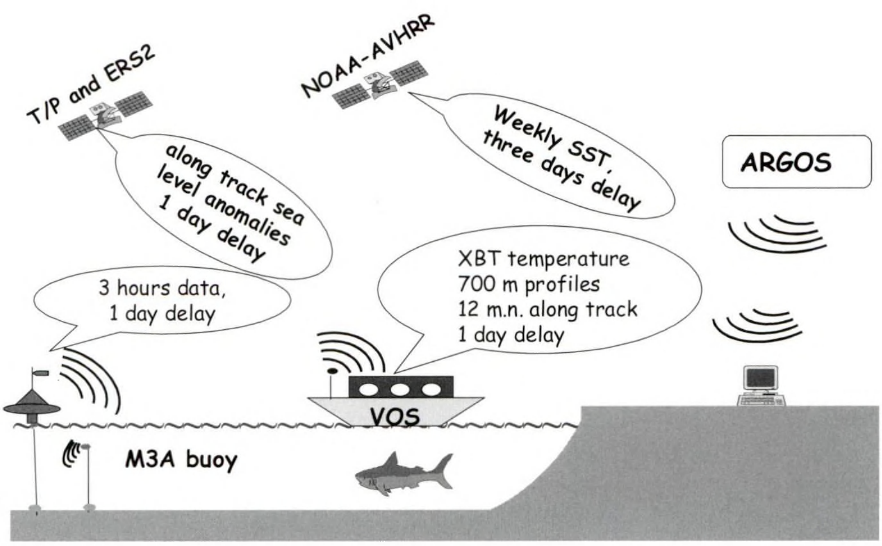

Figure 1: *Schematic of the Mediterranean ocean Forecasting System multi-platform monitoring elements*

The VOS network is composed of seven tracks (Fig. 2) repeated approximately every fifteen days with XBT data collection at 12 N.M. resolution. These sampling parameters were decided based upon a compromise between resources available, the knowledge of the internal Rossby radius of deformation (approximately 10-15 km) and the large-scale structure of the basin gyres. These sampling requirements are typical of semi-enclosed areas that require high sampling rates with respect to the World Ocean VOS. The system is semi-automatic, with research personnel on-board but a satellite data telecommunication system for the release of data in real time. The actual seven tracks implemented in the Mediterranean are working with a GTS (Global Telecommunication System using the ARGOS satellite communication channels) data telemetry system which transmits decimated profiles in the first 700 meters of the water column. Due to the steep gradients in the shallow thermocline, 15 points instead of the traditional 12 were selected as decimation points. A land based data collection centre (http://estaxp.santateresa.enea.it/www/ec/new/mfs2.htm) collects the data from the land based ARGOS station (Toulouse, France) before they go on the GTS. At the *in situ* data centre, the decimated XBT profiles are quality checked and put on a free-from-charge local ftp site, available to global users. The VOS-XBT system is not satisfactory in terms of reliability of the decimation procedures and the ARGOS telemetry failures. The next phase should consider the full profiles transmission with cellular phone and internet technology.

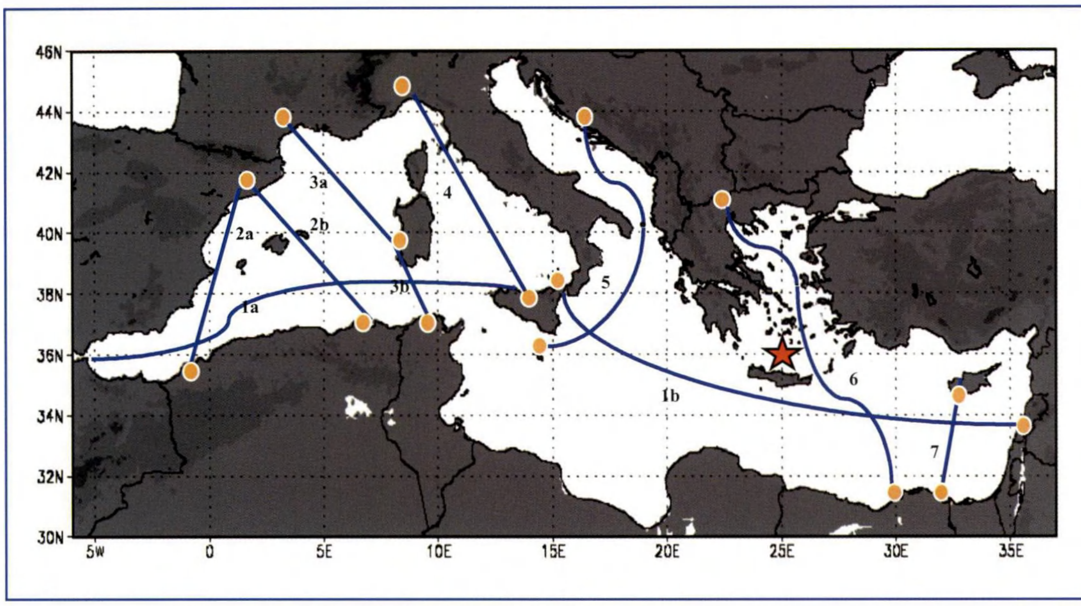

Figure 2: *The seven tracks of the VOS XBT system in the Mediterranean Sea. The star indicates the position of the M3A buoy*

A buoy system, called Mediterranean Multi-sensor Moored Array (M3A), was deployed in the Cretan Sea (Fig. 2). This mooring system has a large surface buoy which allows the measurement of air-sea interaction parameters. The subsurface is sampled by a set of three moorings, one connected to the surface buoy, with fixed position temperature and salinity sensors in the first 500 meters. The second and third mooring are completely subsurface. Lines two and three are located at a distance of about 1 km from the central mooring: line three consists of an upward looking ADCP and line two consists of fixed position sensors located in the first 100 meters (the euphotic zone). The fixed position sensors for line two are irregularly spaced in vertical and measure temperature, salinity, oxygen, turbidity, fluorescence, PAR and nitrates. Line two transfers data to line one through an underwater hydro-acoustic system. Line one then collects all the parameters and sends them through GSM link to the receiving land station. Data are put on the web within a day delay (http://www.poseidon.ncmr.gr/m3a/). These data will be initially used for validation of the Ocean General Circulation Model (OGCM) and calibration of the one dimensional ecosystem model for this near shelf area.

The near real time analysis of satellite sea level anomalies (SLA) and sea surface temperatures (SST) is done for the entire Mediterranean Sea area and it is disseminated on the internet within a few days after the last data collection. The SLA is measured from Topex/Poseidon and ERS-2 satellites and it is given along track for both satellites (Fig. 3). In addition, the combination of the two satellites along track SLA is mapped on the model regular grid for display purposes. The SST is produced as a weekly mean map on the model grid and it is used as a flux correction for the heat forcing of the model.

The data management system organises multiple levels of quality control procedures and provides the near real time dissemination to the outside community via WWW and ftp communication systems. The initial quality control system consists only of the detection of outliers with respect to climatology for all the near real time data sets. For climate studies, the full resolution VOS-XBT profiles, the M3A and satellite data are archived in conventional historical data banks. The Web system used in the project works adequately making possible the release of a ten days forecast with a maximum delay of three days with respect to the actual start day of the forecast. Furthermore, it allows the research community to rapidly communicate with the data acquisition systems and it can generate easily multiple users of the data itself as explained by Molinari (1999).

