Modeling and Simulation for a Global Ocean Observing System

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Abstract Modelling and simulation are fundamental to the development and evolution of oceanography as a science, and as a long-term, viable operational activity. The role of models is discussed in general terms, focussing on their function as a processor of information, at the heart of the chain of information flow from observations to products, many of which are of significant societal value. The context for this paper is provided by the emergence of a Global Ocean Observing System, the conceptual umbrella for the development of operational oceanography. Models in their role as forecasting tools epitomise the objectives of this system, providing information for decision making and other applications that might otherwise be unavailable. In oceanography there is also great emphasis on the ability of models to enhance interpretation of data and to integrate and extrapolate information. Data assimilation, either through forcing fields or through direct merging of data and model fields, is also identified as a key activity in oceanography. It is emphasised that models will never be perfect and that by carefully examining the model errors we can learn how to improve both the observing network and the model. Several examples are presented of ocean models in action including forecasts of El Niño, climate change predictions, estimates of global and regional ocean circulations and short-range ocean forecasts. The Global Ocean Data Assimilation Experiment is introduced and its objectives discussed. It is argued that this experiment is vital if oceanography is to take the step from a curiosity driven field, with the consequent necessity for proposal-led support for observing and modelling, to one where real applications motivate and sustain investment in the global ocean observing system and in turn provide an even more energetic and vital research effort.

1. INTRODUCTION

Scientific research over recent decades has realized tremendous advances in oceanography, for regional and global problems, and over a broad range of temporal and spatial scales, from climate prediction (large scales, long periods) to understanding of oceanic microstructure (small scales, high frequencies). These advances are leading physical oceanography from a predominantly curiosity-driven field to one where practical applications and routine delivery of valuable products is possible. Meteorology made this transition some time ago, culminating in global meteorological observing and numerical weather prediction systems that are now often taken for granted.

The concept of a global ocean observing system, roughly emulating the global atmospheric system, was developed to take oceanography into this "operational" mode. The system would encompass routine and regular observations, modelling, data assimilation and forecasting. This paper focuses on the "processor" part of this concept, that is on the model and data assimilation tools that can be used to translate a suite of inhomogeneous and irregular inputs into regular fields.

This paper takes a very selective look at ocean modelling, in the context of a developing operational capability. Due to the author's interests, the focus is mostly on physical oceanography and climate. Smith [1993] gives a rather more detailed review of the role of ocean models in climate and the reader is referred to that paper, and the references therein, for a more general account.

2. MODELS AND GLOBAL OBSERVING SYSTEMS

2.1 The essential role of models

A mature modeling activity, with assimilation of ocean data, is seen as fundamental to the development of viable and effective operational oceanographic activities. By combining oceanographic data with our knowledge of physics and dynamics (which are encapsulated in our model equations) we begin to exploit the true potential of both, extrapolating information collected locally, and irregularly, into remote regions and into other areas of the time domain (forecasting), and inferring other important properties of the ocean. Integration, assimilation, interpretation and extrapolation are each important features of the application of models, unlocking the true potential of the total system. At the most fundamental level, models allow us to form descriptions and representations of oceanographic phenomena based on irregular and dis-integrated sets of information. They are processors of raw information, and generators of refined, processed outputs, in a form that is "useful". A hierarchy of models are needed in this chain, ranging from models for translating signals sensed by satellites into physical variables, to the complex coupled ocean-atmosphere general circulation models used for climate change studies.

Having just extolled the fundamental virtues of models in oceanography, it is important to remember that models and their products are utterly dependent on the supply and quality of the incoming information. Without real data models are no more than scientific toys, of little practical use. Without observations, models lose their power; they are processors but without anything to process.

