EUROPEAN SCIENCE FOUNDATION

Marine Board

Modelling in Coastal and Shelf Seas – European Challenges

Marine Board – ESF

ESF Marine Board Position Paper 7

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It maintains close relations with other scientific institutions within and outside Europe. By its activities, the ESF adds value by cooperation and coordination across national frontiers and endeavours, offers expert scientific advice on strategic issues, and provides the European forum for science.

Marine Board – ESF

The Marine Board operating within ESF is a non-governmental body created in October 1995. Its institutional membership is composed of organisations which are major national marine scientific institutes and funding organisations within their country in Europe. The ESF Marine Board was formed in order to improve co-ordination between European marine science organisations and to develop strategies for marine science in Europe.

Presently, with its membership of 25 marine research organisations from 17 European countries, the Marine Board has the appropriate representation to be a unique forum for marine science in Europe and world-wide.

In developing its activities, the Marine Board is addressing four main objectives: creating a forum for its member organisations; identifying scientific strategic issues; providing a voice for European marine science; and promoting synergy among national programmes and research facilities.

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Modelling in Coastal and Shelf Seas – European Challenges

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Foreword

The Marine Board of the European Science Foundation regularly establishes Working Groups of experts to address marine science and technology topics which need to be elaborated on. These Working Groups facilitate scientists to get together, reinforce their relations, create new opportunities and establish common approaches on projects, while also heightening awareness and visibility.
The expected output of such a Working Group is, in principle, a position paper to be used subsequently at national or European levels.

The issue of Hydrodynamic Modelling of Coastal and Shelf Seas was identified by the Marine Board as a subject appropriate for the establishment of a Working Group. This Working Goup, chaired by David Prandle, concentrated its analysis on operational oceanography and the implications of this in terms of modelling and data assimilation.

The analysis by this Working Group does not cover the entire breadth of the subject; aspects such as mathematically innovative modelling, new types of ecosystems models, coupling of physical to fishery ecosystem models, the approach to open source models, quality standards and skill scores were not considered within the scope of this report. However, this report does illustrate the development effort needed to transform research tools into services for the many users of ocean space and resources.

The Marine Board thanks the Working Group for its work on a subject crucial to the future of coastal oceanography.

Jean-François Minster
Chairman of the Marine Board

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Executive Summary

Diverse applications of models range from nowcasting of waves, tides and storm surges to coupled ocean-atmosphere-sea-river scenario forecasting of the effects of Global Climate Change on terrestrial, fluvial and marine ecology over millennia. The validity of models is limited by the degree to which the equation or algorithms synthesise the governing processes. The accuracy of model simulations depends further on the availability and suitability (accuracy, resolution and duration) of both observational and linked meteorological, oceanic and hydrological model data to set-up, force and assess calculations. Modelling is at a stage where major investments are required in infrastructure and organisation: e.g. access to supercomputers, software maintenance and data exchange. Europe needs to develop a strategic vision and translate this into internationally-competitive modelling capabilities to address issues of both local and global governance of the marine environment. A few major European marine modelling centres are likely to emerge in the next five years, collaborating closely with existing meteorological institutions, with an associated network of centres addressing local applications.

Well-recognised requirements to support the diverse needs of the research community include:

- Access to supercomputers and ancillary services for data management, visualisation, and analysis.
- Teams with adequate resources to both develop existing modelling systems and introduce new innovative technologies, with attendant programmes for visiting fellows, workshops, training, capacity building, etc.
- Long-term programmes to match the time-scales of technology development and international scientific programmes concerned with Global Climate Change and holistic sustainability.
- Enhanced provision of and links to:
  (i) observational technologies and test-bed sites,
  (ii) permanent monitoring networks,
  (iii) meteorological and climate data (attendant assimilation from future satellites),
  (iv) data centres providing quality-controlled information for coastal seas, and
  (v) enhanced methodologies for data assimilation, using the expertise within meteorological agencies.

Background and Introduction

Objectives of the Marine Board – ESF include promoting the science needed for effective management of coastal and marine resources. Related scientific and technical challenges are summarised in the Marine Board publication *Integrating Marine Science in Europe* (Marine Board – ESF, 2002). The objective of the Working Group on Hydrodynamic Modelling of Coastal and Shelf Seas, whose work is presented in this report, was to identify initiatives to foster scientific and technical excellence in the modelling of coastal and shelf seas.

The Marine Board recognised three primary drivers underlying the development of hydrodynamic models:

1. Understanding and predicting impacts of, and feedbacks from, ocean climate change.
2. Establishing scientific and socio-economic bases for sustainable development of shelf seas and their resources.
3. Advancing marine science and technology.

This development involves two discrete, but inter-related, pathways: (i) scenario testing (pre-operational); (ii) real-time forecasting (operational). Maintaining associated state-of-the-art capabilities in Europe is essential both to underpin EU policies for marine governance of its coastal seas and to inform its approach to international issues such as Global Climate Change.

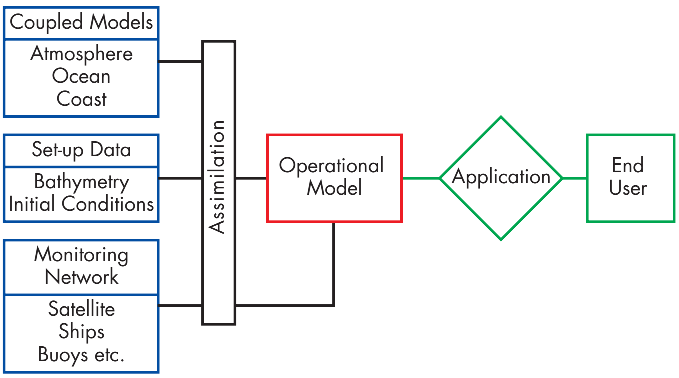


Figure 1: Components of a modelling simulation system (EuroGOOS)

Coastal and marine resource management requires linking of science and decision making, using theory, models, and measurements of the physical, chemical, and biological marine environment. Models synthesise theory into algorithms and use observations to set-up, initialise, force, assimilate, and evaluate simulations in hindcast, nowcast, and forecast modes. Assimilation involves the combination of information provided by observing networks with the systematic temporal and spatial resolution of holistic knowledge incorporated within numerical models. In operational forecasting, assimilation involves structured incorporation of near real-time observations to improve nowcasts and forecasts. In non-operational modes, assimilation may be used in calibrating parameters (boundary conditions, surface roughness, etc.) to improve the accuracy of simulations.

Over the past 40 years, numerical modelling has developed rapidly in scope (from hydrodynamics to ecology) and resolution (from one-dimensional, 10^2 elements to 3-D, 10^8 elements) exploiting the contemporaneous development of computing power. Unfortunately, concurrent development in observational capabilities has not matched this resolution, despite exciting advances in areas such as in remote sensing and sensor technologies.

The following sections of the report seek to articulate these capabilities and limitations, indicating past and present approaches adopted in Europe. Associated challenges and future options to sustain the science and technology to meet the requirements of the end-user are identified. In reviewing future strategies for the development of modelling, subsequent sections examine sub-components of this system, namely: the requirements of the end-user; scope and development of modelling; operation of models; data requirements from observations and coupled models; and European collaboration (Figure 1).