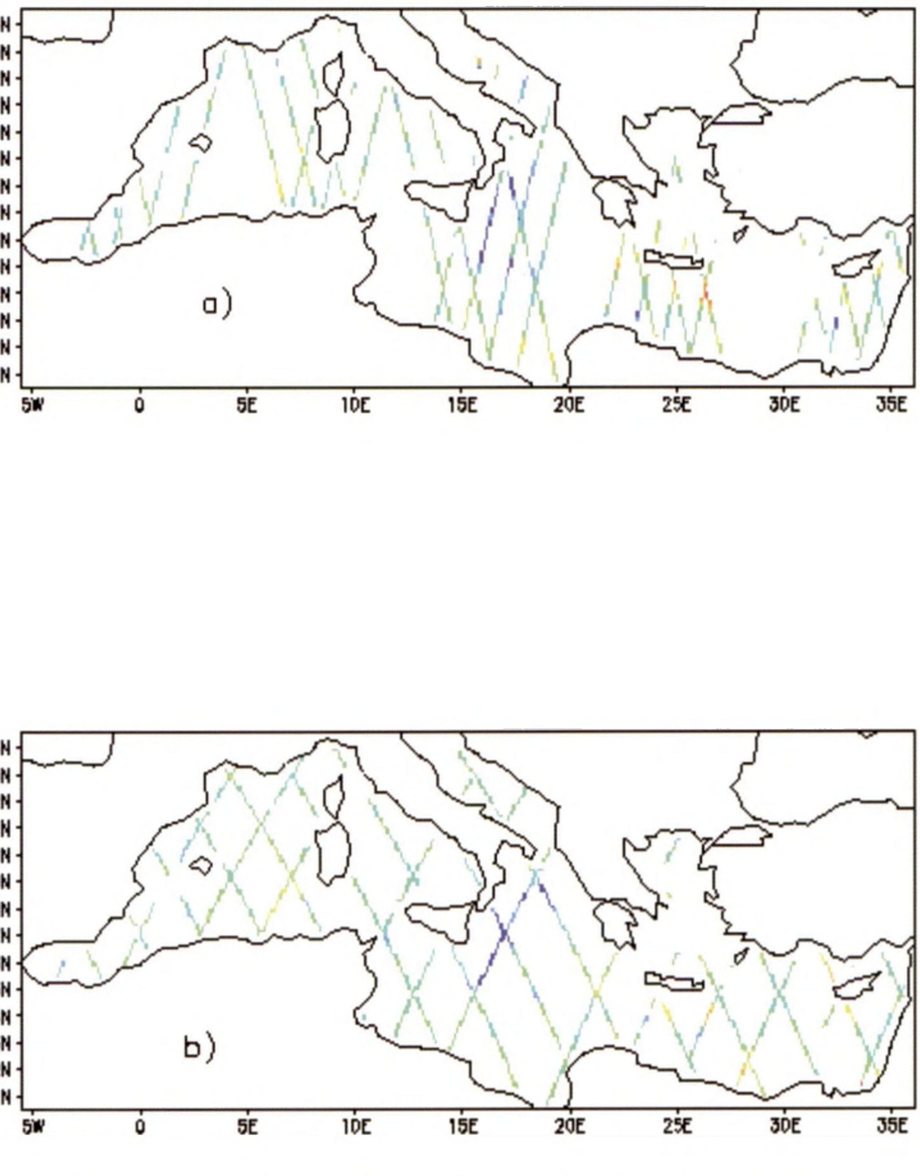

Figure 3: *The ERS-2 (a) and Topex-Poseidon (b) satellite tracks in the Mediterranean Sea. The Sea Level Anomaly (SLA) is shown along the tracks for a typical two weeks time period, in particular from September 4 to 18, 2000. The palette gives the range of SLA values in meters.*

Ocean modelling for forecasting at the basin scale and in the shelf areas

In the past ten years the Mediterranean research community has developed a suite of OGCM and regional models capable of simulating the seasonal and interannual variability of the basin currents with relatively good accuracy (Korres *et al.*, 2000). The forecasting OGCM is at 1/8 x 1/8-degrees resolution (approximately 12.5 x 12.5 km) and 31 vertical levels and the assimilation/forecasting system is composed of four modules:

1. The first consists of an assimilation engine partially developed in the project (DeMey and Benkiran, 2001) which uses a reduced order Optimal Interpolation scheme which uses vertical Empirical Orthogonal Functions (EOF) in order to project in an assimilation subspace. Both SLA and XBT are assimilated with multivariate EOF computed from climatological data or previous model results. In practice, SLA and XBT are assimilated sequentially following the scheme shown in Fig. 4 and using a filter time window of one week. Starting from a week inside the assimilation cycle, SLA is assimilated in a smoother mode considering data in a two weeks time window around the middle day of the two weeks. This first assimilation cycle produces an analysis that is used as a first guess for the assimilation of XBT data in a filter mode procedure, which give rise to an analysis for a week later which is supposedly the start day of the forecast. In order to produce the next week forecast initial condition the procedure is repeated but this time the XBT are assimilated in a smoother mode and the SLA in a filter mode. The sequential assimilation allows the usage of different EOF for each analysis step. The EOF are optimised separately for the two different data sets: the SLA EOF set is composed of one EOF for the whole basin which is different from zero starting at 100 meters. The XBT EOF set is composed of 10 EOF for 13 different regions, defined on the basis of historical data and the water mass structure of the different sub-regions. The satellite SST is not properly assimilated but it is used, in the analysis mode, to correct the surface heat fluxes by means of a flux correction term.

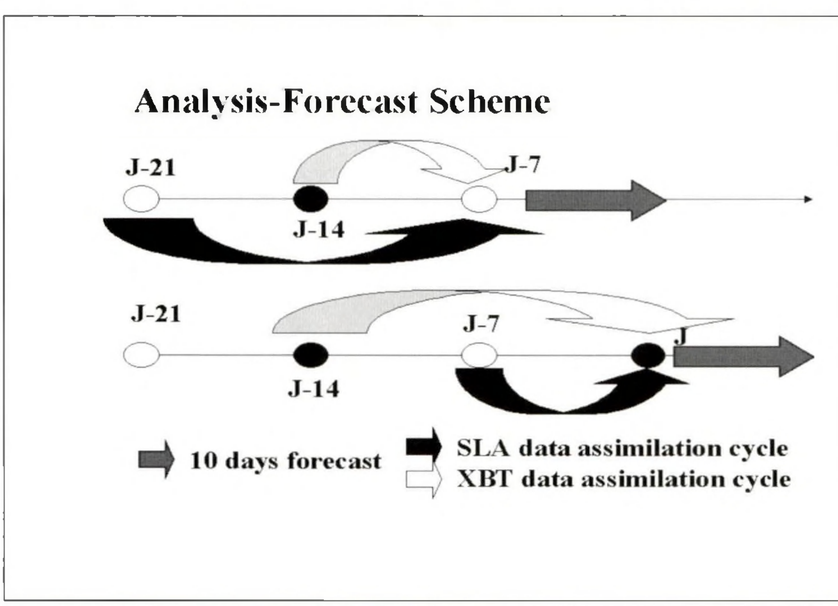

Figure 4: *Schematic of the multivariate weekly assimilation cycle. The one-week arrow indicates an assimilation cycle done in filter mode, while the two-week cycle is done in smoother mode. XBT and SLA assimilation alternates in different weeks in filter and smoother mode to give the initial condition for the forecast.*

2. The second module is the coupler between the atmospheric forcing parameters and the OGCM for forecast and analysis steps. This interface computes the momentum, heat and water fluxes that drive the ocean model from the previous week forecasting day (J-7) to the present week starting forecast day (J) with atmospheric analyses fields (ocean analysis mode). Then the same interface couples the OGCM with ten days atmospheric forecast surface parameters (ocean forecast mode). The atmospheric forcing parameters are at six hours time resolution and at 0.5 x 0.5 latitude and longitude degrees for the horizontal resolution. They are taken from ECMWF (European Centre for Medium range Weather Forecast, Reading, UK) operational fields interpolated to the model grid. An example of analysis SST and flow field at 30 meters is shown in Fig. 5.

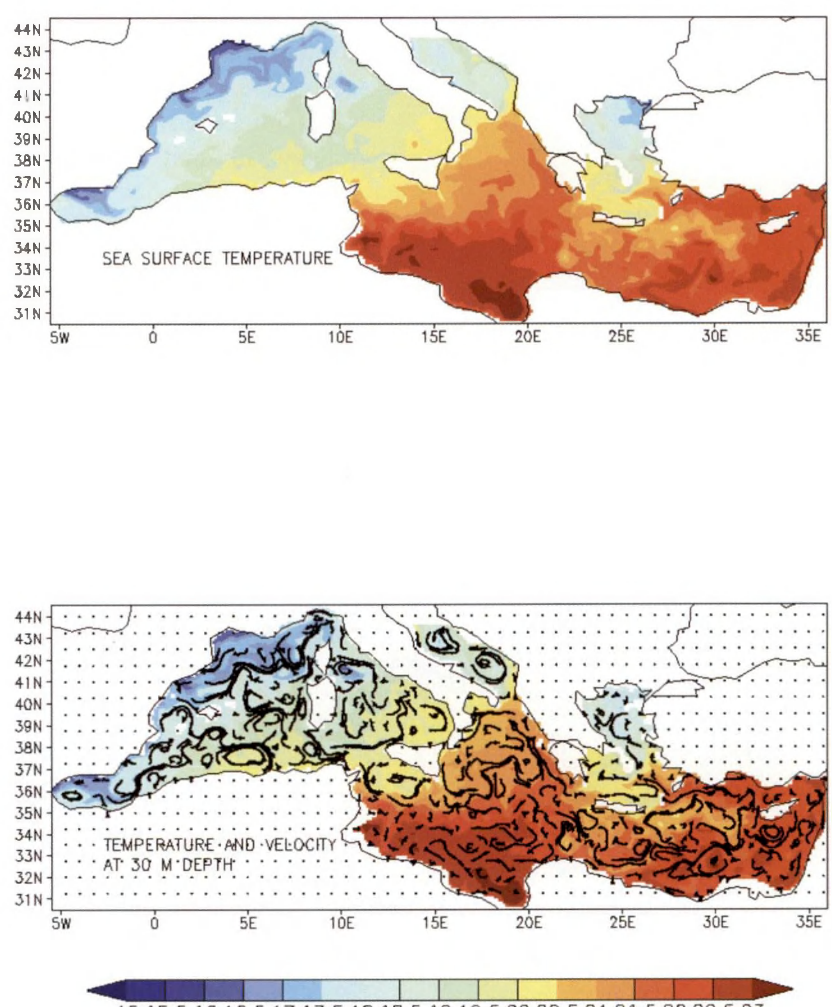

Figure 5: Upper panel: analysis SST for a week in September 2000. Lower panel: for the same week, the 30 meter temperature analysis field with analysis velocity trajectories. The palette indicates temperature values.

