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Oceans: Observation and Prediction

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Abstract
The ocean is a complex and difficult sample, and our understanding of how it operates and its future trajectory is poor. This has implications for humanity as increasing numbers are living in coastal zones. To better understand the ocean, it is necessary to adopt new sampling strategies that consist of coupling new observational technologies with numerical ocean models. New observational technologies are becoming available to oceanographers. Fixed assets include moorings, sea floor cables, and shore-based radars. These fixed assets are complemented with mobile platforms that provide spatial maps of subsurface data. The mobile platforms include profiling floats, gliders, and autonomous underwater vehicles. The observational data is complemented with numerical models. Many simulation models are becoming available to the community and the appropriate model is a function of the specific need of the user. Increasingly, observational data are used to constrain the models via data assimilation. The coupled observational and modeling networks will provide a critical tool to better understand the ocean.

INTRODUCTION

The oceans cover the majority of the Earth's surface and despite centuries of exploration they remain relatively unexplored. This gap of knowledge reflects the difficulty of collecting physical, chemical, and biological data in the ocean, as it is a harsh and unforgiving environment in which to operate. Despite centuries of ship-based exploration, the immense size and hazards associated with wind, waves, and storms limit the ability of humans to sustain a coherent global sampling network. Satellite and aircraft remote sensing approaches provide powerful tools to map global synoptic properties (Fig. 1); however, satellite systems largely provide information on the surface ocean. Fixed and mobile sensors deployed in the ocean can provide subsurface data, however, their numbers, while expanding, are limited and the technology still struggles with issues related to the onboard power availability and the number of available robust sensors. These sampling shortcomings have significant implications for human society especially as there is increasing evidence that the physics, chemistry, and biology of the ocean have changed over the last few decades. These changes reflect both natural cycles and the anthropogenic forcing from human activity.

Quantitatively understanding the relative importance of the natural and anthropogenic forcing in the ocean remains an open question, which needs to be resolved as the environmental impacts associated with human activity will increase, reflecting the growth of human populations.[1] The current projections suggest that human population growth at coastlines will be the most rapid and largest on the planet.[2] This will increase the importance of marine systems in national economies around the world making managing coastal systems critical. The close proximity of large populations will expose them to potential natural and man-made disasters associated with the oceans. These disasters include tsunamis, hurricanes, offshore industrial accidents, and human health issues such as outbreaks of waterborne disease. Our current capabilities to predict, respond to, manage, and mitigate these events is astonishingly poor. Improving our ability to observe and predict changes in the ocean will require technical improvements combined with an increased fundamental understanding of physical, chemical, and biological processes.

WHAT IS THE PATH FORWARD?

Improving our understanding and management of the ocean system will require an improved ability to map ocean properties in the present and improving our ability to forecast future ocean conditions. The ability to map ocean

