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Interdisciplinary oceanographic observations: the wave of the future

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SUMMARY: Oceanographic measurements, though difficult and expensive, are essential for effective study, stewardship, preservation, and management of our oceanic and atmospheric systems. Ocean sciences have been driven by technologies enabling new observations, discoveries, and modelling of diverse interdisciplinary phenomena. Despite rapid advances in ocean sampling capabilities, the numbers of disciplinary variables that are necessary to solve oceanographic problems are large and increasing. In addition, the time and space scales of key processes span over ten orders of magnitude; presently, there remain major spectral gaps in our sampling. Thus, undersampling presents the main limitation to our understanding of global climate change; variability in fish biomass and regime shifts; and episodic and extreme events. Fortunately, recent advances in ocean platforms and *in situ* autonomous sampling systems and satellite sensors are enabling unprecedented rates of data acquisition as well as the expansion of temporal and spatial coverage. Consequently, improved sampling strategies will lead to a reduction in ocean forecasting error for predictions of a multitude of atmospheric and oceanic processes. Nonetheless, major challenges remain to massively increase the variety and quantity of ocean measurements and to effectively coordinate, synthesize, and distribute oceanographic data sets. In particular, numbers of measurements are limited by the costs of instruments and their deployment as well as data processing and production of useful data products and visualizations. Looking forward, many novel and innovative technologies involving computing, nanotechnology, robotics, information and telemetry technologies, space sciences, and molecular biology are being developed at a fast pace for numerous applications (Kaku, 1997; Kurzweil, 1999). It is anticipated that several of these can and will be transitioned to the ocean sciences and will prove to be extremely beneficial for oceanographers in the next few decades. Already, autonomous, 'robotic' *in situ* sampling, high spectral resolution optical and chemical instrumentation, multi-frequency acoustics, and biomolecular techniques are being utilized by a limited number of oceanographers. Also, increased temporal and spatial sampling capabilities for expanding numbers of interdisciplinary variables are being accelerated thanks to both new technologies and utilization of data assimilation models coupled with autonomous sampling platforms. Data networks coupled with internet connectivity are rapidly increasing access to and utilization of data sets. In this essay, we review recent technological progress for solving some key oceanographic problems and highlight some of the foreseeable challenges and opportunities of ocean science technologies and their applications.

Keywords: technology, instrumentation, platforms, modeling, interdisciplinary, observatories, observational systems.

RESUMEN: OBSERVACIONES OCEANOGRÁFICAS INTERDISCIPLINARES: NUEVAS TENDENCIAS. – Las medidas de parámetros oceanográficos son difíciles y caras de obtener, no obstante son esenciales para una eficaz conservación y gestión de los sistemas marinos y atmosféricos. Las ciencias marinas han avanzado a medida que la tecnología permitía nuevas observaciones y procesar modelos de fenómenos de diversa interdisciplinaridad. No obstante, el número de variables necesarias para resolver preguntas en el sistema marino es muy alto y el rango de las escalas de tiempo y espacio asociadas a procesos clave es de diez ordenes de magnitud. Actualmente todavía existen intervalos dentro de este rango sin muestrear. Por tanto, la falta de medidas representa la mayor limitación para un buen conocimiento del cambio global, y de las causas que provocan la variabilidad de la pesca, de los regímenes de las corrientes marinas y de los eventos extremos. Afortunadamente, los avances recientes relacionados con sistemas automáticos de toma de muestras tanto in situ como remotamente han permitido mejorar tanto la rapidez en la adquisición como la cobertura espacial. Estas mejoras en las estrategias de muestreo nos ayudan a reducir el error en las predicciones de procesos oceánicos y atmosféricos. No obstante, el mayor reto continua siendo por un lado aumentar la diversidad y cantidad de medidas, y por otro conseguir una coordinación efectiva que permita la síntesis y distribución de los datos adquiridos. En particular el número de medidas están limitadas por el coste de los instrumentos, del tratamiento de los datos y de los métodos de visualización de éstos. Mirando hacia el futuro, las innovaciones en los campos de la informática, la nonotecnología, la biología molecular, la robótica y la telemetría aumentarán rápidamente y permitirán nuevas aproximaciones (Kaku, 1997, Kurzweil, 1999). Actualmente, un número limitado de oceanógrafos ya trabajan con sistemas automáticos de adquisición de datos que combinan técnicas acústicas, químicas, biomoleculares etc. Además, la capacidad de toma de datos a distintas escalas de tiempo y espacio está continuamente aumentando gracias a las nuevas tecnologías y a la mejora de los sistemas de tratamiento de datos. Las redes de sistemas de base de datos y la rápida comunicación por internet están incrementando el acceso y la utilización de los datos. En este trabajo nosotros revisamos el progreso de las tecnologías recientes para solucionar preguntas claves en la oceanografía y remarcamos algunos de los retos futuros, así como las tecnologías aplicadas a las ciencias del océano.

Palabras clave: instrumentación, plataformas, modelos en ocenografía, interdisciplinariedad, sistemas de observación.

INTRODUCTION

The oceans must have fascinated early humankind living adjacent to them in similar ways that they fascinate us even today. For example, they are tantalizingly accessible from shorelines, but their great depths and remote reaches make them virtually inaccessible to most. The history of oceanographic research begins with the age of exploration and discovery by adventurous people willing to risk their lives in quest of knowledge of the oceans as they sailed in small crafts. Oceanographic advances have been stimulated by individual and group creativity and resourcefulness in the development and use of simple to complex instrumentation based on capabilities of contemporary societies. For example, 19th century oceanographers used devices such as thermometers to determine ocean temperatures, lead lines to plumb the ocean depths, and nets to sample oceanic organisms. 20th century oceanographers used mechanical current meters and electronically based sensors for a variety of physical measurements. Importantly, they also began to capitalize on satellite-, optically-, and acoustically-based measurements in the late 1970's. Early in the 21st century, we can speculate on the future of oceanography and form visions of global observations using a host of remarkable *in situ* and remote sensing platforms, sensors, and information technologies (e.g. Curtin *et al*., 1993; Kaku, 1997; Kurzweil, 1999; Glenn *et al*., 2000; Koblinsky and Smith, 2001; Griffiths *et al*., 2001; Dickey, 2002, 2003; Oceanography, 2000, 2003, 2004).

The purpose of this essay is to briefly review progress in sampling and studying the ocean, to suggest some of the possible future directions of oceanographic research, and to speculate on a few of the means of answering vexing problems facing oceanographers in the next decades. Several other reports and papers have reviewed specific ocean technologies and sampling issues (e.g. Bidigare *et al*. 1992; Dickey, 2001, 2002, 2003, 2004; Glenn and Dickey, 2003; Bishop *et al*., 2001, 2002; Davis *et al*., 2001; Dickey and Chang, 2001; Eriksen *et al*., 2001; Jaffe *et al*., 2001; Chang *et al*., 2004), therefore emphasis here is placed more upon our personal views of some of the remaining oceanographic problems and the types of technologies that may be used for advanced ocean sampling technologies.

Our essay begins with a discussion of some fundamental considerations for ocean sampling. Next, recent progress in ocean sampling is summarized and some examples of interesting and challenging ocean problems are presented. Then, we outline some promising approaches and technologies, and provide some visions of a future ocean experiment designed to study mesoscale eddies. Finally, we conclude with some perspectives on future ocean research and technologies and outline a few challenges and opportunities for the next few generations of oceanographers.

CONSIDERATIONS FOR OCEAN SAMPLING

Oceanography personifies interdisciplinary science of the 'blue' planet, Earth. Diverse scientific disciplines are required to successfully solve almost all oceanographic problems. The need for an oceanographer to be knowledgeable in several scientific disciplines, along with the ocean's complexity and variability at spatial and temporal scales spanning over ten orders of magnitude (Fig. 1) and environmental adversity, makes it one of the most challenging, yet appealing, fields of science. Further, episodic events (Table 1), which are difficult to include in time-space diagrams such as Figure 1, present especially great sampling challenges. Much of oceanography necessarily has been devoted to the difficult task of measuring ocean variables to infer, quantify, and understand a variety of processes, which themselves are often interacting via positive and negative feedbacks.