3. The third module is a quality control interface between the observed data and the assimilation engine, to feed the observations in the appropriate format to the model and to crudely check the observations before insertion in the assimilation engine. The XBT are checked against climatology and gravitational stability. The quality control is done only for the NRT *in situ* data while the SLA and SST are taken without any further check.

4. The fourth module is a post-processing interface that translates the model forecast to image products for Web publication and dissemination of the information.

The whole system is represented schematically in Fig. 6.

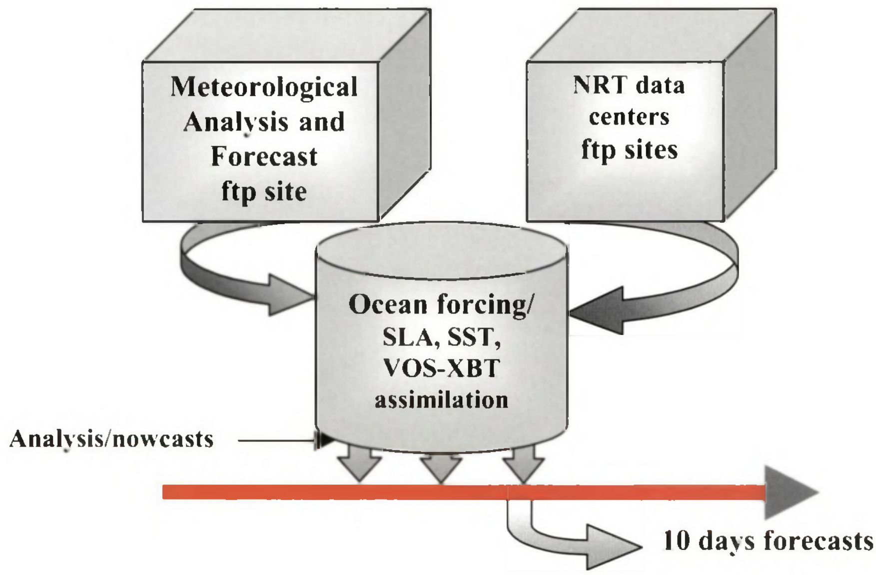

Figure 6: *The schematic of the Forecasting system interfaces and network*

The OGCM simulations are also used to initialise regional and shelf models that receive boundary fields at different time frequencies. The downscaling brings the OGCM 12.5-km resolution fields down to 1-2 km resolution in the shelf areas. This is at the base of the coastal forecasting system of the next phase (Pinardi *et al.*, 2001), where the initialisation of the regional and shelf models will crucially depend upon the OGCM forecast fields. The Mediterranean Sea shelf area is narrow and the general circulation can determine a large portion of the coastal hydrodynamics variability. Thus two and three fold nesting is necessary to develop the near real time forecasting in the coastal areas. Finally, ecosystem models are also implemented and validated during MFSPP at several coastal test sites. The aim is to calibrate the ecosystem model parameters in a one-dimensional set up since it has been found that this is useful to understand non-generic model parameters. In the next phase, it is hoped to start the simulations of the ecosystem variability with a fully coupled 3-D ecosystem model based upon the shelf models developed in MFSPP.

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The Arctic test case: use of satellites and models in ice monitoring and forecasting

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Introduction

Monitoring and forecasting of the ice-ocean system in the Arctic and surrounding seas is important for climate change research and for support to sea transport and offshore operations. The requirements for operational monitoring and forecasting services in Arctic seas have been investigated in several recent studies (Johannessen *et al.*, 1997, 2000; Sandven *et al.*, 1999) showing that there is a clear need for better observation systems at high latitudes due to several factors:

- The highest predicted global warming will take place in the Arctic
- Growing human activities in the Arctic (i.e. offshore operations, ship transport, tourism, etc.)
- Vulnerable environment which requires particularly careful management

Recent analysis of the ice cover in the Arctic Ocean has established that significant changes have occurred in the latter part of the last century. Based on analysis of upward looking sonar observations from US nuclear submarines it has been shown that the average ice thickness has decreased by 1.3m, from 3.1m in the 1958-1976 period to 1.8m in the 1990s, in average 4cm per year, or 40% of the total ice volume (Rothrock *et al.*, 1999). Furthermore, analysis of microwave satellite observations has established that the total area has decreased by 6% over the last two decades (1978-1998) (Johannessen *et al.*, 1995; Bjørhgo *et al.*, 1997; Cavalieri *et al.*, 1997), while the multi-year ice area has decreased 14% over the same period (Johannessen *et al.*, 1999). Comparison of observations (*in situ* and satellites) since 1900 with trends seen in two coarse resolution global climate models, forced by observed greenhouse gases and tropospheric sulphate aerosols correlates very well. This is "suggesting strongly" (Vinnikov *et al.*, 1999) that the observed decrease in sea ice extent since 1950 is related to the anthropogenic global warming. Prediction by these two coarse resolution global climate models suggests furthermore a substantial decrease of the ice extent in this century (Vinnikov *et al.*, 1999), as indicated in Fig. 1. However, the elevated indices of the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO) (the correlation between these two indices are very high suggesting that they are parts of the same system) has pumped warm air and water masses into the Arctic from the North Atlantic, causing ice melting as well as a mechanism for exporting multi-year ice through the Fram Strait (Rothrock *et al.*, 1999; Hurrell, 1995; Thompson and Wallace, 1998). Even some effects on the variability of the sea ice from El Ninõ has been reported (Gloersen, 1995). Therefore it is very important to assess the natural variability of the ice cover in the last century in order to further investigate if an abrupt change will take place during this century.

Extrapolating the ice thickness decrease of 4 cm/year indicates that the Arctic Ocean could be ice free 50 years from now, causing a dramatic change in the albedo, with significant effects on the global climate system. However, we should also be aware that Russian ice thickness estimates based on dispersion relationships between the damping of swell propagation into the Arctic Ocean measured from the North Pole Stations during the period 1972-1991 (Johannessen *et al.*, 1999, Nagurny *et al.*, 1994, 1999) indicates an average of 0.5-1.0 cm decrease per year. This is 4-8 times less than the results form the nuclear submarine data. This demonstrates the need to assess objectively all available ice thickness observations from the Arctic Ocean during the last century in order to estimate the natural variability and trends of the ice volume and mass.

The effects and impact of a decreasing ice cover are multiple:

- We hypothesise that an Arctic Ocean with decreasing ice cover with cold water, which has high capacity for CO_2 absorption, could become a new region for an important sink of the atmospheric CO_2, which will tend to mitigate global warming.
- Rough estimates based on observations of carbon fluxes in the Greenland Sea (Anderson *et al.*, 2000) indicate that 0.3-0.6 Pg of carbon can be absorbed each year by an ice free Arctic Ocean. This is an increase of 15-30% from what the world oceans absorbs today and 5-10% of the 6-7 Pg anthropogenic carbon emissions or in the same order of magnitude as the agreed reductions in the Kyoto agreement.
- Other positive effects of a decreasing ice cover in the Arctic and surrounding seas are on marine transportation and easier and safer logistics for offshore oil activities in the Arctic region (Johannessen *et al.*, 1997, 2000).
- Increased fisheries in new previously ice-covered regions will contribute positively to the global food supplies.
- A negative effect could be that the melting of the ice drastically will change the stratification of the upper layer in the Nordic Seas and North Atlantic Ocean, slowing down the deep water formation and furthermore the thermohaline circulation (conveyor belt) (Mauritzen and Hakkinen, 1999). A reduced transport of heat by the Gulf Stream/ North Atlantic current (Samiento *et al.*, 1998) will cause a significant impact on the climate in Europe.
- Change in the marine ecosystem (e.g. less plankton in the North Atlantic caused by melting of sea ice (Reid *et al.*, 1998) will have a negative impact on the marine biodiversity (including polar bears, which are totally dependent on the ice cover) for the Arctic and sub-Arctic regions.

