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Emerging Interdisciplinary Technologies and Their Potential Utilization in the Global Ocean Observing System

Tommy D. Dickey
Ocean Physics Laboratory
University of California, Santa Barbara
6487 Calle Real, Suite A
Santa Barbara, California, USA
email: tommy.dickey@opl.ucsb.edu
Ph: 805 893-7354 Fax: 805 967-5704

Introduction

Ocean observations benefiting from developments in instrumentation and technologies have led to major advances in ocean sciences. Solutions of oceanographic problems involving global climate change are limited by undersampling, which also hampers model formulation. There is a well-recognized need to massively increase the variety and quantity of ocean measurements. These measurements are expensive, but vital. 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 efficiently capitalize on these developments.

In this paper, we present a brief summary of the challenges of observing the ocean environment, describe a variety of observing platforms, and introduce emerging interdisciplinary sensors and systems.

Challenges to Ocean Observationalists

It is vital to improve measurements of critical variables in order to distinguish natural from anthropogenic changes. Virtually all important environmental problems require interdisciplinary approaches and atmospheric, physical, chemical, biological, optical, and geological data sets. The requisite data should be collected simultaneously and span time and space scales to observe the relevant processes of interest. For global problems, this requires that variability extending well over ten orders of magnitude in space, and much longer in time, for climate problems be encompassed. Although capabilities for obtaining needed atmospheric and physical oceanographic data are quite well advanced, new advances are clearly needed for chemical, biological, optical, acoustical, and geological measurement systems. However, remarkable advances are being made in these areas as well. In fact, several bio-optical, chemical, geological, and acoustical variables can now be made on the same time and space scales as physical variables; however many more are needed.

The oceans are naturally dynamic with large amplitude periodic and episodic variability, which is especially confounding for quantifying long-term trends and changes. At present, limited numbers of variables can be directly measured in the marine environment, so it is essential that we select those variables which are the most critical. 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. The following sections summarize information according to platforms and sensors and systems.

Platforms

Interdisciplinary oceanographic programs have utilized or are utilizing multi-platform approaches. These include: the World Ocean Circulation Experiment (WOCE), the Tropical Ocean Global Atmosphere (TOGA) program, the Joint Global Ocean Flux Study (JGOFS), the Global Ocean Ecosystem Dynamics (GLOBEC) program, and the Climate Variability and Prediction Study (CLIVAR). Carefully selected combinations of mooring arrays, drifters, voluntary observing ships (VOS), and satellite data are commonly selected. The Global Ocean Observing System (GOOS) likely will follow this approach, enabling studies of El Nino-Southern Oscillation (ENSO) and interdecadal phenomena such as the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO), and the Arctic Oscillation (AO). Two important aspects are near real-time data telemetry and data assimilation modeling.

A variety of platforms, several of which can utilize physical, chemical, bio-optical, acoustical, and geophysical sensors or systems, are now available or are being developed. Nesting of platforms can optimize utilization of these observational assets. Brief summaries of capabilities and future directions using different platforms are given below.

Ships and submarines

Today, ships are used for 1) direct observations and data collection and 2) deployment of other sampling platforms such as moorings, drifters, and others described below. One of the advantages of ships is that advanced analytical instrumentation, which cannot presently be deployed *in situ* from other platforms, can be utilized. Examples of such instrumentation include flow cytometers and mass spectrometers. Modes of ship sampling include 1) on-station profiling of instruments, 2) underway sampling of surface waters using flow-through systems, 3) underway sampling using towed undulating or fixed depth bodies or chains, which act as platforms for sensor suites, and 4) underway acoustical measurements (e.g., for acoustic Doppler current profilers (ADCPs), hydrophone arrays, and sidescan sonar). It should also be noted that commercially operated voluntary observing ship (VOS) or ships-of-opportunity observational programs have been valuable, especially for obtaining data in remote oceanic regions where few dedicated research sampling programs can be routinely executed. Some interesting examples of data collection from submarines have been reported as well.

Ships will likely continue to serve as essential oceanographic platforms. Their utilization for process-oriented and transect sampling will continue, but likely with less weighting than for autonomous sampling platform deployment and recovery operations. Ships used for direct sampling will likely utilize more advanced instrumentation, often using fiber optics for greater data bandwidth. Lightships and specialized manned platforms with unique sampling capabilities (e.g., R/P FLIP) can play important roles as well. Most submarines are used for military purposes, but more may become available to the research community in the future.