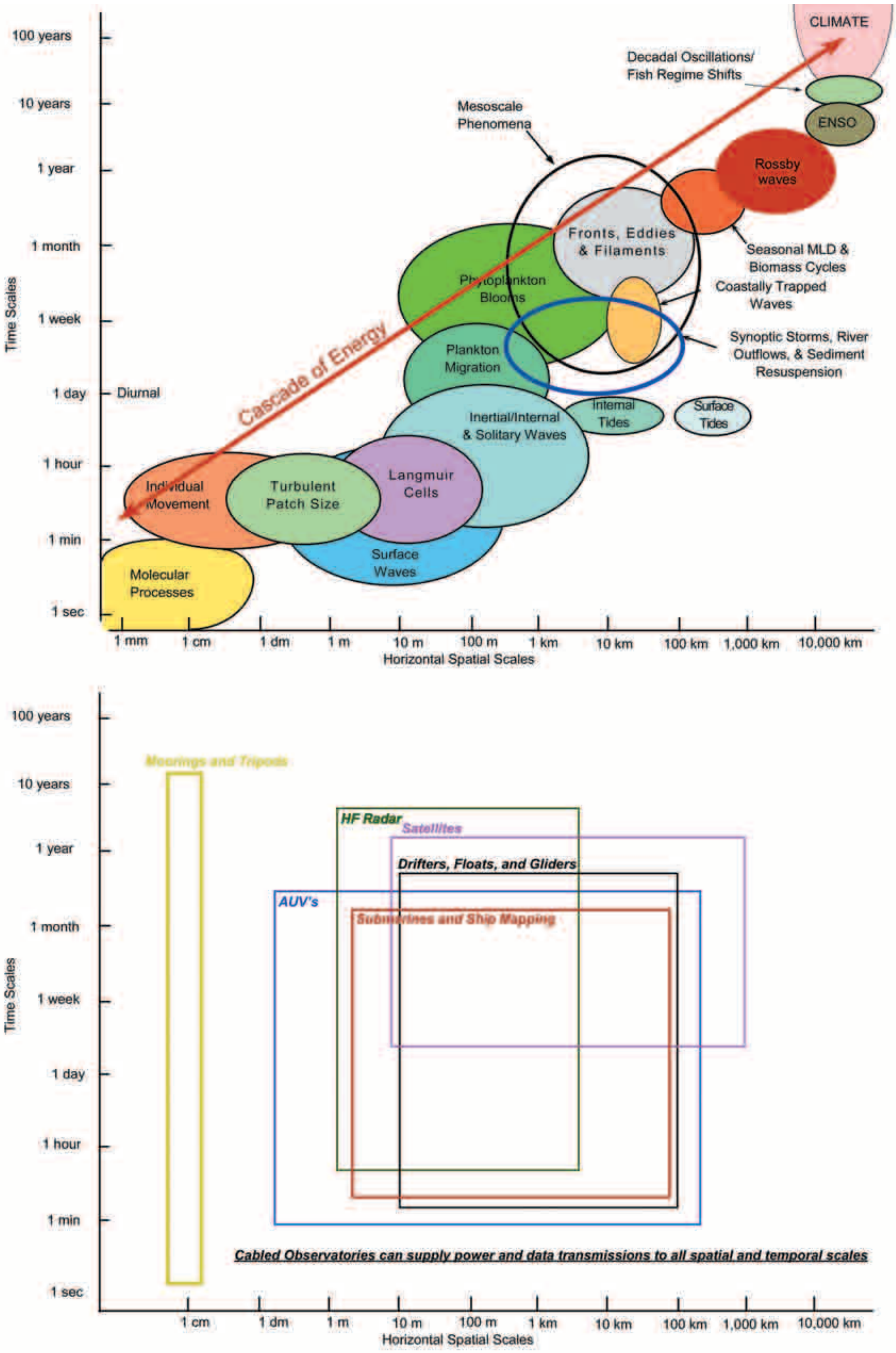

FIG. 1. – Time and horizontal space plot indicating a variety of ocean processes (top) along with rough coverage domains of various oceanographic platforms (bottom). The arrows on the figure are intended to draw attention to the cascade of energy and information from large to small scales as well as small to large scales.

TABLE 1. – Examples of episodic oceanic events or processes and implications.

Examples of episodic oceanic event or process	Implications and importance
Tsunamis	Death and destruction, sediment resuspension, change in ecosystems
Hurricanes, typhoons, and cyclones	Death and destruction, mixing, blooms, sediment resuspension, change in ecosystems
Storm surges	Death and destruction, sediment resuspension, change in ecosystems
Dust storms	Blooms, climate effects
Episodic ozone depletion	UV damage and ecosystem implications
Solitary waves	Mixing, sediment resuspension
Submarine volcanic eruptions	Generation of tsunamis, change in ecosystems
Submarine mud slides	Tsunamis, methane hydrate decomposition, abrupt climate change
Submarine earthquakes	Tsunamis, methane hydrate decomposition, abrupt climate change
Harmful algal blooms (HABs)	Human health and death
Human pathogen outbreaks (e.g. cholera)	Human disease and death
Oil and other spills/leakages	Human health, ecosystem changes
Invasive species outbreaks	Ecosystem changes
Storm runoff	Human health, ecosystem changes, blooms
Ice shelf breaking and glacial calving	Sea level change, ecosystem changes

As an observational Earth science, oceanography began as a highly interdisciplinary observational endeavour with ships sampling the ocean as a system to be understood in its entirety – physics, chemistry, biology, and geology were all part of the observational mix. However in the mid-decades of the 20th century, disciplinary oceanography came to the fore (e.g. programs such as MODE, POLYMODE, INDEX). Interestingly, this rather 'reductionist' approach was also holding sway as physicists sought to understand the smallest bits of matter and biologists studied the essence of life at the molecular scale to unravel the mysteries of DNA. It is worth noting that the emerging triumvirate of quantum mechanics, computing, and molecular biology have all complemented and benefited from each other as suggested by some of the synergies and cross-fertilizations depicted in Figure 2. For example, as noted by Kaku (1997), the book entitled *What is Life?* written by Erwin Schrodinger (one of the fathers of quantum theory) inspired the work of James Watson and Francis Crick, who used X-ray crystallography to explain the atomic structure of the DNA molecule. Schrodinger, the physicist, had boldly asserted that life could be explained via a 'genetic code' characterizing molecules within a cell. Increased computing power certainly enabled advances in quantum mechanics and high energy physics, but perhaps an equally important and powerful application has been DNA sequencing (i.e., the Human Genome Project completed ahead of schedule in 2003 was designed to map the roughly 25,000 genes of DNA of the human body with sequencing of 3 billion chemical base pairs; http://www.ornl.gov/sci/techresources/Human_Genome/home.shtml). The developments and synergism of quantum mechanics, molecular biology, and computing have clearly proven to be key to oceanographic research as well as illustrated in Figure 2.

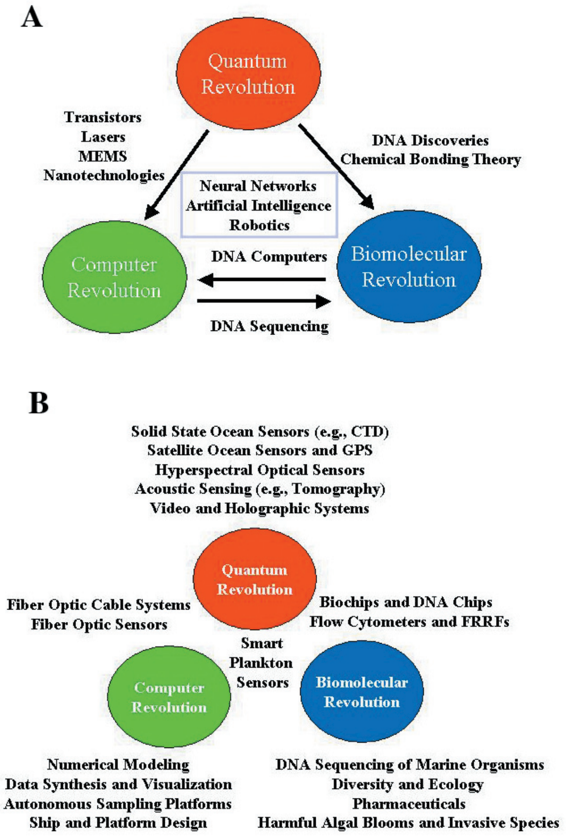

FIG. 2. – A. Schematic illustrating the relationships of three breakthrough areas (quantum, computer, and biomolecular) of science in the 20th century (after Kaku, 1997). B. Schematic analogous to A. showing some of aspects of ocean sciences and technologies that have benefited from the quantum, computer, and biomolecular revolutions.