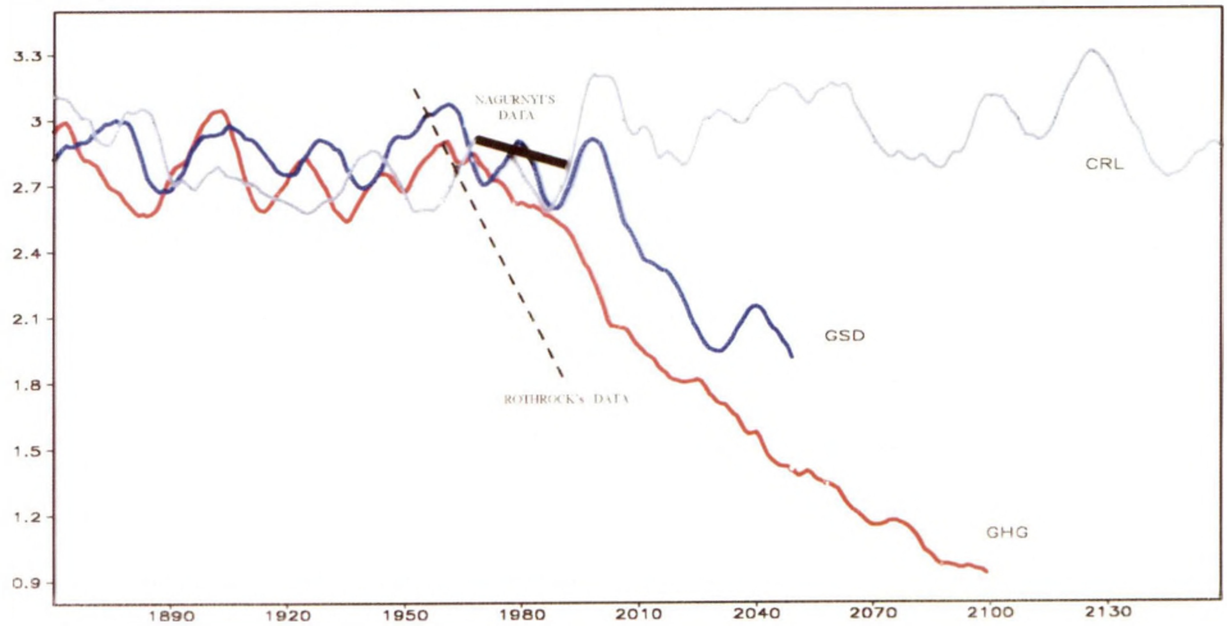


Figure 1: *Spatially averaged ice thickness in the Arctic from three simulations with ECHAM-4: control run, forcing by greenhouse gases - GHG, and forcing by greenhouse gases and aerosols - GSD. Data from Nagurny et al (1999) and Rothrock et al (1999) are superimposed.*

The role of satellites in Arctic ice observation

Satellite data have been used as part of the data sources in ice monitoring for many years. The most commonly used data in large scale mapping are NOAA AVHRR data (optical and infrared data) and DMSP SSM/I data (passive microwave data). But these data have limitations due to either cloud cover or coarse resolution. They are therefore not optimal for regional ice mapping which requires detailed and regular data. The role of the most common satellite data in ice monitoring is summarised in Table 1 and 2.

Table 1: Satellite data used in ice monitoring

Sensor	Satellite	Start	Comments
Visual and IR radiometer	NOAA AVHRR	1978	• Most commonly used satellite data to observe sea ice • Easy access and no data cost • Limited by cloud cover and do not provide regular daily ice information
	METEOR & RESURS	1967	• Used by Russian ice service • Same limitations as for NOAA AVHRR
Passive microwave radiometer	DMSP SSM/I	1978	• Daily coverage globally • Independent of cloud and light conditions • Low spatial resolution • Very useful for large scale and regional mapping • Easy access and no data cost
Radar imaging systems	ERS-1/2 SAR	1991	• ERS-1 operated from 1991-1996 ERS-2 operated in tandem with ERS-1 from August 1995 to June 1996. • ERS-2 operated alone since June 1996 • The first satellite to provide extensive SAR coverage in 100km swath over all major ice areas • Most useful for regional and local ice mapping which requires more details • High cost of data
	RADARSAT SAR	1996	• First satellite providing wideswath SAR images for operational ice monitoring • High cost of data
	Okean SLR	1983-	• Used for ice monitoring by Russian institutions combined with passive microwave and optical sensors.

Table 2: Role of satellite data in different scales of monitoring

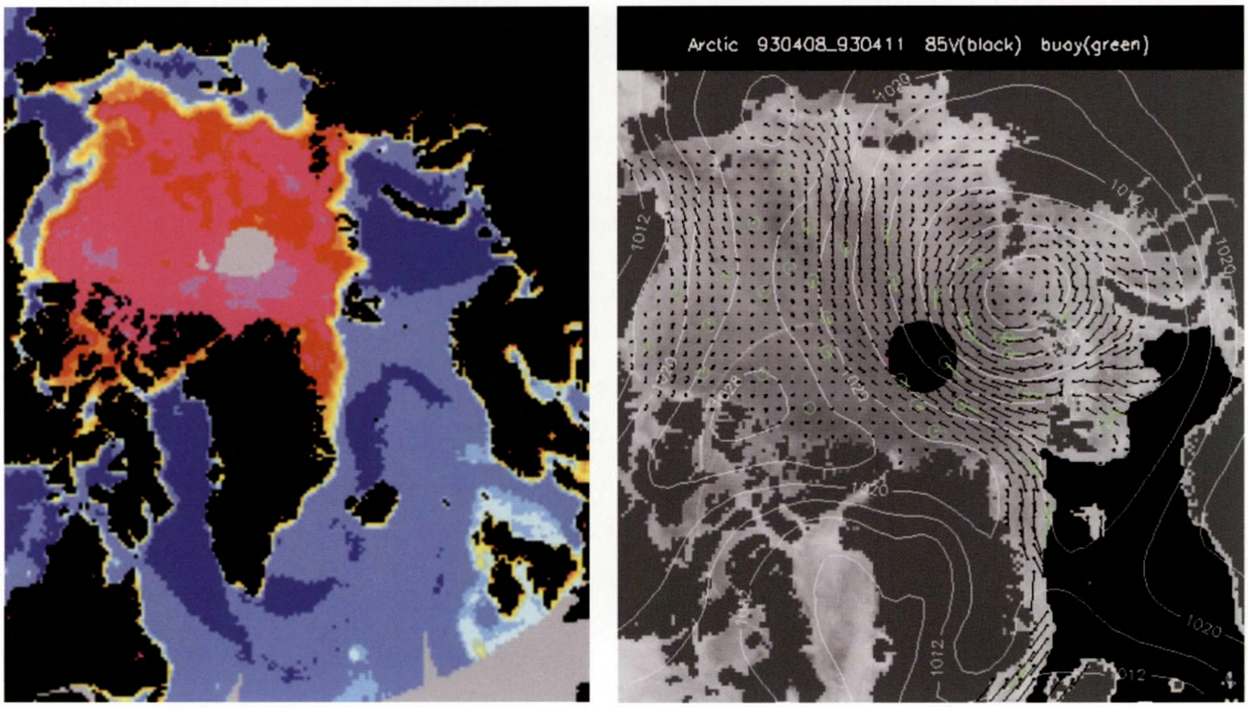
Scale of monitoring	Areas	Role of satellites and other platforms
1. Large scale global monitoring	Arctic, Antarctic	SSM/I and AVHRR are essential. SAR and SLR important supplement. Global mapping not possible without satellite data
2. Regional mapping	Baltic Sea Greenland Northern Sea Route Gulf of St. Lawrence/ St. Lawrence Seaway	AVHRR: used whenever possible Okean/Meteor: used in Russia SAR: growing importance as a result of wide swath data from RADARSAT Aircraft surveys tend to be replaced by more satellite data.
3. Local monitoring	In straits and sailing routes, near off-shore operations	Aircraft and helicopters most important. SAR will play a growing role Important for tactical ice navigation.

Since 1991 the ERS-1 SAR data with 100m resolution have been obtained in many sea ice research and demonstration projects around the world. The Canadian RADARSAT, operational from 1996, has ice monitoring as the prime objective and will provide SAR data of ice covered areas on operational basis. With RADARSAT data, a new era in operational ice monitoring by satellites has begun. The SAR has proven to be a very powerful instrument for sea ice observations due to high spatial resolution in combination with weather capability. SAR is now used as the main instrument in operational sea ice monitoring in several countries such as USA, Canada, Greenland, Finland, Sweden (Sandven *et al.*, 1999).

Several technical improvements are needed for the satellite data used in ice monitoring. The available EO SAR data are single frequency and polarisation which limits the possibility to classify ice types. Existing microwave radiometers (SSM/I) offer multi-frequency dual polarisation data which make ice classification possible. These data are important in global ice monitoring and in climate change studies, but they are of little use on a regional basis because the resolution is too coarse for operational ice navigation. In the future it is envisaged that optional missions for operational ice monitoring should carry both active and passive microwave instruments, with resolution, coverage and repeat cycle suitable for observing the key ice parameters.