End-user Requirements

Models are used for:

1. **Improving weather forecasting, climate prediction, and to warn of hazards, e.g. storm surges, oil or chemical spill movement, search and rescue, eutrophication, toxic algal blooms, and the consequences of future changes.**
2. **Assessing and understanding the current state of health of marine ecosystems and resources – their likely sensitivity to changing conditions.**
3. **Developing environmental management policies which account for both anthropogenic influences and natural trends.**
4. **Advancing underpinning science and technology.**

A wide variety of modelling and monitoring approaches exists, reflecting the diverse range of interests and end-user concerns. Applied interests include surface ice in the Arctic, ecosystem dynamics for fish recruitment in the Bay of Biscay, eutrophication in the Baltic Sea (coupled sea-hydrological model including predictions of river flows), and pollutant transport in the Mediterranean. Appendices 2 and 3 summarise the development and pertinent issues relating to hydrodynamic and ecological models. Alongside such applied interests, models are used to address many generic issues and develop scientific and technical capabilities including development of numerical algorithms and validation procedures, optimal design of monitoring networks, and assimilation techniques.

Models are widely used for management and policy strategies, such as assessment of absorptive capacity for licensing of discharges, evaluating environmental impacts of intervention (reclamation, dredging, etc.), and in both hindcast and forecast modes for climate change scenarios.

The coastal – marine area is generally the focus of end-user interests. Improved forecasting capabilities for storm surges, sediment transport, and wave action are important to address user needs in relation to flood protection, fisheries, coastal erosion, and prevention of pollution. An accurate description of the state of the offshore ocean is required to define boundary conditions for local coastal models. Links between meteorological and global operational models need to be incorporated from the initial design phase. Awareness of evolving end-user requirements by developers of these ocean models is essential.

To deliver the full range of benefits from our models over the diverse scope of habitats in Europe, interfaces with socio-economic-political concerns must be established. This may require simplification of our complex models, or aggregation of their results, in a form that can be accommodated in related total-system models.

End-users, especially from developing countries, will be most interested in solving problems directly related to their environment, primarily in the coastal area. Capacity building must include training of skilled young scientists for the creation of know-how in modelling and forecasting, which will enable these countries to solve problems locally. Two-way mobility must be encouraged.

Challenges

Introduction of the EU Water Framework Directive (WFD) emphasises the need for development of well-validated, reliable models for simulating water quality-ecology-fisheries in European coastal waters. To enhance our understanding of the threat of Global Climate Change, we need whole-system models to indicate related impacts both from and on coastal seas (including the impacts on marine biota and their potential biogeographic consequences). For both pre-operational and operational (pre-operational models – tested and validated codes used for real-life applications; operational models – routinely used for marine forecasting; see Appendix 4) hazard forecasting, improvements are required in accuracy, reliability, and resolution together with extended warning periods; such improvements also provide enhanced design statistics for coastal development.

Scope & Development of Models

The diverse applications of models range from short-term nowcasting of waves, tides and storm surges to coupled ocean-atmosphere-sea-river simulations of the effects of Global Climate Change on terrestrial, fluvial, and marine ecology over millennia. Associated practitioners range from scientists and engineers to coastal managers.

Models encompass:
(i) non-dimensional conceptual modules encapsulated into whole-system simulations,
(ii) one dimensional (1-D), single point vertical process studies or cross- sectionally averaged representations for rivers and estuaries,
(iii) two dimensional (2-D), representations of horizontal circulation, and
(iv) fully three dimensional (3-D).

In shelf seas, model applications have progressed from the 2-D barotropic models of the 1960s to the 3-D baroclinic (incorporating temperature and salinity induced density variations) of the 1970s. Initially, these 3-D baroclinic models used prescribed density fields, calculating resultant circulations in a diagnostic mode. These were superseded in the 1980s by prognostic models, which calculate evolving temperature and salinity fields. Such 3-D models are now used widely for applications from limnology, estuaries, harbours, coastal bays to shelf seas and oceans.

Parameters of interest include tides, surges, waves, currents, temperature, salinity, turbidity, ice, sediment transport, and an ever-expanding range of biological and chemical components. Table1, extracted from the Marine Board publication *Integrating Marine Science in Europe* (2002), shows a comprehensive (but incomplete and not prioritised) set of such parameters.

The scope of the models involves simulations across ocean-atmosphere-seas-coasts (Figure 2) and between physics-chemistry-biology-geology-hydrology extending over hours to centuries and even millennia. This connectivity spans meteorological agencies, satellite missions, international scientific, and survey programmes (IGBP, CLIVAR, GOOS etc.) that also introduce specific coupling issues.

Coastal sea models are influenced immediately and directly by meteorological forcing. Likewise, though generally less immediately and directly, they are impacted by conditions along the ocean-shelf boundaries. Hence, coastal modellers need to maintain close links with developments in

Table 1: Key parameters in the coastal area and shelf seas (*Integrating Marine Science in Europe*, Marine Board – ESF, 2002)

Physical	Chemical	Biological	Geophysical
Temperature	NO_3, PO_4, Si, NH_4	Phytoplankton biomass (chlorophyll) and diversity	Seismicity
Salinity	Trace metals, pH, radionucleides	Bacterial and phytoplankton cytometry	Bathymetry
Density, pressure	Dissolved gases (O_2, CO_2, DMS)	Viral particles	Gravimetry
Light, bioptics	Volatile organic pollutants	RNS, DNA, proteins key enzymes	Magnetism
Turbidity, particle size distribution	Pesticides	Pelagic animals	Acoustic signals
Velocity, turbulence	PCB, PAH, CFC	Benthic communities	Seafloor characteristics

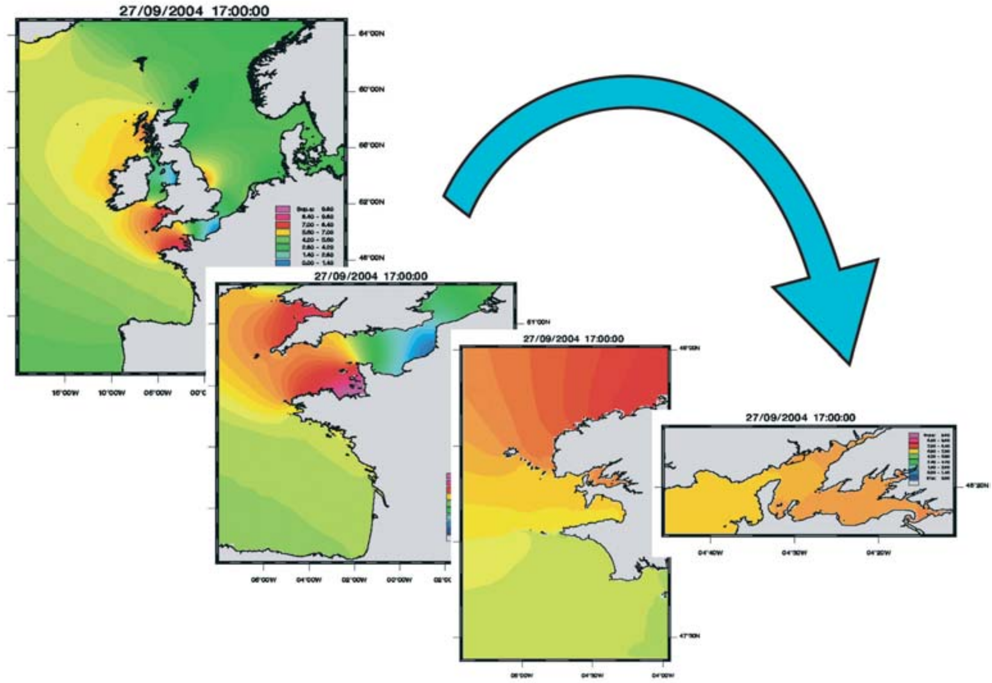


Figure 2: Four embedded models run simultaneously, forced by tidal constituents and meteorological forecasts (IFREMER)

ocean modelling and awareness of issues producing medium and longer-term variability, such as the Thermohaline Circulation of the Atlantic, the North Atlantic Oscillation, El Niño, etc. We anticipate extension of coupled ocean-atmosphere models to incorporate sea-surface exchange fluxes within coastal-marine areas, with the latter utilising unstructured grids.

