OCEAN WEATHER FORECASTING

Ocean Weather Forecasting

An Integrated View of Oceanography

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This book is dedicated to Christian Le Provost (1943-2004), an eminent scientist in the domains of ocean physics, tides, satellite altimetry, and ocean modeling. He was also a pioneer in the development of operational oceanography.

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PREFACE

Progress in a wide range of ocean research and applications depends upon the prompt and dependable availability of ocean information products. The field of physical oceanography has matured to a point where it is now conceivable to combine numerical models and observations via data assimilation in order to provide ocean prediction products on various spatial and time scales. As a result, many nations have begun large-scale efforts to provide routine products to the oceanographic community. The Global Ocean Data Assimilation Experiment (GODAE) provides a framework for these efforts, i.e., a global system of observations, communications, modeling, and assimilation that will deliver regular, comprehensive information on the state of the oceans, in a way that will promote and engender wide utility and availability of this resource for maximum benefit to the community. The societal benefit will be an increased knowledge of the marine environment and ocean climate, predictive skills for societal, industrial, and commercial benefit and tactical and strategic advantage, as well as the provision of a comprehensive and integrated approach to the oceans.

We therefore considered it timely, given the international context, to bring together leading scientists to summarize our present knowledge in ocean modeling, ocean observing systems, and data assimilation to present an integrated view of oceanography and to introduce young scientists to the current state of the field and to a wide range of applications. This book is the end result of an international summer school held in 2004 that aimed, among other things, at forming and motivating the young scientists and professionals that will be the principal movers and users of operational oceanographic outputs in the next 10 years. The chapters collected in this volume cover a wide range of topics and are authored not only by scientists, but also by system developers and application providers.

We would like to thank all the speakers for providing a stimulating series of lectures at this GODAE Summer School. We also express our appreciation to the members of the scientific committee and to the GODAE IGST who contributed in numerous ways to the success of the school. We thank all the attendees (see list in Appendix) for participating actively in the lecture review process and for creating a most cordial atmosphere. We thank Jean-Michel Brankart, Laurence Crosnier, Nicolas Ferry, and David Rozier for preparing and putting together a superb set of student exercises. Finally, our thanks go to Yves Ménard, Joëlle Guinle, Véronique Huix, Nicole Bellefond, and Josiane Brasseur who spent a considerable time with the logistics of the school before and after. A special thank goes to Josiane Brasseur for her help in formatting the manuscripts.

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April 15, 2005

Chapter 1

PERSPECTIVES FROM THE GLOBAL OCEAN DATA ASSIMILATION EXPERIMENT

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Abstract : The Global Ocean Data Assimilation Experiment (GODAE) is introduced, including a discussion of the historical basis and conceptual framework. GODAE aims to develop a global system of observations, communications, modeling and assimilation that will deliver regular, comprehensive information on the state of the oceans in a way that will promote and engender wide utility and availability of this resource for maximum benefit to society. The overall strategy and guiding principles are introduced and the core components discussed. The data and modeling and assimilation systems are intended to provide infrastructure serving a broad range of users and applications. The targeted applications include open-ocean forecasts, coastal and regional prediction, climate assessments and prediction, and reanalyzes for scientific and other purposes. Both internal and external metrics have been developed to assure the quality and reliability of the product streams. The focus at present is on developing an understanding and more intimate relationship with the user community.

Keywords : Ocean, data assimilation, observations, prediction.

1. Introduction

The concept of a Global Ocean Data Assimilation Experiment (GODAE) emerged from the Ocean Observation Panel for Climate (OOPC) in 1997 and derived from concern that attracting the investment for an adequate long-term global ocean observing system depended upon a clear demonstration of the feasibility and value of such a system (Smith and Lefebvre, 1997). Using the First GARP (Global Atmospheric Research Program) Global Experiment (FGGE) as a model, OOPC proposed GODAE as an experiment in which a comprehensive, integrated observing system would be established and held in place for several years and the data

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assimilated into state-of-the art models of the global ocean circulation in near real-time to demonstrate utility.

GODAE recognized the pioneering work in operational oceanography in the U.S. (see Peloquin, 1992, and other papers within that special volume) and the fact that interest in building a broader global capability was emerging in several nations (for example, MERCATOR in France; Bahurel, this volume). This work, among others, guided the development of the concept and ultimately the strategy (International GODAE Steering Team (IGST), 2000) and implementation plan (http://www.bom.gov.au/GODAE/).

As with many international initiatives, GODAE by itself does not provide resources or develop capacity. Rather it relies on the resources and capacity derived from national or regional initiatives and GODAE's role is one of coordination and cooperation and, for example, introducing standards and references for the business of operational oceanography.