Use of high resolution SAR images requires automated processing combined with human interpretation skills in order to extract reliable ice information form the imagery. The RADARSAT Geophysical Processor System has been developed to extract key ice parameters from large amounts of SAR imagery (Kwok, 1998). The products from this system are very useful for further analysis and use of SAR ice data, primarily in the western Arctic. For the European sector of the Arctic there is no such standard system for retrieving ice parameters from SAR data. The SAR imaging of different ice conditions is not yet fully understood. Existing scattering models which relate physical ice parameters to SAR parameters are not good enough and improved automatic ice classification algorithms are needed.

The main development trend is that microwave data, especially SAR, are expected to replace NOAA AVHRR data as the most important data source in ice monitoring. There will also be a development towards multi-channel and multi-polarisation SAR data which will enable better classification of ice types. The rapid development of computer and network technology, and the improvements in marine communication, will facilitate more use of satellite data in real-time onboard ships. Access to satellite data and derived products is continuously improved through the development of Internet services which makes it possible to download data sets, images, ice charts and many other products from various providers very efficiently.



a b

Figure 2: *Passive microwave data from SSM/I are used for large-scale observation of ice concentration and extent (a) and for derivation of ice drift (b). The ice concentration picture in (a) shows the ice-covered area of the Arctic in October 2000, when the seasonal ice extent is at a minimum. An example of optimally interpolated ice velocity field for the three-day period 8-11 April 1993, using SSM/I data in combination with drifting buoys (circles with arrows) is shown in (b). The velocity data are produced by The Polar Remote Sensing Group at JPL, California Institute of Technology*

New techniques have recently been developed to directly measure sea ice freeboard using space-borne altimetry from which thickness can be inferred (Laxon and Peacock, 2000). The separation of echoes from ice and water offers a clear potential to directly measure sea ice freeboard and hence estimate ice thickness (fig. 3). Initial investigations using the ERS-1 and ERS-2 radar altimeter show promising results. Key to the success of ice freeboard retrieval is the estimation of the (unobserved) sea surface height beneath the ice floe. The largest variation in sea surface height, due to the marine geoid, is eliminated using repeat track analysis. Mean profiles are generated for each of the 501 orbits which make up a 35 day repeat cycle. Superimposed on the time-invariant component of sea surface height are small temporal variations caused by dynamic topography. These are estimated by constructing a smoothed sea surface height anomaly field estimated from specular returns gathered during a particular repeat cycle. This field is then used as a reference against which estimates of the ice surface elevation are compared to retrieve sea ice freeboard. Thickness can be determined from freeboard if the density of the ice is known. The translation of ice freeboard to thickness depends critically on knowledge of the overall ice density which in turn depends on the thickness and density of the ice and snow layers respectively. The draft to freeboard ratio, R, can be expressed as:

$$R = \frac{\rho_i h_i + \rho_i h_s}{h_i(\rho_w - \rho_i) + h_s(\rho_w - \rho_s)}$$

according to Wadhams *et al.* (1992). Co-incident surface measurements of ice freeboard and draft show that use of a constant ratio generally leads to errors of less than 30 cm in thickness retrieval. Regression of ERS freeboard retrievals against ice draft measurements suggest that variability in R is probably responsible for scatter of a similar magnitude around a linear fit. Nevertheless Wadhams *et al.* (1992) using the above model showed that, in theory, uncertainties in snow thickness can lead to considerably higher variability in R. The impact of variability in R, and particularly in snow thickness, will be investigated using models and surface observations.

These data provide the first basin-wide estimates of monthly sea ice thickness, for the period 1993-1999, at a resolution of 100 km and an accuracy of ~0.5m. These estimates will provide the first indication of the seasonal and inter-annual variability of sea ice thickness on a regional basis in the Arctic Ocean. This technique will be developed further in this proposal, by comparing satellite altimeter data with ice thickness data provided by the various *in situ* observation methods discussed above. The altimeter technique will be the principle used to derive ice thickness from CRYOSAT, scheduled for launch in 2003 (Wingham *et al.* 1998).

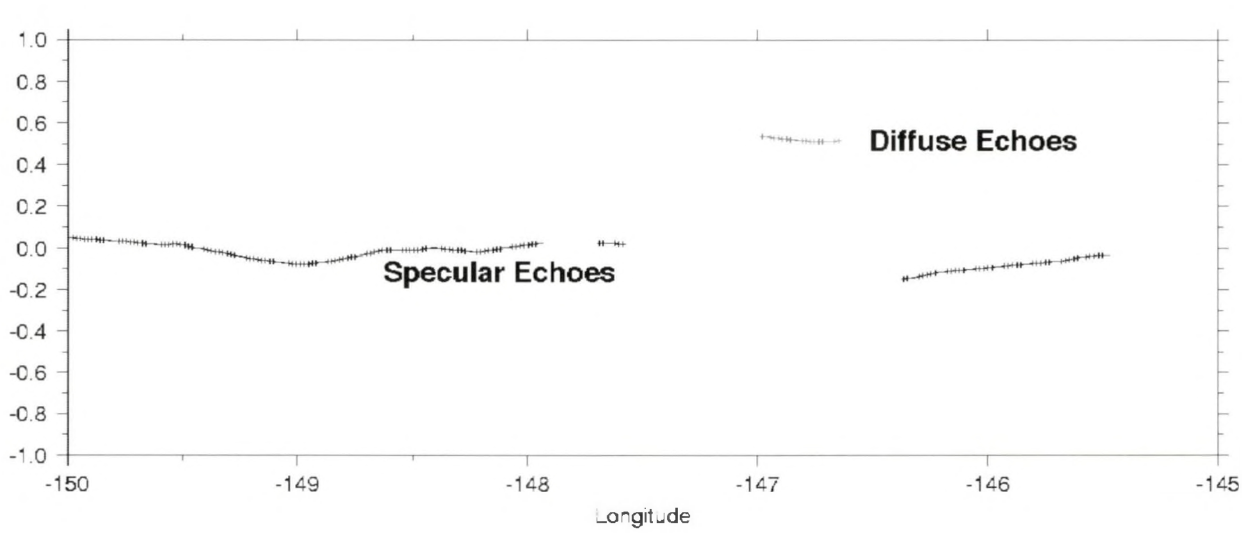


Figure 3: *Example of residual height profile from ERS altimetry over the Arctic Ocean. Diffuse echoes originate from open water or new ice between ice floes. The height difference is used to estimate ice freeboard (Courtesy. S. Laxon).*

Use of coupled models and data assimilation

Model description

At the Nansen Center, the MICOM (Miami Isopycnic Coordinate Ocean Model) (Bleck *et al.*, 1992) has been coupled to a dynamic-thermodynamic sea ice model using Hibler's viscous-plastic rheology modified by Harder (1996). The coupled model has been developed and used during the previous 7-8 years, mostly in connection with global and/or regional climate simulations. However, for the monitoring and prediction system to be designed here, a more sophisticated model will be used for the ice thermodynamics and dynamics. The existing ice dynamics model is based on Hibler's viscous plastic rheology (Hibler, 1979) and was developed by Harder (1996) but the model is not very numerically efficient. Standard models for sea ice dynamics treat the ice pack as a viscous-plastic material that flows plastically under typical stress conditions but behaves as a linear viscous fluid where strain rates are small and the ice becomes nearly rigid. Because of large viscosities in these regions, implicit numerical methods are necessary for time steps larger than a few seconds. Current solution methods for these equations use iterative relaxation methods, which are time consuming, scale poorly with mesh resolution, and are not well adapted to parallel computation. A favourable aspect of MICOM is the ability to provide high vertical resolution in regions of strong vertical density gradients and to suppress artificial numerical diffusion across isopycnals, both are important properties of the modelling of the Arctic Ocean.

The most appropriate atmospheric forcing fields for ice-ocean modelling are developed by the NCEP/NCAR Reanalysis Project which is a joint project between the National Centers for Environmental Prediction (NCEP, formerly "NMC") and the National Center for Atmospheric Research (NCAR). The goal of this joint effort is to produce new atmospheric analyses using historical data (1957 onwards) and as well to produce analyses of the current atmospheric state (Climate Data Assimilation System, CDAS).

The NCEP forcing fields have been used to run the coupled MICOM ocean and Harder ice dynamics model for the Arctic and Atlantic Ocean for the period 1957 – 1998. A simulation period of 40 years is sufficient to resolve interannual as well as decadal variability. The atmospheric forcing field is the NCEP data set which is currently the best climatological data set available and goes back to 1957. This model provides prognostic ice variables as well as ocean variables needed to study the sensitivity of freshwater budgets, thermohaline circulation and deep water formation to sea ice volume fluxes. Simulations will be carried out with time steps of 6 hours, but for climate studies it will be sufficient to use weekly averaged output ice parameters from the model. The model grid cell within the Arctic Ocean is about 50 km. Examples of model output are shown in Fig. 4.

