Key Future Research Priorities in Ocean Forecasting

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Abstract

The next decade will spawn new research activities that will build on the success of GODAE. The grand vision and key research challenge is to develop coupled initialisation systems of numerical weather prediction and eddy-resolving ocean models. These systems will contribute to and benefit from recent progress in earth systems modelling. With increasing computing resources the next decade is also likely to see an even stronger emphasis on “seamless” integrations across time and space scales, covering global, regional and coastal/near-shore ocean prediction systems and addressing a variety of user applications. Improvements will be driven as much by scientific innovation as by user demand. The integrative approach plus the increasingly multi-disciplinary character of ocean forecasting demand state-of-the-art science leadership.

Many research approaches developed in GODAE are just at their beginning and will require ongoing international research collaboration and coordination prior to wide-spread operational implementation and uptake by end users. Examples are:

- Data assimilation:
  - development of data assimilation tools such as coupled atmosphere-ocean initialisation techniques that are fit-for-purpose for a wide range of applications, including short-range, seasonal-to-decadal and climate change prediction (in collaboration with WMO programs);
  - the development of efficient data assimilation techniques for biogeochemical and ecosystem modules of ocean circulation models that are fit for operational purposes;
  - representation of model and data errors using ensemble methods based on various forecasting systems thus delivering more accurate background error estimates; and
  - multi-scale data assimilation and joint estimation of interior and open boundary solutions in nested systems.
- Observing systems:
  - the use of new types of observations (e.g. remotely sensed sea surface salinity);
  - in collaboration with international programs such as IMBER and SOLAS support the research on and implementation of real-time biogeochemical and ecosystem ocean observing systems, e.g. cost-effective sensor-technologies; and
  - an enhanced focus on observing system design and assessment; and its analogue of adaptive sampling will allow assessments of individual components of the observing system and provide scientific guidance for improved design and implementation of the ocean observing system.

- Coastal ocean:
  - further develop the notion of a critical path from routinely-available information (satellite, in situ, basin-scale estimates) to the coastal and littoral applications, and importance of the role of the coastal ocean link on this path;
  - enhancements to existing systems and development of new coastal ocean forecasting systems that downscale the global basin-wide model estimates as part of the local data assimilation problem, resolving the rich scale interactions, tides and high frequencies, and experimenting novel approaches such as coupled modelling and unstructured grid modelling; and
  - contribution to the objective design of observing systems for the coastal ocean, such as new satellite sensors, coastal observatories, etc.; use of such observations in the local forecasting system and upscaling of the information to the basin-scale systems.

This paper presents recent international trends and projected future advances in the underlying science.

Key words: forecasting systems, biogeochemistry, ecosystem, coastal, observing systems, ocean modelling, data assimilation

1. Introduction

GODAE aimed at advancing ocean data assimilation by synthesizing satellite and in-situ observations with state-of-the art models of global ocean circulation. In the past few years, a suite of GODAE systems have been developed to produce global and basin-scale ocean analyses and short-term forecasts. GODAE products are also increasingly being used for environmental protection applications and provide lateral open boundary conditions for regional and coastal physics and ecosystems. The specific requirements of these applications are important to the ocean forecasting product developers as well as to the understanding of the need for large-scale and coastal observing systems.

Nowadays, diverse applications involving ocean forecasting systems range from short term prediction of the three-dimensional circulation and density fields, waves, tides and storm surges to coupled ocean-atmosphere-land scenario forecasting of the effects of global climate change on terrestrial, fluvial and ecology over millennia. The accuracy of model simulations depends 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 (Shapiro et al, 2008). However, despite these opportunities and challenges it should be noted that more research on fundamental processes (e.g. to provide parameterizations) is still required. Many of the fundamental modelling issues that were evoked in the book edited by Chassignet & Verron (1998) are still unresolved.

More specifically, the accuracy of present-day ocean simulations and forecasts depends on: (i) the degree to which the equations, algorithms and parameterisations synthesise the governing processes; (ii) the accuracy and resolution of the observational data used to set-up, initialise, force, assimilate, assess, and fine-tune the simulations; and (iii) the adequacy of surface forcing specified from coupled atmospheric and ocean models. Advancing ocean forecasting involves two discrete, but inter-related, pathways: scenario testing/reanalysis; and real-time operational forecasting.

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 three-dimensional, 10^8 elements) exploiting the contemporaneous development of computing power. Unfortunately, concurrent development in observational capabilities has not matched this resolution, particularly in areas demanding high spatial resolution such as coastal domains, and despite exciting advances in areas such as in remote sensing and sensor technologies.

The following sections of this paper seek to articulate existing capabilities and limitations. Associated key future research challenges and future opportunities to meet the requirements of end-users are identified.

The information provided herein draws on numerous sources quoted in the text but particularly on the report of the 3rd GODAE Symposium, held in October 2006 in Beijing, China, the GODAE Coastal and Shelf Seas white paper (De Mey et al., 2007), and the reports by Prandle et al. (2005), Robinson et al. (2008) and Parslow (2008).

2. Ocean Modelling

We have the advantage in physical modelling of having a rigorous and concise mathematical formulation of the equations of motion underpinning the circulation. But of course in any numerical solution, there are limits to the spatial resolution, and we must approximate the (chaotic) processes occurring at finer scales. A rich theoretical and experimental science has led to the formulation of advanced numerical schemes to represent bottom topography (Fig. 1) and to numerical turbulence closure schemes, now widely implemented in ocean models. This science about turbulent closure schemes is now fairly mature, but there may still be surprises associated with subtle aspects of vertical mixing in the deep ocean that may have important consequences on long time scales. Vertical mixing is also critically important for biogeochemical cycles, because it controls the return of nutrients to the surface euphotic zone, and therefore the magnitude of primary production. Another area where there still seems to be room for improvement in process formulation concerns the exchanges of heat, momentum and freshwater across the ocean surface.

