For Observing World's Oceans, Emerging Sensors, Systems

Chemical, Optic & Bio-Optical, Biology & Bio-Acoustic Sensors, Interdisciplinary Systems & Needs; Sensor Platforms; Local, Global Aspects

By Professor Tommy D. Dickey
Ocean Physics Laboratory
University of California, Santa Barbara
Santa Barbara, California

The oceans are naturally dynamic with large amplitude periodic and episodic variability. Solutions of oceanographic problems involving global as well local change are limited by undersampling of this variability. In particular, it is vital to improve the quantity and quality of measurements of critical variables in order to distinguish natural versus anthropogenically-induced changes. Virtually all important environmental problems require interdisciplinary approaches and data sets. The requisite data need to be collected simultaneously and span time and space scales spanning up to 10 orders of magnitude to observe relevant oceanic processes. Ships and satellites continue to be valuable observing assets; however, autonomous sampling from moorings, drifters, floats, profiling floats, gliders and autonomous underwater vehicles (AUVs) is becoming increasingly important. Arrays of these collective platforms placed in nested sampling configurations have already been proven highly effective. Because of the paucity of data, interdisciplinary numerical models capable of synthesizing observations and predicting variability over broad time and space scales are needed as well.

Although capabilities for obtaining needed atmospheric and physical oceanographic data are improving rapidly, new advances are clearly needed for chemical, biological, optical, acoustical and geological measurement systems. Importantly, many innovative technologies involving computing, robotics, communications, space exploration and physical, chemical, biomolecular and biomedical research are being developed at unprecedented rates for a host of applications. A challenge for observational oceanography is to effectively capitalize on these developments. The present review focuses on several emerging sensors and systems, which have the potential of accelerating global ocean observational capabilities. Readers interested in more detailed information are directed to recent papers (e.g., Tokar and Dickey, 2000; Dickey, 2001a, 2001b; Dickey et al., 2000, 2001; Dickey and Chang, 2001; Dickey and Falkowski, 2001; Glenn et al., 2001a, b) and the website www.opl.ucsb.edu which includes an extensive bibliography and several illustrative examples.