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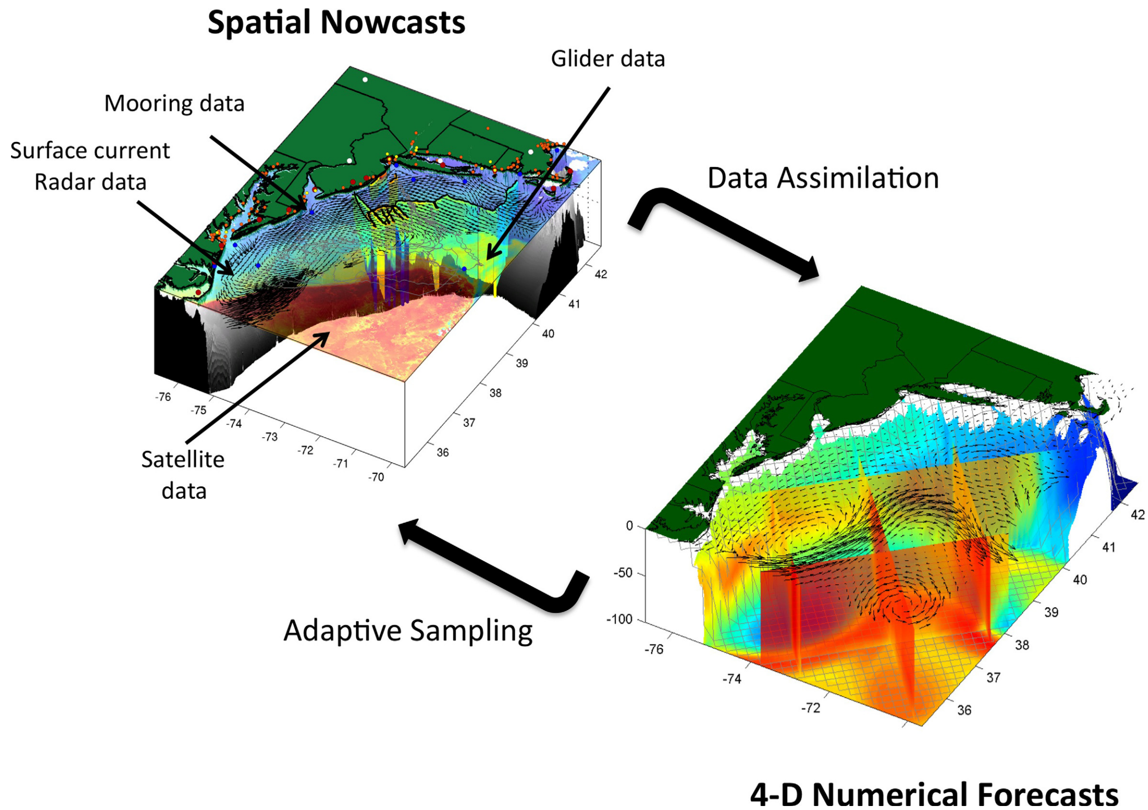

Fig. 1 An example of a coupled ocean observation and modelling network along the East coast of the United States. The spatial nowcast consists of observational data delivered in near real-time to shore. The nowcast consists of satellite data (sea surface temperature is shown), surface current radar (black arrows on the ocean), mooring data (black dots), subsurface data collected from gliders (water temperature shown here), and weather data collected by shore based stations (small white dots). The nowcast provides data to simulation models via data assimilation. The simulation model provides a 48-hour forecast, which is used to redistribute observational assets to provide an improved data set before the next forecast cycle.

properties will require a distributed portfolio of ocean infrastructure that will be linked together through an increasing number of ocean models.[3] The observation networks will collect quantitative data about the current status of the ocean. The forecasts are driven by numerical models that use current scientific understanding to project how the ocean will evolve. The combined observatory and numerical modelling capacity will improve our fundamental understanding and ability to respond to changes in the physics, chemistry, and biology of the marine systems.

The observations will assist the modelling efforts in several ways. Observations will provide data required to parameterize processes within the models. If the data are delivered in real-time they will be assimilated into the model to improve the predictive skill of the forecast. Finally, as new data are collected, they will be used to validate the predictive skill of the model. In turn the model forecasts will assist the observational efforts by providing forecasts that will allow scientists to adjust the spatial configuration and sampling rates of sensors to better sample future ocean conditions. These coupled systems are a rapidly maturing technology and builds off the more mature science of weather forecasting, which has its roots in the early 19th century. The fundamental approaches are based on the seminal work of Lewis Fry Richardson who is considered the father of numerical weather prediction in the 1920s. These approaches are computationally intensive and it was not until the advent of electronic computers that the science moved forward to become an indispensable tool for humanity. Modern computer models use data as inputs collected from automated weather stations and weather buoys at sea. These instruments, observing practices and timing are standardized through the World Meteorological Organization.

Oceanographic efforts are evolving in a similar fashion where observations inform operational models. The weather and ocean models, most often run by federal agencies, provide forecasts that are used by scientists, the maritime industry, state and local communities. Most often they are used to issue warnings of unsafe conditions due to storms and high waves. The motivation for global standardized ocean forecast systems can be traced back to the sinking of the Titanic in 1912, which prompted the international community to call for development of systems to improve safety at sea. Modern approaches and forecasting tools for the ocean did not mature until the 1980s and are rapidly evolving as the computing and ocean observation technologies are rapidly improving.

HOW ARE OBSERVATIONS MADE IN THE OCEANS?