In the coastal ocean, we have also seen the rapid development of physical models. Coastal ocean models encompass not only the coastal strip but also the coastal transition zone and interactions with the large-scale circulation. Coastal ocean modelling and forecasting is a major challenge for the scientific community because of the specific and rich dynamics of those regions, and because of the various couplings with the lower atmosphere and exchanges with the near-shore and offshore regions. These issues, needs and challenges have led to the development of a wide range of models of various types. Phenomena of interest include coastal current interactions, coastal mesoscale, tides and storm surges, tsunamis, shoreline change, coastal currents and hydrography, coastal upwelling, river plumes and regions of freshwater influence, atmosphere-driven processes, surface waves, and sea ice. Coastal ocean systems can have very high spatial gradients in both the vertical and horizontal, especially near river mouths, requiring the use in models of sophisticated mixing schemes, and high order numerics. The key constraints on the accuracy of these models now lie with the specification of input data (bathymetry, bottom roughness, lateral and surface forcing). In these shallow systems, and especially along exposed shorelines, wave-current interactions play an important role. Measuring and predicting exchanges between the underlying sediment and the water column is critical for coastal biogeochemistry, and is still a key challenge. Sediment models attempt to represent the effects of re-suspension and deposition of particulate material, and their interaction with the circulation, on suspended concentrations (turbidity, important for optical properties and hence primary production) and bed thickness and composition (geomorphology). Models of these processes are still under active development.

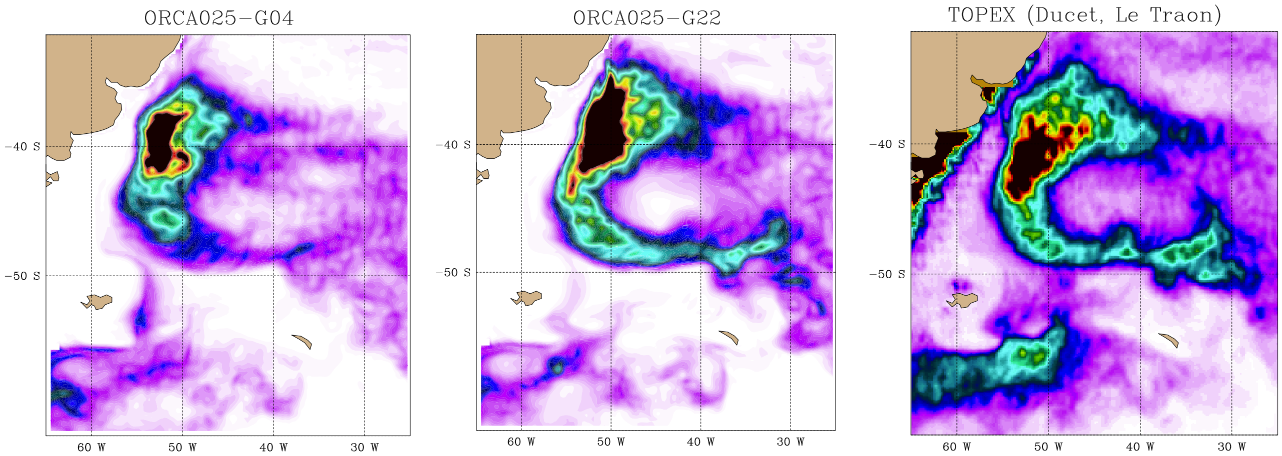

Fig. 1: The use of new advanced numerical schemes to represent bottom topography and momentum advection produced significant improvements in the simulation of eddy-topography interactions and their consequences on the large scale circulation features. An example in the Argentine basin is presented here, extracted from the NEMO-based 1/4° resolution global model ORCA025 that has been jointly developed in the framework of the DRAKKAR and the MERSEA projects (Barnier et al., 2006). The above figure compares the distribution of the mean eddy kinetic energy (MEKE) in simulations carried out with (left) the OPA model (the former version of NEMO before the advanced numerical schemes were introduced), and (centre) the NEMO model using the advanced numerical schemes, with that (right) estimated from satellite altimetry. The good representation of the characteristic C-shape of the MEKE in the Argentine basin in NEMO is a clear result of the impact of improvements of the model numerics. Despite those significant progresses, the representation of current-topography interactions remains a current issue in numerical modelling of the general circulation, especially the simulation of gravity currents, and friction/dissipation in boundary currents.

With respect to biological processes, we are faced with the general problem of ecosystem modelling; namely, choosing the right level of abstraction and approximation in describing and predicting the structure and function of a complex system with many nested levels of complexity. There is of course no “right” choice in an absolute sense; the best choice at any time will depend both on the problem to be addressed, and the prior knowledge and new data available to support model implementation and calibration.

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.

3. New Research Directions in Data Assimilation

The assimilation of observations into present-day ocean models is still far from being optimal. Improved estimates of the state of the physical ocean, marine ecosystems and ocean/atmosphere interactions will rely upon new cross-cutting research directions in terms of both methods and operational implementations.

3.1 New Methodologies

New methodological avenues of future research in data assimilation can be roughly classified according to five categories:

- those that are motivated by conceptual progress,
- those that are induced by the emergence of new instruments or new instrumental capabilities,
- those that are subject to operational constraints and requested by operational services;
- those that are suggested by biogeochemistry, and
- those regarding data assimilation in the coastal ocean.

The subsequent paragraphs explore these options in more detail:

- Conceptual: In meteorology (the history of which predates the evolution of ocean forecasting), the implementation of data assimilation methodology has followed a progressive pace starting with optimal interpolation, followed by sequential approaches and today most larger NWP centres are investing in 4D-VAR variational approaches with a noticeable increase in interest in ensemble approaches. Operational oceanography is today at the stage of applying sequential approaches but variational methodologies are on the verge of being used, at least for seasonal forecast applications (c.f. Cummings et al. paper in the same issue). Because of the specificities of oceanography (e.g. the mesoscale non-linearities) it is still unclear whether 4D-VAR is fully applicable (Luong et al., 1998) and further research must be undertaken in this direction. A promising way might be the hybridization between variational and sequential approaches thus combining advantages of both methodologies (Robert et al., 2006). However, 4D-VAR systems have not been comprehensively tested for highly non-linear applications. For instance, as we move to higher resolution and longer predictive time scales, the assumptions that underpin VAR systems (e.g. linearity in tangent-linear models) become less valid.