This paper recounts the development of GODAE and some perspectives drawn from experience and from those who are thinking of the future of operational ocean analysis and prediction. In order to provide a little context for GODAE in relation to the evolution of ocean science and the development of weather prediction, Section 2 discusses some historical aspects and section 3 some of the lessons learnt from numerical weather prediction. Section 4 discusses the rationale and scope while section 5 introduces the core components. Other chapters of this volume examine these components (e.g., observations, models, assimilation) in more detail. Section 6 discusses applications and the utility of GODAE products and some of the issues surrounding the use of model products. Again, there are several papers in this volume (e.g., Hackett et al.) that go into this area in more detail. Section 7 discusses methods the GODAE community is using to test and validate their products and services. Section 8 discusses the user community and implications for the systems and methods being developed within GODAE. The final section provides some brief conclusions.

2. A little history

Scientific observation of the oceans did not begin in earnest till about the nineteenth century; till this time, exploration and expanding ocean trade routes were the primary concern. Advances in communication technology led to the idea of using under-sea cables to connect the American and European continents. This required knowledge of the sea bed and thus led to exploration of the depth of the ocean; until this point, almost all knowledge of the oceans was derived from surface observation. Along with the improvements in knowledge of the depth of the sea, it was discovered that life did exist at great depth. Scientific cruises for systematic exploration were born. The British *Challenger* expedition from 1872 to 1876 and German exploration on the *Gazelle* from 1874 to 1876 were two of the early successful deep sea expeditions, taking systematic measurements of ocean currents, temperature, chemistry and biology, as well as sampling bottom sediments.

Valuable trading routes had been started on the open seas and travel time was a critical element of commercial success. M.F. Maury, superintendent of the Depot of Charts and Instruments at Washington, D.C., began to collect and collate information on surface currents and weather conditions leading to the publication of *The Physical Geography of the Sea* (Maury 1859), making it one of the first practical applications of ocean science and ocean observations. If a point in time has to be chosen to mark the beginning of operational oceanography, this time is it. Maury led the organization of an international system for regular observation; sailors on all vessels at sea would regularly record certain observations (e.g., sea state, sea surface temperature, weather, etc.) and, in exchange, they would be provided with charts of ocean currents and weather conditions in order to plan their voyage. The legacy of these early efforts can still be appreciated in the GODAE systems of today.

These scientific endeavors marked the start of what Neumann and Pierson (1966) termed the first era of oceanographic research. The three-dimensional structure of the ocean was being observed for the first time. The second era was born out of the realization that the ocean was not stationary and that its circulation could be partly explained by theoretical relationships (e.g., Ekman, 1905). Exploration of the oceans moved into the four-dimensional era; expeditions of the early twentieth century were making more accurate physical and chemical measurements and the station spacing was closer, driven in part by theoretical revelations. While this era probably marked the first awareness of spatial and temporal sampling problems, it was to be many years later before the ramifications of aliasing and poor spatial resolution were to be fully appreciated.

The third era was characterized by significant technological advances, such as the bathythermograph, and by highly organized, intensive oceanographic surveys which sought quasi-synoptic sampling of large regions. This era also marked the introduction of non-ship instrumentation such as drifting and moored buoys. One of the more imaginative innovations of this period was the neutrally buoyant float (Swallow 1955), a technology that lies at the heart of the Argo campaign of today. This period was also marked by significant advances in theory, not the least being the first theoretical explanations of the gyres and intense western boundary current depicted in Maury's chart (e.g., Stommel, 1948; Sverdrup 1947).

The modern era of oceanography has been shaped by at least three factors. First, costs and logistical considerations have driven the development of mooring and autonomous underwater and surface technology. These advances combined with real-time telemetry not only make synoptic observation of the ocean practical, but allow data to be delivered to models quickly.

A second significant factor is satellites. The vastness of the oceans has, and will forever, preclude near-simultaneous sampling of the oceans by conventional, *in situ* instrumentation, even at the surface. Remote sensing offers the promise of ocean data over all regions of the globe, near-simultaneously, though restricted to a surface view.

A third factor is related to both the previous factors - computing. The growth in computational capacity over the last 50 years has been phenomenal. For observationalists, it has revolutionized instrumentation, allowing more detailed and accurate recording and near-instantaneous processing, both on research ships and on moorings and autonomous devices, and in land-based laboratories. Computing power was the key enabling technology for satellites. Computers have revolutionized the capacity of ocean modelers to represent the circulation of the actual ocean. It is this capacity, as much as any other, which has underpinned the evolution of modern oceanography to the point where routine, operational oceanography is feasible and the concept of GODAE, makes sense.

The legacy from ocean research experiments such as the Tropical Ocean Global Atmosphere Experiment (TOGA; McPhaden et al.,1998) and the World Ocean Circulation Experiment (WOCE; e.g., Smith 2001) is also very important. TOGA developed systematic observation and routine prediction of seasonal-to-interannual climate variations (e.g., El Nino) with requirements closely related to those of GODAE and operational oceanography. WOCE introduced many innovations in observation and developed the models and assimilation methods that are the basis for many GODAE systems.