In the horizontal, rectangular grids are widely used and are suitably adjusted to polar coordinates (latitude and longitude) in regional seas. Irregular grids, generally triangular or curvi-linear, are used for variable resolution. In Computational Fluid Dynamics, continuously adaptive grids provide a wide spectrum of temporal and spatial resolution in multi-phase processes. This facility is now used in ocean models to address localised anomalies such as non-hydrostatic conditions or eddy shedding. Immediate improvements in the accuracy of simulations can be achieved with adaptable and flexible grids alongside more sophisticated numerical methods.
The vertical resolution may be adjusted for detailed descriptions near bed, near surface or at the thermocline. For example, the sigma coordinate system accommodates bottom-following with a uniform number of coordinate surfaces occupying the water column.
Understanding and enhanced representation of turbulence effects in models is a central issue for future marine studies. Development of turbulence models is proceeding via international collaborations (see GOTM in Appendix 1). This work is supported by new measuring techniques like the microstructure profiler, providing a direct comparison of simulated dissipation rates with in situ measurements. Presently, efforts are focused on applications of 1-D (vertical) models; there is still no clear consensus on the best turbulence scheme to be implemented into 3-D models. Resolution of horizontal turbulence is less advanced; values specified often relate to numerical stability requirements or to observed values from dye dispersion experiments.
In shallow coastal waters, the influence of turbulence on the interacting dynamics of currents and waves remains to be clearly understood – this is especially true for near-bed processes.

Operation of Models – Hardware & Software Requirements

Effective operation of both ocean and coupled shelf-sea models requires access to supercomputers and continuous maintenance of software. Major infrastructural investment is needed if European modellers are to remain competitive. A small number of major European marine modelling centres are likely to emerge over the next five years with links to existing meteorological institution. These will support an associated network of centres addressing local applications.

The evolution of models can be usefully categorised as:
Generation 1: development of algorithms to synthesise representations of processes;
Generation 2: quantitative simulations of specific environments (pre-operational); and
Generation 3: fully operational systems with nowcasting and forecasting capabilities (see Appendix 4).

For pre-operational shallow water engineering applications, licensed codes are used internationally, with three EC countries as the major providers thereof. For scientific applications, open-code community models are more commonly adopted; these generally originate from the USA. These distinctions can blur because open-codes require support and licensed codes are often free for academic research. Commendably, the USA's Office of Naval Research (ONR) has supported the conversion of previously commercial EC codes to the public-domain. European networks (fostered by EC Framework funding) continue to support world-leading specialist code modules in areas from waves to turbulence to ecology (for a list of widely used model codes see Appendix 1.)

Model codes are becoming ever-increasingly complex. Assimilation techniques may require multiple simulations. Specialist technologies are required to provide requisite speed and sophistication of inputting and outputting of data. Formalised approaches for model validation and verification are necessary, including procedures for quality control of modules and assembly of a range of bench-test observational data sets. Specialist software is required for diagnostic analyses, visualisation, and communication. Both the proprietary and public-domain model codes mentioned above typically involve investment of tens of years in software development and continued maintenance by sizeable teams. Such effort is increasingly beyond the scope of most European modelling groups.

Existing operational forecasting systems in European waters provide real-time and near real-time products describing wind field, wave height spectra, temperature, salinity, floating sea ice, chlorophyll, tides, currents, and storm surges. Movements of oil slicks and algal blooms are also predicted on an emergency operational basis. Effective operation of real-time forecasts requires the resources of a meteorological agency for communications, processing and dissemination of forcing data, alongside oceanographic data centres responsible for dissemination of quality-controlled marine data. Such agencies also provide access to data required for

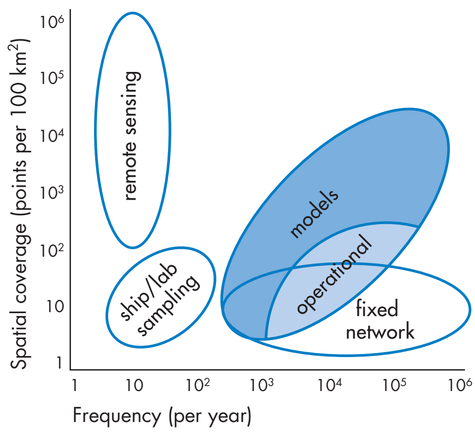


Figure 3: Spatial and temporal resolution of oceanographic data (Proudman Oceanographic Laboratory)

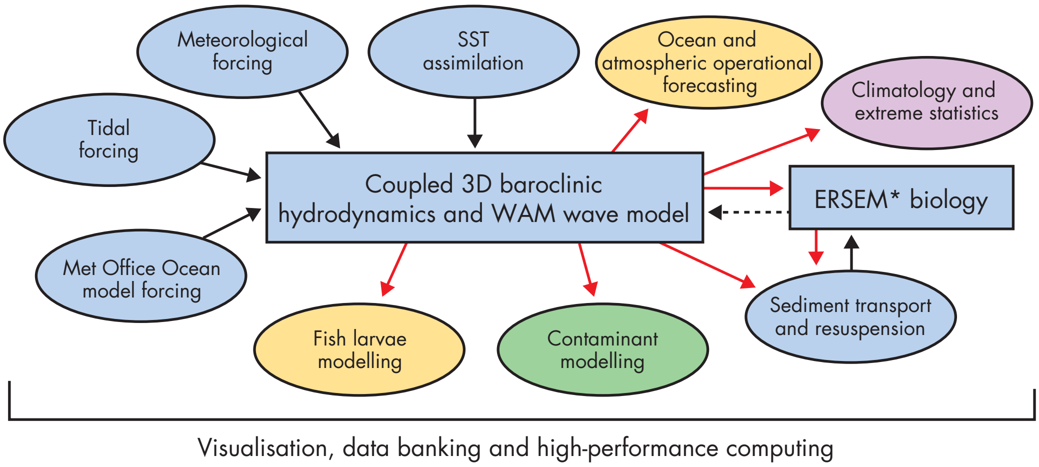


Figure 4: Ecological simulation system-component modules (Proudman Oceanographic Laboratory)

assimilation in hindcast or what-if projections by the dispersed academic community.

Computing capacity restricts the optimum resolution in many simulations. The application of ecosystem models, often involving combinations of Lagrangian and Eulerian methods for simulation of sediment and plankton movement, is severely limited by their computing requirements. New computing systems, such as massively parallel or parallel-vector machines, are extensively used.

This problem makes it vital for software to be adaptable for running on different hardware platforms. Exploitation of future hardware developments will pose challenges for the optimisation of software architectures to combine scalar and vector capabilities.
In addition, development of algorithms to represent processes over varying temporal and spatial scales, and ranges of complexity will continue – especially for ecological applications.