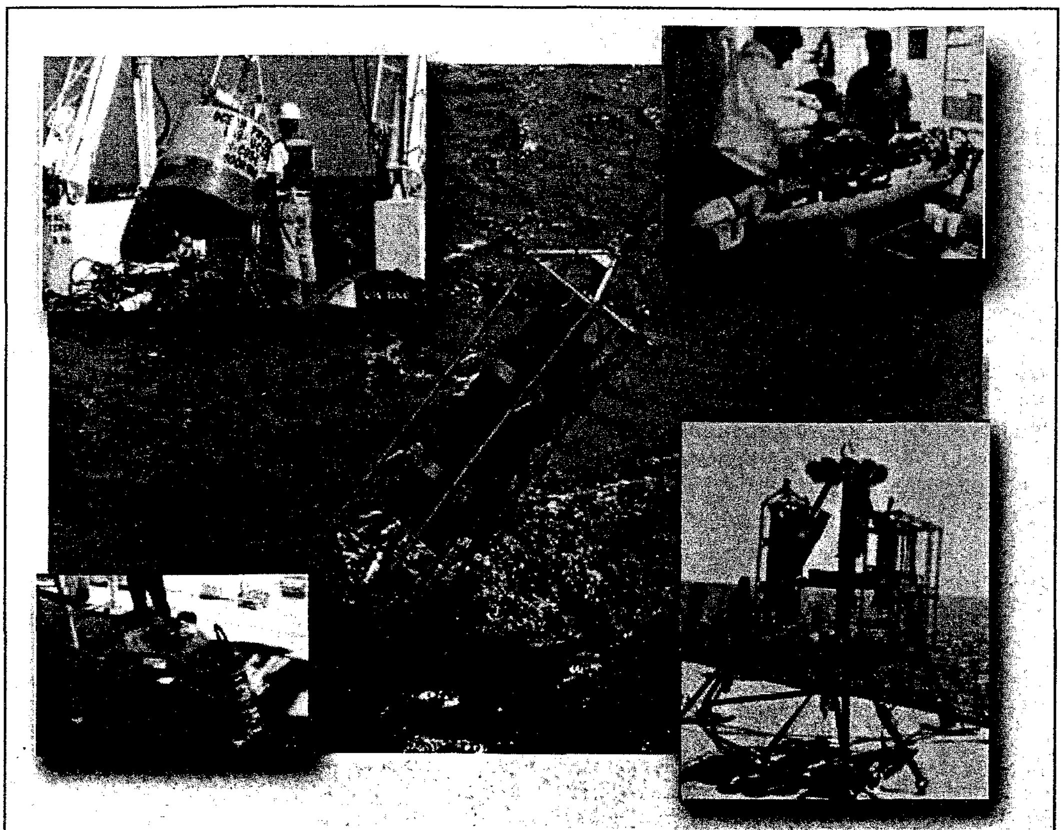
Sensors and Systems

More capable sensors and systems for oceanographic applications are resulting from (1) technology transfer (e.g., Tokar and Dickey, 2000), (2) support of projects specifically devoted to development of relevant ocean technologies (e.g., Dickey et al., 2001), and (3) formation of partnerships among academia, government laboratories and private industry (e.g., Dickey et al., 2000). One of the problems facing sensor and system developers and users is proper interpretation of the instruments' signals. For this reason, testbed sampling programs, which utilize multiple platforms for intercomparisons and "ground-truthing" are critical for optimal utilization of ocean technologies (e.g., Dickey et al., 2001).

In the discussion below, sensor and system descriptions are subdivided according to their primary disciplinary use: chemistry, optics and bio-optics, and biology and bio-acoustics. The areas of physics and marine geology and geophysics are not included here (see Dickey, 2001a). It should be emphasized, however, that interdisciplinary measurement suites are desirable if not imperative because of the need for simultaneous, complementary observations and cost effectiveness gained through sharing of platforms and telemetry systems (e.g., Glenn et al., 2000a, b).

Chemistry. Recent topics of particular relevance to ocean chemistry include global warming due to the greenhouse effect, nutrients and their role in primary productivity and the biological pump (for transporting carbon to the deep sea), ocean pollution and hydrothermal vents. Natural and artificial chemical tracers are important tools for circulation, mixing and dispersal studies. A few of the important advances in chemical sensors and potential future applications are described below (also see Tokar and Dickey, 2000; Dickey, 2001a; Dickey et al., 2000, 2001).

Specially designed water samplers have also been used to sample key chemical components of venting hydrothermal fluids from manned submersibles and ROVs. Moored serial water samplers are being developed and used to obtain discrete preserved samples periodically over the course of a few months to create chemical time series (e.g., see Dickey et al., 2001). Similar systems have also been developed for drifters. Trace metals, as well as macronutrients, can be ana-



A moored system for measuring dissolved oxygen, spectral irradiance and radiance, photosynthetically available radiation, temperature and pressure. This system has been deployed from the Bermuda Testbed Mooring. Examples of systems designed for measuring AOPs and IOPs are shown.

lyzed using the water samples, because of improved laboratory analytical systems.

Several new sensors and systems are capable of making *in situ* time series measurements with sampling intervals of a few minutes and durations of months (see Dickey et al., 2000, 2001). Some of the measurements include nitrate and other nutrients, dissolved oxygen, pCO2, pH and alkalinity. Measurements utilize a variety of methods including polarigraphic electrodes, colorimetry (multiple reagents used for different analyses) and spectrophotometry. It should be noted that some chemical sensors and analyzers have been successfully deployed from moorings, drifters and AUVs. Real-time and near real-time telemetry of chemical variables has also been demonstrated. The importance of atmospheric input of dust and aerosols into the ocean has been recognized recently (e.g., role of iron fertilization). Samplers for dust and aerosols are being developed for deployment from surface buoys to avoid land contamination.

Several other chemical methodologies will likely be utilized in the future. For example, laser Raman scattering systems, which can be deployed from ROVs and manned submersibles, are planned for examining the time course of hydrate formation for deep-sea CO2 disposal and other applications. Chemical analyzers will likely become more available for users of the various platforms. Verification of data using discrete water samples will likely be necessary in the early phase. There is a need for increasing capabilities of sampling broader suites of chemicals autonomously. Applications to problems of pollution, with diverse chemical species of concern (e.g., PCBs, DDT, toxic metals, etc.), will be quite demanding. It is expected that chemical sensors rather than analyzers will be preferable, if not required, for some platforms.

A new technology utilizes fiber-optic sensors for ocean applications. An optical sensor or modulation device is one element of an integrated system that also includes an excitation light source, optical fibers, a photodiode detector and other associated components such as connectors, couplers and signal processing/data logging equipment. The fiber-optic chemical sensor is usually made up of analyte specific sensing reagents immobilized on the side or located at the tip of an optical fiber. Fiber-optic sensors normally fall into two major categories: intrinsic and extrinsic. Intrinsic sensors use the optical fiber to sense the parameter being measured. For example, intrinsic refractive-index sensors have been used to measure hydrocarbons (HC) in water. A number of extrinsic fiber-optic sensors have been designed and tested both in the laboratory and the field to measure selected analytes in water. Examples of successfully measured chemical species using fiber-optic sensors include ammonia, methane and dissolved carbon dioxide. Another example of a pCO2 fiber-optic sensor for seawater is based upon fluorescence using a combination of dyes and coupled to a commercial fiber-optic fluorometer.