Perspective #1: Scientific and technical advances over the last century, including accrued knowledge of the dynamics and physics of the ocean, provide the basis for developing the systems of GODAE.

3. Lessons from meteorology

At the First GODAE Symposium, Dr. Tim Palmer delivered a lecture "En Route to GODAE: A brief history of NWP" (see www.bom.gov.au/GODAE) and, within that lecture, he cited from Charney et al. (1969) concerning US participation in the then Global Atmospheric Research Program (GARP): “It is estimated that the data requirements of computer models are met for only 20 per cent of the earth’s surface. Vast oceanic regions remain unobserved… the earth-orbiting satellite affords the opportunity of developing an economically feasible global observing capability.” Meteorologists were concerned with their ability to observe the relevant atmospheric variables, at all levels and globally, and to have that data available each day for models and forecasts. Moreover, on the basis of progress made with atmospheric models, they wished to test the hypothesis that models and data assimilation could extend useful predictability and provide useful forecasts, at lead times several days ahead of what was possible at that time.

The goals of GARP were effectively (a) deterministic weather forecasting and (b) understanding climate. The First GARP Global Experiment (FGGE) was conceived to address the challenges above and set down several specific goals:

(i) Development of more realistic models for extended range forecasting, general circulation studies, and climate.
(ii) To assess the ultimate limit of predictability of weather systems.
(iii) To develop more powerful methods for assimilation of meteorological observations and, in particular, for using non-synchronous data...
(iv) To design an optimum composite meteorological observing system for routine numerical weather prediction.

Bengtsson (1981) discusses the impact of FGGE on numerical weather prediction, the meteorological counterpart of the systems GODAE is developing. It is clear that significant progress was made against each of the goals of FGGE and that that experiment was critical in the development of modern weather prediction systems. Palmer also showed the evolution of forecast skill since FGGE, around 2 extra days in lead time in the Northern Hemisphere, and over 3 for the Southern Hemisphere. This progress has been made possible by better observations (particularly remote sensing), better models, faster computers, and most importantly, a vastly improved knowledge of the dynamics and physics of the atmosphere. The improved skill however only tells part of the story. The information content of a modern numerical weather prediction system bears little resemblance to its predecessors during FGGE. Regional models are often operating at scales of 5-10 km or better, and these broad measures of skill do not capture the immense value added through finer resolution (indeed, in some cases, the systems are penalized!). Many forecasts systems are also producing more than one forecast (ensembles) so that the users can now apply forecasts with knowledge of the probability of an event occurring. Assimilation systems are also being extended, for example to consider ozone, air quality and carbon dioxide. Finally, these same systems are being used to produce consistent (re-)analyses of the atmospheric state.

While there are significant differences between the goals of numerical ocean prediction (the GODAE focus) and numerical weather prediction, it is also clear that our community can benefit from the experiences of that community, including their failures. We will discuss objectives and products that closely parallel those discussed here. It is also likely GODAE systems will utilize and/or share a great deal of the infrastructure developed for weather prediction, including observational networks, data and product communication networks, computers and organizational infrastructure.

One difference that is worth considering is that at this time the numerical ocean prediction community does not have the benefit of a dedicated ocean research program. GARP has morphed into the World Climate Research Program, which does consider climate aspects, but its Programmes do not provide the focus that we need now and in the future.

Perspective #2: We have a good model to follow in the development of numerical weather prediction and we can deliver efficiency and effectiveness by partnering and sharing with this community.

4. The concept of and rationale for GODAE

4.1 The vision

The key to harnessing the powerful resources of the ocean and mitigating and/or exploiting its impact on our environment is knowledge - knowledge of the way the ocean has behaved in the past and of how it is likely to behave in the future. Monitoring and forecasting the behavior of the ocean is one of the major challenges for this century, as a prerequisite to sustained development of the marine environment and the implementation of seasonal prediction and climate forecasting systems.

The vision of GODAE is (IGST, 2000):

> "*A global system of observations, communications, modeling and assimilation, that will deliver regular, comprehensive information on the state of the oceans in a way that will promote and engender wide utility and availability of this resource for maximum benefit to society.*"

Regular depictions of the ocean state will be obtained through synthesis of observations with ocean model estimates. The models will allow us to assimilate and integrate complex information in a way that is consistent with our knowledge of ocean dynamics and physics.

Scientifically, in the totality of its complexity, the problem is enormous. Yet, it is evident that most aspects are now tractable. The benefits of assimilation of ocean observations into ocean and climate models has been demonstrated (e.g., Ji et al., 1998; Giraud et al., 1997; Burnett et al., 2002, and papers within that Volume; Wunsch, 2001). A system of ocean data collection and modeling of the ocean that will allow us to follow the state of the ocean routinely seems in the realm of feasibility (see also Smith and Lefebvre, 1997).