As progress in understanding the ocean was being made following the reductionist approach, new challenges and problems (i.e. global climate change, fisheries, pollution) faced oceanographers. These stimulated a renewed interest in 'holistic' research, that is, truly multi-disciplinary and interdisciplinary oceanography—the former implying concurrent disciplinary observations and studies; the latter connoting research involving interactions among physical, biological, chemical, and geological processes. Vital new observational tools in the biological, chemical, and geological oceanographic sub-disciplines (e.g. Figs. 1 and 2) have clearly facilitated the re-emergence of interdisciplinary ocean science. Examples of some of the interdisciplinary international programs that have benefited from these tools have included CUEA (Coastal Upwelling Ecosystem Analysis program), JGOFS (Joint Global Ocean Flux Study), and GLOBEC (Global Ecosystem Dynamics program).

While coastal regions have always been easier to access, the blue waters of the open ocean became the focus of many oceanographers in the 1950's to the 1990's in part because of the Cold War, which spawned the internet, acoustical (i.e. SOSUS, SOund SUrveillance system), bio-optical, and microstructure sampling of the ocean, and ocean numerical modelling among many other important research areas. However, the urgent societal issues of the coastal zone (e.g. pollution, tsunamis, storm surge, coastal erosion, red tides, fisheries, etc.) and the recognition of the challenging science embodied by the coastal oceans have drawn many oceanographers to coastal waters. Further, the ocean has been treated primarily as a continuum fluid for most physical oceanographic research, but particulates and dissolved matter (organic and inorganic) are of principal concern for many biological and geochemical oceanographers. While some ocean modellers focus on large-scale processes and resort to parameterization for resolving the small scales, others devote their research to various organisms and microbes (e.g. viruses and bacteria), their interactions with each other and their immediate environs. Simultaneous physical sampling over spatial domains of even a few kilometers with resolution down to a meter on time scales of minutes to hours remains a dream—an even more interesting challenge is to sample a full suite of complex interactions and coupling of physical, chemical, biological, and geological processes as well (Fig. 1). In this essay, we describe how oceanographers have moved well beyond sampling capabilities that were limited to a single ship carrying only nets, bottles, and a few thermometers just a few decades ago.

TABLE 2. – Summary of some of the common observational issues faced by oceanographers.

Most involve multiple subdisciplines of oceanography and require interdisciplinary linkages and couplings for solution
Processes of interest involve variability over time and space scales spanning several magnitudes–in some cases up to ten orders of magnitude
Many of the key variables and rates remain inaccessible via present technologies
Contemporaneous (synoptic) sampling over three-dimensions is needed, but is rarely possible
Cumbersome water sampling remains necessary for many, if not most, biological, chemical, and geological measurements
Multi-platform, nested sampling schemes coupled with models appear to be essential to fill in information in the requisite time-space continuum. Adaptive sampling (in concert with data assimilation models) can be used to effectively improve sampling
Many chemical elemental (or compound) analyses and biological measurements at the species or group levels are not possible at present using autonomous sampling platforms, but are highly desirable or essential
Real-time data acquisition is typically deemed very important or critical, because of societal and management needs; however, data telemetry is a limiting factor for many sensors (e.g. seismic, hyperspectral optics and acoustics, imaging). Dedicated fiber-optic cables or cables-of-opportunity can be effectively used for sampling requiring high informational bandwidth
Power requirements for some advanced sensors and systems remain restrictive for some of the *in situ* autonomous sampling platforms. Importantly, power cables can be utilized in combination with data telemetry fiber-optic cables.

Many oceanographic problems (including those described in Section 4) have several aspects in common as articulated in Table 2. Clearly, sufficient oceanographic data sets remain difficult to obtain. In addition, several limitations constrain the development, testing, and advancement of simple to highly evolved ocean models.

PROGRESS IN OCEAN SAMPLING

To set the context of the oceanographic community's progress in ocean sampling, it is worth reminding ourselves that only a few decades ago, biological oceanographic sampling was done almost exclusively using nets, hydrographic samples were collected with bottles activated by wire messengers, basic physical data were recorded on paper strip charts, and manipulation of data was done by using hand calculators or in many rooms full of large computers with capabilities that are surpassed today by even modestly priced laptop computers. In the 1960's, many considered the potential use of satellites for obtaining meaningful oceanographic data near folly. Today, most oceanographic cruises would not venture from port without satellite data and communication links. Position information obtained by global positioning satellites is now considered routine for ships, autonomous sampling buoys (e.g. Dickey, 2003), autonomous underwater vehicles (AUVs are essentially oceanographic robotic oceanographic systems; e.g. Griffiths *et al.*, 2001; Yu *et al.*, 2002), autonomous surface vehicles (Griffiths *et al.*, 2001), gliders (Eriksen *et al.* 2001; Perry and Rudnick, 2003), drifters (e.g. Perry and Rudnick, 2003; Dickey, 2003, 2004), and profiling floats (Wilson, 2000; Argo Science Team, 2001; Davis *et al.*, 2001; Bishop *et al.*, 2002; Perry and Rudnick, 2003), but many of our generation can still recall the days of navigational fixes and spotty LORAN-fixes. Today, a growing number of platforms are sending data to shore in near real-time or in real-time.

The number of types of sampling platforms that are available presently has grown as have their capabilities–sampling is now only one of today's ships' missions as the deployment of autonomous sampling platforms including moorings, bottom tripods, autonomous underwater vehicles, remotely operated vehicles, profiling floats, drifters, and gliders is becoming an important primary or secondary function (Table 3). In fact, Henry Stommel's vision of studying the world ocean ('Slocum Mission') using a fleet of winged, profiling 'Slocum' floats (now called gliders), rather than ships, is nearing reality (Stommel, 1989).

Perhaps the greatest revolution in oceanography within the past three decades has been the development of satellite oceanography (e.g. Yoder *et al.*, 2001; Robinson, 2004; Martin, 2004). Virtually all disciplines of oceanography have benefited from unprecedented regional to global depictions of oceanic features. Oceanographic satellites have also provided data for estimating phytoplankton biomass distributions and primary production rates (using data coupled with models); sea surface temperature and ocean color data for studying upwelling, mesoscale eddies, and climate variability; altimetry data for studies of bottom topography, currents, mesoscale eddies, Rossby waves, and El Nino-Southern Oscillation events; and key wind data for understanding ocean mixing, surface driven currents and transport, upwelling and downwelling, and the occurrences of divergent and convergent zones of the ocean.

TABLE 3. – Examples of some of the key oceanographic platforms developed during the past several decades.

Platform	Optimal Use
Ships (on station)	Time series
Ships (surface underway)	Spatial coverage
Ships (towed bodies)	Spatial coverage
Buoys and moorings	Time series
Manned surface platforms (R/P FLIP)	Time series
Manned subsurface habitats	Local exploration
Bottom tripods	Time series
Drifters	Spatial coverage
Floats	Spatial coverage
Profiling floats	Spatial coverage
Airplanes	Spatial coverage
Satellites – Sea surface temperature	Spatial coverage
Satellites – Color	Spatial coverage
Satellites – Winds and waves	Spatial coverage
Satellites – Heat flux	Spatial coverage
Satellites – Altimetry (sea level, bathymetry, currents)	Spatial coverage
Satellite – Sea surface salinity	Spatial coverage
Satellites – Sea ice	Spatial coverage
Satellites – Data telemetry	Spatial coverage
Bathyspheres and submersibles	Deep ocean studies
Remotely operated vehicles (ROVs)	Deep ocean studies
Autonomous underwater vehicles (AUVs) and gliders	Spatial coverage
Piers	Time series
Offshore platforms	Time series
Shore-based radar	Spatial coverage/Time series
Tagged organisms	Biological studies
Cabled observatories	Spatial coverage/Time series

In the near future, it is likely that a suite of sampling platforms for many experiment will include: ships, AUVs, drifters, profiling floats, moorings, bottom tripods, satellites, shore-based radars and acoustic systems, and perhaps even instrumented marine mammals and fiber-optic/electromagnetic cables with at least subsets of the data being sent back to laboratories instantaneously or within hours of collection (Fig. 3). Such arrays can in principle incorporate physical, biological, chemical, and geological sensors sampling on time scales as short as a few seconds to minutes (see Fig. 1). The maximal deployment periods for some autonomous sampling systems including moorings, profiling floats, drifters, and gliders are now typically on order of months to a year and much longer sampling capabilities are highly desired. However, propelled platforms such as AUVs are still generally power limited, but will greatly benefit from advances in fuel cell technologies and mooring/cable systems designed for AUV docking, battery recharging, and data transfer. The rate limiter for AUVs is energy, so fuel cell advances are especially critical. Generally, biofouling of instrumentation, rather than power or data storage, is the primary limiting factor for other autonomous sampling platforms.