2.2 Knowledge and research

If the inputs-processing-outputs chain is viewed as the paradigm for a functional operating ocean system, then knowledge and research are the foundations upon which the system is built. Without fundamental knowledge of the variability and principal processes of the ocean system, it is impossible to construct a processor which exploits the input information effectively. In reality, communication within the ocean, and between the ocean and surrounding media, is carried out through a complex combination of, among other things, advection (currents), waves, mixing and overturning, diffusion and other microscale processes. It is this complex combination which we presume to represent by a model, and it is through assimilation that we try to blend samples of the actual ocean state, which of course is subject to all the above processes, with a model approximation. Model approximations, and any lack of understanding of the true ocean, will lead to mismatches as we ingest information, which in turn manifest as errors in the outputs.

In order to exploit the ability of models to extrapolate into the future (forecast), we must have a proper understanding of the variability and predictability of the system. That is, for the signals and phenomena that we seek to forecast, we must understand how much can be determined on the basis of the inputs, and what part is due to inherent instabilities and chaos in the system. If the latter dominate, then there is only limited potential for forecasting while, conversely, if there is a dominant deterministic component, then we might hope to develop a skilful prediction system.

The OOSDP [1995] discussed some of the aspects of models and research in observing system design (their Section III.D). They argued that there must be a multi-staged approach, starting with fundamental research and studies of variability, and culminating in a partnership between operational applications and research whereby the quality and effectiveness of the products are used as the motivation for scientific study of elements in the chain. In this mode, scientific research and improved understanding are the basis upon which the system evolves and matures. The Tropical Oceans-Global Atmosphere Experiment (TOGA) and the World Ocean Circulation Experiment (WOCE) have been particularly important in this regard.

2.3 Applications

The existence of useful and practical applications, and a long-term "market", distinguishes operational oceanography from oceanographic research. This does not mean that *science* is not important for an operational system but that the viability and existence of the system is based on practical applications and a mature, long-term user community.

It is the nature of the applications which ultimately determines the form of the processing system. For example, for some applications it is important that data are available within several hours of it being collected, but the spatial sampling requirements may be less severe, as might the quality requirements. For other applications, such as climate change assessment, the emphases will be different, with delays being tolerable, but high quality and spatial coverage assuming greater importance. Both cases imply different types of processing/modelling systems.

2.4 GOOS and GODAE

It is appropriate at this point to introduce two acronyms which figure prominently in the motivation behind this paper. The Global Ocean Observing System (GOOS) is the international, programmatic manifestation of the concepts described above, though with a far broader remit than just physical oceanography. Its general aim is to put in place a routine, long-term systematic program of ocean measurement, processing and services. The principal application areas are climate, living marine resources, health of the oceans, coastal monitoring and prediction, and marine analysis and prediction (in effect the non-climate aspects of physical oceanography).

Products with global dimensions have global dependencies, so proof of the GOOS concept requires significant up-front investment. This is unlikely to eventuate by chance so the concept of a Global Ocean Data Assimilation Experiment (GODAE) has been put forward. GODAE is envisaged as the proof-of-concept for GOOS, at least for the physical components, and would comprise a concerted data gathering, modelling and assimilation effort for a fixed period, nominally 2003-2005. This is discussed in greater detail later.

3. MODELLING AND SIMULATION

As noted above, models are a fundamental element of oceanographic research and applications. While the majority of models discussed in this paper have their foundations in geophysical fluid dynamics and the Navier-Stokes equations, it should be acknowledged that many statistical and empirical models have also enjoyed wide use in the scientific and applied communities.

Modelling in oceanography is a relatively immature field, though with some notable exceptions (e.g., tidal models). Through the first half of this century several of the fundamental papers on models in geophysical fluid dynamics, such as the study of Rossby waves, owed as much to oceanography as they did to meteorology. However, through the second half of the century, the demand for weather forecasts, and their obvious strategic importance, drove meteorological research and observing to new levels, so that today we enjoy the benefits of a global, cooperative observing system (the World Weather Watch) and very skilful numerical weather forecasts. Through the ability of models to assimilate data and then produce forecasts, this community now enjoys, perhaps even takes for granted, skilful forecasts at greater than 5 days lead time.