Many platforms are available for making ocean measurements and, although the list below is not exhaustive, it provides a snapshot of the major platforms. The platforms carry sensors that can measure physical, chemical, and biological properties of the sea; however, most new novel sensors can only be carried on ships. A smaller number of sensors can be deployed on autonomous platforms and the discussion in this entry is focussed on those sensors that can be deployed on a variety of ocean platforms.

The most mature sensors are those that measure physical and geophysical variables, such as temperature, salinity, pressure, currents, waves, and seismic activity. Except for seismic variables, most of the physical sensors can be deployed on most of the platforms listed below. Many of the physical properties are the key variables in ocean numerical models. Currently, chemical sensors can measure dissolved gases (primarily oxygen) and dissolved organic material; however, recently the sensors capable of measuring nutrients (primarily nitrogen) are becoming commercially available. Biological sensors currently consist of optical and acoustic sensors. The optical sensors are used to provide information on the concentration, composition, and physiological state of the phytoplankton. Acoustic sensors can provide information on zooplankton to fish depending on the acoustic frequency band that is chosen.

Ships

The primary tool for oceanographers for centuries has been ships and will remain a central piece of infrastructure for the foreseeable future.[4] Ships are ideal as they are extremely flexible and allow teams to conduct experiments at sea. Ships are expensive to operate and must avoid hazardous conditions, such as storms, which limit the ability to make sustained measurements.

Satellites

Satellites are the most important oceanographic technology in modern times (beyond the ships).[5] Satellite observations have resulted in numerous advances in our fundamental understanding of the oceans[6] by resolving both global features associated with the mesoscale circulation of physical and biological properties. Satellite datum is fundamental to weather and ocean state prediction. Physical parameters available from space-based sensors include ocean surface temperature, wind speed and direction, sea surface height and topography, and sea ice distribution and thickness. Biological and chemical parameters can be derived from ocean colour radiometers.

High-Frequency Radar

High-frequency radar measures ocean surface current velocities over hundreds of square miles simultaneously. Each site measures the radial components of the ocean surface velocity directed towards or away from the site[7,8] and the estimated velocity components allow surface currents (upper meter of water column) to be estimated.[9] These systems are cost effective and have many applied uses.

Ocean Moorings

The modern ocean moorings grew out of the weather stations established in the 1940s. Since the 1960s, modern buoys have enabled a wide range of studies addressing the ocean's role in climate, weather, as well as providing insight into the biogeochemistry of the sea. Moorings provide the backbone to many of the global ocean networks studying ocean–atmosphere interactions and are the foundation for the global tsunami warning system network. They will continue to be a key element of ocean observing infrastructure for the foreseeable future.

Seafloor Cables

Scientists often require high bandwidth and power for sustained periods of time. Seafloor electro-optic cables provide a means for maintaining a sustained presence in the ocean. Cables have been deployed off the east and west coasts of the United States, Canada, Japan, and Europe. Many other countries are planning to deploy seafloor cables.

Drifters and Floats

Passive Lagrangian platforms are tools for creating surface and subsurface maps of ocean properties. These platforms are relatively inexpensive and thus allow thousands of these platforms to be deployed. Drifters have historically been a key tool for oceanography as evidenced by the important works by Benjamin Franklin[10] and Irving Langmuir.[11] The drifters can carry numerous sensors to create global maps of surface circulation. The first neutrally buoyant drifters were designed to observe subsurface currents.[12] The subsurface profiling drifters were enabled in the early 1990s with communication capabilities[13] and now anchor the international ARGO program, which has over 3000 floats deployed in the ocean.

Gliders are a type of autonomous underwater vehicle (Fig. 2) that use small changes in buoyancy in conjunction

Fig. 2 A Webb underwater glider being deployed in the Ross Sea Antarctica in February 2011.
Source: Photo credit Chris Linder.

with wings to convert vertical motion to horizontal motion, and thereby propel itself forward with very low-power consumption.[14] Gliders follow a saw-tooth path through the water, providing data on large temporal and spatial scales. They navigate with the help of periodic surfacing for Global Positioning System (GPS) fixes, pressure sensors, tilt sensors, and magnetic compasses. Using buoyancy-based propulsion, gliders have a significant range and duration, with missions lasting up to a year and covering over 3500 km of range.[15–17]

Propeller-driven autonomous underwater vehicles (AUVs) are powered by batteries or fuel cells and can operate in water as deep as 6000 m. Similar to gliders, AUVs relay data and mission information to shore via satellite. Between position fixes and for precise maneuvering, inertial navigation systems are often available onboard the AUV to measure the acceleration of the vehicle, and combined with Doppler velocity measurements, it is used to measure the rate of travel. A pressure sensor measures the vertical position. AUVs, unlike gliders, can move against most currents nominally at 3–5 knots, and can therefore systematically and synoptically survey a particular line, area, and/or volume.