  A basic assumption of linear data assimilation is the Gaussian statistics of the error distributions. Several approaches have been developed to overcome these limitations or to manage them using non-linear estimation methods (e.g. SIR filter; van Leeuwen and van Scheltinga, 2008). This issue is of particular importance in biogeochemistry, but inequality constraints encountered in physics (e.g. the condition of hydrostatic balance in OGCMs) can also create similar problems and possibly impact the response of ecosystems in coupled simulations (Lauvernet et al., 2008).

- New instruments are clearly a source of evolution and ideas for research (c.f. section 4.1). Examples are:
    - the use of salinity from space,
    - the use of satellite ocean colour data to constrain physical and biogeochemical ocean properties in a consistent manner (Fig. 2),
    - using Lagrangian features of some instruments (often seen today as Eulerian), e.g. ARGO and gliders, and
    - enhanced applications of altimetry to shelf seas and/or high resolution (cases of SARAL/AltiKa and SWOT).

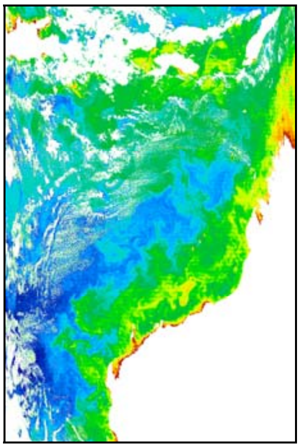

Fig. 2: MODIS image of ocean colour off Australian NW shelf. The figure illustrates the complex processes acting in the coastal zone due to blending of different time/space scales (e.g. ocean-shelf topographic interaction). Forecasting systems operating in such complex environments require sophisticated multi-scale (nested) models and scale-sensitive observing systems for accurate initialisation.

- Operational:
    - Reanalysis: ocean data bases are growing, especially their time span. It is therefore likely that in the future ocean forecasting will perform more longer-term reanalyses. Variational methodology is in principle more adapted than filtering to handle this. But some form of Kalman smoothing can be thought of and should be developed further in this perspective (e.g. SEEK smoother).
    - Parameter estimation/error control: data assimilation should not be seen only as a way to control a sequence of ocean states. It is also a powerful tool for the design of observing systems (c.f. Oke et al. paper in the same issue) and for guiding the design of new model parameterizations. Furthermore, operational ocean model predictions suffer from inaccurate or incomplete surface forcing functions. Further research must be undertaken on how to successfully introduce such wind/flux uncertainties into the assimilation system so that data assimilation controls both the ocean state but also the forcing functions (Skachko et al., 2008).
    - Time « Smoothing »: A major drawback of sequential assimilation methods is the time discontinuity of the solution resulting from intermittent corrections of the model state. The initialisation step can induce shocks in the model restart phase, causing spurious high-frequency oscillations and data rejection. Bloom et al. (1996) propose a solution with the implementation of an incremental analysis update but research must go beyond the current level of knowledge.

- Biogeochemistry:
  The increasing demand for accurate and timely information about the present and future state of our marine ecosystems will see an enhanced use of physical information supporting ecosystem modelling. In

this context, a close multi-disciplinary scientific collaboration and coordination among key bodies representing the physical (post-GODAE) and ecosystem communities (e.g. IMBER and SOLAS) will be essential. The ultimate goal here is the development of efficient data assimilation techniques for biogeochemical modules of ocean circulation models that are fit for operational purposes. However, there are also significant challenges for operational oceanography to accommodate marine ecosystems . These challenges include:

- links to medium and higher trophic levels,
- suitability of physical models and issues with physical data assimilation, and
- biogeochemical and ecosystem observing network status and issues.

What is the current status of marine ecosystem modelling and data assimilation? Despite their limitations, ecosystem models can provide useful information, but ecosystem modelling is much less mature than physical modelling. Consequently, there is a strong need for both on-going development and validation of ecosystem models.

Two approaches are useful when discussing the interaction between ecosystem models and models of higher trophic levels: primary production predictions feeding into models of higher trophic levels (and the need to interpret the results using acoustic sounder data, predator tag and catch data); and alternative simpler approaches. For example, use of physical models to estimate advection of fish larvae, with the larvae represented by time-evolving individual based particle models.

The impact of the physical models on the accuracy of the ecosystem models is of particular importance (e.g., Berline et al., 2007). High horizontal and vertical resolution physical models are required to resolve the physical features that are critical to the ecosystem. Errors in physical model are problematic and can render outputs from ecosystem models meaningless. Vertical velocities are a particular example as they are critical for nutrient transport. In coastal areas correct representation of optical depth is also critical for primary production. This requires accurate suspended sediment concentrations. These requirements for accuracy present a challenge for physical models.

Furthermore, physical data assimilation has been seen to be detrimental to ecosystem simulations, for instance through initialisation shocks. Future developments in physical data assimilation should take into account requirements for ecosystem modelling when developing and implementing assimilation schemes.

Schemes under development for assimilation of biogeochemical data and their initial results are encouraging, and real-time marine ecosystem forecasting will become feasible in the future (e.g. Besiktepe et al., 2003). However, the capabilities of any such system will initially be limited, and understanding of these limitations will be essential. Consequently, thorough validation of offline models will be vital.