Model resolution is also effectively limited by the corresponding paucity of resolution in observational data (especially bathymetry) used for setting-up, initialising, forcing (meteorological and along model boundaries), assimilation and validation (Figure 3).
This paucity of data is a critical constraint in environmental applications.

Challenges

Effective operation of both ocean and coupled shelf-sea models requires access to supercomputers and the software requires continuous maintenance. The mechanisms by which such integration can be facilitated need to be explored along with the needs for infrastructure investment in very high performance computers, high performance data networks, new numerical algorithms, etc.

The organisational efficiency developed by meteorological agencies must be used to attract the investment for observational networks, data services, computational facilities, training, etc. needed to stimulate parallel developments of marine science.
The success of the European Centre for Mid-range Weather Forecasts (ECMWF) in stimulating European research into meteorology, climate, and oceanography is noted – some (virtual) analogues in the marine community might be conceived. An expedient collaboration might involve separate institutes assuming delegated responsibilities for support and development of specific modules.
A range of these is shown in Figure 4.

Data Requirements from Observations & Coupled Models

The accuracy of model simulations depends on: (i) the accuracy and resolution of the observational data used to set-up, initialise, force, assimilate, assess, and fine-tune the simulations; and (ii) the adequacy of forcing specified from coupled atmospheric and ocean models.

Use is made of observations from on-shore (radar, tide gauges etc.), off-shore moorings, ships, moored and drifting buoys, aircraft, and satellites. More and better observational data, extending over longer periods are essential if modelling accuracy and capabilities are to be enhanced. International collaboration is an obvious and valuable means of achieving this goal. While international funding supports satellite programmes, synergistic in situ monitoring presently relies on national funding.

Observational data

Formulation of coastal models requires accurate fine-resolution bathymetry, and ideally, corresponding descriptions of surficial sediments. Subsequent operations require river flows and their associated temperature, sediment, and ecological signatures. Similar requirements apply to wind and irradiance data for model forcing together with related data for open-sea/ocean boundary conditions. Real-time observational data are needed both for assimilation into operational models and for parameterisation-validation in pre-operational models.

Development of model simulations for tides, surges, and waves is constrained by limited accuracy and resolution of both bathymetry and wind forcing (data assimilations may be used to circumvent these limitations). Simulations of temperature, salinity, suspended sediment, water quality, and ecological parameters are constrained by the availability of: (i) initialisation and forcing data, and (ii) subsequent assimilation data being absent or restricted to surface values.

Observational data can be obtained from satellites, aircraft, radar, buoys, floats, (cabled) moorings, gliders, AUVs (Automated Underwater Vehicles), instrumented ferries, and VOS (Voluntary Observing Ships) together with meteorological and ocean models (Figure 5). Over the past two decades, remote sensing techniques have matured to provide useful products of ocean wind, waves, temperature, ice conditions, suspended sediments, chlorophyll, eddy, and frontal locations. Unfortunately, these techniques provide only sea-surface values and in situ observations are often necessary both for vertical profiles and calibration. For coastal applications, improved spatial resolution, as provided from aircraft surveillance is especially valuable. High frequency radars can also provide synoptic surface fields of currents, waves, and winds on scales appropriate to the validation of coastal models.

Despite these advances, the range of marine parameters that can be accurately measured is severely restricted – especially in operational mode (Figure 3). Moreover, the cost of these observations is orders of magnitude greater than that associated with the development or the operation of models. Consequently, the effectiveness of simulations is severely limited by shortcomings in the accuracy, spatial and temporal extent, and resolution of such data.

Instrumentation is already lagging seriously behind model development and application, and this gap is expected to widen. New sensors are needed, in particular sensors suitable for installation on ferries and ships of opportunity and through-flow sensors for moorings. A new generation of instrumentation is needed for the validation of multi-species, size-class and species-resolving ecosystem models.

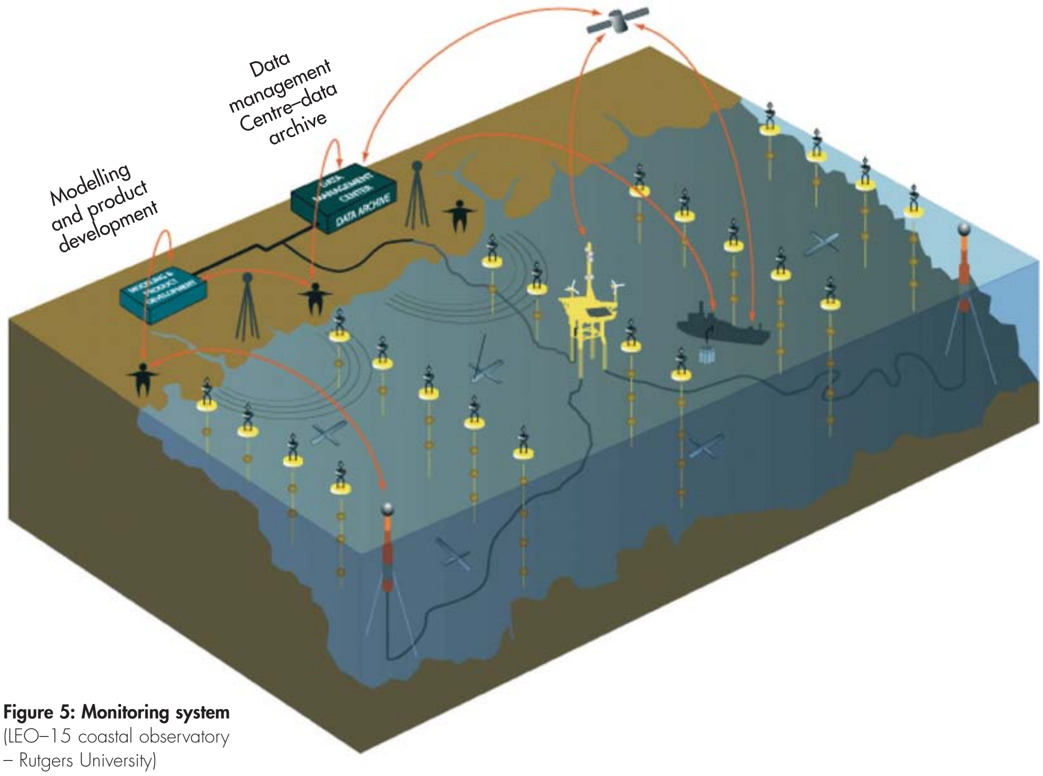


Figure 5: Monitoring system
(LEO–15 coastal observatory
– Rutgers University)

Assimilating in situ observations with remote sensing data, alongside rapid data processing and appropriate communications is essential for operational modelling. Particular attention is required for assimilation in models of coastal seas – because of their rapid response times and (often) large tidal excursions.

New cost-effective instrumentation (gliders, drifting buoys, and yoyo quasi-Eulerian profilers for the shelves) is developing rapidly. However, permanent in situ observations are likely to be the most expensive component of an operational system, and it is important to optimise the observational network in relation to the modelling system for the requisite forecasts.