Model validation

The validation of the MICOM-Hibler model has been done by comparing ice extent and concentration with passive microwave satellite data since 1978 (Lisæther *et al.*, 2000). The main objective of the validation is to examine how the sea-ice model can reproduce the sea-ice concentration, the fractional area of ocean covered by sea-ice, for the Arctic. To validate the model we used passive microwave satellite data spanning the period from November 1978 - October 1998 (Johannessen *et al.*, 1999).

Examination of the parameters sea-ice area (the total area of ocean covered by ice) and sea-ice extent (the total area of ocean with 15 % or higher sea-ice concentration) showed that the model tends to underestimate these quantities, especially in summer. The time series of sea-ice area and extent from model and satellite data are shown in Figure 5.

The error of the sea-ice model can also be studied by comparing anomalies in sea ice extent, which are derived by subtracting the mean seasonal signal (inserted graph in Fig. 5) from the time series. These anomalies, which are presented in terms of ice volume in Fig. 4 (lower right fig.), show a significant discrepancy between model and observations in 1982. In this case the model estimates gave too little ice which is due to erroneous atmospheric forcing, i.e. too high temperatures). After 1984 the anomalies had opposite signs on several occasions, with model estimates higher than the observations. For instance, in 1994 - 1995 more ice was observed than the model simulations indicated. In general, the model is capable of picking up inter-annual variability and trends in sea-ice extent and area which are in agreement with observations (Bjørgo et al., 1997, Parkinson et al., 1999). However, errors in the forcing data and inaccuracy in the satellite-derived observations can easily generate significant differences between the two data sets which can be detected by comparing their anomalies.

In addition an EOF analysis was done of the model error in sea-ice concentration. This analysis show that the error is confined to the marginal ice zone in winter. In summer the error is distributed over the entire ice pack. The project has shown that the sea-ice model suffers from summertime errors in sea-ice extent and area. The model picks up trends in sea-ice area and extent, which suggests that its overall performance can be improved by modification of sub-grid parameterisations. The process of implementing more efficient sea-ice dynamics is also in the works, and could improve the sea-ice models response to atmospheric stresses.

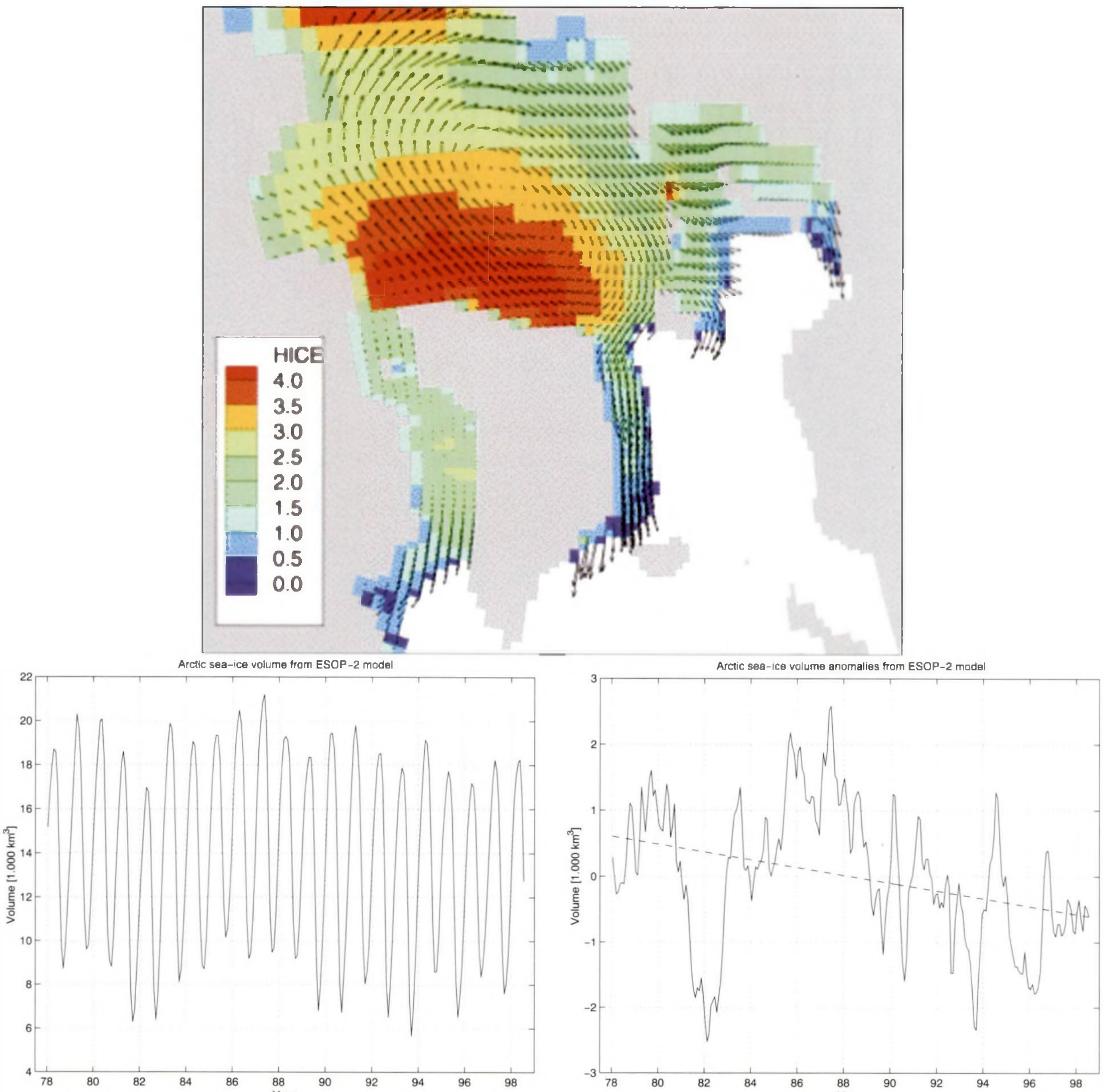


Figure 4: *Results from the NERSC coupled ice-ocean model simulations of the Arctic Ocean: upper figure shows an example of ice extent, thickness and velocity, while the lower left figure shows the seasonal variability in total Arctic ice volume 1978 - 1998. The lower right figure shows anomalies and trend in ice volume for the same period, after the seasonal signal is removed*

The simulated ice thickness has been compared with available submarine upward-looking sonar from US SCICEX and UK cruises in the Arctic Ocean over the last 2 - 3 decades (Rothrock *et al.*, 1999; SCICEX, 1998). These data provide profile of ice draft along the cruise tracks, and they are compared with model simulations for the same month and area. The comparison shows that the model reproduces the general thickness variability across the Arctic Ocean quite well (Fig. 6). The largest discrepancy is found in the ice edge region in the Beaufort Sea where the model underestimates the thickness. This is in agreement with the model's underestimate of ice area shown in Fig. 5.