- <u>Assimilation in the coastal ocean:</u>
  The development of data assimilation into physical coastal ocean models has lagged behind its development in basin scale models, and is still in its infancy. Current methods need to be tested and enhanced for coastal applications. Data assimilation in costal models has a vital role to play, not only as a tool to provide short-term forecasts, but more importantly for the rigour it brings to the analysis of model error, and to the design of observing systems. As coastal management decisions are more vigorously contested, coastal ocean forecasting systems developed to inform these decisions are placed under ever increasing scrutiny. Traditional ad hoc or heuristic methods of assessing model error or reliability are proving inadequate under those circumstances.

  Several important issues related to coastal data assimilation are mentioned below (they are given detailed coverage in the CSSWG White Paper, De Mey et al., 2007):

- Rich spectrum of coastal processes, of variables to be predicted and of models to predict them;
- Complex physics and range of scales of variability, open system;
- Many data types potentially available for assimilation, some of them with uncertain representativity;
- Issues related to which larger-scale model information can be used and how;
- Non-stationary, non-homogeneous, non-Gaussian, biased error subspace;
- Need for assimilation methods in coupled coastal-deep ocean models and unstructured-grid models;
- Limits to predictability and skill assessment; need for increased-range and higher-resolution atmospheric forcings; need for model testing approaches.

A limited range of methods are presently used to assimilate data in coastal ocean models and for parameter identification. Because of the non-stationary, non-homogeneous error statistics characterizing coastal ocean processes, the successful approaches include at least some degree of built-in physical consistency of the error subspace: Ensemble OI (e.g., Oke et al. 2002), Ensemble Kalman filter (e.g. Mourre et al., 2004), adjoint-based approaches (Taillandier et al., 2004; Kurapov et al., 2005). Variational balanced analyses (e.g. Auclair et al., 2006) are used to suppress transients, and to adjust solutions when projecting a coarser solution onto a finer model grid.

A coordinated and sustained effort by the scientific community will be required to inter-compare, and improve, assimilation schemes fit for coastal ocean problems, for science and operational use. Along with the integration of downscaling within the data assimilation problem, coupled data assimilation, and assimilation in unstructured grid models will be potentially important issues. At this stage, because of the differing situations regarding processes, objectives and data availability, a generic approach does not seem to be the way forward. Instead, science venues could be used for sharing experience among and between geographical focus groups regarding coastal ocean data assimilation and the links with the basin-scale problem.

3.2 Model and Data Errors

Research on the estimation of “model and data errors” includes several techniques that are able to simulate variations between physically distinct regions (e.g. frontal zones, the continental shelf break, coastal waters and polar waters) in the correlations of the errors in model fields. The techniques include ensemble methods, multivariate EOFs and physically-based coordinate transformations:

- Background State Errors: Methods on estimating the background state errors include computation of errors from observations and/or model state anomalies, and from time-averaged ensembles of model forecasts. Background modelling of errors in the surface forcing or system dynamics can readily be implemented in terms of accounting for their temporal correlations in EnKF and 4D-Var methods, and in the estimation of surface forcing parameters controlling air-sea fluxes in coupled model data assimilation systems. Future developments in background modelling of state errors will have to include fully multivariate (T, S, u, v, SSH) constraints in covariance models. Various approaches are being pursued, including balance operators, multivariate EOFs, and model ensembles (e.g. Mercator uses a SEEK filter that includes multivariate, time-evolving error estimates; TOPAZ uses a full EnKF). All of the above methods require estimates of observation errors as well as an understanding of the source of model errors (covariances and biases).
- Observation Errors: All existing global ocean forecasting systems must specify both the measurement and representation components of observation error for essentially the same types of observations. Correlated error is also introduced when satellite retrievals or other data are processed onto regular grids for use in assimilation. Future approaches in data assimilation will have to take into account a combination of observed error estimates, correlation functions and parameters used in the interpolation of the observations to grids. A recent practical method to meet this need includes that of Oke and Sakov (2008).
- Uncertainty: With the increasing number of applications of ocean forecasting there is also a growing demand for analysis and forecast products to be accompanied by a posteriori error estimates.

Downstream users of these products need to make risk management decisions that are facilitated by knowing the accuracy or the likelihood of the predicted value. The accuracy of single model error estimates often suffers from model biases. More reliable error estimates of the forecast products, however, can be obtained using ensemble methods, but the computational requirements of the high resolution global models, and the need for products in near real-time, currently preclude the possibility of each of the forecasting groups producing independent, ensemble-based forecast error estimates. Future developments will see multi-model approaches being pursued to obtain uncertainty estimates for forecast products.

4. New Applications

4.1 Coupled Ocean-Atmosphere Initialisation and Forecasting

Coupled data assimilation means that observations in one medium impact the state of the other medium. In 4D-VAR fully coupled assimilation means simultaneous minimization of the cost function of the component models, e.g. atmosphere and ocean.

A major trend in environmental research in the coming decade will see the development of the next generation weather, climate, and Earth system monitoring, assessment, data-assimilation, and prediction systems (Shapiro et al., 2008). These systems will no longer focus on individual components of the earth system (such as the oceans) but aim at treating the complex physical and biogeochemical components as one system. An example of a less complex system is coupled ocean-atmosphere modelling. Although the present focus is on coupled ocean-atmosphere initilisation a comprehensive earth-systems approach means that ultimately truly coupled physical/biogeochemical initialization systems need to be developed, whereby the ocean, sea-ice, land surface, and atmosphere are initialized in unison.

Consequently, a key challenge in data assimilation over the next decade will be the development of data assimilation techniques for earth system modelling that are fit-for-purpose for a wide range of applications, including ocean-atmosphere weather forecasting, seasonal-to-decadal and climate change prediction (in collaboration with WMO programs). The following section draws on the summary report of a workshop which focused on coupled assimilation for seasonal-to-interannual prediction models that was held in 2003 (Rienecker, 2003).

What are the reasons for approaching data assimilation from the coupled perspective?