Data from coupled models

Accuracy, resolution, and extent (in time ahead) of wind forecasts are the primary limiting factors for sea-state and surge forecasting. Likewise, sea surface heat exchange is clearly a determining factor in forecasting ocean mixed-layer depth and ice formation. In both cases, the need for dynamically coupled ocean-wave-ice-atmosphere models is an essential element to improve atmospheric forcing. Ocean basin modelling requires better understanding of the processes associated with fluctuations in the Gulf Stream and North Atlantic Current, the formation of Atlantic bottom water, ventilation, convection, and inter-annual changes in the state of the Atlantic oscillation.

Coupling of regional sea and ocean models is a pre-requisite for longer term simulations (especially hindcasting) in shelf seas. Such coupling requires the resolving of differing representations of specific processes – for example the omission or exclusion of tides. For accurate simulation of European seas, we need improved understanding of the shelf edge and slope processes along the Atlantic margin. This includes non-hydrostatic codes to resolve critical mixing processes. At the land boundary, coupling with hydrological models will complete the water cycle – although this is similarly dependent on development of related monitoring systems.

In addition to the continual demands to enhance model performance in terms of accuracy, reliability, finer resolution, and extended forecast periods, there is an increase in the requirements to extend their scope from physics-chemistry-biology to ecology in fully coupled ocean-atmosphere-terrestrial simulations.

Human intervention in the marine environment continues to expand beyond the coastal margins to shelf-wide activities including: fisheries; oil, gas and aggregate extraction; offshore energy installations and other industrial and commercial offshore developments. Since associated regulatory regimes must encompass operation of these activities alongside their environmental impacts, we need to link our marine models with their socio-economic counterparts.
In such cases, coupling might be limited to sub-set representations (statistical emulators) encapsulating integrated parameters such as stratification levels or flushing times.
To overcome the limitations of individual modules in such total-system-simulations, methodologies are required both to quantify and to incorporate the range of uncertainties associated with model set-up, parameterisation and (future scenario) forcing. This requirement can be achieved by ensemble simulations providing relative probabilities of various outcomes linked to specific estimates of risk.

Challenges

The design of new comprehensive networks, exploiting synergistic aspects of the complete range of instruments and platforms, integrally linked to modelling requirements or capabilities is a prospect as exciting as it is daunting. Furthermore, specialist skills and systems are required to assimilate such observational data in real-time. Enhancing and linking investment in these network designs and associated assimilation techniques is a top priority.

Lead-times between proof-of-concept, laboratory tests, and availability of commercial marine packages have traditionally been in the order of one or two decades. Hence, the pace of development of coastal modelling will be governed by the foresight of scientists and technologists in responding to challenges (such as the EC Water Framework Directive) and prioritising areas of investment to provide longer-term observations with enhanced accuracy and resolution.

European Collaborations & Initiatives

Modelling has moved into an era that requires major investments in infrastructure and organisation (as in meteorology). Having developed a strategic vision, Europe needs to translate this into effective modelling capabilities to address both long-term global issues and more immediate national and local concerns about the marine environment. The specific challenge to scientists is to develop firstly the vision and then secondly the implementation of the framework to exploit these new opportunities created by an integrated European approach.

Extensive European collaboration has been fostered via initiatives such as the ESF Grand Challenges, EC Framework Projects, EuroGOOS Regional Task Teams and Panels etc. These collaborations have stimulated programmes aimed at providing accurate fine-resolution bathymetry, routine standardised sampling along ferry routes, effective exchange of marine and meteorological data, specifications for future satellite missions, interaction between ocean-sea-coastal scientists. However, longer term continuity remains a problem.

Support of community model codes (e.g., GOTM, COHERENS, SWAN, in Appendix 1) involves quality assurance, documentation and version control, training, user workshops, etc. While Europe can only support a limited number of such systems, the growing importance of ensemble forecasts (for uncertainty estimates) emphasises the importance of maintaining diversity and retaining expertise in international codes. Future accommodation of a diverse range of modules (model sub-systems) may be facilitated via couplers such as OASIS or PRISM. Taking into account the implementation plans for the Water Framework Directive, an adoption of standardised modules can allow individual modelling groups to concentrate on more specialised sub-modules. Appropriate validation benchmarks and protocols for model outputs will be required. (Note, the CATCHMOD development towards agreed standards for implementation of the WFD.)

The EC FP6 project *Marine Environment and Security for the European Area (MERSEA),* directly related to the Global Monitoring for Environment and Security (GMES) initiative, serves as an example of the value of collaboration at the programme level. The overall objective of MERSEA is to facilitate the visibility, understanding and exchange of the ocean modelling data, output products for users, and evaluate the strengths and weaknesses of the European capacity for ocean monitoring and forecasting. This collaboration integrates the following existing modelling-monitoring systems: FOAM (Met. Office, UK), MERCATOR (MERCATOR-OCEAN, France), MFS (INGV, Italy), and TOPAZ (NERSC, Norway). The aims of MERSEA are to embed a range of modelling applications (e.g., oil spill, ecological and regional) into ocean-scale systems. The Global Ocean Data Assimilation Experiment (GODAE) is another initiative that might eventually lead to a stronger cooperation between European and world-wide partners.

Challenges for Europe

Long-term leadership in science requires the recruitment of the most original, talented and trained staff supported by state-of-the-art technologies linked to active global communication networks. Hence, an obvious high priority and readily achievable initiative is to link existing European funding and networks spanning: post-graduate training courses and fellowships, specialist summer schools, workshops, conferences, journals, and international or national science programmes, such as the International Global Biosphere Programme (IGBP), etc. This will facilitate the exchange of skills and experience, software and data to enhance modelling capabilities and guide strategic planning. Institutionally, Europe needs to consolidate the successful but occasionally transient collaboration achieved through EC Framework Programmes and elsewhere.

The diversity of marine systems makes it unlikely that a single integrated model will evolve, as is the case for weather forecasting in the national meteorological agencies. Moreover, there is a continuing need for a wide range of types of models with different characteristics to provide genuine ensemble envelopes and cater for a range of environments (such diversity does not obviate the requirement that all models be validated and robust). A systems approach is needed, capable of integrating marine modules and linking these into holistic simulators (geological, socio-economic etc.). Rationalisation of modules to ensure consistency with the latter is an important goal, together with standardisation of prescribed inputs such as bathymetry, tidal boundary conditions, etc. Finally, there will be a continuing need for a limited number of global ocean models.

Appendix 1: Model Codes

The following figures indicate material from EC Community Model web sites: (a) Coherens, (b) SWAN, and (c) GOTM (list of Community and Commercial models).

COHERENS Home Page

COHERENS

Dissemination and exploitation of a
COupled Hydrodynamical Ecological model for
REgioNal Shelf seas

Marine Science and Technology Programme (MAST-III)
MAS3-CT97-0088

COHERENS is a three-dimensional hydrodynamic multi-purpose model for coastal and shelf seas, which is coupled to biological, resuspension and contaminant models, and resolves mesoscale to seasonal scale processes. The program has been developed over the period of 1990-1998 by a multinational European group, as part of the MAST projects PROFILE, NOMADS and COHERENS funded by the European Union.

The main features of COHERENS are:

i. a physical component with modules for currents, salinity and temperature;
ii. a module for simulating biological cycling processes,
iii. a sediment module describing the deposition and erosion of suspended organic and inorganic material;
iv. Eulerian and Lagrangian modules to simulate the advective-diffusive transport of contaminants.

