A strategic basis for Coastal modelling

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ABSTRACT

Global Climate Change threatens coastlines worldwide. To address this threat and to maintain a balance between exploitation and conservation, there is an urgent need for improved scientific understanding, expressed in computer-based models able to differentiate and predict the impact of man's activities from natural variability. Long-term data sets are vital for such programmes; systematic marine monitoring programmes must be initiated, involving combinations of remote sensing, moorings and coastal stations. International co-ordination is necessary to minimise uncertainty and to ameliorate the threats.

1 INTRODUCTION

While the immediate threats to coastlines concern the changing magnitudes of tides, surges and waves, the underlying longer term (decadal) issue is how bathymetries will adjust. The urgency, magnitude and ubiquity of these questions demand effective international collaboration.

In addition to the pressing flood risk, there is growing concern about sustainable exploitation, in particular how economic and natural environment interests can be reconciled in the face of increasingly larger scale developments.

While tides, surges and waves are physically the most energetic, many parameters exhibit pronounced seasonal cycle (e.g., temperature, light, waves, stratification, nutrients, oxygen, and plankton). Changes to these seasonal cycles (or to related episodic events) may be extremely significant for ecology, e.g., adjustments in vertical stratification from variations in salinity and temperature. Likewise, changes to the larger-scale background circulations may affect the pathways and distributions of persistent tracers.
The 'decay-time' for tidal, surge and wave energy is usually measured in hours, as is the vertical mixing rate in strongly tidal shallow waters. However, the flushing time for persistent contaminants extends over days, as does the vertical mixing rate for weak tidal currents in deep waters. Hence, while simulation of the former is relatively independent of initial conditions, simulation of the latter is complicated by 'historical' dependence and associated accumulation of errors.

Figures 1 and 2 show how the scope and foci for modelling have developed alongside the related observational capabilities

TIDES
SURGES
WAVES
TEMPERATURE
SALINITY
BLOOMS
SPM
SLICKS
NUTRIENTS
CHEMISTRY
ECOLOGY
FISH STOCKS

Improve:
ACCURACY
RESOLUTION
FORECAST PERIOD

ESTABLISH
VALIDITY

INCREASE
SCOPE

COAST

SHELF
SEAS

OCEAN

Figure 1. Extension in parameters, time and space scales of application of marine models, alongside developments in observational technologies.

2 MODELS

Models synthesise theory into algorithms and use observations to set-up, initialise, force, assimilate, and evaluate simulations in operational, pre-operational and ‘exploratory’ modes. Models are limited by the validity of the basic algorithms, by numerical and discretisation accuracy and by the quality of the observational data used both to prescribe the external forcing and to evaluate results, Figure 3 .Their restricted capabilities to simulate long term changes (more than a few years ahead) is widely recognised. A particular concern is the uncertainty in predicting longer-term (decadal) bathymetric evolution, where incremental changes can depend on antecedent bathymetry, resulting in random or chaotic model outcomes.

Uses

Models are used for:
1) Forecasting - waves, surges, contaminant distributions, search & rescue etc.
2) Assessing and understanding ecological status and associated sensitivity to change.
3) Developing management policies encompassing future ‘interventions’ and trends.
4) Advancing underpinning science and technology.