A priori:

- the real world is coupled so state estimation should be performed in coupled mode
- ocean models need improved surface fluxes
- atmospheric models need improved SSTs
- the real forecast errors contain coupled modes that should be minimized in the initial conditions

A posteriori:

- we expect more accurate field information/analyses
- we might get better initial conditions for forecasts
- it could potentially improve coupled model simulations
- flux corrections must be consistent in both components of the system – this is automatic in a coupled system

In recent years, there has been some discussion in the community about the need for coupled ocean-atmosphere data assimilation/initialization for seasonal-to-interannual prediction. However, few attempts have been made to operationalise these systems since the problem is very complex, particularly due to the difference in scale between the ocean and atmosphere. Data stream integrity and reliability, data impacts, code maintenance, code performance, not to mention the theoretical and practical aspects of models and assimilations systems are all important technical and scientific aspect to be considered in this context. The key consensus recommendations by Rienecker et al. (2003) for coupled initilization can be summarized as follows:

- Further progress is needed in correcting model biases, uncoupled and coupled. High priority should be assigned to improving uncoupled components in the context of the impact on the coupled system. Coupled models are still not adequate for (seasonal-to-interannual) prediction and we need to invest in improving these models before we invest in comprehensive coupled data assimilation systems.
- For initialization of (seasonal-to-interannual) prediction systems, more research is needed into
  - best initialization compared with best analysis
  - initializing coupled modes
  - statistical corrections to compensate for biases.
- The only sustained demonstration of coupled initialization has been with the Cane-Zebiak model (Cane and Zebiak, 1987). Work needs to be done on how to translate the experience with the Cane-Zebiak, intermediate and hybrid coupled models to fully coupled operational GCMs, particularly in relation to:
  - best initial conditions
  - “noise” representation – e.g., for intra-seasonal oscillations, the patterns seem to be more important than the timescales
  - statistical correction of forecasts to compensate for biases/shocks.

4.2 Regional Seas and Coastal Waters

Future applications of ocean forecasting will see an enhanced focus on large-scale (i.e. gyre or basin-scale) forecasts to provide valuable information for shelf seas and coastal waters (e.g. the EU MyOcean project). The modelling systems to be used can be based on either large-scale high-resolution studies or regional high-resolution studies within large-scale systems. There are currently many techniques for downscaling to coastal waters from large-scale systems including techniques for specification of boundary data and near-shore atmospheric fluxes, model initialisation, characterisation of relative errors in the large-scale and coastal systems and data assimilation in the coastal systems. It is particularly important to examine how the suitability of the existing large-scale estimates to coastal downscaling can be improved. Improvements to coastal systems could be aided by intercomparisons and metrics developed in GODAE but applied in coastal regions.

Accordingly, the following areas require further attention in regional and coastal forecasting systems:

- Data assimilation is now used in most regional studies, with some demonstrated benefit. In addition, a lot of effort went into model development, validation, scientific analysis, all of which need to be pushed further to achieve higher skills.
- There is a widespread use of ensemble methods and stochastic modelling (error estimates, EnOI, EnKF), but further optimisations are possible. These efforts will also help to overcome reinitialization shocks and unphysical behaviour.
- Although tidal toolboxes exist (e.g. Egbert and Erofeeva, 2002), the tidal forcing and its corresponding boundary conditions are not often taken into account, although they are an important (sometimes critical) element of coastal/shelf seas dynamics.

Nesting of regional ocean models in basin-scale ocean models is a pre-requisite for longer term simulations (especially hindcasting) in shelf seas (Fig. 3). Such nesting requires resolving different representations of specific processes – for example the omission or exclusion of tides. For accurate simulations in these coastal and shelf-scale models, we need improved understanding of the shelf edge and slope processes along their margins. This includes appropriate use of 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.

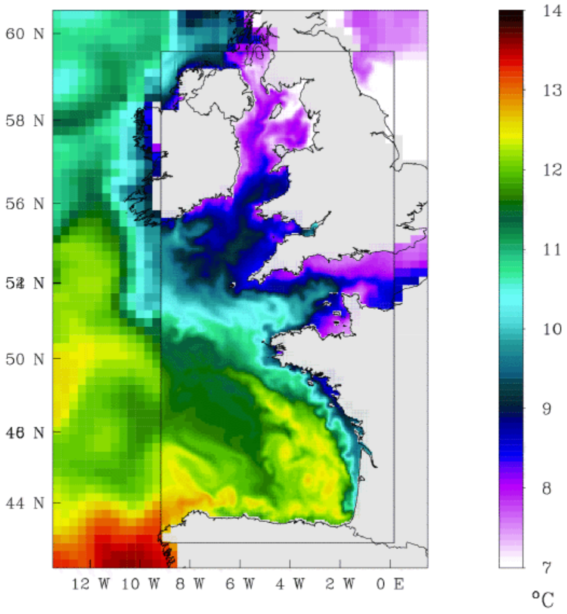

Fig. 3: Application of the 2-way grid-refinement software AGRIF to the Bay of Biscay, tested in the framework of the MERSEA project (Cailleau et al., 2008). The large-scale model is a 1/3° (Mercator grid) North Atlantic configuration of the NEMO Ocean general circulation model. The fine-scale model is regional configuration of NEMO at a resolution of 1/15° (Mercator grid). Both models are run simultaneously and interactively for years of simulation on either vector or massively parallel super computers. The computational surcharge induced by the 2-way coupling of the grids is very small (just a few percent). The regional model benefits from the smooth and regular behaviour of the large-scale model at its open boundaries. On longer time-scales, the large-scale model benefits from the local improvements brought by the high resolution to the representation of the dynamics in the Bay of Biscay, especially the slope current. The above figure displays a sea surface temperature snapshot on 22 March 1996. One shall notice the fine-scale and the intense eddy field of the fine-grid model, but also the continuity at the limit between the two grids.