4.2 The rationale

GODAE is inspired by both opportunity and need. There is a genuine user demand for ocean products, for a range of time and space scales (e.g., Flemming 2001, Altalo, this Volume). There is also a concern for future ocean research. A capability for providing regular ocean analyses is required as a framework for scientific research and development. In addition, if we are to build a future with a robust, routine, permanent and well-supported network of ocean observations, then a clear and convincing demonstration of the feasibility, practicality and value of maintaining such a network is required.

The opportunities arise because of 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; the genuine enthusiasm of the ocean community to promote and implement integrated global observing systems; and the critical advances provided by research programs (see Section 2).

The underlying rationale for the organization of this activity as an international experiment is that achieving the GODAE vision will not happen serendipitously and that the needed capacity will not be realized without a concerted effort to ensure, first, proper integration of the components and, second, the commitment to proving value and viability.

4.3 The approach

Smith (2000) and IGST (2000) introduce the objectives and scope of GODAE and the reader is referred to those publications and the GODAE web site for details.

One premise is that GODAE is not just concerned with prediction in the traditional sense (looking forward in time), but prediction in its most general form, where information is extrapolated and interpolated in space and time, and between fields (Figure 1). The objectives intentionally imply a broad scope in the belief that wide utilization and exploitation of products are essential for cost-efficiency and relevance to society.

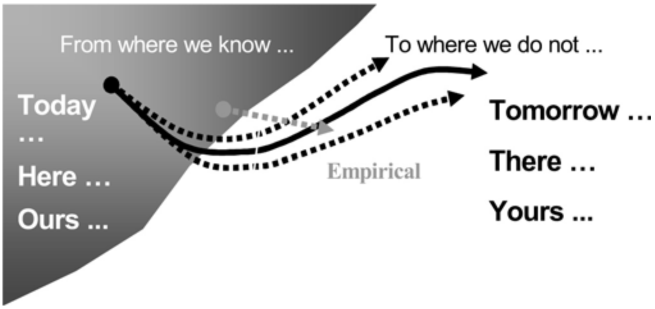

Figure 1. Schematic of the processes used to exploit data. In some cases we use linear, perhaps empirical relationships to relate the current state to, say, a likely future state. In other cases forecasts are produced based on current data ("today"), perhaps at a specific location ("here"), and perhaps for a subset of the total variable space ("ours"), in order to forecast the state in the future ("tomorrow"), at some remote location ("there") or for some variables that are not part of the observables ("yours"). The process involves extrapolation (e.g., a forecast), interpolation (e.g., discrete points to a grid) and interpretation (e.g., inferring winds from sea surface topography).

The strategy for the development of these products is built on the concept of a GODAE "Common" which is shared by all GODAE Partners responsible for realizing the goals and objectives of GODAE. The GODAE Common concept is essential for GODAE, and must also be transported into the "operational" environment, for example through data policies and scientific cooperation.

5. Building the systems

The essential building blocks of GODAE are observations, models and estimation tools (Figure 2). In the GODAE context, these elements are inextricably linked, with obvious two-way interdependencies. The generation of globally consistent fields of ocean temperature, salinity and velocity components through the synthesis of multivariate satellite and in situ data streams into ocean models is a central theme of GODAE.

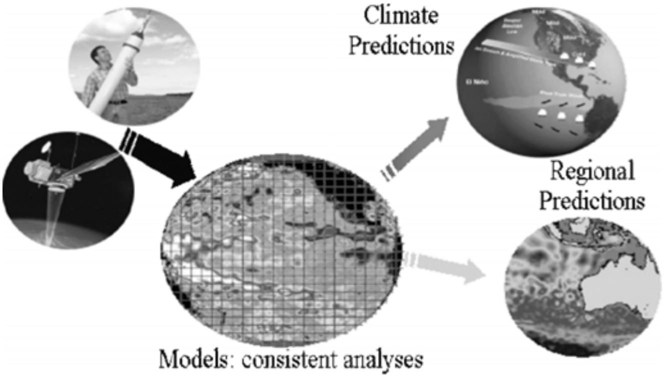

Figure 2. Illustration of the process for taking in situ and remotely sensed data (left) through a model-based assimilation system to produce a self-consistent analysis, which is then used to produce products such as a climate or regional/coastal forecast.

The scope and international nature of GODAE requires distributed data assembly and serving, a multiplicity of assimilation products, distributed product serving and archiving, and a multiplicity of application centers (Figure 3).

5.1 GODAE observational and data needs

Data needed for GODAE model/assimilation systems can be separated into four main classes: atmospheric forcing (wind stress, wind speed, air temperature, specific humidity, precipitation) and sea-ice, data for assimilation (e.g., altimetry, Argo, SST), validation data (e.g., hydrography) and ancillary data (climatologies, bathymetry). Note, however, that the separation into data types is neither definitive nor unique (e.g., forcing data can be used as one of the controls on the assimilation process).