History

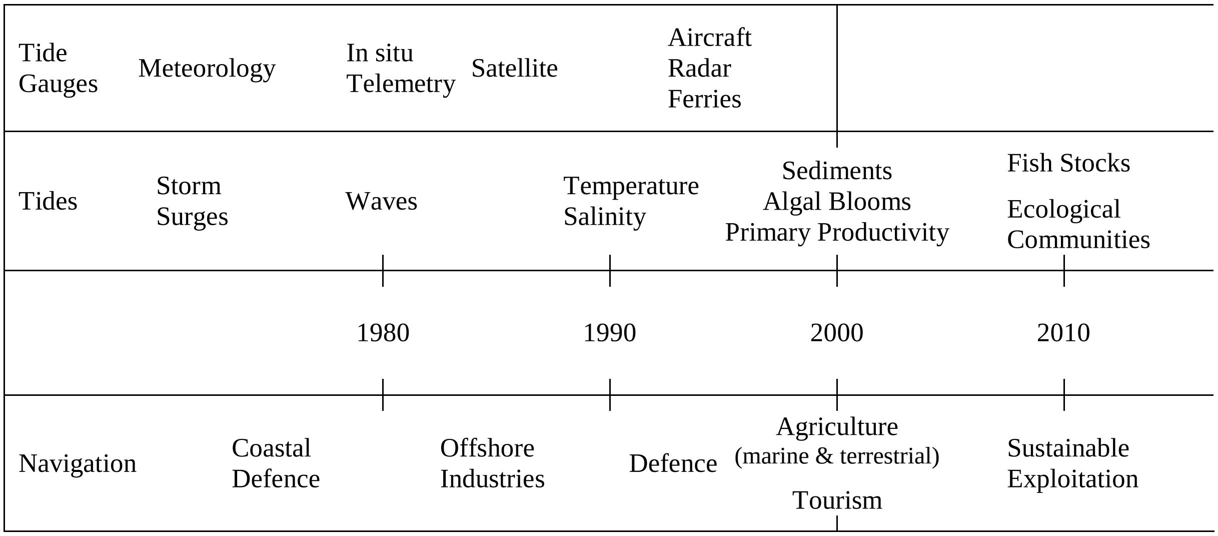

Figure 2. Historical development of marine modelling, issues and observational technology

Applications

Operational uses include tidal predictions and hazard warning for: storm surges, oil or chemical spill movement, search and rescue, eutrophication, toxic algal blooms etc.

Pre-operational simulations often involve assessing and understanding the health of marine ecosystems and resources and their likely sensitivity to changing conditions. These are typically concerned with assessment of absorptive capacity for licensing of discharges, evaluating environmental impacts of intervention (reclamation, dredging, etc.) and climate change.

Exploratory applications extend from formulation of environmental management policies to developing the underpinning science and technology to address both anthropogenic influences and natural trends.

Parameters of interest include tides, surges, waves, currents, temperature, salinity, turbidity, ice, sediment transport, and an ever-expanding range of biological and chemical components. The full scope of models involves simulations across ocean-atmosphere-seas-coasts and between physics-chemistry-biology-geology-hydrology extending over hours to centuries and even millennia.

Human intervention in coastal environments impacts on: flooding, fisheries; ecology, industrial and commercial developments. Regulatory regimes must encompass operation of these activities alongside their environmental impacts; hence we need to link marine models with their socio-economic counterparts. In practice, 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.

Both proprietary and public-domain model codes typically involve investment of tens of years in software development and continued maintenance by sizeable teams. Such effort is increasingly beyond the resources of most modelling groups. The diversity of marine systems makes it unlikely that a single integrated model will evolve. 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.

Limitations and development

The validity of models is limited by the degree to which the equation or algorithms synthesise the governing processes and by numerical and discretisation accuracies. 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.

Numerical modelling of tidal and surge elevations in estuaries is well developed, and generally requires only a limited number of elevation measurements for validation. However, tidal currents vary over much shorter spatial scales with localised changes in bathymetry, creating small-scale variability in both the vertical and horizontal dimensions. These changes in velocity produce even more localised variability in erosion, deposition and transport of suspended material. Thus, numerical modelling of contaminant fluxes is less well developed and requires more detailed spatial resolution, with a corresponding increase in the resolution of observational surveys used for validation.

Immediate improvements in the accuracy of simulations can be achieved with adaptable and flexible grids alongside more sophisticated numerical methods. In the horizontal, rectangular grids are widely used often employing polar coordinates of latitude and longitude. Irregular grids, generally triangular or curvilinear, 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. 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. In estuaries, the influence of turbulence on the dynamics of currents and waves and their interaction with near-bed processes remains to be clearly understood. Here, understanding and enhanced representation of turbulence effects in models is a central issue. Development of turbulence models 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; 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.