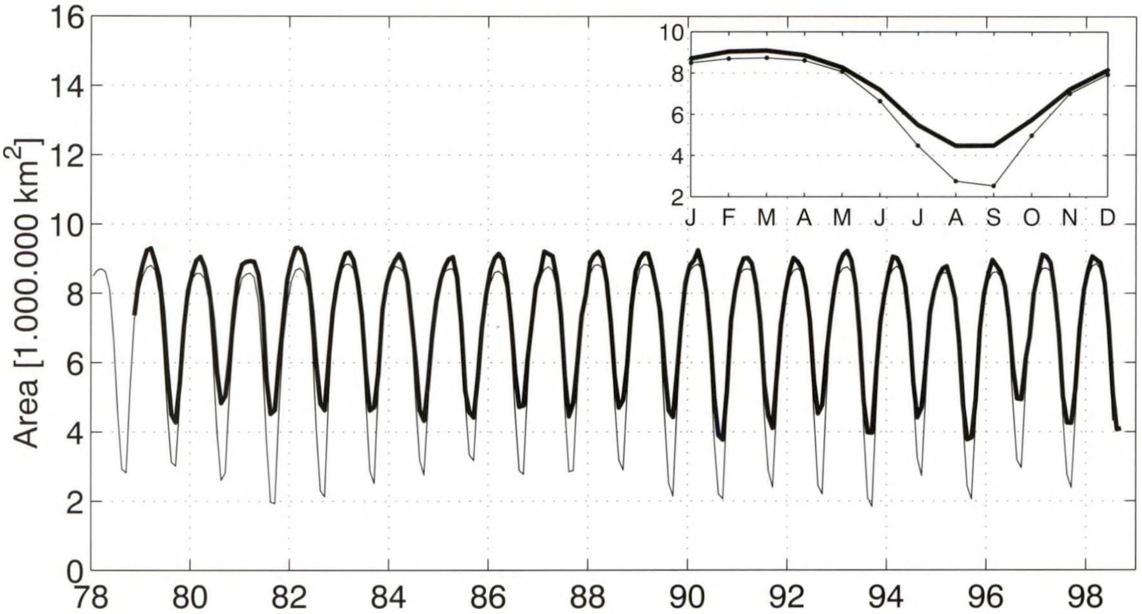
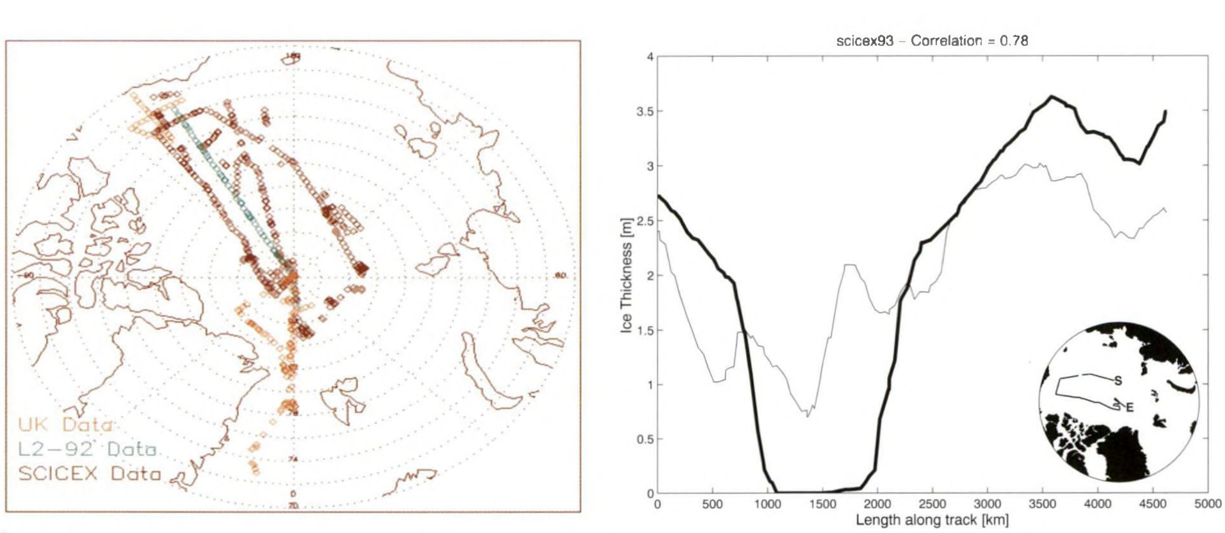


Figure 5: *Time series of modelled (thin line) and observed (thick line) ice extent from 1978 to 1998. The inserted graph shows the averaged monthly ice extent for the two decade period.*



a

b

Figure 6: *(a) Tracks of selected submarine cruises where ice draft data have been made available from http://www-nsidc.colorado.edu/NOAA/ULS_drafts. (b) comparison of NERSC model simulation (bold line) with one the cruise track from SCICEX93 (thin line). S and E in the inserted map indicate start and end point of the graph.*

Conclusion

Deployment of *in situ* observations systems in the Arctic is logistically difficult and very expensive due to the year-round presence of sea ice. Therefore satellite data used in combination with coupled ice-ocean models will be particular important in monitoring and forecasting of the Arctic and surrounding seas. The models for the Arctic ocean needs to be run with sufficient resolution to simulate fluxes through the straits in a realistic manner. The current NERSC model for the Arctic Ocean is run with a grid cells of 50 - 100 km. Ice extent and thickness from this model show quite good agreement with observations. Further model validation will be very important before reliable forecasting can be established. Data from a few fixed moorings and a network of drifting ice buoys under International Arctic Buoy Programme, submarine cruises and other specific field experiments will be important for validation of the satellite and model results.

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Annexe 1

Conference Programme

EG00.34

EUROGOOS CONFERENCE ON
OPERATIONAL OCEAN OBSERVATIONS FROM SPACE

Final programme: Dated 25 September 2000

Sessions, times, speakers and chairmen of sessions

THURSDAY 5 OCTOBER

0900-1000 Registration

Opening Session

1000-1020 Opening address: *Dik Tromp*
Opening address: *Tillmann Mohr*

Session 1 **Chairman: *Dik Tromp***
EuroGOOS Assessments

1020-1050 1a) EuroGOOS analysis of the need for operational remote sensing
Nic Flemming

1050-1120 1b) Developing a European oceanographic satellite system
Trevor Guymer, Jordi Font, Philippe Gaspar, Johnny Johannessen, Gerard van der Kolff

1120-1150 **Coffee break**

Session 2 **Chairman: *Dik Tromp***
Developments in observations and applications

1150-1220 2a) Space-based observations in the Global Ocean Observing System: Status, plans and operational perspective
Alain Ratier

1220-1250 2b) The private sector use of ocean remote sensing, industrial requirements and commercial services
Ralph Rayner

1300-1400 **Lunch**

Session 3 **Chairman: *Erik Buch***
Application sectors: sectoral analysis

1400-1425 3a) Pelagic fisheries and operational ocean services
Mario Alves, Sylvie Giraud, and Eric Dombrowsky

1425-1450 3b) Offshore oil and gas operational oceanographic requirements
Hans Jorgen Saetre

1450-1515 3c) Operational ocean observations and Ship Routing
John Blackwood

1515-1545	**Coffee break**	
1545-1610	3d)	Operational applications in North Sea coastal zone management *Raymond Feron*
1610-1635	3e)	The marine observing system of Puertos del Estado, Spain *Ignacio Rodriguez*
1640-1700	Discussion of applications sectors	
Session 4	**Chairman: *EuroGOOS Space Panel*** **First review of Draft Conference Statement**	
1700-1730	Discussion of Draft Conference Statement. Review of document clause by clause. Agreement on tasks for re-drafting required, to report in final session of Conference	
1730	**End of session**	

FRIDAY 6 OCTOBER

Session 5	**Chairman: *Tillmann Mohr*** **Timescales of ocean observing systems**	
0900-0930	5a)	Climate modelling and forecasting, medium to long term, methods and benefits *Jean-Francois Minster*
0930-1000	5b)	ECMWF marine forecasting programmes *David Anderson*
1000-1030	5c)	Requirements for remotely-sensed data for operational ocean modelling: the European shelf seas and ESODAE *Howard Cattle*
1030-1100	**Coffee Break**	
Session 6	**Chairman: *Philippe Gaspar*** **Applications sectors : sectoral analysis, continued**	
1100-1120	6a)	BOOS and the use of operational ocean remote sensed observations *Erik Buch*
1120-1140	6b)	The Atlantic Ocean forecasting system *Christian le Provost*
1140-1200	6c)	The Mediterranean Forecasting System Pilot Project: remote sensing and first results *Nadia Pinardi*
1200-1220	6d)	The Arctic Test Case: use of satellites and models in ice monitoring and forecasting *Stein Sandven and Ola Johannessen*
Session 7	**Co-ordinating Panel: *EuroGOOS Space Panel*** **Discussion and endorsement of Conference Statement**	
1220-1300	Review new texts or revised text for the Conference Statement Endorse final agreed text	
1300	**Conference Closure**	

Annexe 2

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Annexe 4

Acronyms

AATSR	Advanced Along Track Scanning Radiometer
ADCP	Acoustic Doppler Current Profiler
ADEOS	Advanced Earth Observing Satellite
ALOS	Advanced Land Observing Satellite
Alphascat	Ku band scatterometer in the Japanese GCOM-B1 Spacecraft
AMI	Active Microwave Instrument
AMRS	Alliance for Marine Remote Sensing Associations
AMSR	Advanced Microwave Scanning Radiometer
AO	Arctic Oscillation
ARCANE	Actions de Recherche sur la Circulation dans l'Atlantique Nord-Est (IFREMER/SHOM, France)
Argo	Array for Real-time Geostrophic Oceanography
ARGOS	Satellite-based system for environmental data telemetry and geopositioning
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BOOS	Baltic Operational Oceanographic System
CAMBIOS	French cruise programme
CANIGO	CANary Islands Azores Gibraltar Observations (MAST III)
CBA	Cost Benefit Analysis
CDAS	state (Climate Data Assimilation System
CEOS	Committee on Earth Observation Satellites
CHAMP	CHAllenging Minisatellite Payload - German small satellite mission for geoscientific and atmospheric research and applications
CLIVAR	Climate Variability and Predictability (of WCRP)
CLS	Collecte Localisation Satellites, France
CMC	Canadian Meteorological Centre
CME	Community Model Experiment
CMIS	Conical Scanning Microwave Imager/Sounder
CMO	Centre Militaire d'Océanographie (SHOM)
CNES	Centre National d'Études Spatiales
COSMO	COnstellation of small Satellites for Mediterranean basin Observation
COSMO-SKYMED	Program to promote the use of satellite remote sensing by a variety of clients
CRYOSAT	Satellite dedicated to observations of the polar regions (ESA)
CSA	Canadian Space Agency
CT	Conductivity-Temperature
CTD	Conductivity Temperature Depth
CZCS	Coastal Zone Colour Scanner
DBDB5	Digital Bathymetry Data Base 5
DEM	Digital Elevation Models
DGXII	Directorate General XII
DIADEM	Operational data assimilation system for the North Atlantic and the Nordic Seas
DLR	Deutschen Zentrum für Luft- und Raumfahrt (German Aerospace Research Establishment)
DMSP	Defense Meteorological Satellite Program
ECHAM	General Circulation Model of the atmosphere based on ECMWF forecast models, modified and extended in Hamburg
ECMWF	European Centre for Medium Term Weather Forecasting
EKE	Eddy Kinetic Energy
ENSO	El Niño Southern Oscillation
ENVISAT	Environmental Satellite Mission (of the European Space Agency)
EO	Earth Observation