Koblinsky and Smith (2001) discusses the data system and other papers of this Volume discuss details and issues that are of specific concern for GODAE. Remote sensing data is naturally central to the success of GODAE and GODAE has placed particular emphasis on surface topography, surface wind and sea surface temperature data.

GODAE itself has taken two specific initiatives to address specific gaps. In the early stages of GODAE it became clear that the in situ coverage was inadequate for both climate and ocean assimilation purposes. The Argo Pilot Project (Argo Science Team, 1998) was established soon after GODAE was born, and has realized a near-revolution in our capability to observe the ocean in real-time (see papers by Send and by Pouliquen, this Volume). A second Pilot Project arose in a somewhat unexpected area, sea surface temperature; a field that the community had believed was being estimated well. The GODAE High-Resolution SST Pilot Project (see chapter by I. Robinson in this volume) aims to deliver integrated, high-resolution products, derived from a range of different, but complementary observing systems, that properly respect our understanding of the near-surface temperature structure (e.g., the skin effect) and addresses issues such as the diurnal cycle.

Various data servers will be responsible for maintaining and monitoring the data flow to assimilation groups and to those undertaking validation/evaluations. The GODAE Monterey server and the CORIOLIS Centre (see chapter by S. Pouliquen in this volume) are two examples of this important functionality. One of the tasks is to link the server functions together so that the data users will have a consistent and transparent interface to the variety of data that are available. One of the challenges facing GODAE (and others) is the establishment of adequate metadata to facilitate data tracking, intercomparisons, and distribution of data which may undergo revision through various quality control procedures.

Perspective #3: The real impact of GODAE will come through its ability to bring its complex data and information to applications and users.

5.2 Models and data assimilation

Because of the irregular and incomplete nature of the datasets relative to the scales of interest, a considerable burden in ocean state estimation and forecasting is placed not only on the assimilation components but also on the model. The model provides a capacity to extrapolate information, enabling past data to be used for present analyses, and present data to be used as a basis for predictions of the ocean state at future times (forecasts). Other papers in this Volume discuss approaches to modeling and data assimilation and some of the issues faced by the GODAE community.

Most of the target applications require good representation of, at least, temperature and velocity components and sea level. High resolution operational oceanography requires accurate depiction of mesoscale ocean features such as eddies and the meandering of currents and fronts and of upper ocean structure. Coastal applications require accurate sea level and cross-shelf transport estimates. Seasonal-to-interannual climate forecasts require a good representation of the upper ocean temperature and salinity fields. Decadal climate monitoring and research requires attention to the thermohaline circulation, among other things. Biogeochemical applications require attention to the upper ocean physical parameterizations and the vertical transports (upwelling). All require considerable computational resources for global simulation and so rely on advanced software developments to take advantage of state of the art computer technology.

Perspective #4: Global high-resolution ocean model assimilation systems are the main focus of GODAE. Regional prototypes have proved critical for development and for regional applications. Sector-specific systems (e.g., for global climate estimates) are also an important aspect. Reanalyses are an important strategy.

An outstanding issue for GODAE, with implications for assimilation and prediction, is the degree to which the key fields mentioned above are predictable and, secondly, the extent to which provided fields (boundary conditions, initial conditions, other inputs) in effect enhance predictability (skill) to the target systems. The applied nature of GODAE only allows it to address these issues in passing, so again it is important that supporting research is fostered to test and understand all aspects of predictability. Note that in the context of GODAE, such research applies not only to temporal predictions (forecasts) but to the more general context (see Fig. 1).

The use of a variety of approaches to modeling and assimilation is regarded as a strength in the strategy of GODAE. Within a framework of intercomparison and progressive evaluations, the diversity of approaches can be used to quantify uncertainties and test reliability of ocean state estimates and initial conditions and forecasts.

Perspective #5: The oceans are predictable ... but when and where, and for how long? What are the dependencies and limitations? Observations? Representation of ocean dynamics and physics? Assimilation? Parameterizations? GODAE will provide only the first installment in our quest to address these issues.

6. The utility of GODAE outputs

The key outcome will be significant improvement in the detail, quality, timeliness, availability and usefulness of ocean analysis and prediction products. The reader is also referred to the GODAE Implementation Plan on http://www.bom.gov.au/GODAE/ for detail of activities by different groups and a more complete description of applications.

Coherent, organized data sets: GODAE aims to develop more coherent, better organized, more widely available and more useful data sets. Such outputs will be realized through:

(a) More effective assembly and availability. From the outset, the GODAE participants recognized that they must work to build coherent data streams that remove the mysteries associated with specific measurement techniques and the confounding problems associated with merging data of different types and formats.

(b) Improving data utility. GODAE places a high-premium on the wide use of data and products to ensure observing efforts realize their full potential in operational systems.