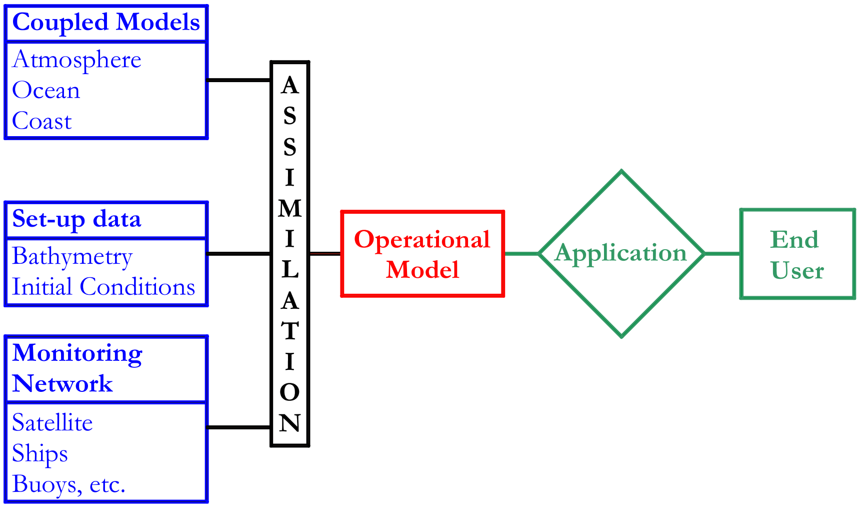

Figure 3. Components of an Operational Modelling System.

3 OBSERVATIONAL TECHNOLOGIES

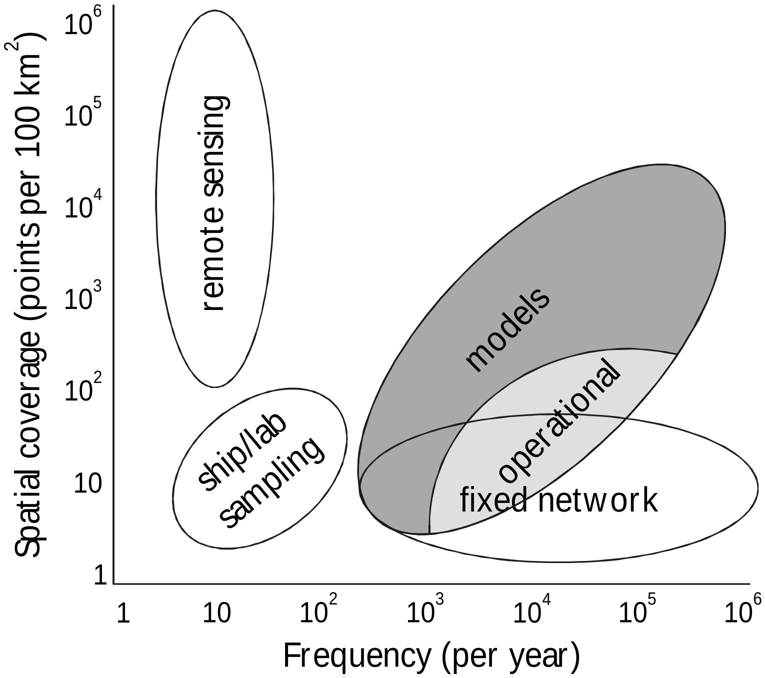

Figure 4 The spatial and temporal resolution of models and monitoring systems: remote sensing, ship-borne and fixed networks.

Rigorous model evaluation or effective assimilation of observational data into models requires broad compatibility between resolution and accuracy in models and observations – temporally, spatially (horizontal and vertical) and in parameter range. (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.)

Requirements and sources of data

Setting-up coastal models requires accurate fine-resolution bathymetry, and ideally, corresponding descriptions of surficial sediments/bed roughness. Subsequent forcing requires tide, surge and wave data at the ocean boundary together with river flows alongside their associated temperature, sediment, and ecological signatures.

Observational data can be obtained from satellites, aircraft, radar, buoys, floats, (cabled) moorings, gliders, AUVs (Automated Underwater Vehicles), instrumented ferries. Associated data is provided by meteorological and shelf-sea models. 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 necessary both for vertical profiles and calibration. The improved spatial resolution provided from aircraft surveillance is especially valuable. High frequency radars also provide synoptic surface fields of currents.

Satellite measurements only apply to properties at the sea surface, synergistic in situ monitoring systems can provide data for both calibration and vertical extrapolation.

In addition to the immediate, localised requirements, information may be needed about possible changes in Ocean circulation – both on regional climates and on the supplies and sinks for nutrients, contaminants, thermal energy, etc. Careful monitoring may indicate how such impacts are conveyed. Recognising the long inertial lag of the oceans to impacts from Global Climate Change, detection of systematic regional variations may provide early warning of impending impacts in shelf seas and estuaries.