Oceanography did not keep pace with meteorology for several reasons. First and foremost, there was not the imperative to drive development of operational oceanography. Second, the modelling problem, in terms of the scales that must be resolved, is several orders of magnitude more difficult, making it a challenging computational task. Moreover observing the ocean is a logistical challenge at the best of times. To observe the global ocean, through its depth, even once, requires a supreme effort, such as WOCE. To do it regularly and routinely, even for just the upper ocean, remains a daunting objective even today.

3.1 Processing information

The role of models in oceanography is fundamentally the same as that of models in weather prediction. They are processors of information, provided via observations or perhaps as products of other models, permitting richer interpretation of the information. This "richness" may simply lead to a better understanding. Or it may lead to simulations of fields that cannot be directly observed, or to field estimates in places of space (and time) that were not sampled. There is probably greater (relative) importance attached to interpretation and hindcasts in oceanography compared with meteorology, for example, in coastal management, environmental studies and in offshore engineering, to name but a few applications. The logistical problems associated with observing the ocean have placed greater emphasis on the ability of models to interpret and extrapolate information, and thus extract value commensurate with the investment in observations.

3.2 Model hierarchies

At the most basic level, models and their realisations are often used a means of verifying data interpretations, or hypotheses. For example, a simple coastal model with particular attributes might be used to test an hypothesised mechanism for an observed circulation feature. In turn, data might be used to verify the ability of a model to simulate a particular phenomenon, for example, climate change.

At the next level, there is a non-trivial form of data ingestion, often through boundary conditions, but also through assimilation of interior ocean data. The challenge is to find an appropriate method to blend the model and the observations, extracting that part of the observations which is useful, and can be used by the model, and developing a model which can use the available information and which has skilful information interpreting and carrying properties.

The next level provides for more sophisticated interaction between the observing and modelling components. Most forms of data assimilation generate, along with the field estimates, statistics of how well the model data assimilation worked with the observations provided. In this mode, the assimilation process plays an active role in the evolution of the observing system, and the observations and products play a non-trivial role in the evolution of the processing system.

4. MODELS IN ACTION

The discussion here is, through necessity, selective and eclectic. These examples have been chosen as an indication of the leading-edge in model sophistication and application, and come from areas which at present enjoy high profiles.

4.1 Seasonal-to-Interannual Climate Prediction

The 1997 El Niño is truly the "event of the century" in terms of media coverage and attention, and is clearly among the most significant tropical climate variations ever observed. It is also distinctive with respect to the number and sophistication of the models available to predict its evolution. Many theories have been put forward in an effort to explain El Niño, but it was TOGA which brought about real success through dedicated real-time measurements and advanced modelling.

The first successful forecast of an El Niño-Southern Oscillation (ENSO) event was due to Cane and Zebiak [1997] who used what is now termed an "intermediate" class coupled model. The basic premise behind their model was that ENSO is inherently a coupled tropical ocean-atmosphere phenomenon, so by capturing the essential features of the oceanic and atmospheric system and, in particular, the positive feedback provided through SST-forced surface wind changes, they were able to capture the unstable mode that we call ENSO. Such models typically have modest horizontal resolution, and only one or two vertical modes, and highly simplified physics, rendering them extremely cost-effective. The 1986-87 event was forecast several seasons in advance and, in so doing, heralded in an unprecedented growth of activity in modelling of ENSO.

Many different models have followed. Kleeman et al. [1995] introduced an intermediate class model, similar to

Cane and Zebiak, but with the addition of ocean data assimilation. This model was probably the first official operational ENSO forecast model, at the Bureau of Meteorology, Australia. The model is used routinely in producing climate advice for Australia.

There are now several coupled general circulation class models being used routinely to forecast ENSO. Ji et al [1994, 1995] describe the forecast model operating at the National Centre for Environmental Prediction, USA. This model has provided the benchmark for this class of models and, for the present event, has proved extremely effective at predicting the amplitude of the event though, like many other models, it was not able to provide a long-lead forecast. Several models of this class have demonstrated significant skill from initial conditions from early 1997, prompting the thought that perhaps this class is about to assume pre-eminence in terms of skill [the complete failure of the Cane and Zebiak model has fueled this speculation].