EXAMPLE OCEAN PROBLEMS

Oceanographers study such a richly diverse spectrum of interesting problems that it is difficult to

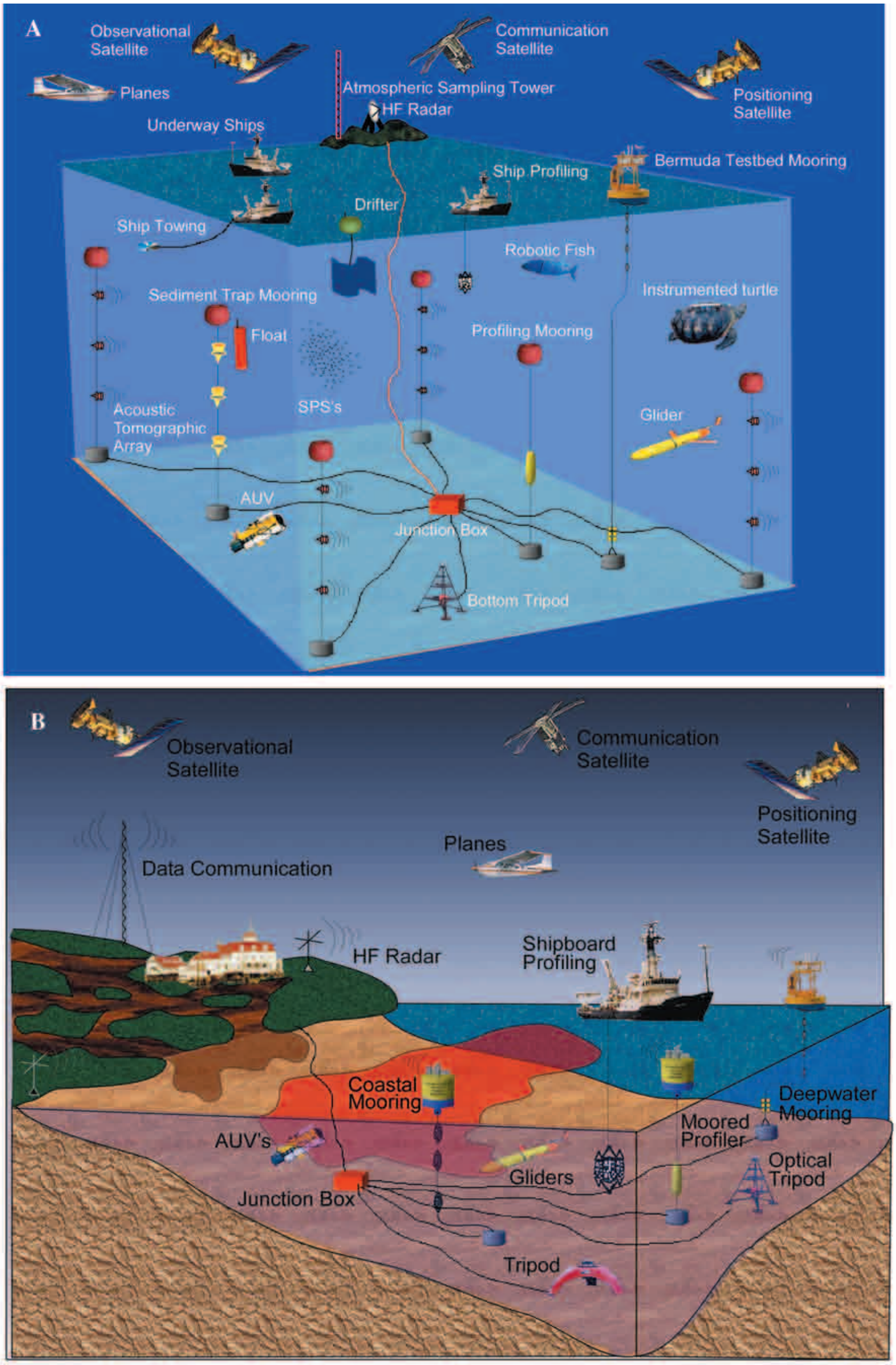

FIG. 3. – Schematics depicting platforms that could be used in future studies of the open (A) and coastal (B) ocean.

focus on even a few representative examples. However, several relevant, forward-looking reports devoted to future outstanding problems have been published within the past decade (e.g. National Research Council, 2000; Glenn and Dickey, 2003). Four interdisciplinary problems that strike us as intriguing and challenging are briefly summarized here to motivate and set the context for the ensuing discussion of possible directions of future sampling and measurement systems and approaches.

Biogeochemical variability and global climate change

Time series measurements that document rapid increase of atmospheric carbon dioxide concentration over the past several decades have stimulated interesting interdisciplinary research since the 1980's (e.g. Oceanography, Vol. 14, No. 4, 2001). Programs including the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS) have been devoted to improving our understanding of ocean circulation and processes, and the distributions and fluxes of biogeochemically relevant elements. Related climate research utilizing geological records including the Antarctic and Greenland ice cores has added greatly to our knowledge of climatic and ecological changes on much longer time scales.

Future progress in understanding of biogeochemical variability and global change will require concurrent measurements on finer and more expansive time and space scales than has been possible to date. Deep circulation measurements are especially challenging, as space-based measurements are not effective and *in situ* current and water mass measurements are especially difficult; additionally, the numbers of *in situ* platforms required for deep flow determinations are extremely large. Platforms such as moorings (with fixed-depth and profiled instrument packages), bottom tripods, buoyancy controlled profiling floats, autonomous underwater vehicles (AUVs), and buoyancy-driven gliders (i.e. after Stommel's 'Slocums') offer promising opportunities for both circulation and biogeochemical observations. Biogeochemical and environmental sensors, which can measure a large number of variables and process rates from these collective platforms, remain as especially important future needs (e.g. Varney, 2000; Tokar and Dickey, 2000). Syntheses and visualizations (i.e. perhaps some using 3-dimensional optical holography) of data sets obtained from arrays of platforms will require computational routines and models to provide information that can be used to isolate, quantify, and understand specific processes and their relationships and interactions with other processes on broad time and space scales (e.g. Dickey and Falkowski, 2001; Dickey, 2003). Examples include small-scale mixing related to tides in the deep and coastal ocean, internal gravity waves and mixing as they affect deep circulation (and *vice versa*); mesoscale features and Rossby waves and their impacts on ocean productivity and deep sea carbon fluxes; the influences of various organisms from viruses and bacteria to the highest trophic level organisms on carbon concentrations, fluxes and carbon dioxide sequestration; and cascades of energy and variance from larger to smaller scales and from smaller to larger scales. Understanding the influence of changing oceanic conditions on climatic time scale phenomena and *vice versa* is especially challenging.

Impacts of hurricanes and typhoons on the ocean

Hurricanes and typhoons receive much public attention when they make landfall and cause large-scale loss of life, injuries, and financial damages that often impact national and international economies. Their impacts on the open and coastal ocean have remained largely documented by anecdotal reports and fortuitous passages over sampling platforms. Understandably, ships have quickly transited away from paths of hurricanes and typhoons, but leaving behind opportunities to learn about the ocean under intense forcing that is so ideal for the development and testing of theories and models.

While the feedbacks of slow versus fast moving and intense versus weaker hurricanes and typhoons have been discussed qualitatively, we presently know little about the key processes—especially in regard to the evolution of fully three-dimensional distributions of physical let alone biological, chemical, and geological variables. The primary issue rests again with adequate sampling in time and over three dimensions in space. Recent studies of hurricane passages over moorings in the open ocean and over moorings and bottom tripods in the coastal ocean have provided new insights into oceanic effects on currents, mixing, biological productivity, gas exchange, and sediment resuspension (e.g. reviewed by Dickey, 2001; Dickey and Chang, 2001). However, we have yet to be able to observe hurricane or typhoon responses over broad regions except with limited satellite data, which do not allow for robust inferences of processes and responses beneath the sea surface. Nonetheless, remote sensing data sets have recently suggested that major phytoplankton blooms occur in the wakes of hurricanes (i.e. Babin *et al.*, 2004). Synoptic sampling with broad spatial and temporal coverage is clearly required for the problem of ocean responses to hurricanes and typhoons. Moorings (perhaps air-deployed), AUVs, and gliders could be valuable assets, especially when their real-time data sets are input into predictive data assimilation models.