(c) Improving data quality. A sub-project has been launched to coordinate and standardize the GODAE approach (see www.bom.gov.au/GODAE/). As operational oceanography systems mature, they will provide routine, regular and immediate testing of data and thus add value to data sets.

These outputs depend upon adequate devotion of effort to all stages of data handling. Efficiency is realized through rationalization and streamlining of the procedures.

Reanalyses and synoptic ocean analyses: GODAE is most readily associated with products of ocean model assimilation, usually in the form of space-time gridded fields. GODAE includes the continual revision and improvement of analyses, either through re-analysis or through intercomparison activities. The great worth of reanalyzes lies in the fact that they provide dynamically and physically consistent estimates over a period, in a form that is readily used by research, but also by the broader marine community who have interests (dependencies) on knowledge of ocean variability and predictability.

Short-range ocean forecasts: GODAE will have a leading role in short-range ocean prediction and a supporting role in coupled air-sea prediction and surface wind waves via the provision of related ocean fields to application centers. While we might argue that 4-dimensional assimilation is at its roots simply a means for projecting and synthesizing data in space and time, the capacity to extend this projection (initial condition) forward in time to produce forecasts gives the system special value.

Climate applications: The most common application for the GODAE ocean state estimate is as an initial condition for a coupled model forecast (e.g., Ji et al., 1998). One of the primary issues to be faced by this community is how best to use the state estimate; for example, the nature of the problem might favor an ensemble of initial conditions rather than a single, high-fidelity product. For decadal variability and longer-term change, GODAE focuses on the provision of consistent, high-quality analyses and re-analyses of the ocean.

Coastal applications: Coastal applications will use GODAE ocean state estimates as boundary conditions for coastal/ littoral zone hindcasts and forecasts and analyses (Figure 3).

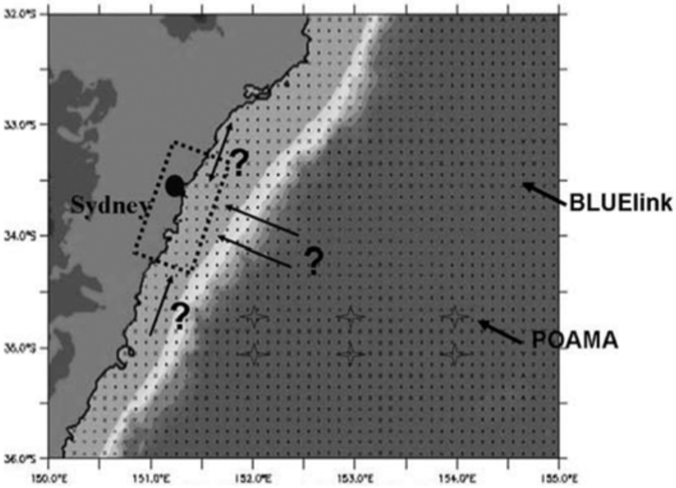

Figure 3. A schematic of the hypothetical nesting of a coastal application near Sydney within the BLUElink ocean forecasting system (indicated by fine dots; see Schiller and Smith, this volume) or a coarser seasonal prediction system "POAMA" (Wang et al., 2001).

It is not yet clear what the accuracy requirements are. Development of GODAE products for these applications will represent a significant research effort within the community. Issues of nesting of models of different resolution, the importance of regional wave and surge models, consistency in bathymetry, forcing, boundary configurations, and input to ecosystem models are critical elements for collaboration. The end users will include regional/local governments responsible for coastal management, as well as coastal industries such as fishing and recreation.

The GODAE approach provides efficiency because the systems can provide information/boundary conditions to multiple users, in a variety of ways. In some prototypes the regional/local modeling is in-built to the modeling system. In other cases the coastal modeling is part of the same project so the interface issues are being solved as part of the project. In yet other cases, boundary conditions are being provided to third parties who may have knowledge of the source model (and vice versa) but otherwise are running completely independent systems/applications.

There are a large number of issues that impact the utility of GODAE products. We are for the present slave to the errors of our atmospheric partners. Accurate ocean surface current predictions and simulations may prove as elusive as atmospheric fluxes and winds, and we do not yet fully understand the extent to which subsurface currents can be predicted. We do not yet know how well can we “predict” boundary conditions for coastal applications, and how much it matters when we get it “right”.

7. How to measure success?

The demonstration of the quality and value of GODAE products for research and operational applications is the central objective of the experiment. We need to set standards for data and products that are testable and defensible. There are two levels of evaluation criteria. Internal (technical) evaluation criteria should measure the performance of the components and functions, effectively within the GODAE Common. External measures and feedback will come from GODAE users and applications.