Moorings, bottom tripods, off-shore, and shore-based platforms

Moored and bottom tripod measurement systems and sensors are being used by the research community to study environmental changes in the ocean on time scales from minutes to years. An increasing number of bio-optical, chemical, geological and acoustical parameters are being measured from moorings. This work has led to discoveries of new processes such as primary production variability associated with ENSO and equatorial long waves, sediment resuspension through internal solitary waves, cloud-induced and diel fluctuations in phytoplankton biomass, phytoplankton blooms associated with incipient seasonal stratification, and frontal- and eddy-trapped inertial waves. Measurements of nitrate, partial pressure of carbon dioxide (pCO_2), and dissolved oxygen (DO) have enabled new insights into primary and new production and gas exchange across the air-sea interface. Interestingly, several diverse and often adverse oceanic regions have been studied using interdisciplinary moored systems. These range from the equatorial Pacific to high latitude areas south of Iceland and in the Southern Ocean. Because of biofouling of sensors, useful data from moorings has often been limited to a few months in the open ocean and less in coastal waters; however, work is underway to mitigate this problem. Moored systems have proven to be valuable in the research realm and need to be deployed in critical regions for studies of seasonal through decadal variability and longer term monitoring purposes. High temporal resolution data will continue to be needed to minimize sampling induced uncertainties (via undersampling and aliasing). Benthic processes may be studied and monitored using instrumentation deployed on bottom tripods. The chemical species and geological parameters of interest will vary depending on the type of environment (e.g., harbor, coastal, or open ocean).

Offshore platforms, including dedicated and oil production platforms, provide unique opportunities for conducting oceanic and meteorological research and monitoring. They offer several advantages over shipboard platforms, including absolute stability in high sea states, suitability for time series measurements, and capability for housing personnel. It should be possible to launch autonomous underwater vehicles (AUVs) and other mobile sampling devices from these platforms for spatial sampling as well.

Time series observations in the coastal ocean and at selected sites of expected high environmental consequence (e.g., equatorial Pacific, high latitude sites of water formation and/or CO_2 uptake) or special long-term monitoring value (e.g., oligotrophic areas of the gyres of the Pacific and Atlantic Oceans, the Arctic region, the Southern Ocean, and near Antarctica) will require the aforementioned platforms. Increased multi-use of platforms for interdisciplinary sensors and systems is imperative. For example, a mooring designed for a tsunami warning system has been used in the Pacific for measuring upper ocean parameters relevant to global climate change.

Novel uses of the platforms will evolve. In particular, moored profilers (e.g., buoyancy or mechanically driven for the open ocean (wave-driven in the coastal zone) have been and can be used to for situations requiring high vertical resolution data.

Increased bandwidth for telemetry of data should enable transmittal of multi-frequency acoustical and multi-wavelength optical as well as video data. Shore-based instrumentation is being used to obtain surface current and wave data in some coastal regions. Coastal sites and piers may also be used for other ocean observations (e.g., sea level, acoustics, horizontally oriented ADCPs, etc.). New acoustic instruments are also becoming available for measurements of wave directional spectra, bottom pressure, and currents in the surf zone.

Drifters and floats

The platforms described in the previous section can be used to provide high temporal resolution, long-term measurements at fixed locations (Eulerian). However, drifters and floats may be used to provide spatial data by effectively following water parcels (Lagrangian method). Drifters and floats can collect data in regions of the world oceans, which are rarely visited by oceanographic cruises. These collective Lagrangian samplers now utilize the Global Positioning System (GPS) giving very accurate position data (accuracy of less than 10's of meters down to a few meters). Surface drifters provide important upper ocean data (e.g., temperature, salinity, and meteorological variables). Early floats typically moved at pre-determined depths. More recently, profiling floats have been used to provide data (e.g., temperature, salinity, and reference velocity) during rise and descent through the water column as part of their function to telemeter data back to the scientific community. Present projections suggest that roughly 1000 surface drifters and 3000 profiling floats (near surface to 2000 m) will be in operation annually within the next few years.