Harmful algal blooms

Harmful algal blooms (HABs), commonly called red tides, are thought to be increasing in coastal regions worldwide (i.e. Anderson, 1989; Hallegraeff, 1993; Babin and Roesler, 2005; Chang *et al.*, 2005). Societal implications of HABs include human health, adverse impacts on ocean ecosystems including higher trophic level organisms, fisheries, and economies of coastal communities. A variety of causes (i.e. transport of non-indigenous toxic algal species via cargo ships) have been suggested (Hallegraeff and Bolch, 1992), but definitive explanations and predictive methods remain elusive. These are critical for HAB prevention and mitigation. The HAB problem has parallels with other coastal ocean study topics (i.e. eutrophication, urban runoff, outfall discharges, and chemical spills) that require multi-faceted approaches and inclusion of research concerning virtually all aspects of oceanography – e.g. physical circulation and mixing, sediment resuspension, chemical property distributions and variability, marine community trophic interactions, and ocean policy and management strategies.

The technologies that appear to be required to make significant progress in understanding and modelling HABs and some of the other analogous problems will likely be far reaching and include nearly all of the general technologies suggested in the previous two examples. The identification of HAB species and other species (e.g. DNA sequencing) that affect or are affected by HAB species is a necessary starting point for HAB research. Additionally, physical, chemical, biomolecular, and optical measurements that bear on the life cycles of HAB species and toxin production will be critical. Since HABs generally have their greatest impacts in coastal environments, the complexity of the coastal ocean comes into play. In particular, the time and space scales of coastal processes are generally shorter and necessitate three-dimensional sampling at small to large scales and over time scales of less than a day and for long periods of time because of episodic events and diurnal, seasonal, interannual, decadal variability.

Oceans and human health

The marine biosphere is one of the Earth's richest, but least characterized, habitats. It is home to a large number of diverse marine organisms that are found in environments ranging from temperate to extreme. Biodiversity is now widely accepted as a source for biotechnological discovery and innovation (NRC, 1999, 2002). The application of biotechnology to the marine biosphere can provide new drugs and processes that serve a broad array of sectors, including human health, environmental, and homeland security. Though not generally perceived as being an "extreme" environment, the surface waters of the subtropical ocean are now recognized as a "treasure chest" of biodiversity and a sea of potential for new discoveries. Every *drop* of seawater in the upper ocean of the subtropical Pacific Ocean contains thousands of diverse, free-floating phytoplankton and millions of bacteria and viruses. Assessments of microbial biodiversity based on genetic analysis have revealed that <1% of this diversity is currently represented in existing culture collections of marine microbes. In addition, recent studies have shown that certain members of the Cnidaria possess novel compounds with anti-bacterial and anti-fungal activities as well as an abundance of terpenoid and prostanoid congeners, many of which exhibit marked anti-tumor activity. Today, we are poised to make a quantum leap into a new era of marine biomedical research. The tools of molecular biology and analytical chemistry as well as information technology are not only revolutionizing our ability to characterize marine organisms, but also our ability to access novel secondary metabolites and the genetic information required to develop the next generation of marine-derived pharmaceuticals.

Tropical coastal waters remain uncharacterized with regard to conditions, which are responsible for higher transmission of diseases in the use of these waters. Uncontrolled urbanization leading to coastal water pollution is one problem. Another problem is the reliance on hygienic, bacterial water quality guidelines developed for temperate countries, which are not applicable to tropical countries because the fates of microorganisms are controlled by their environment. In tropical regions, climatic conditions allow microorganisms to interact with humans and the environment throughout the year, even allowing some pathogens to grow and possibly gain virulence genes. A major gap lies in understanding the causal link between disease transmission during the use of coastal waters and the ecological processes at the terrestrial-marine interface that control the kinds and concentrations of pathogens in coastal waters. Future research should focus on: 1) determining the sources, survival, and ecology of indicators of pathogens and pathogens in sediments, marine foods, and water in tropical coastal waters and 2) assessing the prevalence of virulence genes within the meta-genome of coastal microbial communities.

EMERGING APPROACHES FOR STUDYING THE OCEAN

Progress in solving most oceanographic problems is still largely limited by technological barriers—however, powerful techniques that are applicable to ocean problems are emerging in other sectors of science and engineering. It is worth re-emphasizing that oceanography has and will continue to greatly benefit from the quantum, biomolecular, and computer revolutions (Fig. 2). We begin this section with a view toward platforms and then move on to sensors and systems.

Platforms

Ships will continue to serve as essential oceanographic platforms. They will likely continue to be used for process-oriented and transect sampling, but probably with less weighting, as they will also be used for autonomous sampling platform deployment and recovery operations. Future ships used for direct sampling will likely be capable of supporting more advanced instrumentation, often using fiber optics with greater data transmission bandwidth. Volunteer observing ships (VOSs) will be capable of carrying more sophisticated autonomous sampling systems requiring no intervention aside from setup and downloading of data and much of the data (including ADCP currents) could be telemetered in real-time or near real-time and input into data assimilation models (e.g. Hofmann and Friedrichs, 2001; Robinson and Lermusiaux, 2002). Newly designed ships are likely to be faster and with improved sea-keeping characteristics (e.g. SWATH vessels). Specialized manned and unmanned platforms with unique sampling capabilities (e.g. *R/P FLIP*) and commercial offshore platforms can play important roles as well. Plans are underway to place large buoys with power generation and/or cable connectivity in harsh and remote ocean locations such as the Southern Ocean as part of a U.S. National Science Foundation (NSF) Ocean Observatory Initiative (OOI; see Schofield and Tivey, 2005). The NSF OOI will include a range of platform and cable (fiber optic and electromagnetic for data transfer and power) capabilities enhancing spatial and temporal data acquisition in the coastal and open ocean and on plate scales (e.g. Glenn and Dickey, 2004). The next generations of these platforms may utilize lighter, stronger composite resin—opposed to steel-based materials (e.g. Kaku, 1997).

Sensors and genetic probes

There is a major need to increase capabilities for sampling broader suites of chemicals autonomously. Applications to problems of pollution, with diverse chemical species of concern (e.g. PCBs, DDT, toxic metals, etc.) are demanding. New types of chemical sensors and analyzers will become more readily available for users of the various platforms. Chemical sensors rather than analyzers will be preferable, if not required, for some platforms such as towed bodies, floats, drifters, gliders, and AUVs. One promising new technology uses fiber optic sensors for ocean applications (e.g. Tokar and Dickey, 2000). Here, an optical sensor or modulation device is one element of an integrated system, which also includes an excitation light source, optical fibers, a photodiode detector, and other associated components including connectors, couplers, and signal processing/data logging equipment. Various types of light sources can be used. The modulated optical parameters of light can include amplitude, phase, color, state of polarization, or combinations of these. A 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.

Miniaturization of lasers and electronic components is especially interesting. For example, tens of millions of transistors can be placed in an area as small as 1 square centimeter and lasers are now being integrated directly on silicon chips, effectively eliminating the need for optical fibers for some computing applications. Another interesting type of sensor system is the microelectromechanical system (MEMS; Kaku, 1997; Tokar and Dickey, 2000). MEMS is based on a technology, which is used for making and combining miniaturized mechanical, electronic, and sensing components out of silicon wafers with micromachining. A variety of sensors can in principle be used as part of a common MEMS chip (silicon substrate). These could involve mechanical, thermal, optical, magnetic, chemical, and biological sensing. MEMS have shown encouraging results for sensing physical parameters, however work is needed to realize their full potential for chemical and biological sensing. Work with MEMS has been done primarily in laboratory settings thus far, although MEMS devices are already used as motion sensors in airbags in automobiles. Tiny systems have been designed to provide atmospheric data and to telemeter information from module to module to satellite to laboratory in terrestrial environments (i.e. Great Duck Island, Maine; see http:www.tinyos.net/). The Center for Embedded Networked Sensing (CENS), supported by the National Science Foundation is developing tiny networked smart sensors and actuators that are designed to eventually be 'embedded' in environments including the ocean to adaptively sample physical and biological variables including a variety of microorganisms (see http://www.cens.ucla.edu/).

Transitioning of MEMS to *in situ* oceanographic applications appears feasible. Some of the foreseeable advantages of MEMS include: auto-calibration, self-testing, digital compensation, small size, and economical batch production. Nanotechnologies concern technologies involving building of machines atom by atom; scales of say the width of 5 carbon atoms or ~ 1 billionth of a meter or a nanometer (e.g. see Kaku, 1997; Kurzweil, 1999). Nanotechnologies and nanoengineering were first proposed by Nobel Laureate Richard Feynman who suggested no physical reason could be found to preclude construction of machines the size of molecules. Of course, nanomachines are even more ambitious in many ways than MEMS (see p. 267 of Kaku, 1997, for an interesting depiction of a molecular machine). An amazing potential attribute of such atomic micromachines is self-replication. More information on MEMS and nanotechnologies can be found at http://www.memsnet.org and in Kaku (1997), Kurweil (1999), and Bishop *et al.* (2001).