5. Observing Systems

5.1 New Types of Observations

Nowadays, use is made of observations from satellites, autonomous floats, on-shore devices (radar, tide gauges etc.), off-shore moorings, aircraft, AUVs (Automated Underwater Vehicles) and VOS (Voluntary Observing Ships). Especially in the coastal zone 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 some satellite programmes, synergistic *in situ* monitoring presently relies on national funding (e.g. Argo, TAO/TRITON (USA and Japan) array in Pacific, PIRATA (France, USA and Brazil) in Atlantic and IndOOS (India, USA and Japan) in the Indian Ocean). These basin-scale observing systems are subject to international coordination whereas design and implementation of coastal ocean observing systems are largely the responsibility of individual national efforts. The ECOOP (www.ecoop.eu) European Union project attempts to overcome this national activity by harmonising coastal observing systems across the five EuroGoos regions.

Formulation of coastal models requires accurate fine-resolution bathymetry, and ideally, corresponding descriptions of surfacial 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 preoperational models. Development of model simulations for tides, surges, and waves is constrained by limited accuracy and resolution of both bathymetry and wind forcing (data assimilation may be used to locally and partially 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.

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. 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.

Assimilation of altimeter data is sensitive to the specification of the mean dynamic topography field and further joint work on these fields would be valuable. The new gravimetric satellites (CHAMP, GRACE, GOCE) will be very beneficial in this matter; for example the improvements of the GRACE satellite in determining the mean dynamic topography of the tropical Pacific Ocean was shown by Castruccio et al. (2008). However, the satellite geoid estimate resolution will not be sufficient in the coastal ocean, particularly in the vicinity of the shelf break; good bathymetry estimates and adequate methodology will be needed there to extrapolate the gravity field to the shorter scales.

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. Observing array design studies with a particular focus on coastal domains are required, permitting the exploration of the relative/complementary value of observations in coastal and shelf seas (SST, altimetry, drifters, tide gauges, HF radars, etc.). An example is the Coastal Observatory in Liverpool Bay (http://cobs.pol.ac.uk) with Fig. 4 indicating simultaneous multi-parameter measurements. Altimetry provides a useful direct constraint in global systems; it is of more indirect use in coastal systems, where direct assimilation of classical (nadir) altimetry is difficult. This can be partially overcome through the use of good initial and boundary conditions from larger-scale systems assimilating altimetry. New concepts of altimetric missions such as SARAL/AltiKa (Vincent et al., 2006) and SWOT (Andreadis et al., 2007) will certainly enhance the altimetric capabilities near the shorelines.

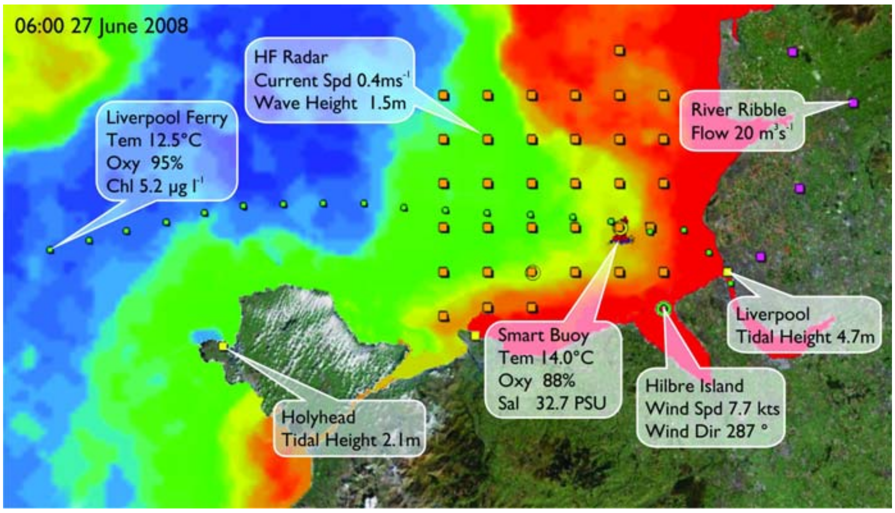

Figure 4: Liverpool Bay Coastal Observatory in the Irish Sea, indicating simultaneous multi-parameter measurements and satellite AVHRR sea surface temperatures.

5.2 Biogeochemical and Ecosystem Ocean Observing Systems

A long-term goal for many operational forecasting systems is the inclusion of near real-time observations of chlorophyll for assimilation into biogeochemical/ecosystem models, in order to constrain the phytoplankton population within the ecosystem model to follow the same timing and spatial distribution as in the ocean itself. However, there are currently limitations to shelf-scale ocean colour remote sensing. Stated simply, the problem with using ocean colour-derived satellite data products in shelf sea ecosystem models is that the measurements lack sufficient accuracy. Compared with the assimilation of sea surface temperature (SST) or sea surface height (SSH) into physical ocean models where the data accuracy is better than 0.3^{o}K or 3cm respectively, the most reliable chlorophyll concentrations retrieved from ocean colour data have errors of around 30% using the standard algorithms. This is for optimal open ocean conditions where the colour of the water is determined entirely by its phytoplankton content. In shallow coastal seas, the water colour is also influenced by dissolved organic material and suspended sediments that derive from land drainage, coastal erosion and river discharge, resuspended bottom sediments, as well as the local phytoplankton population. In these conditions the algorithms for retrieving chlorophyll concentration from the measured spectral reflectance lose accuracy and may fail entirely, with errors in excess of 100% (Robinson et al., 2008).