Another promising type of sensor is the microelectromechanical system (MEMS). MEMS is based on a relatively new technology (e.g., Tokar and Dickey, 2000), which is used for making and combining miniaturized mechanical and electronic components out of silicon wafers using micro-machining. MEMS has shown encouraging results for sensing physical parameters, but work is needed to realize their full potential for chemical sensing. Most work with MEMS has been done in laboratories; however, transitioning to *in situ* applications seems feasible. Potential advantages of MEMS include: auto-calibration, self-testing, digital compensation, small size and economical production.

Optics and bio-optics. Optics and bio-optics have gained increasing attention in part because of new technologies and the realization of their central importance to several ocean problems involving biological-optical-physical interactions. Applications include: ocean primary productivity, upper-oceanecology, biogeochemical cycling, sediment resuspension, ocean pollution and bio-optically modulated variability in upper-oceanheating rates (e.g., see Dickey, 1991, 2001a, b; Dickey and Chang, 2001; Dickey and Falkowski, 2001).

Two operational classifications of bulk optical properties are most useful for the following discussion. These are inherent optical properties (IOPs) and apparent optical properties (AOPs). IOPs depend only on the medium and are independent of the ambient light field. AOPs are defined to be those properties, which depend on both the IOPs and the geometric structure of the subsurface ambient light field. Instruments designed for underwater light observations are usually described as performing either IOP (e.g., spectral beam attenuation, absorption and scattering coefficients) or AOP (e.g., spectral diffuse light attenuation coefficients) measurements. Recently developed instruments are capable of measuring light absorption, scattering and attenuation at multiple wavelengths (from nine to about 100 wavelengths). Likewise, measurements of diffuse light attenuation have increased spectral resolution, achieving resolutions of a few nanometers in the visible. The power of these types of instruments lies in the ability to distinguish phytoplankton from detritus and dissolved materials and potentially phytoplankton (perhaps including harmful algae), at least by community groups.

Estimation of primary productivity is an important goal and several different optical measurements have been used. Examples include the use of chlorophyll fluorescence and photosynthetically available radiation (PAR) measurements in empirical models and more sophisticated measurements using "pump and probe" fluorometers. The latter instruments have the advantage of providing information about biophysical parameters related to photosynthesis. Many of these optical instruments have been deployed from ships, moorings and drifters.

An important of use of *in situ* optical measurements has been for groundtruthing and algorithm development of ocean-color imagers (e.g., Dickey et al., 2001). In addition, variability of phytoplankton biomass and primary productivity and upper-ocean-radiant heating rates (and penetrative component of solar radiation) have been estimated using both in situ and remotely sensed data sets. Determination of bottom bathymetry using optics in coastal areas is another important applied research objective.

One of the thrusts of *in situ* optical instrumentation is in the area of scattering of light, particularly in terms of angular dependence (volume scattering function) and backscattering. These data types, along with absorption, are important for fully characterizing the underwater light field, which has great implications for underwater visibility and remote sensing as well as fundamental optical radiative transfer problems. Simultaneous measurements of key IOPs and AOPs are critical for developing inversion models so that IOPs can be determined from AOPs and vice versa. Another new type of instrument involves spectral fluorescence. One such instrument using six excitation wavelengths and 16 emission wavelengths has measured dissolved organic materials as well as other dissolved substances associated with aging sewage discharge waters.

Other optical instruments, using the Frauenhofer effect, have been used successfully to obtain particle size distributions, primarily in bottom boundary layers. Flow cytometry has been successfully used onshore and onboard ships for counting and distinguishing particles and phytoplankton as well as for characterizing their optical properties. The time series (from moored systems) obtained from many of the aforementioned *in situ* optical systems are showing remarkable variability associated with high frequency and episodic events as well as longer term processes. Presently, most bio-optical sensors are deployed from ship-based profilers. With advances in microprocessor technologies, data processing and storage are not generally limiting.

A growing number of optical as well as chemical oceanographers are moving toward autonomous sampling from moorings, AUVs, drifters, floats and gliders. Capabilities for the telemetry of these data are also increasing rapidly.

Biology and bio-acoustics. An important goal of current research is to understand and ultimately predict how populations of marine animal species respond to natural and anthropogenic changes in global climate. Such research is driven in part by the waxing and waning of fisheries. Large volumes of data will be required along with interdisciplinary models capable of extrapolating and integrating these data sets.