New tools for biological oceanography include molecular genetic and species-specific molecular probes (DeLong et al, 1999; Pace, 1997; Schmidt *et al.*, 1991; Stahl and Tiedje, 2002; Stein *et al.*, 1996; Zehr and Hiorns, 1998). Ribosomal RNA genes are beginning to be used for detection and determinations of abundance of some bacterioplankton species and to study evolutionary relationships among various species. Species-specific fluorescent *in situ* hybridization (FISH) probes for harmful algal blooms (HABs) have been developed and show great promise in helping us to understand the context of HAB events. Applications of genetic techniques to higher trophic levels (zooplankton to whales) are being pursued as well.

Examples of transitional technologies include: flow cytometers for identifying and characterizing organisms and there properties, mass spectrometers, and radioisotopes for chemical and biological rate measurements, and tomographic methods for studying ocean current patterns. Genetic (rRNA and functional gene sequencing) methods are being adopted by increasing numbers of biological oceanographers and offer future oceanographers the opportunity to obtain information at the species level (diversity, growth physiology, and gene expression). Many chemical and biological variables presently require large volumes of water, which must be collected from ships and analysed with specialized instruments either onboard or later in research laboratories. A grand goal of chemical and biological oceanographic sampling is to greatly reduce dependence on water collection. Relevant new sensors and systems that are small, yet capable will likely emerge from microelectromechanical sensor (MEMS) technologies and nanotechnologies (e.g. Tokar and Dickey, 2000; Bishop *et al.*, 2001; Kaku, 1997; Kurzweil, 1999). Microbe identification in the future will routinely be performed by using 'biochips' or 'DNA chips.' These miniature devices, which are made possible through both quantum and biomolecular advances, may be used for *in situ* rRNA gene identification using 'homologic' searches (homology involves finding genes with similar functions in different organisms or viruses).

In many cases, artificial intelligence or AI (i.e. Kaku, 1997; Kurzweil, 1999; Russell and Norvig, 2002) and neural networks (i.e. Kaku, 1997; Kurzweil, 1999; http://www.statsoftinc.com/textbook/stneunet.html#apps) can be effectively used in conjunction with some chemical and perhaps biological measurement systems. Artificial intelligence (AI) concerns the scientific understanding of mechanisms underlying thought and intelligent behavior along with their embodiment in machines. In other words, AI is the emulation of human intelligence in a machine. A neural network is essentially a computer simulation of the human brain. Neural networks involve analytical techniques patterned from processes of learning in the cognitive system and the neurological functions of the human brain; they are in principle capable of making predictions based on previous observations following a 'learning process.' Highly diverse applications have included stock market prediction, detection of health abnormalities, chemical analyses (e.g. 'smart noses'), and monitoring of machinery (see http://www.statsoft-inc.com/textbook/stneunet.html#apps).

Artificial intelligence and neural networks are good examples of cross-fertilization of physics, computer science, and biomolecular science (see Fig. 2). Already, image identification of marine organisms and development of complex ocean color algorithms for coastal ocean environments are being accomplished using artificial intelligence.

In principle, very small interdisciplinary sensors, collectively dubbed here as 'Smart Plankton Sensors (SPSs),' that use MEMS, nanotechnologies, neural networks, lasers, and other technologies may be capable of measuring and transmitting a broad range of biological, chemical, and physical data. These SPSs, could represent a new paradigm in ocean sampling as they could be mass produced, reducing cost, and easily deployed from virtually all ocean platforms by scientists or by average citizens with access to the ocean. Intercomparisons and verification of data using discrete water samples will continue to be necessary during the developmental phases of SPSs as well as less ambitious sampling systems.

Satellites and tracking systems

New satellites will need to be capable of sampling on smaller scales to capture important phenemona, especially in the coastal zone where scales are considerably less than those in the open ocean. The number of variables that can be sampled from space also needs to be expanded. Space-based salinity sensors are under development and will be especially important for many estuary, coastal, equatorial, and climate research efforts. Optical sampling of a variety of physical and biological parameters has been advancing rapidly. Hyperspectral imagers capable of resolving the light spectrum at nanometers level, sampling with spatial resolution down to 10's of meters or less are currently being evaluated (e.g. Chang *et al.*, 2004; Oceanography, volume 17(2), 2004). Applications of hyperspectral imagery to many coastal problems such as HABs, bottom bathyemetric mapping, and underwater visibility are already being actively pursued. Higher spatial resolution altimetric and wind data sets hold the key for advancing our understanding of coastal physical dynamics and mesoscale and submesoscale features as well as fronts, jets, and meanders.

Data integration

The use of the satellite global positioning system (GPS) system for tracking marine mammals, sea turtles, and other organisms has been demonstrated to be valuable. Small interdisciplinary instrument packages with data telemetry capabilities could be attached to provide data in the local ambient environment of the organisms (Fig. 2). Many biologists desire just such measurements.

The integration of data derived from diverse platforms, each with its own strengths and weaknesses is an important step for oceanographers as improved descriptions and predictions of phenomena characterized by variability spanning ten orders of magnitude in time and space are required. Computational capabilities as well as clever nested modelling approaches are showing great promise, as data assimilation of interdisciplinary as well as physical data sets is becoming a major thrust of many research programs . Increased temporal and spatial sampling capabilities for expanding numbers of interdisciplinary variables are being accelerated thanks to both new technologies and utilization of data assimilation models (i.e. Hofmann and Friedrichs, 2001; Robinson and Lermusiaux, 2002) coupled with autonomous sampling platforms (i.e. adaptive sampling strategies discussed by Dickey, 2003). Key work in the area of atmospheric data assimilation and weather forecasting will benefit oceanography. The visualization of ocean data and model results is important as evidenced by the public's access to and interest in weather information provided in forms that are understandable and useful. An increasingly important goal of oceanography is to provide oceanographic data that are educational and effective for general use and management and decision-making situations. For example, useful forecasts of storm surges, red tides, ocean pollution via runoff, ocean temperatures, ENSO events, and waves are likely well within reach within the next few years to a decade. Worldwide tsunami warning remains a pressing need for the global ocean despite the present availability of relevant technologies and capabilities—here international cooperation, coordination, and funding are key to successful implementation.

Computing power and information technologies have advanced at a rapid pace as have available oceanographic data, especially with the advent of satellite data and *in situ* instruments that collect multi-frequency, multi-wavelength data for extended periods of time. Massive volumes of data are of course important in view of the sparseness of sampling of the vast oceans and needs for long-time series to tackle problems ranging from ocean turbulence to waves to decadal oscillations and climate change. However, data alone are insufficient and need to be deciphered, analysed, interpreted, and modeled. The culture for oceanographic data sharing and distribution has evolved over the past couple of decades for several reasons. First, the sizeable infrastructure and its cost in obtaining oceanographic data, like the atmospheric counterpart, has necessitated the distribution of data and scientific information for maximum utilization by the oceanographic community. The value of sharing data, often in real-time or in near real-time has been demonstrated by several programs and perhaps most importantly by individual investigators.

The computer revolution has often been quantified using Moore's Law, i.e. the doubling of computing power every 18 months (e.g. see Kaku, 1997; Kurzweil, 1999). Presently, the world's most powerful computer is the IBM Blue Gene/L. Blue Gene/L has weather forecasting as one of its major applications. The third most powerful computer is the Japanese Earth Simulator System (ESS), which is dedicated to geophysical problems including oceanography, atmospheric science and global climate change. The ESS is actually comprised of 640 supercomputers, which are connected by a high-speed network with a data transfer speed of 12.3 Gbytes (12.3 billion bytes). Altogether, the ESS is capable of a total of nearly 40 TFlops (40 trillion floating point operations per second) at peak performance, and possesses a total main memory of 10 TeraBytes (see http://www.thocp.net/hardware/nec_ess.htm). Blue/Gene/L has sustained a performance of over 70 Teraflops.