EOIA	European Ocean Industries Association
EOS-AQUA	Earth Observing System 'Aqua' Satellite (NASA)
EOS-TERRA	Earth Observing System satellite (NASA)
EPS	EUMETSAT Polar System
ERS1/2	European Remote Sensing Satellite
ESODAE	North West European Shelf Seas Ocean Data Assimilation and Forecast Experiment
ESTEC	European Space Research and Technology Centre
EU	European Union
EUMETSAT	European Meteorological Satellite organisation
EuroGOOS	European Global Ocean Observing System
EUROMAR	European Marine Research Programme within EUREKA
FPA	Forecast Productions Assistant
FOAM	Forecasting Ocean Atmosphere Model
GANES	Global AssimilatioN applied to modelling of European Shelf seas
GCOM-B1	Global Change Observation Mission
GCOS	Global Climate Observing System
GEM	Geotechnical, Environment, Metocean (Faeroes)
GEOSAT	Geodetic Satellite
GFO	GEOSAT FO radar altimeter satellite
GHG	Greenhouse Gases
GLI	Global Imager
GOCE	Gravity field and steady state Ocean Circulation Explorer (ESA)
GODAE	Global Ocean Data Assimilation Experiment
GOOS	Global Ocean Observing System
GRACE	Gravity Recovery and Climate Experiment (NASA)
GRGS	Groupe De Recherche En Géodésie Spatiale
GSC	GOOS Steering Committee
GSD	Greenhouse gases and aerosols
GTS	Global Telecommunication System
GYROSCOPE	EU project linked to Argo to provide up to 100 profiling floats in the Atlantic
HELCOM	Helsinki Commission (Baltic Marine Environment Protection Commission)
HIRLAM	High Resolution Limited Area Model
HYCOM	Hybrid Coordinate Ocean Model
IACMST	Inter-Agency Committee on Marine Science and Technology
IBSFS	International Baltic Sea Fisheries Commission
ICES	International Council for Exploration of the Sea
ICEWATCH	Real-time sea ice monitoring of the Northern Sea Route using satellite radar
IGOS	Integrated Global Observing Strategy
IMAR	Institute of Marine Research (University of the Azores)
INFOTERRA	Global Environmental Information Exchange Network (UNEP)
IOC	Intergovernmental Oceanographic Commission (UNESCO)
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
IRS-P	Indian Remote Sensing Satellite - Panchromatic
ISOOS	Integrated Ocean Observing System
ISOPE	International Offshore and Polar Engineering Conference
JASON-1/2	Oceanographic monitoring satellites
JCOMM	Joint Committee for Oceanography and Marine Meteorology
JPL	Jet Propulsion Laboratory
JRC-Ispra	EC Joint Research Centre at Ispra, Italy
KPP	K-Profile Parameterization
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiale
LODYC	Laboratoire d'Océanographie Dynamique et de Climatologie
MAST	Marine Science and Technology (DG-XII CEC)

MERCATOR	French operational high-resolution global ocean prediction project
MERIS	Medium Resolution Imaging Spectrometer
METEOR	Russian meteorological satellite
MetNet	Network of offshore metocean stations on Shell oil installations in the North Sea
METOP	Polar orbiting weather satellites
MFS	Mediterranean Forecasting System
MFSPP	Mediterranean Forecasting System Pilot Project
MICOM	Miami Isopycnic Co-ordinate Ocean Model
MNZ	Meetnet Noordzee, Netherlands
MODIS	Moderate Resolution Imaging Spectroradiometer
MOS	Modular Optoelectronic Scanner
MTCTT	Mediterranean Test Case Task Team
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration (USA)
NASDA	National Space Development Agency of Japan
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction (USA)
NDP	Norwegian Deepwater Programme
NERSC	Nansen Environmental and Remote Sensing Center, Norway
NESDIS	National Environmental Satellite, Data and Information Service
NESS	North European Storm Study
NIVMAR	Storm surge forecast system for the Iberian Peninsula
NMC	National Meteorological Center (now NCEP)
NOAA	National Oceanographic and Atmospheric Administration (USA)
NORSOK	Norsk sokkels konkuranseposisjon (the competitive standing of the Norwegian offshore sector)
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NRT	Near Real-time
NWAG	North West Approaches Group
NWP	Numerical Weather Prediction
OCEANOBS	International Conference on the Ocean Observing System for Climate - St. Raphael, France 25 - 27 Oct. 1999
OECD	Organisation for Economic Co-operation and Development
OGCM	Ocean General Circulation Model
OGP	Oil & Gas Producers
OPA8	Océan PAralléllisé - ocean model developed at LODYC
OPERALT	Pre-operational ocean current measurement system using satellite altimetry
OSIMS	Operational Sea Ice Monitoring by Satellites in Europe
OTC	Offshore Technology Conference
PAs	Port Authorities
PLEIADES	A French remote sensing satellite system with both SAR and optical sensors
POESS	Polar Orbiting Operational Environmental Satellites
POM	Princeton Ocean Model
QG	Quasi-Geostrophic
QuikSCAT	Quick Scatterometer (NASA)
RADARSAT	Canadian Space Agency satellite
RAYO	Red de Alerta Y Observación - Warning and Observation Network
RESURS	Earth remote sensing satellite (Russia)
RWS-MD	Rijkswaterstaat Meetkundige Dienst, Netherlands
SAR	Synthetic Aperture Radar
SCICEX	Scientific Ice Expeditions (USA)
SEANET	Data interface group
SEASAT	First satellite designed for remote sensing of the Earth's oceans with SAR
SEASTAR	Satellite carrying the SeaWiFS instrument
SeaWiFS	Sea-viewing Wide Field-of-view Sensor for ocean colour monitoring

SGLI	Second Generation Global Imager
SHOM	Service Hydrographique et Océanographique de la Marine
SLA	Sea Level Anomaly
SLR	X-band side-looking radar
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture Ocean Salinity
SNDI	SeaNet Data Interface
SOFA	Reduced-order optimal interpolation code
SOPRANE	Systeme d'Observation de la PRevision de l'Atlantique du Nord Est
SPOT Pan	Satellite Pour l'Observation de la Terre with Panchromatic sensors on board
SPS	Spanish Ports System
SSH	Sea Surface Height
SSM/I	Special Sensor Microwave/Imager
SSMR	SEASAT microwave radiometer
SSS	Sea Surface Salinities
SWH	Significant Wave Height
TERRASAR	Commercial two-satellite X-band radar imaging system
TIROS	Television Infrared Observation Satellite
TM	Thematic Mapper
TOGA	Tropical Ocean Global Atmosphere Experiment
TOPAZ	Towards an Operational Prediction system for the North Atlantic and the European Coastal Zones
TOPEX/POSEIDON	Joint US/French Ocean Topography Experiment
TRAC	Trinidad Rings Advisory Co-Operation
TRMM	Tropical Rainfall Measuring Mission
UCM	Ultrasonic Current Meter
UNESCO	United Nations Educational, Scientific and Cultural Organization
UTC	Universal Time Clock
VIIRS	Visible Infrared Imager/Radiometer Suite
VOS	Volunteer Observing Ship
VPA	Virtual Population Analysis
WAVAD	Numerical spectral wave generation and propagation model
WCRP	World Climate Research Programme (WMO, ICSU)
WHOI	Woods Hole Oceanographic Institution (USA)
WINDSAT	Ocean Surface Wind Vector Measurements from Space
WMO	World Meteorological Organisation
WOCE	World Ocean Circulation Experiment
XBT	Expendable Bathythermograph

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