Ocean observing systems and prediction - the next ten years

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Toward a new era of oceanography

The twentieth century was a remarkable period for oceanography. We learned much about the fundamental distribution of properties of the seas and the balances that govern our ocean. We now know, among other things, why the ocean surface currents do not follow the wind; why the circulation in the Oceans is dominated by large basin-wide gyres; why there are swift currents in the west; why the tropical circulation is different from that at high latitudes; why coastal regimes differ from open ocean regimes; why the water properties in the Southern Ocean are intimately connected to conditions in the North Atlantic; why the temperature of the tropical Pacific Ocean matters to climates in the United States, South Africa and Australia; and why human activities now may change sea level toward the end of this century. The advances in knowledge have been great.

If we were to characterize the last century, it might be in terms of science and discovery and the building of knowledge and understanding (Smith 2001). The advances have required innovation in observations, in theoretical research, and in the development and construction of numerical models. Technological innovation has been critical, first to construct instruments that could measure, with accuracy and precision, in the harsh environment of the ocean, and more recently, to enable remote and autonomous measurements; to paralle code, run and analyze ocean models; and to provide rapid exchange and analysis of data via the Internet.

Other speakers will have to summarize the many accomplishments from the many individual and collaborative scientific and technical endeavors of recent decades. As we look forward to the next decade, we see opportunities to exploit our ocean knowledge and our growing technological capabilities for the betterment of humankind and the advance of our understanding of how the ocean affects the physical, chemical and biological state of our planet.

In this paper we place particular focus on the possibilities of a global ocean observing system and the gradual move toward oceanography as a more operational activity. In several ways oceanography is following the path developed by meteorology, implementing operational observation and forecast systems, yet in other ways there are significant differences. For meteorology, forecast skill is the dominant paradigm, an exemplar that seems equally applicable to climate forecasting, particularly that associated with El Niño. However, the rich living and non-living resources of the ocean, the critical importance attached to the coastal and marine environment, and the rich biodiversity of the oceans, among other things, make quantitative knowledge of the ocean state important in its own right. The market for ocean state estimates and forecasts ("marine services") exists now and we will attempt to show that we have the knowledge, technology and community "spirit" to develop a robust, sustained system of ocean observations, products and services that will serve us for this decade and beyond.

For the most part we focus on physical oceanography, and systems that have been developed with a view toward operational oceanography. There are of course many aspects that we ignore within this discipline, and even more from related disciplines.

The global ocean observing system

The history of widespread ocean observation began in the middle of the nineteenth century, when merchant sailing vessels started a systematic effort to collect and exchange information on weather and the state of the seas on their trade routes. Well over a century passed before any attempt was made to build on these pioneering efforts a systematic system for ocean observation. A major step forward in basin-scale observing efforts was implemented during Tropical Ocean Global Atmosphere (TOGA), for which a tropical Pacific-wide research observing system was designed, deployed and operated. In the last decade of the twentieth century, it became clear that a permanent observing system for the ocean was viable and sustainable. It took many years of planning and discussion before the ocean community started to widely endorse such an effort. The Ocean Observing System Development Panel (OOSDP 1995) provided a template for the global ocean observing system for climate, and this template has been adapted and modified by many as we move toward a sustained observing system (Nowlin 1999; Nowlin *et al.* 2000).

At the First International Conference for Ocean Observing Systems for Climate, agreement was reached on the essential elements of the observing system for the next decade and beyond (Smith and Koblinsky 2001). The system would include:

- Sea surface temperature measurements from satellites (visible, infrared, microwave) and *in situ* platforms (surface drifters, moorings, volunteer observing vessels);
- Surface vector winds from satellites and *in situ* instruments;
- Sea surface height variability from satellite altimeters and *in situ* measurements from tide gauges for the long-term climate record and validation (also needs good sea surface level pressure measurements);
- Upper ocean temperature and, where practical, salinity measurements from a variety of networks including the tropical moored buoys, Argo, the ship of opportunity XBT network (now principally in high-density and frequently repeated modes), other moorings and hydrography;
- Surface and upper ocean current measurements;
- Tracers and carbon measurements from hydrography for transport and inventory calculations; and
- Air-sea fluxes from ocean reference sites and lines, and from operational met models.