Just as important as computing power, the cost of computing is decreasing very rapidly with near term projections of reasonably capable $100 computers on the horizon and perhaps computing and sensing devices may be very inexpensive and ubiquitous because of mass production. Marc Weiser of Xerox PARC has suggested that personal computers will some day be replaced by 'scrap computers' in the spirit of today's 'scrap paper'. Already, many of us carry around microchips, small lasers, and cell phones with remarkable informational and telecommunication and even video and positioning (e.g. GPS) functions. The rates of DNA sequencing and internet advances have been estimated to be similar to that of computing (i.e., estimates of doubling at about 2 year intervals). The capability to continue this progress at these high rates has been suggested to be finite and new approaches using DNA computers (e.g. each DNA molecule has the capacity to store large volumes of information very compactly), neural networks, and hybrid-computing systems are likely to come to the fore in the future (e.g. Kaku, 1997; Kurzweil, 1999). These next phases of development of 'ubiquitous sensing and computing' should be especially beneficial for oceanographers as we clearly need finer resolution and much larger variable numbers for our interdisciplinary data and models. A future generation may be immediately warned of an approaching tsunami via a personal device that is linked to a worldwide tsunami warning system.

Observation systems

Ocean observing systems, whether ship-, mooring-, float-, drifter-, glider-, AUV-, or cable-based, are tacitly becoming 'collaboratories.' The term 'collaboratories,' which to our knowledge was coined several years ago by a U.S. National Research Council committee, connotes two important concepts: 1) *collaboration* among scientists and 2) shared *laboratories* or facilities. Examples of oceanographic collaboratories include multi-platform, interdisciplinary time series sampling facililties and infrastructures such as those provided via the Hawaii Ocean Time-series (HOT) and the Bermuda Atlantic Time Series (BATS) programs, which were initiated by the U.S. JGOFS program in 1988. Together, these programs have facilitated sharing of oceanographic and atmospheric data sets collected from a variety of sampling platforms and sensors with scientists around the world. These 'collaboratories' have enabled investigators, many of whom will never have been to either island facility or ocean sampling site, to conduct scientific studies with shared data sets.

Engineers and scientists have utilized the Bermuda Testbed Mooring (BTM) and the HALE-ALOHA (H-A) mooring, which are separately funded but essentially co-located with the HOT and BATS ship sampling sites, for testing newly developed sensors and systems, for calibration and validation of satellite sensors, and for scientific studies of phenomena that are difficult to sample with ships. In particular, hurricanes and mesoscale eddies have been observed as they passed these sites, enabling scientists worldwide to study and model previously inaccessible episodic, extreme events. There are plans to continue to utilize the BTM and H-A moorings and other emerging platform and sensor technologies to more fully measure a multiplicity of variables over expanding time and space scales. Already, profiling floats, AUVs, and gliders have sampled at these sites. The power of the HOT/H-A and BATS/BTM programs is multiplied through extensive use of ocean satellite data sets and numerical models as well as the intellectual forces of international users of the data sets.

The concepts of a global ocean observing system and ocean observatories have been developing rapidly in recent years (e.g. Oceanography, 2000, 2003; Glenn *et al.* 2000; Koblinsky and Smith, 2001). In a sense, the Hawaii and Bermuda time series programs and comparable programs in many nations and national alliances are providing the beta tests and testbeds for emerging ocean sensors, ocean observing systems, and observatories as well as data assimilation modeling. An especially good example of an operational observing system is the Mediterranean Forecast System Toward Environmental Predictive (MFSTEP, Pinardi *et al.*, 2005). MFSTEP investigators are presently utilizing most available observing platform types and supply Mediterranean Sea predictions using a variety of models (including data assimilation, see Dickey, 2003) for interested organizations (over 150 at present) including coast guards, fishermen, and environmental managers. Again, development of cabled observatories, deep-sea buoys, and various mobile autonomous sampling platforms is central to the globalization of ocean observations (e.g. see Glenn and Dickey, 2004). National and international planning activities as well as pilot studies have been instrumental in moving toward operational oceanography in analogy to world meteorological and climate operational organizations. The view of the ocean as a connected, integrated system—certainly the case for the atmosphere as well—requires such global strategies and of course large-scale data and model sharing. The business and culture of oceanographic research will certainly look quite different as we move in this direction. Planning for funding, utilization of shared research assets, deployment strategies, and data management are becoming more global by necessity–again, this is good considering the magnitude of the challenging problems faced by oceanographic, atmospheric, and climate research. In addition, public involvement in oceanographic research and utilization of operational oceanographic products is envisioned to increase as more of humankind live near the oceans, are affected by them, and have interest in their well-being. Already, many non-governmental organizations are actively promoting good stewardship of the oceans and some are also conducting valuable research and monitoring programs. The rapid development of the internet (e.g. see Kurzweil, 1999) is especially important for the transmission of information among oceanographers gathering data from various observing platforms and from oceanographers to the public and *vice versa*. Perhaps the most important quality of internet access for observing systems is the ability to provide near real-time or real-time data and forecasts. Societal interest is growing in accurate predictions of tsunamis, storm surges, and HABs on short time scales and of global climate change and its environmental effects. Telemetry of data is advancing, but more work is needed as bandwidth (i.e. amount of information that can be transmitted per unit time) remains constraining for many important data sets (i.e. video, hyperspectral optics, seismic data, etc.).

VISIONS OF A FUTURE OCEAN EXPERIMENT

This section was written as the authors conducted research studies with colleagues, postdoctoral fellows, and students aboard the *R/V Ka'imalino-O-Kanoake* (KOK) and the *R/V Wecoma* in late 2004 and early 2005. The research was conducted off the Big Island of Hawaii and concerns the spin up and evolution of eddies produced by strong winds that funnel and accelerate between the mountains of Maui (Haleakala) and the Big Island (Mauna Kea and Mauna Loa). Next, we speculate on how oceanographers might conduct a follow-up eddy study to ours in decade or two. As a brief aside, we

TABLE 4. – Technological tools for future ocean eddy experimenters off the Big Island of Hawaii.

Satellite sensors with capabilities that would be used to measure:

- Sea surface temperature, salinity, and high resolution ocean color (few nanometer resolution) without data loss due to clouds on spatial scales of a few meters at intervals of hours (i.e., using geostationary and pointing satellite systems) – products would include a variety of bio-optical and biogeochemical variables or proxy variables (e.g. chlorophyll, colored dissolved organic matter (CDOM), phytoplankton by group or species, etc.) [note: our present eddy experiment used satellite images to find the approximate center of our eddy to within about 20 km; later we determined the location of the center to within about 2 km using *in situ* instruments]
- Sea surface elevation on scales to 10's to 100's of square meters to allow estimates of currents on small scales
- Surface winds and heat fluxes along with rainfall on scales of 100 m

Unmanned autonomous aircraft and aircraft would fly over the eddy region to provide high-resolution spatial data (meters) including sea surface temperature, salinity, and color. Light detecting and ranging (LIDAR) instruments mounted on aircraft would be used to map mixed layer depths and retrieve vertical profiles of selected bio-optical variables

A fleet of autonomous underwater vehicles (AUVs) and gliders.

- These would carry a large number of tiny chemical and biological sensors we earlier dubbed 'Smart Plankton Sensors (SPSs)'
- Acoustic Doppler current profilers (ADCPs) and turbulence sensors mounted on AUVs and gliders would be used to map small scale current and mixing parameters
- Sensors would be used for measuring tracer or dyes placed in the water column for special mixing and advection measurements
- Tiny cameras and video imagers would be used to provide visual information for identifying the biota and for education of the public using links to aquariums, museums, and classrooms
- The AUVs and gliders would telemeter data to shore in near real-time using mooring-based acoustic and satellite communication links and possibly cable systems that would also provide power replenishment for the AUVs and gliders
- One glider would be deployed in the center of the eddy and serve as a virtual profiling mooring.

Smart Plankton Sensors (SPSs) that would be ballasted for specific depths or even isopycnal surfaces; they would measure several physical, biological and chemical variables, and telemeter their positions and data among themselves using small lasers and to a central communication buoy located toward the central portion of the eddy.