WHAT NUMERICAL OCEAN MODELS ARE AVAILABLE?

Over the last 30 years, there have been significant developments in three-dimensional numerical models for the ocean.[18] Many models exist spanning from global ocean scales down to the scale of individual estuaries. Models vary in their coordinate system (linear, spherical, and others), resolution in space and time, complexity (i.e., number of state variables), and the parameterization of key processes within the model. There are several excellent texts that outline many of the details of numerical ocean modelling[19,20] and one key lesson is that the choice of particular modelling approach depends on its intended application and on the available computational resources. Although an exhaustive list of the ocean models is beyond the scope of this text, several classes are described in the following paragraphs.

Mechanistic models are simplified models used to study a specific process, and are used to provide insight into the underlying processes influencing the physics, chemistry, and biology of the ocean. These models are most often constructed as a learning tool in order to assess processes and feedbacks within marine systems.

Simulation models are complex and describe three-dimensional (3-D) ocean processes using the continuity and momentum equations. For this reason they are called the primitive equation models. These models can be used to simulate many processes, including ocean circulation, mixing, waves, and responses to external forces (such as storms). All these models are constructed using different assumptions. Additionally, the resolution of the models requires that the trade-offs of the computation burdens be measured against the processes that need to be simulated. For example, if the model must resolve mesoscale eddies, it will require the resolution of a few tenths of a degree of latitude and longitude. In contrast, most primitive equation climate models have much coarser horizontal resolution as they were designed to study large-scale hydrographic structure, climate dynamics, and water-mass formation over decadal time scales; however, for a specific question, there are climate models with sufficient resolution to resolve mesoscale eddies if one is willing to accept the computation cost. Simulations are also constructed for coastal systems and can resolve coastal currents, tides, and storm surges. Increasingly the biological and ocean chemistry models are being coupled into these 3-D simulation models. Although these biogeochemical models are rapidly improving, there is unfortunately no set of "primitive" equations yet capable for describing biological and chemical systems in the ocean; however, as these models evolve, they will be increasingly useful tools for managing living resources and water quality in the ocean.

Often models of varying resolutions are combined. Coarser-scale global or basin-scale models provide outer boundary inputs to higher resolution nested models, which allows a myriad of processes to be modelled with a lower computation burden but allow a range of processes to be simulated even if they require high resolution. This is often the case for coastal and continental shelf models. The advantage of this downscaling approach is that it allows basin scale models to resolve large-scale forcing that drives the regional to local-scale processes that are effectively modelled by a higher resolution model. The approach by which one links these models is a difficult problem and remains an area of active research.

Data assimilation is an approach by which model simulations are constrained by observations. For example, model calculations and observations of temperature and salinity can be compared, and then the model can be "adjusted" based on the mismatch. This is a difficult problem as 1) it represents an inverse problem (where a finite number of observations are used to estimate a continuous field), 2) many of the ocean processes of interest are non-linear, and 3) the observations and models both have unknown errors. Descriptions of data assimilation approaches for oceanography have been reviewed.[21,22] These approaches allow modellers to increase the forecast skill of their models by essentially keeping the models "on track" if the observations and data assimilation approaches can be provided in a timely fashion. Many in the ocean modelling community are focusing on using these approaches to increase model forecast skill as it determines how well these approaches will serve a wide range of science, commercial, and government needs.[23]

CONCLUSIONS

Ocean observation and modelling capabilities are rapidly diversifying and improving. These systems are increasingly linked by data assimilation approaches that when combined, provide a coupled observing and forecasting network. These approaches will increase the predictive skill of forecast models that in turn can serve a wide range of applications spanning from basic research to improving the efficiency of the maritime industry. The combined technologies will be critical to improving our understanding of the ocean today and the potential trajectory in the future.