Smith and Koblinsky (2001) and the other papers in that volume provide a more comprehensive account of the many different contributions of which the above form just a part. The most important message is that the technology for a truly global ocean observing system exists now, based on both satellite and *in situ* technologies. There is also ample evidence that there is the collective will to realize such a system. Indeed, many nations have already made significant commitments.

Ocean state estimation

An important complement to the ability to observe the oceans is the ability to routinely assimilate this information, and to provide methods for exploiting this information for broader scientific and socio-economic benefit. In many instances it is not knowledge of the current state of the ocean at some location and depth that matters, but rather the inferences that can be drawn from this information and that at many other locations. These inferences are often applicable at locations far removed from the source information and, in many cases, involve fields and parameters not connected with oceanography (for example, rainfall estimates in North America or Indonesia). It is not the intent here to discuss these many applications in detail, but rather to provide a description of the systems that are being built to underpin synthesis and interpretation, and, in particular, the process of using ocean models to assimilate data, a procedure we refer to here as ocean state estimation.

Ocean state estimation, or ocean data assimilation is an optimization problem. Given a set of dynamical equations with associated estimates of model errors, and a set of ocean data with associated estimates of observational errors, and an error functional ("cost function") that is to be minimized, a variety of data assimilation techniques exist for approximating the ocean state that best satisfies the various constraints. Viewed as a four-dimensional space-time problem, the challenge is to blend measurements of the ocean state distributed irregularly in both space and time to produce regular (gridded) estimates of the ocean state for the present and past, and as appropriate for the future (forecasts).

These procedures are commonplace in meteorology and weather forecasting, and are becoming more common in climate and ocean applications. At present, ocean state estimation is performed operationally by some government efforts, and in research mode by an increasing number of research efforts. Each of these is limited to some extent by the available data, both for making and evaluating the skill of the operational estimates.

Many nations have agreed that a new push to expand our ocean data asssimilation efforts is needed and have begun to participate in the Global Ocean Data Assimilation Experiment (GODAE; Le Traon *et al.* 2001; IGST 2000), which is to have its intensive work period between 2003 and 2005.

The operational meteorology community has been making products with data assimilation for almost half a century, and offers valuable experience for the ocean community to draw upon. GODAE sponsors workshops to ensure that the ocean community benefits from the experiences of the meteorology community.

Issues for ocean state estimation

In comparison with meteorology, operational oceanography is immature. The observing systems are not complete and those networks that are established mostly have short records. The models and data assimilation methods are also immature. The models often display significant biases relative to observations. The data assimilation systems are limited by our ability to measure and model skillfully the many of the energetic scales of the ocean, including strong currents and mesoscale eddies. Nevertheless, considerable progress has been made in operational ocean forecasting and in climate forecasting, using a variety of methods.

The simplest form of data assimilation is objective interpolation, which requires the specification of the data errors and the covariance functions between the variables. Optimal interpolation (OI) has been widely used in oceanography since the mid-1970s, and variants are still used in several operational analysis and climate prediction systems. The method offers valuable perspective, because the utility of OI products is easily seen to depend critically on the specified statements of uncertainty. The OI product is only as good as the data distribution and covariance and error estimates.

Operational meteorology teaches us that we must work hard to learn how best to specify the full range of data and model errors, covariances and cost functions, if we seek useful ocean products. In many parts of the world ocean we do not have enough data to make dependable estimates of these quantities. Indeed, it is probably in the area of knowledge of (parameterized) processes and subgrid scale motions that we suffer most severely from a data shortage. Is the community prepared to invest in "local dynamics" experiments in these regions? In their absence we must go forward with assumptions of unclear utility, having unclear impact on our product skill.

Research based on operational meteorology products also teaches us that it can take some years before such products have sufficient skill to yield the desired insights into the kinematics and dynamics of the atmosphere. Atmospheric science research now depends heavily on operational products and periodic "re-analyses" of the historical atmospheric data set.

We must expect a learning period of increasing skill with our operational ocean products, and not be discouraged by early efforts. Having wide community access to the ocean products and wide community examination and feedback concerning their utility, will be essential for rapid progress in their skill and usefulness.

Data transmission, quality control (QC) and dissemination issues

Getting ocean data back from the marine environment promptly, effectively and cost-efficiently is key for many marine services. There appears to be a need in excess of what Service ARGOS can provide. Access to these data and to the products made from them is also necessary if the ocean community is to benefit.