Because of the variety of marine

life, key indicators and ecologically relevant variables must be carefully chosen; these will often be dictated by special regional aspects. Fundamental physical, chemical and biological observations will form the core measurements.

Studies of phytoplankton have benefited from advances in bio-optical instrumentation whereas studies of higher trophic level organisms are utilizing new video and acoustical techniques (see Dickey, 2001a). One method of sampling zooplankton employs light sheets. These systems are usually profiled or towed behind ships and provide zooplankton biomass and size distributional data. Video imaging systems provide more detailed organismal information. Image analysis is a demanding aspect of this approach. These systems have been profiled and towed from ships; work is underway to deploy them from AUVs.

Acoustics have been used by fishermen for several decades. Breakthroughs in the use of acoustics for research have involved the development of multi-frequency systems. Models have been developed to utilize the multi-frequency data to make estimates of not only total biomass of zooplankton, but also to determine size distributions. Optimally, three-dimensional acoustic, optical and video systems can collect data concurrently, optimizing the advantages of each method. Such sampling could provide information concerning predator-prey interactions. Since the choice of the size ranges of targeted organisms is dictated by the choice of transducers, a nearly complete size spectrum of organisms can be obtained in principal. Interpretation of video and acoustical data is challenging; however, neural network approaches may be valuable.

Emerging tools for biological oceanography include molecular genetic and species specific molecular probes (e.g., Dickey, 2001a). Molecules such as ribosomal RNAs have begun to be used for detection and determinations of abundance of some bacterioplankton species and to study evolutionary relationships among several species. Species-specific probes (DNA antibody) for harmful algal blooms (HABs) have been developed and offer great promise in helping to understand the context of these events. Applications of genetic techniques to higher trophic levels (zooplankton to whales) are being pursued as well.

Some general biological sampling needs remain. The utilization of *in situ* platforms appears to be the most feasible option at present. Novel platforms, which mimic organismal movement or simply travel with targeted organisms, have also been the subject of research and development. In principal, arrays of miniature sensors can be deployed from these "organismal" platforms.

Interdisciplinary systems. The power of measuring the variety of interdisciplinary variables has already been demonstrated in interesting correlations in some cases and confounding lack of correlation in others. Sampling of biology, optics and acoustics on virtually the same time and space scales as physics is certainly a large achievement of the oceanographic community during the past decade. New platforms will carry more sensors and systems in the future. Challenges lie in developing smaller, lighter, more efficient and less power demanding sensors and systems.

Toward the Future

Important challenges remain to ocean observationalists. For example, most of the systems and platforms are not designed for sampling from the shoreline to about 30 meters, which is the most important ocean zone for direct human interaction. AUVs are still power limited, requiring fuel-cell advances. Biofouling of many sensors is problematic for longer duration sampling (e.g., Dickey et al., 2000). Resources for developing and implementing sampling networks (e.g., Dickey, 2001a, 1991; Glenn et al., 2000a, b) must come from a variety of sources and be internationally based.

> *"Perhaps the most important message is that the oceanographic community has never been in such a strong position to make major advances."*

Importantly, new instruments and platforms must be transitioned to the commercial sector for widespread use. Technology is moving so rapidly that many of the measurement systems will become obsolete quite quickly; however, continuity of standardized and well-calibrated measurements must be hallmarks of ocean observing systems intended to quantify long-term change. One possible benefit of advanced technologies may well be simpler sampling systems (e.g., "chip-based" sensors with automated data processing), which could benefit oceanographic programs regardless of present technical capabilities and skill levels. Telemetry of data from all oceanographic systems is becoming more important. Also, more effective use of data will require clever manipulations of data sets.

Perhaps the most important message is that the oceanographic community has never been in such a strong position to make major advances, largely because of the growing technological capabilities and society's growing interest in the ocean environment. The successful development of a Global Ocean Observing System, which will be of great utility for a multiplicity of purposes, will require optimal utilization of the technologies described here.

Acknowledgements

Thanks to the numerous international collaborators and colleagues who have generously shared ideas with me and made this paper possible: the U.S. Office of Naval Research, National Science Foundation, National Atmospheric and Space Agency, National Oceanic and Atmospheric Administration, MMS and the University of California, Santa Barbara for supporting my research. /st/

References

Dickey, T. "The emergence of concurrent high resolution physical and bio-optical measurements in the upper ocean and their applications," *Rev. of Geophys.*, Vol. 29, pp. 383-413, 1991.

Dickey, T., Instrumentation and new technologies, in Oceans 2020: *Science for Future Needs*, eds. J.G.