Although the scientific understanding of the processes underlying ecosystem models has developed in recent years, the methodology has not yet reached sufficient maturity to be relied upon in an operational context. In a few specific situations for monitoring harmful algal blooms three-dimensional ecosystem models embedded in ocean circulation models have been used in a support role. But we are far from realising the vision in which models assimilating observations of phytoplankton can provide a forecasting capability that gives marine research managers the best knowledge of the present state of the ecosystem in a coastal sea. A major obstacle to this goal is that the coupling between observational data and ecosystem models, essential for a successful operational forecasting system, is still at an early stage of development. Numerical ecosystem models require measured data for several aspects of their operation. It is self-evident that observations of the modelled ocean state variables are needed to be able to determine whether the model is providing a realistic description of the ocean. For the most complex ecosystem models this implies that many different biological and chemical properties of the ocean need to be measured, in sufficient spatial detail to resolve the characteristic length scales, and frequently enough to resolve the dominant time scale of variability. The space-time sampling capacity required is very demanding, which is why satellite data are considered to be necessary, even though remote sensing does not sample very well below the surface layer, and there are many ecological variables, such as the zooplankton or nutrient concentration, that are not directly observable by remote sensing. This is compounded by the structure of ecosystem models, which typically seek to describe the behaviour of *functional groups* (i.e. size classes of plankton/zooplankton, sometimes with specific types, e.g. diatoms/flagellates) rather than resolving algal types.

Despite the limited progress in implementing ocean biogeochemical (also known as ecosystem) observing systems there is an increasing user pull for enhanced ocean forecasting capability that includes information about physics, biogeochemistry and ultimately ecosystem components. The biogeochemical and physical systems interact on a variety of processes and scales. Most notable is the impact of biology and associated attenuation depth of light on solar shortwave penetration and thus mixed-layer depth, and the corollary, the impact of suspended material on light scattering and penetration and biological production. Consequently, joint assimilation of physical and ecosystem observations likely will benefit both components though the challenges involved are manifold.

First and foremost is the need of international programs such as IMBER and SOLAS to support the research on, and implementation of, sustained real-time biogeochemical and ecosystem ocean observing systems. There is a need to promote real-time access to existing *in situ* data, and there are prospects for new near-real-time data. Most significant amongst these is the possibility of adding oxygen sensors to Argo floats ("Biological" or "B-Argo") and gliders. Assimilation of satellite-derived chlorophyll data is feasible, but ideally it would be used in conjunction with other (preferably subsurface) observations. As in physical oceanography, a comprehensive biogeochemical ocean observing system will have to exploit synergy between various observations types, and in particular between continuous plankton recorder (CPR) data and ocean colour data in the area of distinguishing plankton groups. Alternative data types are required for medium and higher trophic levels, notably acoustic sounders/predator tag/catch data. Shallow profilers or long endurance ocean gliders, or pelagic animals, might be better platforms for studying processes in the upper ocean and mixed layer.

5.3 Observing System Design and Adaptive Sampling

An enhanced focus on observing system design and adaptive sampling in data assimilating systems will allow assessments of individual components of the observing system and provide scientific guidance for improved design and implementation of the ocean observing system.

OSEs (Observing System Evaluation) assess the impact of *existing* individual components of the observing system on forecast skills, whereas OSSEs (Observing System Simulation Experiments) are tools for planning *new* observing systems. OSEs undertaken during GODAE demonstrate that global and regional forecast systems strongly depend on the availability of high resolution altimeter data (e.g., Pascual et al., 2006). Significant degradation of the performance of these forecasting systems (e.g. forecast skill) and applications (e.g. offshore industry in the Gulf of Mexico) was thus observed when the number of available altimeters was reduced from three to two due to the unavailability of ENVISAT data. Most GODAE applications (e.g. pollution monitoring) require high resolution surface currents that cannot be adequately reproduced without a high resolution altimeter system. OSSEs in the Indian Ocean have provided an estimate of the respective contribution of Argo, XBT and moorings to the observing system in the Indian Ocean (e.g., Sakov and Oke, 2008). They have also shown the influence of equatorial divergence in the dispersion of Argo profiling floats, in particular, when used with a high time sampling rate (5 days). The usefulness of the adjoint sensitivity analysis has been shown for a development of a Kuroshio large meander (Usui et al, 2006). These are extremely valuable tools to develop an improved understanding of the ocean and to help the design of global and regional observing systems.

OSSEs depend on model and assimilation systems and there is a need to identify robust features from larger numbers of OSSEs. A "common" approach (e.g. a set of coordinated OSSEs) could be necessary for making sound recommendations on the observing system and its evolution (one of the GODAE "deliverables"). Related issues are the definition of a common metrics for optimization (global/specific) as well as external metrics (for users).

While OSEs and OSSEs provide an integrated, but methodology-dependent, performance assessment of an observational array, recently proposed approaches based on the representer matrix spectrum (e.g. le Hénaff et al., 2008) focus on the capacity of a given array to detect model errors. This can be achieved independently of any data assimilation method, e.g. from stochastic modelling, or as part of an Ensemble Kalman Filter. Composite arrays with complex space-time sampling schemes can be compared on the grounds of their ability to detect the dominant error-space processes. Using joint probability analysis and ensemble forecast scores (e.g. Jolliffe and Stephenson, 2003), the approach can be extended to the testing of numerical models once data become available.

An evolving method for optimising observing arrays is adaptive sampling (e.g., Wilkin et al., 2005). The key idea of adaptive sampling is that the initial estimate or observation can detect correlations in the environment, providing information about the number of future observing platforms needed or to specify the frequency and spatial distribution required for future sampling certain features in the environment (e.g. eddies, fronts etc.). Thus, adaptive sampling can save costs compared to dense, non-adaptive sampling, and, simultaneously, provide high-resolution information where needed.

6. Summary and Conclusions

This paper tried to identify some of the key future research challenges in ocean forecasting and attempted to provide an outlook about their likely progress and impact.

The last ten years have seen rapid progress in real-time *in situ* observing systems thanks in part to corresponding technological advances and cost reductions in telecommunications and electronic systems. This has facilitated integration of remote sensing with *in situ* data, combining the excellent spatial coverage of remote sensing data with the excellent temporal coverage and extra properties available from *in situ* data. However, significant gaps still exist. Of particular relevance for prediction of shelf sea ecosystems is the development of automated and integrated observing systems capable of delivering a comprehensive set of physical, chemical and bio-optical quantities ranging from measurements of radiance and nutrients to phytoplankton species identification.