Development of monitoring networks

Permanent coastal monitoring networks have been established in coastal seas and estuaries measuring water level, currents profiles, surface winds, waves, temperature, SPM, salinity, nutrients, etc., using tide gauges, mooring and drifting buoys, platforms, ferries alongside remote sensing from satellites, radar and aircraft. Regional monitoring networks are being established via the GOOS network (XX).

Despite these advances, the range of marine parameters that can be accurately measured is severely restricted and the cost of observations is orders of magnitude greater than that associated with 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 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.

FUTURE CHALLENGES

Coastal processes range over wide spectra of temporal, spatial and parameter scales, from physics to ecology, from micro-turbulence to shelf-sea circulation. Exciting opportunities are presented by the rapid advances in: computational power, monitoring technology and systems, scientific understanding and numerical methods. Nonetheless, investment and the associated progress will depend on demonstrable benefits to end users.

An international approach is necessary to quantify the contribution to and effect from Global Climate Change. This extends to: development of models and instruments (and their platforms), planning of monitoring strategies, exchange of data, etc. This collaboration should develop structured research, development and evaluation programmes. The ultimate goal is a fusion of environmental data and knowledge, utilising fully the communications and computational capacities.

Hydrodynamic/mixing models are required as the basis for transporting and mixing contaminants both horizontally and vertically. Since the dynamic processes involved occur over time scales of seconds (turbulent motions), to hours (tidal oscillations), to months (seasonal variations) with corresponding space scales from millimetres to thousands of kilometres, a range of models is required. In addition to hydrodynamic and mixing models, sediment and ecological models require robust algorithms for sources, sinks and biological/chemical reactive exchanges.

In other areas of marine science, standardised, generic modules are perceived as the requisite building blocks of future interdisciplinary, international collaboration. The development of generic modules and the ready availability of public domain model codes have removed much of the mystique that traditionally surrounded estuarine modelling. The diversity of marine systems makes it unlikely that a single integrated model will evolve. Moreover, retention of flexibility at the module level is both necessary and desirable to accommodate a wide range of applications and to provide ensemble forecasts. However, rationalisation of modules within modelling systems is a recognised goal, together with standardisation of prescribed inputs such as bathymetry, tidal boundary conditions, etc. Such enhanced rationalisation will enable the essential characteristics of various types of models to be elucidated including the inherent limits to predictability.

Operational Oceanography is necessary to minimise damage from future events (from storms on a short-scale to longer-term sea level change) by reducing the uncertainties in related forecasting. Operational Oceanography will provide valuable spin-off benefits to modelling required for sustainable exploitation and management of our marine resources. Assimilating in situ observations with remote sensing data, alongside rapid data processing and appropriate communications is essential for operational modelling. Particular challenges arise in estuarine models because of their rapid response times and large tidal excursions.

To understand and quantify the threat of Global Climate Change, whole-system models are required – incorporating the impacts on marine biota and their potential biogeographic consequences. The introduction of Water Framework Directives for governance of Regional Seas and coasts emphasises the need for development of well-validated, reliable models for simulating water quality-ecology-fisheries. 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, and so on.

Successful application of models are generally limited by the paucity of resolution in observational data (especially bathymetry) used for setting-up, initialising, forcing (meteorological and along model boundaries), assimilation and validation. This paucity of data is a critical constraint in environmental applications. More and better observational data, extending over longer periods are essential if modelling accuracy and capabilities are to be enhanced.

Comprehensive observational networks are needed exploiting synergistic aspects of the complete range of instruments and platforms and integrally linked to modelling requirements. Permanent in situ observations are likely to be the most expensive component of any operational system, and it is important to optimise the observational network in relation to the modelling system for the requisite forecasts. There is a parallel requirement for accurate (model) descriptions of the state of adjacent shelf seas to define estuarine boundary conditions.

Up-scaling of knowledge from process studies is required to link small scale (micro) measurements to larger and longer (macro) scale algorithms employed in numerical models. These studies involve measurement programmes extending to water level, currents, temperature and salinity, waves, turbulence, bed features, sedimentary, botanical, biological and chemical constituents. The associated costs dictate these would cover a limited but representative number of estuaries. Specific ‘deliverables’ would be: (i) complete, consistent, documented, accessible bench-test observational data sets for model validation*;* (ii) development of monitoring strategies, elaborating synergistic values of the range of systems and sensors; (iii) assessment and development of sensors, instruments and platforms.