4.2 Climate Change

The Kyoto Conference is focussing unprecedented attention on the effect of enhanced greenhouse gas concentrations on our climate. The scientific basis for the wide-spread concern is encapsulated by the assessments of the Intergovernmental Panel for Climate Change (IPCC; e.g., IPCC 1995). Gates et al. [1995] examined the performance of models being used to produce climate change predictions. A typical ocean model configuration includes around 20 vertical level, 1 to 2° horizontal resolution, complete dynamics and physics, including salinity, and various parameterisations for sub-grid scale processes. The ocean models, when validated in their own right, have significant systematic errors, including poor representation of the equatorial region, missing or grossly inadequate western boundary currents, and large errors in deep water temperatures and salinities. All coupled models suffered from severe climate drift, though it was hard to ascertain just what part of this drift could be attributed to the weaknesses of the ocean model.

Many of these errors have been addressed in recent years, including a more realistic representation for mixing of heat and salt (e.g., Power and Hirst 1997). The improvements in all components of the coupled models (ocean, ice, atmosphere, land) are such that many groups are now running models that exhibit only weak climate drift, thus lessening or removing the necessity for flux corrections. The "natural" climate variability in these models is also of significant interest, at the time scales of ENSO, and at decadal and longer time scales. This variability can have a large impact on climate change predictions.

4.3 Ocean Climate

WOCE has been at the forefront of attempts to improve our knowledge of the global ocean circulation. The first phase of WOCE, which was dedicated to improving our observational base, ends in 1997. The following five years will be dedicated to analysis, interpretation, modelling and syntheses based on these and other data.

With respect to modelling, there have been two key strategies. First, using leading edge computers, and leading edge numerical models, scientists have been attempting to model the ocean circulation (both globally and regionally) at very high resolution. Eddies are permitted at around 40 km resolution but it requires finer resolution (better than 1/10° in many cases) before the natural variability of the ocean is realistically represented. The other approach has focussed on data assimilation, usually with sophisticated assimilation methods (e.g., Wunsch 1996) but modest model resolution (perhaps 1° horizontal resolution). WOCE originally aimed for a "snapshot" of the global circulation (that is, an estimate of the mean circulation) but, in view of the significant interannual variability, many approaches are now focussing on time evolving estimates (e.g., Stammer 1997). Altimeter data is proving particularly effective for these applications.

4.4 Short-Range Ocean Prediction

The climate change and global ocean circulation models discussed above have, as a prerequisite, resolution of the deep circulation. However for many applications it seems the deep ocean can be approximated by climatology, or ignored altogether, instead focussing on the circulation above the thermocline. The coastal regions are clearly of prime importance so considerable effort has been devoted to building useful coastal forecast systems. These models place high premium on the resolution of geometric and bathymetric features.

Another class concentrates maximum effort on horizontal resolution (better than 1/10th degree in many cases) at the expense of vertical resolution (perhaps only 5 or 6 layers) and complex physics. These models give quite realistic eddy fields and have demonstrated potential for short-range (0-14 day) forecasting of the upper ocean circulation.

5. THE GLOBAL OCEAN DATA ASSIMILATION EXPERIMENT

The objective of GODAE is to demonstrate the practicality and feasibility of routine, real-time global ocean data assimilation and prediction. GODAE is founded on the belief that such a demonstration is vital if we are to ever realise a permanent, global ocean observing network and prediction system, with all components functional and operating on a global domain, and delivering useful products in a timely manner. GODAE will emphasise integration of the remote and direct data streams, and the use of models and data assimilation to draw maximum benefit from the observations.

The general objective of GODAE is [GODAE 1997]

> *To provide a practical demonstration of real-time global ocean data assimilation in order to provide regular, complete depictions of the ocean circulation, at high temporal and spatial resolution, and consistent with a suite of space and direct measurements and appropriate dynamical and physical constraints.*

The word "experiment" implies a test of the viability and practicality of global remote and direct observing systems, and the exercise of new and original real-time data processing methods. The concept of GODAE is fired in part by the development and maturity of remote and direct observing systems, making global real-time observation feasible. The steady advances in scientific knowledge and our ability to model the global ocean and assimilate data at fine space and time scales are also critical.