Costs of drifters and floats will likely decrease as more are produced and used. Emerging systems will be simplified and ruggedized to enable easy deployment from ships-of-opportunity and aircraft. New GPS and telemetry (including two-way duplex information exchange) capabilities will continue to improve position accuracy and increase the daily number of reported positions resulting in greater computed current resolution and accuracy along with much greater volumes of data throughput. Within the past decade, a few oceanographers have begun to deploy optical and/or chemical sensors from drifters and floats. It is anticipated that an increasing number of interdisciplinary variables will be sampled from Lagrangian platforms in the future as size, weight, power, etc. become less limiting. Biofouling of conductivity as well as chemical and bio-optical sensors will require special measures as mentioned earlier.

Autonomous underwater vehicles (AUVs)

New technologies and concerted efforts have enabled the development of AUVs and three related types of unmanned oceanographic vehicles: untethered underwater vehicles (UUVs), autonomous surface vehicles (ASVs), and gliders. AUVs and UUVs are designed for a diverse set of activities in coastal or open ocean waters and can carry sensor payloads for specific applications such as seafloor mapping, pipeline inspection, reconnaissance, and basic and applied research. They generally vary in size from about a meter in length to over 10 m and utilize battery or fuel cell propulsion. UUVs are sent on sampling missions and are under remote control or command of personnel some distance away. AUVs are pre-programmed to perform sampling along specified track lines, to dock for downloading of data and recharging of batteries or fuel cells, and to key on specific oceanic cues (e.g., adaptive sampling based on temperature and chemical gradients). ASVs operate similarly to AUVs, but are restricted to surface operations.

Novel autonomous sampling platforms called gliders are the newest class of platforms being tested. Gliders have design elements and attributes of both profiling floats and AUVs. Gliders use buoyancy control to move vertically through the water columns, but utilize wings and hydrodynamic shape to produce horizontal motion. They are intended to perform with two sampling options: 1) performing long transects (e.g., up to 10,000 km) in a sawtooth pattern (down to 2000 m) and 2) as "virtual moorings" executing vertical profiles at fixed location. Key needs for gliders will be improved satellite data telemetry. The use of gliders for carrying interdisciplinary sensors and systems will be more demanding than for some other platforms because of required precision of ballasting, hydrodynamic drag, and limited power.

Most of the UUV, AUV, ASV, and glider activities have been confined to engineering design and some practical field activities. However, a variety of recent activities have begun to exploit these vehicles for scientific studies. This has become possible because of the development of new sensors and systems, which are relatively small in size, consume moderate power, and can be interfaced with the vehicles. Some of the key advantages of the autonomous platforms include cost per deployment, capability to sample in environments generally inaccessible to ships (e.g., in hurricanes or typhoons and under ice), good spatial coverage and sampling over repeated sections, capability of feature-based or adaptive sampling, and potential deployment of several vehicles from moorings, mother ships, offshore platforms, and coastal stations.

Specialized groups are now developing and using autonomous vehicles and the numbers are expected to grow as mission length capabilities increase, costs decline, reliability improves, operation becomes more routine, and more sensors become available for various sampling needs. The future is bright for these platforms, yet there are some cautionary points worth noting. It seems likely that major breakthroughs in fuel cell technologies (allowing longer missions in space and time), improved navigation and telemetry (via acoustic and satellite links) capabilities, and miniaturization of sensors will facilitate and accelerate widespread use of these platforms. Creative uses of the vehicles will involve networking and informational feedback loops to guide sampling programs (in some areas involving predictive models) and responses to extreme natural and anthropogenic driven events.

Sensors and Systems

More capable sensors and systems for oceanographic applications are resulting from 1) technology transfer, 2) support of projects devoted to development of relevant ocean technologies, and 3) formation of partnerships among academia, government laboratories, and private industry. 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 "groundtruthing", are critical elements for optimal utilization of ocean technologies (Dickey et al., 1998).

In the discussion below, we subdivided sensor and system descriptions 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 (for these and more detailed information, please see Dickey, 2000). It should be emphasized, however, that interdisciplinary measurement suites are desirable because of the need for simultaneous, complementary observations and cost effectiveness in shared platforms and telemetry systems.

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.