The scientific rationale for, and a more detailed description of the GODAE metrics are given in Le Provost et al. (2002). The internal metrics will include measures of consistency, quality and performance/efficiency. The so- external evaluation criteria include (a) the impact of GODAE products for the different applications, (b) the utility of GODAE products for the research community, (c) the number of users and their level of satisfaction, (d) the extent of resultant innovation, (e) the utility for observing system evaluation and design, and (f) the extent of uptake by value-adders and other specific users.

Perspective #6: Implementing a rigorous system of internal and external tests and intercomparisons in order to evaluate systems and to set standards is a key task. We need to foster the development of international infrastructure, and national infrastructure, to support and monitor the performance and effectiveness of systems.

8. Users and benefits

At least four types of relationships with end users have been identified.

1. Direct to the Public. This suits the ad hoc and occasional user whose needs are satisfied by directly utilizing the products and services

emanating from GODAE Centers or application centers. There is no intermediary or down-stream value-adding.

2. Via middle-users/value-adders. In this case specialists, varying from private ocean enterprises to sector-specific groups take the output and, perhaps after blending it with other information and/or rendering it in a form that is more useful and "consumable", provide it to their clients. The middle-users have expertise from both the provider and client sides and value-adding is through a partnership.
3. Direct to specific users/sectors. In some cases, specific users may be able to directly exploit GODAE products. The relationship may be commercial. Value-adding is entirely on the user side.
4. Capacity building and education. Here the users do not have access to sophisticated systems or technology and support is needed for the transfer of knowledge.

In simple terms, GODAE faces a challenge of determining the capabilities and product availability relevant to the areas and to build a consolidated view on the requirements for GODAE. Such requirements may not simply be for a particular product but may also involve the timeliness and form of the data and products, or a requirement for GODAE to include certain information in its inputs.

Perspective #7: Determining the utility of products for different users and sectors of the ocean community is the major challenge at this time.

9. Conclusions

The legacy of GODAE will be held in the sustained ocean observing system and in the global and regional operational oceanographic systems that are being developed and tested now and that we envisage being maintained by several nations. GODAE has achieved a level of investment that exceeded its expectations but such investments will only be sustained through proving the utility and use of GODAE deliverables and offset by tangible economic and social returns and outcomes

Like weather prediction, GODAE contains a balance between the practical and applied and the long-term strategic goals. The former represents a commitment to develop practical and useful applications and, through linkages with those able to exploit such products, to promote the development of a rich array of specialist, value-added uses. The latter represents a commitment to provide an appropriate basis for planning and building future research endeavors and for ensuring that the global ocean observing system, once established, remains effective, efficient and scientifically defensible in the future.

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Chapter 2

SOME OCEAN MODEL FUNDAMENTALS

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Abstract The purpose of these lectures is to present elements of the equations and algorithms used in numerical models of the large-scale ocean circulation. Such models generally integrate the ocean's *primitive equations*, which are based on Newton's Laws applied to a continuum fluid under hydrostatic balance in a spherical geometry, along with linear irreversible thermodynamics and subgrid scale (SGS) parameterizations. During formulations of both the kinematics and dynamics, we highlight issues related to the use of a generalized vertical coordinate. The vertical coordinate is arguably the most critical element determining how a model is designed and applications to which a model is of use.

Keywords: Ocean modelling, parameterization, vertical coordinate.

1. Concepts, themes, and questions

Numerical ocean models are computational tools used to understand and predict aspects of the ocean. They are a repository for our best ocean theories, and they provide an essential means to probe a mathematical representation of this very rich and complex geophysical system. That is, models provide an experimental apparatus for the scientific rationalization of ocean phenomena. Indeed, during the past decade, large-scale models have become *the* experimental tool of choice for many oceanographers and climate scientists. The reason for this state of affairs is largely due to improved understanding of both the ocean and ocean models, as well as increased computer power allowing for increasingly realistic representations of ocean fluid dynamics. Without computer models, our ability to develop a robust and testable intellectual basis for ocean and climate dynamics would be severely handicapped.

E. P. Chassignet and J. Verron (eds.), Ocean Weather Forecasting, 19-73.

The remainder of this section introduces some basic concepts, themes, and questions, some of which are revisited later in the lectures. We present some philosophical notions which motivate a focus on fundamental concepts and notions when designing, constructing, and analyzing ocean models.

1.1 Model environments

The field of ocean model design is presently undergoing a rapid growth phase. It is arguable that the field has reached *adolescence*, with further maturation likely taking another 10-20 years as we take the models to a new level of integrity and innovation. Many applications drive this evolution, such as studies of climate change, operational oceanography, and ultra-refined resolution process studies.

One goal of many developers is that the next decade of model evolution will lead to a reduction in code distinctions which presently hinder the ability of modelers to interchange algorithms, make it difficult to directly compare and reproduce simulations using different codes, and increase the burdens of model maintenance in a world of increasingly complex computational platforms and diverse applications. Notably, the distinctions will not be removed by all modelers using a common algorithm. Such is unreasonable and unwarranted since different scientific problems call for different algorithmic tools. Instead, distinctions may be removed by the development of new codes with general algorithmic structures flexible enough to encompass multiple vertical coordinates, different horizontal grids, various subgrid scale (SGS) parameterizations, and alternate numerical methods.