The COHERENS model is now freely available on CD-ROM for the scientific community and management authorities. The program can be considered as a tool for a better understanding of the physical and ecological processes and for the prediction, monitoring of waste material in shelf seas and coastal areas. Its ease of implementation across a range of computing platforms (multiprocessor systems, UNIX workstations, PCs under LINUX/DOS) means that it will be attractive to groups with a sufficient expertise in modelling, who have need of sophisticated model products. Important advantages of the model are its transparency due to its modular structure and its flexibility because of the possibility of selecting different processes, specific schemes or different types of forcing for a particular application. This allows its use for process studies as well as for predictive or operational purposes without prior knowledge of its detailed structure. Future developments can be implemented without affecting the core of the program.
The COHERENS CD-ROM with the FORTRAN source code and an extensive documentation will be sent automatically after completing the Registration Form below. Interested users are requested to read first the License Agreement and the conditions for User Support. For further information contact (P.Luyten@mumm.ac.be)

- Registration Form
- License agreement
- User Support
- Partners of the COHERENS project
- Model description
- Documentation
- Review of COHERENS results

SWAN

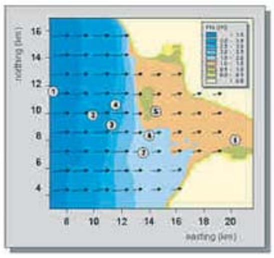
Simulating WAves Nearshore

introduction

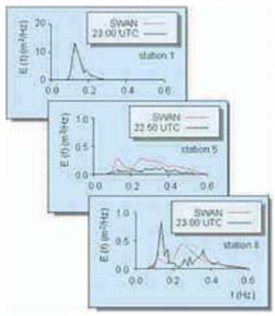
In many engineering studies, knowledge of the operational or of the extreme wave conditions in coastal waters (which may include estuaries, tidal inlets, barrier islands with tidal flats, channels etc.) is required. To obtain realistic estimates of random, short-crested wind-generated waves in such conditions for a given bottom topography, wind field, water level and current field, the numerical wave model SWAN can be used. This SWAN model is a third-generation stand-alone (phase-averaged) wave model for the simulation of waves in waters of deep, intermediate and finite depth. It is also suitable for use as a wave hindcast model.

In order to enable an efficient and a direct coupling between e.g. circulation models (wave driven currents) and sediment transport models (stirring by wave breaking), the SWAN model is presently also integrated under the numerical Delft3D model. SWAN can be applied to: 19

- Nearshore wave modelling for harbour and offshore installation design
- Coastal development and management
- Wave hindcasting



Computed significant wave height pattern and mean direction of energy transport (denoted with vectors) in the Haringvliet (a branch of the Rhine estuary in the south-west of the Netherlands).



Computed wave spectra at 23.00 UTC and observations (scattered around 23.00 UTC) on October 12, 1982 at three stations (1, 5 and 8). Note the differences in energy density scale in the panels.

processes

SWAN simulates the following physical phenomena:

- Wave propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and nonstationary depth.
- Wave generation by wind.
- Nonlinear wave-wave interactions (both quadruplets and triads).
- Whitecapping, bottom friction, and depth-induced breaking.
- Blocking of waves by current.

Note that diffraction is not explicitly modelled in SWAN but diffraction effects can be simulated by applying directional spreading of the waves. Reflections are also not included in SWAN. In strongly diffracting situations or situations with significant reflection effects the SWAN model should be coupled with the WL | Delft Hydraulics wave penetration model PHAROS. This coupling has recently been implemented for use in wave disturbance modelling in harbours.

List of Community and Commercial models
from GOTM web site.

Web interesting links http://www.gotm.net/html/4-HTML/LINK_MAIN.html

GO TM

- Challenge
  - Aim
  - The Idea
  - Key features
- Software
  - Fortran code
  - Test cases
  - Forcing
  - How to run?
- Information
  - What's New
  - Publications
  - E-mail list
  - FAQ
  - User Group
  - Hot Links
  - Who's Who?

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• Marine Circulation Models:

ACOM (Australian Community Ocean Model)
BOM (Bergen Ocean Model)
COHERENS (Coupled Hydrodynamic Ecological Model for Regional Shelf Seas)
DELFT3D (Delft Hydraulics Model)
ECOM (Estuarine Coastal & Ocean Model)
ECOS (Plymouth Sophisticated Spatial Modelling)
FAME (Family of Linked Atlantic Model Experiments)
FRAM (Fine Resolution Antarctic Model)
FLUIDYN (Softwares for Fluid Dynamics)
GMODEL (ENSO Equatorial Pacific Model)
HIM (Hallberg Isopycnal Model)
HOPE (Hamburg Ocean Model)
HSCTM2D (Hydrodynamics Sediment Contaminant Model)
HYCOM (Hybrid Coordinate Ocean Model)
LSG (Hamburg Large-Scale Geostrophic model)
MICOM (Miami Ocean Model)
NCOM (Navy Coastal Ocean Model – NCAR CSM Climate System Model)
NLOM (Navy Layer Ocean Model)
OCCAM (Ocean Circulation & Advanced Modelling)
OPA (Ocean Parallel Model)
OPYC (Parallel Ocean Model)
PCM (Parallel Ocean Model)
POLCOMS (Proudman Oceanographic Laboratory Coastal Ocean Modelling System)
POM (Princeton Ocean Model)
POSUM (Parallel Ocean State University Model)
SCRUM (S-Coordinates Rutgers University Model)
SPEM (S-coordinate Primitive Equation)
SWAN (Wave Near-Shore Model)
TELEMAC (Rivers, estuaries & coastal waters modelling)

• Marine Biological Models:

ECOHAM (Ecological North Sea Model)
ECOBAS_MIF (Ecological Model Formulation Data Base)
ECOFATE (Ecological Risk Assessment)
ECOPATH (Fishery Ecological Modeling Software)
ECOC (Ecosystem Model Validation and Hindcasting)
ERSEM (European Regional Seas Ecosystem Model)
REM (Registered Ecological Model List)
STELLA (Model to Build Model form Flow Chart)
SUCCPP (Platt software for Primary Production)
VGPM (SeaWiFs Vertically Generalized Production Model, Rutgers, USA)

Appendix 2: Hydrodynamic modelling

Previously, we noted that shelf sea model applications have progressed from the 2-D barotropic models of the 1960s to the density-evolving 3-D baroclinic models of the 1980s. Development continues in areas such as: cross-spectral coupling of tides and waves, incorporation of non-hydrostatic internal waves and utilisation of adaptive non-structured grids alongside parallel computer architecture. Moreover, such models are widely applied in areas such as limnology, estuaries, harbours, coastal bays to shelf seas and oceans.

Shelf sea hydrodynamic modelling generally focuses on tides, surges and waves, since these represent the most energetic processes and provide the background conditions for non-linear interactions with other dynamical processes. Explicit solutions for associated gravity-wave propagation introduce severe restrictions on the size of the allowable time-step. Two approaches are commonly used to solve this problem. First, a time step splitting method is implemented in which the gravitational waves and the vertical viscosity and diffusivity, i.e. the most time-step limiting processes, are resolved explicitly with smaller time steps than all the other terms. Second, a complex alternative is the use of synchronous semi-implicit time step in which the gravity-wave-producing term, the surface pressure gradients and their associated terms in the continuity equation, and normally also the vertical viscosity and diffusivity are treated implicitly whereas all other terms are solved explicitly. While this semi-implicit treatment allows for a uniformly large time step, the numerical calculation of this treatment is more complex to implement. However, in terms of actual computational costs, there can be benefits in using this algorithm. On the other hand, the time-splitting method produces disturbances due to the fact that the barotropic and baroclinic modes are not always directly coupled, this can be overcome by a short iterative loop achieving the convergence. While applications involving parallel computing can introduce additional complications, they may make explicit schemes more attractive.