The meteorology community has considerable infrasture dedicated to these tasks, *e.g.*, the World Weather Watch's Global Telecommunications System and the various national meteorological service product distribution pipelines. The ocean community needs capable Information Technology infrastructure to meet its needs.

As "research quality" QC is done on the historical data sets, there is also a need to be able to keep track of what has been done, and make it possible for researcher, policy-makers and re-analysis efforts to find the version(s) of the data sets most likely to be useful to them.

Based on our history, it is unlikely that there will be a "definitive" QC data set for the ocean in the foreseeable future; one group's noise is another group's signal. Various national efforts are in place and under development to address these issues.

GODAE is taking the lead to provide interfaces to the variety of different efforts that are in place and under development. The United States is supporting development and operation of a GODAE real time data and ocean product server sited at Fleet Numerical Meteorology Oceanographic Centre (FNMOC) in Monterey, CA, U.S.A.

The WMO's Joint Commission on Oceanography and Marine Meteorology (JCOMM) is also devoting effort to a range of data set issues. Technology for low power, low cost data transmission and data sharing also exist.

Ocean forecasts

As noted earlier, it is the ability to draw inferences from ocean measurements in regions and fields remote from the data site, that is perhaps the most valuable aspect of the global observing system infrastructure. However, the methodology of ocean state estimation only takes us part of the way. The most immediate way we can use such a data set is as a basis for producing an ocean or climate forecast, the so-called initial-value problem. Given a faithful estimate of the state of the ocean today, we can forecast the ocean state. For some variables we can hope to have forecast skill for several weeks, perhaps even months.

Our ability to do this is limited by several factors. Firstly, we are limited in our ability to observe the current state of the ocean and, secondly, the methods and models we use to produce the estimate have limitations, in many cases quite severe. As the previous sections have indicated, we have made considerable progress in addressing both these issues but most accept that there is still a long way to go (the challenge lies with GODAE and the several operational oceanography centers at the moment).

But more fundamentally the ocean is a chaotic medium, with small perturbations growing over time through non-linear interactions and feedbacks. The growth of such errors places natural limits on predictability, the degree to which one can determine a future state of the system. At present, our knowledge of ocean predictability is scant, principally because there has not been the need to determine predictability limits up till this point. The other issue is that the ocean is being continually forced by the atmosphere, which itself is unpredictable over certain time and space scales. So, while we anticipate internal ocean circulation errors may grow relatively slowly (perhaps 3-4 weeks at mid-latitudes), we must also take account of far more rapid error growth in surface forcing fields.

These issues notwithstanding, considerable progress has been made in ocean and climate forecasting with several centers routinely producing forecasts of the ocean state.

In some cases, such as El Niño, the oceans and atmosphere interact in such a way as to introduce modes of variability that seemingly have much longer time scales of predictability. This is the basis for several experimental and operational climate forecast systems. The extent to which other climate phenomena are predictable is receiving intensive study now, through CLIVAR and other programs.

As noted in the opening section, one of the distinguishing aspects of oceanography is the fact that many applications involve knowledge of the ocean and marine environment, in some cases in the past. We are not only interested in forecasts of the future but also in "forecasts" of the ocean state for locations and variables separated from the measurements. For the oil and gas industry, this might take the form of statistics for extreme currents near the bottom at a specific location. For the fishing industry it might be forecasts of advection and vertical circulation for ocean dispersal of larvae. For coastal management, it might be boundary conditions for local coastal management models. In all cases the challenge is to extrapolate and infer fields that are not directly measurable and, like forecasts in time, errors arise from both the limitations of the methods and from natural error growth (unpredictability).

GODAE is making considerable progress in developing links to value-adding communities where such activities take place. PICES may well be one of those communities though we recognize the immaturity of the endeavor at present. Such connections will require experimentation and much dialogue.

The coming decade

It does seem the ocean communities of the world are willing to embrace the concept of:

- a sustained ocean observing system (satellite and *in situ*);
- modern data transmission and data serving infrastructure;
- dedicated ocean product development and production efforts;
- wide community access and examination of the ocean products;
- community feedback so that the OS and the products will improve.

Given this acceptance, the coming decade will provide many opportunities for innovative applications and science.

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