The word *environment* has recently been proposed to describe these highly flexible and general codes. As yet, no model environment exists to satisfy the needs and desires of most modelers. Yet some models are moving in this direction by providing the ability to choose more than one vertical coordinate. This is a critical first step due to the central importance of vertical coordinates. The present set of lectures formulates the fundamental equations using generalized vertical coordinates, and these equations form the basis for generalized vertical coordinate ocean models. Ideally, the advent of general model environments will allow scientists to use the same code, even though they may use different vertical coordinates, horizontal grids, numerical methods, etc.

Many of the ideas presented here are an outgrowth of research and development with the Modular Ocean Model of Griffies et al., 2004, as well as the MITgcm (Marshall et al., 1997, Adcroft and Campin, 2004). The MITgcm provides for a number of depth-based and pressure-based vertical coordinates. Another approach, starting from an isopycnal layered model, has been taken by the Hybrid Coordinate Ocean Model (HYCOM) of Bleck, 2002. HYCOM is arguably the most mature of the generalized vertical coordinate models.

From an abstract perspective, it is a minor point that different modelers use the same code, since in principle all that matters should be the continuum equations which are discretized. This perspective has, unfortunately, not been realized in practice. Differences in fundamentals of the formulation and/or numerical methods often serve to make the simulations quite distinct, even when in principle they should be nearly identical. Details do matter, especially when considering long time scale climate studies where small differences have years to magnify.

An argument against merging model development efforts is that there is creative strength in diversity, and so there should remain many ocean codes. A middle ground is argued here, whereby we maintain the framework for independent creative work and innovation, yet little effort is wasted developing redundant software and/or trying to compare different model outputs using disparate conventions. To further emphasize this point, we stress that the problems of ocean climate and operational oceanography are vast and complex, thus requiring tremendous human and computational resources. This situation calls for merging certain efforts to optimize available resources. Furthermore, linking modelers together to use a reduced set of code environments does not squelch creativity nor does it lead to less diversity in algorithmic approaches. Instead, environments ideally can provide modelers with common starting points from which to investigate different methodologies, parameterizations, and the like.

The proposal for model environments is therefore analogous to use of a few spoken/written languages (e.g., english, french) to communicate and formulate arguments, or a few computer languages (e.g., Fortran, C++) to translate numerical equations into computer code. Focusing on a few ocean model environments, rather than many ocean models, can lead to enhanced collaboration by removing awkward and frustrating barriers that exist between the presently wide suite of model codes. Ultimately, such will (it is hoped!) lead to better and more reproducible simulations, thus facilitating the maturation of ocean modelling into a more robust and respectable scientific discipline.

1.2 Some fundamental questions

It is possible to categorize nearly every question about ocean modelling into three classes.

1 Questions of model fundamentals, such as questions raised in this section.

2 Questions of boundary fluxes/forcing, from either the surface air-sea, river-sea, and ice-sea interactions, or forcing from the solid earth boundary. The lectures in this volume from Bill Large touch upon many of the surface flux issues.

3 Questions of analysis, such as how to rationalize the simulation to enhance ones ability to understand, communicate, and conceptualize.

If we ask questions about physical, mathematical, or numerical aspects of an ocean model, then we ask questions about ocean model fundamentals. The subject deals with elements of computational fluid mechanics, geophysical fluid mechanics, oceanography (descriptive and dynamic), and statistical physics. Given the wide scope of the subject, even a monograph such as Griffies, 2004 can only provide partial coverage. We consider even less in these lectures. The hope is that the material will introduce the reader to methods and ideas serving as a foundation for further study.

For the remainder of this section, we summarize a few of the many fundamental questions that designers and users often ask about ocean models. Some of the questions are briefly answered, yet some remain unaswered because they remain part of present day research. It is notable that model users, especially students learning how to use a model, often assume that someone else (e.g., their adviser, the author of a research article, or the author of a book) has devoted a nontrivial level of thought to answering many of the following questions. This is, unfortunately, often an incorrect assumption. The field of ocean modelling is not mature, and there are nearly as many outstanding questions as there are model developers and users. Such hopefully will provide motivation to the student to learn some fundamentals in order to help the field evolve.

Perhaps the most basic question to ask about an ocean model concerns the continuum equations that the model aims to discretize.

- Should the model be based on the non-hydrostatic equations, as relevant for simulations at spatial scales less than 1km, or is the hydrostatic approximation sufficient? Global climate models have all used the hydrostatic approximation, although the model of Marshall et al., 1997 provides an option for using either. Perhaps in 10-20 years, computational power will be sufficient to allow fully non-hydrostatic global climate simulations. Will the simulations