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REFERENCES

1. De Souza, R.; Williams, J.; Meyerson, F.A.B. Critical links: Population, health, and the environment. Popul. Bull. **2003**, *58* (3), 3–43.
2. Vitousek, P.M.; Mooney, H.A.; Lubchenco, J.; Melillo, J.M. Human domination of Earth's ecosystems. Science **1977**, *277*, 494–499, DOI: 10.1126/science.277.5325.494.
3. National Research Council. *Critical Infrastructure for Ocean Research and Societal Needs in 2030*; National Academy Press: Washington, D.C., 2011.
4. National Research Council. *Science at Sea: Meeting Future Oceanographic Goals with a Robust Academic Research Fleet;* National Academy Press: Washington, D.C., 2009.
5. Munk, W. Oceanography before, and after, the advent of satellites. In *Satellites, Oceanography and Society*, Halpern, D., Ed.; Elsevier Science: Amsterdam, 2000; 1–5.
6. Halpern, D., Ed. *Satellites, Oceanography and Society*; Elsevier Science: Amsterdam, 2000; 361 pp.
7. Crombie D.D. Doppler spectrum of sea echo at 13.56 Mc/s. Nature **1955**, *175*, 681–682.
8. Barrick, D.E.; Evens, M.W.; Weber, B.L. Ocean surface currents mapped by radar. Science **1977**, *198*, 138–144.
9. Stewart R.H.; Joy J.W. HF radio measurements of ocean surface currents. Deep Sea Res. **1974**, *21*, 1039–1049.
10. Franklin, B. Sundry marine observations. Trans. Am. Philos. Soc. **1785**, *1* (2), 294–329.
11. Langmuir, I. Surface motion of water induced by wind. Science **1938**, *87*, 119–123.
12. Swallow, J.C. A neutral-buoyancy float for measuring deep currents. Deep Sea Res. **1955**, *3*, 74–81.
13. Davis, R.E.; Webb, D.C.; Regier, L.A.; Dufour, J. The Autonomous Lagrangian Circulation Explorer (ALACE). J. Atmos. Ocean. Tech. **1992**, *9*, 264–285.
14. Rudnick, D.L.; Davis, R.E.; Eriksen, C.C.; Fratantoni, D.M.; Perry, M.J. Underwater gliders for ocean research. Mar. Technol. Soc. J. **2004**, *38*, 73–84.
15. Sherman, J.; Davis, R.E.; Owens, W.B.; Valdes, J. The autonomous underwater glider "Spray." IEEE J. Ocean. Eng. **2001**, *26*, 437–446.
16. Eriksen, C.C.; Osse, T.J.; Light, R.D.; Wen, T.; Lehman, T.W.; Sabin, P.L.; Ballard, J.W.; Chiodi, A.M. Seaglider: A long-range autonomous underwater vehicle for oceanographic research. IEEE J. Ocean. Eng. **2001**, *26*, 424–436.
17. Webb, D.C.; Simonetti, P.J.; Jones, C.P. SLOCUM: An underwater glider propelled by environmental energy. IEEE J. Ocean. Eng. **2001**, *26*, 447–452.
18. Bryan, K. A numerical method for the study of the circulation of the world ocean. J. Comput. Phys. **1969**, *4* (3), 347–376, DOI: 10.1016/0021-9991(69)90004-7.

19. Kantha, L.H.; Clayson, C.A. *Numerical Models of Oceans and Oceanic Processes*; International Geophysics Series, Elsevier: Amsterdam, 1995; 750 pp.
20. Haidvogel, D.; Beckmann, A. *Numerical Ocean Circulation Modeling*; Imperial College Press: London, 1999; 318 pp.
21. Wunsch, C. *The Ocean Circulation Inverse Problem*; Cambridge University Press: Cambridge, 1996; 442 pp.
22. Malanotte-Rizzoli P. *Modern Approaches to Data Assimilation in Ocean Modeling*; Elsevier Science: Amsterdam, Netherlands, 1996; 455 pp.
23. Pinardi, N.; Woods, J. *Ocean Forecasting: Conceptual Basis and Applications*; Springer Verlag: Berlin, Germany, 2002; 472 pp.