To incorporate the effect of turbulence into three-dimensional models a large number of different parameterisations have been applied. At the beginning, purely empirical formulas or algebraic expressions were used. However, nowadays so-called two equation models have been proven to be a good compromise between accuracy and efficiency, because these models still assume a local equilibrium. Most well-known are the Mellor-Yamada and k-e-models, which have been shown to be equivalent. In the turbulent closure approaches the vertical eddy viscosity depends on either the turbulent kinetic energy with the length scale of the turbulent motion or the turbulent kinetic energy with the dissipation rate. Two major factors that are used to infer these quantities are the vertical velocity shear, which increases the vertical viscosity and the buoyancy which in contrast suppresses it.

Two other water column mixing processes, where further work is necessary, are internal wave dynamics and convective mixing.

It is known that breaking internal waves significantly contribute to vertical mixing but an adequate parameterisation of this process, for use in regional scale models, has yet to be achieved. Convection in the ocean is a downward sinking processes caused by instability of the water column. This process can be described by a non-hydrostatic formulation which introduces a new level of complexity, or alternatively by a special treatment in the turbulent closure scheme. The use of a localised scheme is problematic because convection can also produce a counter-gradient flow and overshooting, neither phenomena can be described in terms of a local equilibrium. Thus, a reasonable description of the full convective process would require a non-local turbulence model, such as the KPP model; here further research is needed. Fortunately, for applications over scales of kilometres, much simpler convective adjustment schemes produce satisfactory results.

Appendix 3: Ecological modelling

The development of conceptual and mathematical models has played a central role in marine biology and ecology as a tool for synthesis, prediction, and understanding. It is clear that significant progress has been made over the past 20 years in the development of numerical process models of the marine environment. The development of large-scale models started in the early eighties and included elements of phytoplankton kinetics. In the first generation models, processes were described by rather simple equations. In these early models, the transport was based on 2-D hydrodynamic calculations for average conditions (i.e. one representative day). Some models were comparatively refined and used computational elements in the area of about 20x20 km. This allowed for some gradients in coastal areas. Most ecosystems models were lumped together in so called “box models” of which only about 10 to 20 were considered for the whole of the North Sea.

In recent years, important progress has been made on the scale of ocean basins, overall circulation patterns and the distribution, and abundance of algal groups (e.g., dinoflagellates, flagellates etc.) as a function of water mass distributions, large scale current regimes, and frontal systems. Examples of large-scale 3-D ecosystem models applied to the North Sea and parts of the Northwest European Continental Shelf are ERSEM (Figure 6), NORWECOM, POLCOMS-ERSEM, ECOHAM,

Figure 6: Ecosystem model (Proudman Oceanographic Laboratory)

COHERENS, Delft3D-ECO and ELISE. The models differ in the way they interact with the physical models, the complexity of the trophic structure, and the way the interaction with the sea bed is included.

With respect to the interaction with the physical model, two modes exist: on-line and off-line coupling. Some models can optionally be run either way. The main advantage of the on-line coupling method is the possibility to include feedback between all relevant processes. On-line interfacing may be the only feasible option for detailed hydrodynamic models run for a long simulation period because the amount of information to be stored for an off-line simulation model may be impractically large. In contrast, the off-line method offers more options to differentiate because of the level of aggregation and the time-scale. So running offline may be (much) faster because of the use of a somewhat coarser grid and a longer time-step, but still being accurate enough for many management and research questions. As a compromise some modelling systems allow for a distinction in the level of detail by using curvilinear and/or nested grids.

Within the water phase, the models show great variation in the level of detail. Most, but not all recent models include Nitrogen, Phosphorus, Silicate and Oxygen as parameters. Variation in the number of individual processes also has to be taken into account. Some models include only one group of phytoplankton, others differentiate between functional groups based upon eco-physiological characteristics such as nutrient and light requirements or edibility, whereas some models focus in particular on harmful algal species. Few models include explicit equations for grazing, nor for the trophic interactions with fish, and existing models pay surprisingly little attention to suspended particulate material (SPM), although high concentrations in several coastal waters considerably affect the light climate, and hence, the local rate of primary production. Furthermore, existing SPM models are not very accurate; hence, an improvement is necessary.

Large discrepancies exist in the way the water-sea bed interface is simulated. A number of models do not include a functional sea bed at all or they just consider a pool of sedimented dead organic material, whereas other models include several bed layers and different forms of nutrients, and some even include formulations for the benthic community. These differences may partially, but not completely, be explained by differences in scope of models. Obviously, the interaction between the water and sea bed is much more intense in shallow coastal areas or estuaries compared with off-shore, deep areas. In addition, the important interactions between the biological organisms at or in the sea bed, and physical factors such as stability, erosion, morphology or local hydrodynamic conditions are only now being introduced in the mainstream operational models. A revision of the appropriate level of details and the importance of bio-geomorphologic processes seems necessary.

Many models are, and will in the future be, developed for specific regions. To apply these models, they need adequate approved data for boundary conditions. In many cases, it is impossible to obtain a complete set of conditions from measurements; thus, the most appropriate source for these data is large-scale models. These models should be set-up and maintained at a supra-national level. Meteorological data, including modelling results, should also be available at a central European level. Lack of approved data on discharges is another factor hampering the development of regional models. To solve this problem, databases of loadings should be publicly available at a European rather than national level. Monitoring data are urgently needed to validate model results, for nutrients and total phytoplankton biomass quite a number of data are available, although mainly on a national level and mainly data from below the surface interface. There is a lack of data on vertical profiles and data on grazers are much less abundant and irregular. There is a lack of relevant data for both formulation, as well as validation, of the water-sea bed interface.

Present operational models pay little or no attention to toxic substances because problems related to organic pesticides and heavy metals have declined considerably in the European marine waters since the 1990s. Recently, concern about the impact of new types of toxic substances such as hormones is increasing. Thus a new generation of toxic substance models might have to be developed in the near future to cope with these impacts.

Fisheries are an important economic activity in marine waters with potential implications for the ecosystems (Figure 7).

Current operational models for fish stocks and fisheries do not take these implications into account, nor do they interact directly with primary and secondary production models. Hence, it is unclear to what extent changes in fish stocks relate to changes in the plankton community or to changes in the fishery itself. Developing operational models for these interactions is, therefore, of major significance and necessary to implement an ecosystem-based approach to marine management. One Grand Challenge is the exploration of global-climate-change induced latitudinal migration of species; this will require incorporation of species-specific behaviour.