A selection of sub-objectives, the related drivers and needs, and expected character of the associated products are listed in Table 1. There is significant diversity in the objectives and applications, so that GODAE will be a truly multi-purpose experiment. GODAE embodies a range of processes and applications, drawing power and strength from the fact that they all require ocean data and models, and that there are important commonalities in all components.

GODAE will require significant investment of intellectual and human resources (people keen and able to do the work and meet the challenges), as well as investment in instruments, communications, computers and infrastructure.

The draft schedule is:
(1) Definition of the experiment: 1997
(2) Feasibility studies and scoping: 1998-1999
(3) Testing (pre-operational): 1999-2002
(4) **Realisation of GODAE**: 2003-2005

The lead time is frighteningly short for such an undertaking, but this should not deter us from trying. We have nothing to lose from trying, and a tremendous amount to gain.

6. SUMMARY REMARKS

Models are an integral part of the evolution of oceanographic research and operational applications. Models are "processors" of information, information that arrives either directly or indirectly from observation of the ocean and/or its boundaries. This processing can lead to a variety of useful outcomes, including improved understanding, forecasts with societal value, input for management and decision making, and products for coastal and ocean "users", such as fisherman and merchant traffic. Models provide the heart of the input-output chain, the ability to take irregular observations, perhaps of uneven quality and different types, and turn this information into useful products.

Like all processing chains, the processor and outputs are utterly dependent on the information supply. The best model in the world is useless in the absence of observations. Moreover, the unstable or chaotic nature of oceanic variability means that information renewal is mandatory. At the other end of the chain, it is critical to

Objective	Driver/Needs	Output Characteristics
Extend predictability of coastal and regional sub-systems.	Coastal forecast systems; regional monitoring, prediction	scale ~ week, 100 km fields: T, $\underline{u}$, SL
Provide several -> 20 day high-resolution, upper open-ocean forecasts and nowcasts.	ship routing, transport, safety at sea, naval applications	rapid delivery, scales ~ 10km. Fields: $\underline{u}$, SL, $\underline{u}$(surface), T(z_{upper})
Integrated analyses for research and development. Reanalysis	CLIVAR, GLOBEC, etc. Hypothesis testing, process studies	~ 10 day, 150-100 km res., but high quality; delayed delivery OK; full depth, 10 v. modes; T, S, SL, $\underline{u}$
Initial conditions for climate forecasts; e.g. Kuroshio, NAO, ENSO.	Western boundary current prediction; seasonal prediction; climate change.	~ 10 days, 100-200 km; SST, SL, heat content, high quality
Sustain and design for a permanent global ocean observing system, including remote and direct.	GOOS, GCOS, operational oceanography, multi-purpose applications	Managed data streams. QC systems Efficiency. Guided evolution.

Table 1. Objectives of GODAE, listing the principle drivers for each objective and the expected characteristics of the model outputs.

continually evaluate and test outputs and products. Such examinations assist the observing and modelling components to evolve, develop and improve. Forecast skill is one measure, but it is often in the detail of the data-output residuals that we find the richest information.

Several examples of ocean model applications were discussed, some from scientific experiments such as WOCE, and others from the quasi-operational field of seasonal-to-interannual climate prediction. We noted that oceanography appears on the threshold of a major change, from a primarily experimental and curiosity-driven field, to one where there is a major operational component. This latter component, in turn, has the potential to motivate and foster increased scientific activity, particularly with respect to modelling.

Based on this changing environment, a Global Ocean Data Assimilation Experiment has been proposed. Its purposes are manifold, but at the most fundamental level it aims to mobilise a long-term and routine operational oceanographic community. GODAE is building on past and on-going scientific experiments. In intends to call on a major effort from the remote and direct observing communities, from modellers, and from those involved in value-adding processes, to take oceanography toward a truly global observing system, with appropriate processing and computing powers, and with a mature, stable user community.

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