For the open ocean the massive deployment of autonomous measurement platforms, such as the ARGO profilers or gliders, has provided an enormous increase in information on the vertical structure of water masses (salinity and temperature), complementing surface information from remote sensing and less reliable but more complete information from models. For shelf seas the deployment of these robots is less simple: horizontal and vertical space constraints increase the likelihood of failure by grounding and the denser ship traffic raises important issues of safety for navigation and legal responsibility for operators of these observing platforms.

As well as the improvements in satellite and *in situ* data, continued advances in computer technology will lead to improvements in the spatial resolution and complexity of physical and ecosystem models and in prospects for data assimilation. Finally, by looking back twenty years to the pre-internet era we should learn to expect that revolutionary new technologies may arise that will further stimulate development of blue-water and shelf-sea forecasting systems. While the specifics are unpredictable it seems certain that remote sensing will continue to progress very significantly in the next twenty years driven by technological advances in microelectronics and telecommunications. It is important that these should be steered towards solving the present technological limitations faced by science. For that reason it is important that a strong dialogue be maintained between agencies concerned with Earth Observation technology, the community of ocean scientists and those responsible for the emerging field of marine forecasting.

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 workshops, training, capacity building, etc.
- Long-term programmes to match the timescales of technology development and international scientific programmes concerned with Global Climate Change and holistic sustainability.
- Enhanced provision of and links to:
    - observational technologies and test-bed sites
    - permanent monitoring networks as components of a global earth observations network
    - global ocean data centres and coastal observatories providing quality-controlled information in the coastal ocean
    - enhanced methodologies for ocean and coupled data assimilation, using the expertise within meteorological agencies
    - in coastal seas improved availability of land-based runoff and associated loads

In addition to the continual demands to enhance model performance in terms of accuracy, reliability, finer resolution, and extended forecast periods, another future research objective is the verification of forecasts on all spatial and temporal scales of interest to operational oceanography. The skill of large-scale solutions, particularly with regard to providing boundary conditions for regional and coastal models and the definition of metrics – consistency, quality of analyses and forecasts, value – are associated issues. GODAE has managed to promote the implementation of verification metrics within the large-scale ocean forecasting systems; the development of appropriate metrics for coastal ocean forecasting systems (physics, biogeochemistry, ecosystems) is a future challenge.

There is an increase in the requirements to extend the scope of ocean analysis and forecasting systems from physics-chemistry-biology to higher trophic level ecology in fully coupled ocean-atmosphere-terrestrial simulations. Human intervention in the marine environment continues to expand beyond the coastal margins to shelf-wide and ultimately basin-scale 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. 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.

More specifically, what major developments in ocean forecasting can we expect to see in the next ten years? Current trends would suggest some fairly predictable advances in physical oceanography. We can expect to see a maturing of the eddy-resolving data-assimilating models, and likely an extension of these to global models, and stronger integration into climate modelling. At the same time, the user community is looking to extend these models inshore, across the shelf, and even into bays and estuaries. We might expect to see high-resolution data-assimilating coastal models in routine use, a challenge in tidally-dominated regions. Better methods for nesting models, or for variable resolution and adaptive model grids, are likely to emerge. In particular, it is important in coastal ocean systems to consider the forcing information (atmosphere, freshwater fluxes, basin-scale models via the lateral boundaries) along with their error characteristics as part of the local data assimilation problem.

The extension of data-assimilating models inshore assumes that we can develop coastal observing systems to support them. Although continuous progress is made towards the better use of existing satellite data in the coastal ocean, the community should support new instruments towards those goals, such as SARAL/AltiKa and SWOT. As a natural complement to satellite observations, coastal radar systems could become routine rather than research tools. One major challenge will be to develop cost-effective in-situ coastal observing systems and local facilities (coastal observatories) to assemble and quality-control the data. We might expect to see more widespread use of gliders and moored networks of sensors. Acoustic data transmission within coastal sensor networks potentially offers a way to avoid surface buoys and reduce losses. Recent ensemble-based approaches to assess arrays in the coastal ocean should be pursued and extended to model testing in a few identified data-rich coastal sites.

Physical observing systems at basin-scale are likely to face the challenge to maintain the current density of ARGO, and satellite altimeters. It also does seem likely that deployment of smart tags on pelagic animals will increase.

We can expect to see improved integration of wave models into coastal hydrodynamic models, and consequently improved sediment model predictions of turbidity and coastal geomorphology. This will be partly driven by concern about effects of increased sea level and storm frequency/intensity on coastal erosion, and partly by concerns about water quality (‘good ecological status’). We might also expect to see coastal models routinely integrated with local area nested atmospheric models, utilising the highest resolution meteorological forcing to better resolve coastal topographical effects. These coastal modelling systems might ultimately become part of high-resolution Earth System models.

For chemistry and biology, there do seem to be prospects for significant advances in observations at the basin-scale over the next five years. The GEOTRACERS program will add substantially to our knowledge of the distribution of micronutrients. We can expect to see further integration of biogeochemical models with ecosystem models. The traditional boundary between these models, drawn at the level of herbivores, is arbitrary, and creates closure problems for both sides. The IMBER research program is largely targeted at eliminating this boundary, and establishing end-to-end models. The key integration challenge here is not about process representation, but about spatial representation and links to physics. Arguably the most important advances in biogeochemical modelling over the next ten years will not involve specific process improvements, but instead involve better methods of treating error and uncertainty.

We can expect to see continued convergence and consolidation of models internationally, through community modelling initiatives. We might confidently predict that there will be fewer independent modelling “platforms”, but more options and versatility within each platform. The choice of platform, and the partners inherited with the platform, will be a critical decision for any research group.

Innovation is a living process, involving in particular education and the formation of the movers and the users of operational oceanography. A structure such as GODAE has played a very beneficial role in this matter keeping the international dimension and interactions between the various groups and interests. There is a need for keeping alive this role even though the various ocean forecasting projects in the world have reached a certain level of maturity whereas they were just at their birth at the beginning of GODAE.

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