While analyses of ship-derived water bottle samples are still important, other methods are gaining increasing attention and are being put into use. For example, underway surface water sampling is done using shipboard water intake systems and automated laboratory chemical analyzers. Pumping systems are also used to bring subsurface samples onboard ships for similar analyses and water collection. 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. Similar systems have also been developed for drifters. Trace metals, as well as macronutrients, can be analyzed using the water samples, because of improved laboratory analytical systems.

In situ measurements have major advantages in sampling for ocean chemistry as these samples do not suffer degradation and are representative of the local environmental conditions at depth. 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. Some of the measurements include nitrate and other nutrients, dissolved oxygen, pCO_2, pH, and alkalinity. Measurements utilize a variety of methods including polarigraphic electrodes, colorimetry (multiple reagents used for different analyses), and spectrophotometry. Spectrophotometry takes advantage of long pathlength absorbance spectrometry enabled by using fiber optics liquid core waveguides. 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 and there are a few examples of actually modifying sampling (gain changes, etc.) using two-way or duplex data telemetry systems. 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 CO_2 disposal, and for gas hydrate geochemistry, bacterial mats, particulate geochemistry, and sulfate profiling in sediments. Nuclear magnetic resonance (NMR) technology has been used by oil companies to detect the presence of water and to find the porosity of marine sediments and rocks in boreholes. Large and small bore hole tools offer powerful opportunities to examine gas and hydrate sediment geochemistry experimentally under deep ocean conditions using ROVs. The use of NMR to directly measure advection rates of fluids in sediments is another possibility. Autonomous water tracer sampling from moorings and other platforms could provide a valuable complement for shipbased survey tracer sampling. 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. Different light sources can be utilized. The modulated optical parameters of light may include amplitude, phase, color, state of polarization, or a combination of these. 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. This becomes possible when the fiber is altered by the physical or chemical external variable being sought. These external variations cause an alteration of the optical properties (total internal reflection) of the fiber, resulting in measurable light intensity, phase, or polarization changes.

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 pCO_2 fiber optic sensor for seawater is based upon fluorescence using a combination of dyes and coupled to a commercial fiber optic fluorometer. A renewable-reagent fiber optic sensor has also been developed. Currently, there are a limited number of fiber optic sensors available for use in seawater. Additional research and development is needed to improve response time, reproducibility, and long-term reliability.

Another promising type of sensor is the microelectromechanical system (MEMS). MEMS is based on a relatively new technology, which is used for making, and combining miniaturized mechanical and electronic components out of silicon wafers using micro-machining. MEMS have 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 (see reviews by Dickey, 1991, 2000). Applications include: ocean primary productivity, upper ocean ecology, biogeochemical cycling, sediment resuspension, ocean pollution, and bio-optically modulated variability in upper ocean heating rates.

Two operational classifications of bulk optical properties are most useful for the following discussion: 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. Until quite recently, direct *in situ* measurements of IOPs were generally limited to single wavelength (usually 660 nm) beam attenuation (660nm). However, recently developed instruments are capable of measuring light absorption, scattering, and attenuation at multiple wavelengths (from 9 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. 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 6 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 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 observationalists are moving toward autonomous sampling from moorings, AUVs, drifters, floats, and gliders. Capabilities for the telemetry of optical 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. 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. 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 in the areas of 1) quantifying the gross numbers of organisms in the sea and eventually estimating their changes regionally and globally, 2) species and larval stage identification, and 3) rates of feeding/predation, swimming, reproduction, and mortality. The challenges of sampling zooplankton and higher trophic levels are arguably greater than for any other ocean parameters. 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 m, 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. Resources for developing and implementing sampling networks must come from a variety of sources and be internationally based. Many of the new sensors, systems, and platforms are presently in developmental phases or in the hands of a few researchers. Interpretation of many of the signals remains an issue and intensive cross-sampling and inter-calibrations are critically needed.

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. Telemetry is discussed in detail in Dickey (2000).

More effective use of data will require clever manipulations of data sets. For example, many of the processes of interest are nonlinear in nature, so newly emerging methods of analysis will need to be utilized. Another concern is that oceanographers are already collecting more data than they can possibly analyze. Thus, increased numbers of ocean scientists and analysts will be needed worldwide.

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 the optimal utilization of the technologies described here.

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