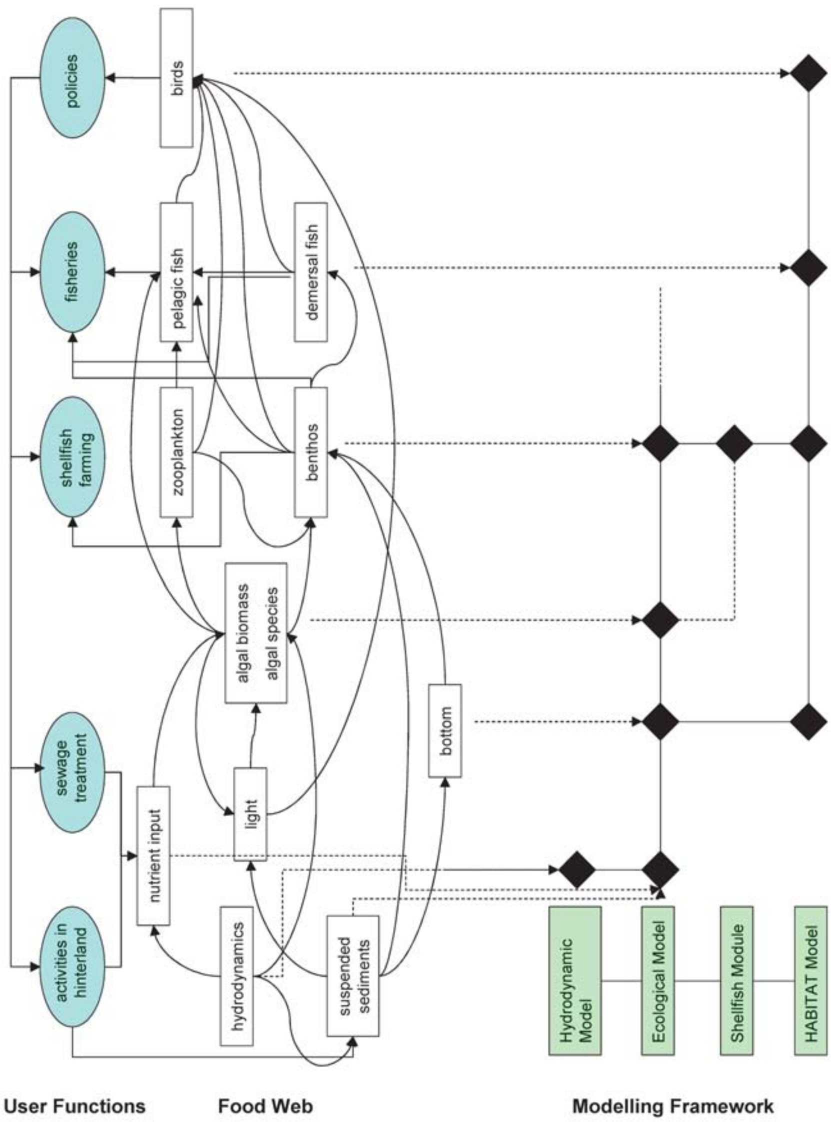

Figure 7: Fisheries model (Proudman Oceanographic Laboratory)

Appendix 4: Operational Oceanography

Operational oceanography is defined as the activity of routinely making, disseminating, interpreting measurements of seas, oceans, and the atmosphere to provide forecasts, nowcasts, and hindcasts.

Forecasting

Forecasting includes real-time numerical prediction of processes such as storm surges, wave spectra, sea ice occurrence, climatic statistical forecasts, and seasonal and inter-annual variability. Forecasts on a climatic or statistical basis may extend forward for hours, days, months, years, or even decades. Accumulation of errors, both from model inaccuracies and from uncertainties in forcing, limit realistic future extrapolations.

Nowcasting

In nowcasting, observations are assimilated in numerical models and the results are used to create the best estimates of fields at the present time, without forecasting. These observations may involve daily or monthly descriptions of sea ice, sea surface temperature, toxic algal blooms, state of stratification, depth of the mixed layer, or wind-wave data.

Hindcasting

Observational data for hindcasting are assimilated into a model to compile sets of historic fields and distributions (typically monthly or annually) of variables such as sea surface elevation, water temperature, salinity, nutrients, radio-nuclides, metals, fish stock assessments, etc.

Model generations

Numerical modelling has been used in marine science for almost 50 years. A convenient distinction is as follows:
Generation 1: models where algorithms, numerical grids and schemes are being developed often utilising specific measurements focused on process studies.
Generation 2: pre-operational models with (effectively) fully-developed codes undergoing appraisal and development, generally against temporary observational measurements or test-bed data sets.
Generation 3: operational models in routine use and generally supported by a permanent monitoring network.

A cascade time of approximately 10 years is typically required to migrate between each Generation.

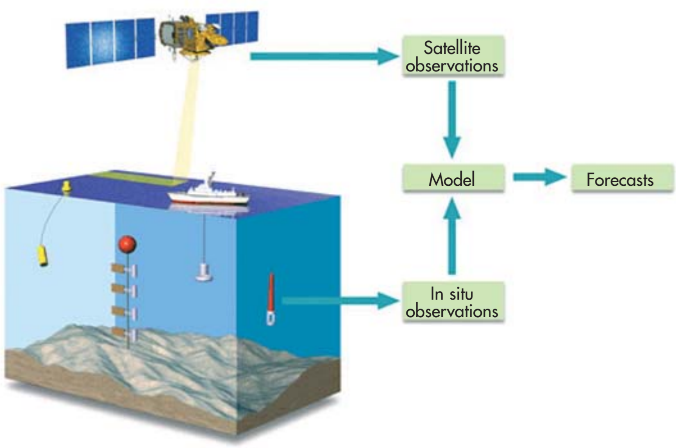

Figure 8: Operational oceanography: an example of the MERCATOR system

Appendix 5: Terms of Reference and Membership

Terms of Reference for Marine Board Working Group on *Innovative Modelling of Coastal and Shelf Seas*

Goals of the Marine Board – ESF include promoting the quality of, and access to, the science needed for effective management coastal and marine resources – underpinning governance to ensure sustainable exploitation of this invaluable resource. Parameters of interest include: surges, waves, currents, temperature, salinity, ice, sediment transport through to an ever expanding range of biological and chemical tracers The diversity in nature, usage and hence challenges in European coasts requires fostering of localised scientific expertise with access to s-o-a facilities to maintain excellence, and effectiveness.

Models synthesise theory into algorithms and use observations to set-up, initialise, force, assimilate and evaluate simulations in hindcast, nowcast and forecast modes. Thus the use of models range from: gaining insight and understanding, hypotheses testing, quantifying the stage of scientific development, forecasting (flood warning to scenario testing), to sensitivity testing of dependence on algorithms, computational resolution, accuracy and extent of observational data. The scope of the models involves linkages across ocean-atmosphere-seas-coasts and between physics-chemistry-biology-geology-hydrology, this connectivity spans: meteorological agencies, satellite missions, international scientific and survey programmes such as IGBP, CLIVAR, GOOS etc.

Extensive European collaboration has been fostered via initiatives such as: the ESF Grand Challenges, EC Framework projects, EuroGOOS Regional Task Teams and Panels etc. Whilst these activities have been highly successful, longer-lasting initiatives are necessary to maintain European leadership in the range of technologies involved. This ESF Marine Board Working Group will aim to identify such initiatives for innovative modelling of Coastal and Shelf Seas.

Issues to be examined by the Working Group will include:

- fostering of a European Marine Coastal Modelling Community
- coupling aspects of meteorology-physics-ecology-hydrology
- requirements for test-bed experiments and long-term monitoring (networks)
- future opportunities and requirements from: in situ, satellite and other remote sensing instruments
- development of assimilation techniques in the coastal zone
- the range and success of community-model groups
- future plans and requirements of engineering consultancies
- the needs for infrastructure investment for integrated modelling
- training and career planning.

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