Robotic organismal mimicking devices would be deployed for specialized biological experiments (e.g. vertical migration, predator-prey interactions)

An array of re-locatable moorings and bottom tripods would be deployed from a ship or possibly even an aircraft at specific locations based on initial satellite and AUV/glider surveys. The mooring systems would have several functions:

- Profiling moorings would collect interdisciplinary time series data at intervals of hours or less and with vertical resolutions of a meter or less – sensors would be similar to those of the AUVs and gliders; fixed-depth moorings (meaning those with instruments at predetermined depths) would be used for sampling at time intervals of minutes; some more demanding measurements could be incorporated on the fixed-depth moorings and bottom tripods
- Obtain surface wind stress and heat flux data along with air-sea fluxes of particles, aerosols, and gases (like carbon dioxide, nitrous oxide, and dimethylsulfide)
- Document variations in macronutrient and trace element concentrations using *in situ* chemical sensors
- Characterize microbial community structure using *in situ* flow cytometers and gene, DNA, and bio-chips
- Assess phytoplankton health and photosynthetic performance via fast repetition rate (FRR) fluorometry
- Provide video feeds obtained from flow cameras for identification of organisms and for public education and outreach
- The moorings and bottom tripods would include sensors for measuring tracer or dyes placed in the water column for mixing and advection measurements
- Telemeter data from the profiling moorings, AUVs, gliders, and SPSs
- An array of moorings would be deployed to collect high frequency data for surface currents and acoustics systems for measuring subsurface physical structure (tomography)
- A central mooring would be used as a docking station for re-powering AUVs and gliders as well as downloading data from the collective platforms to be transferred via satellite or possibly fiber-optic cable to shore-based laboratories
- Selected moorings would be used for calibration and validation of several different satellite sensors.

asked one graduate student during our present cruise what he felt would be the most important technological breakthrough for future eddy experiments. His reply was elimination of the rosette water sampler and replacement with *in situ* sensors. Can you guess who had to stand CTD watches, cock bottles, and carry, sample, and analyze water from over 100 CTD casts with hydro bottles? Note that we do not include ship-based hydrographic bottle sampling below in deference to the next generation! We clearly have more capabilities than the pioneers studying circulation and eddies in our region in the 1960's. However, we were occasionally unable to sample due to high winds and adverse sea state (as a reminder, we were near Hawaii!)—unfortunately, budgetary constraints precluded moorings, gliders, and AUVs that could in principle have been sampling while we were hove to. Perhaps, these oceanic conditions and constraints provide a palpable inspiration for this essay!

The sampling issues for future eddy studies will likely remain quite the same—namely requirements of high spatial and temporal sampling of a very large number of interdisciplinary variables over a portion of the ocean of dimension of about 200-400 km square extending to the seafloor. But, what tools might be in that next-generation 'oceanographic tool box'? In Table 4 and Figure 3, we present some of the technological tools that may be in the 'tool box' of future oceanographic eddy aficionados studying eddies off the Big Island of Hawaii (or other open ocean or coastal regions).

Even with the data collected using such an idealized futuristic array of platforms and sensors described in Table 4, several important synthesizing and modelling functions would be necessary to:

Plan sampling strategies and placement and movement of observational assets. Spacing and nesting of fixed and mobile platforms would be based on ocean sampling sensitivity experiments (OSSEs) and later by data assimilation model outputs coupled with OSSE's

Redirect sampling platforms to regions of special interest, in need of higher density data (e.g. patches and fronts); i.e. adaptive sampling mode

Modify sampling rates when events occur (i.e. passage of major storms over the eddy region, blooms); adaptive sampling mode

Interpret large volumes of diverse interdisciplinary data and test experimental hypotheses

Provide useful visualizations for scientists and the general public

Make predictions of eddy dynamics, field properties, biological rates, and biogeochemical fluxes.

A host of specialized and complementary experiments could utilize the experimental nested sampling array. The experiment as a whole could be used simultaneously as a "testbed" for technologies and models, and perhaps most importantly for the optimal, coherent integration of the two. Mesocosm, purposeful tracer, and nutrient enrichment experiments could capitalize on the observational and modeling infrastructure of our futuristic eddy experimental configuration. The eddy experiment would benefit from large-scale model simulation and likewise such modelling research would benefit from better understanding of processes at this energetic scale. New subgrid-scale modelling parameterisations would be enabled through the study. Additionally, opportunities would exist for developing even more advanced oceanographic sensors and systems and testing of biofouling mitigation devices and methods.

Experiments such as the one envisioned here appear quite feasible to us as many of the technologies, though not common, are indeed either being tested or developed in some form. Some of the principal activities required to be able to successfully execute our futuristic eddy experiment are not actually technological. For example, efforts must be made to reduce costs of platforms and sensors and to transition promising non-oceanographically-based technologies into oceanography. Nanotechnology- and MEMs- based sensors are especially attractive as they could be effectively produced in large numbers at small costs per item. Partnerships among the private sector, government, academia, and non-governmental organizations will be necessary. International coordination and sharing of expertise and assets will be vital to build a truly global ocean observing system. Technologies requiring varying levels of budgets and expertise must be factored into the plan. It seems entirely possible that the collaboratory concept can be implemented internationally on a large scale. For example, not all ocean scientists should need to go to sea as many of the important aspects described in this essay involve sensor and system development, data processing, manipulation, and visualization, and various types of modelling.

FINAL PERSPECTIVES ON THE FUTURE OF OCEANOGRAPHIC RESEARCH AND TECHNOLOGIES

Challenges

There remain several important challenges for observational and particularly operational oceanography in the next few decades. For example, few autonomous sampling systems have been designed for sampling within 30 m of the shoreline, which is the most important ocean zone for direct human interaction including tourist and recreation interests and for many coastal structures such as piers and beachfront homes, hotels, and businesses. The coastal zone interests are becoming even more vulnerable because of rising sea level.

Despite their great promise, propelled AUVs and surface autonomous vehicles are power-limited, and thus ranges and deployment periods need to be expanded significantly for many research and commercial applications; hence, fuel cell advances are especially critical. Gliders and profiling floats, which require minimal power, will be especially important for many large-scale observational programs; however, instrument payloads are quite limited. The advent of SPSs would solve many problems. New materials (i.e. composite resins) for ships, AUVs, gliders, floats, and other seagoing platforms should improve their performances as well.

Some of the most interesting and important regional problems of the 21st century will be in the high latitudes including the Arctic and Antarctic regions. The environmental and logistical constraints of high latitude oceanography present some of our greatest challenges. Few of our presently available sensors, systems and platforms can effectively sample at high latitudes. However, preliminary work using AUVs operating beneath ice sheets offers cause for optimism.

Power and data storage for mooring applications are no longer prime limiting factors for deployments of at least one year. However, biofouling of many of the biological and chemical sensors is still a problem for longer duration sampling for moorings and all autonomous *in situ* platforms. The visual impacts of space-based images have been especially valuable for ocean scientists and the general public in gaining perspectives on large-scale features and patterns. However, deriving quantitative information has been difficult and remains a compelling research issue, especially for inferring subsurface structure. Additional measurements of radiatively active gases, aerosols and their air-sea fluxes will be needed for climate research—some systems have been tested already from buoys including the BTM and H-A moorings.

While physical oceanographic measurements are generally considered quite advanced, routine turbulence and vertical velocity measurements need development—these are especially vital for many biological as well as circulation studies. Sampling of higher trophic organisms is a major challenge both *in situ* and from space—innovative strategies need to be developed. Many of the new sensors, systems, and platforms described here are presently in developmental phases or in the hands of only a few researchers. Further, interpretation of many of the signals remains an issue and intensive joint sampling and inter-calibrations are critically needed; testbed programs will remain to be essential.

Large numbers of measurement systems will require commercialization and mass production–in principle leading to greatly reduced costs per item. Long-term continuity of measurements is a vital aspect of many oceanographic research problems, thus standardized and well-calibrated instruments must be hallmarks of ocean observing systems. An interesting potential benefit of rapidly advancing technologies may well be simpler sampling systems (e.g. "chip-based" MEMS and nanotechnology types of sensors with automated data processing and data telemetry systems), which would benefit oceanographic researchers regardless of past or even present technical capabilities and skill levels.

Oceanographers are already collecting large volumes of data and finding processing, dissemination, and utilization major problem areas. Advances in computing using quantum- and DNA-based computers (i.e. Kaku, 1997; Kurzweil, 1999) should greatly facilitate data processing and modeling. Also, more ocean scientists and analysts will be needed worldwide. Educational programs emphasizing operational oceanography will need to be developed. Nations not currently involved in collecting oceanographic data should be able to play important roles in data processing and analyses of *in situ* and remotely sensed data sets and modeling. Oceanographic collaboratories should be used as effective vehicles for all aspects of ocean sciences and its applications. Much of the world ocean is presently poorly sampled (e.g. South Pacific and South Atlantic, Indian Ocean, Southern Ocean), thus autonomously sampling mobile and mooring platforms will be necessary in these areas and international coordination will be required (e.g. Send *et al.*, 2001).

Effective use of data will require clever manipulations of data sets. In particular, many of the processes of interest are nonlinear and or chaotic and dependent upon numerous variables in nature, so newly emerging methods of analysis will need to be used. Also, the merging of data and model/simulation products will cause a blurring of information–care will need to be taken to characterize and quantify ocean information. Predictive ocean modeling will require statistical and probability methods that can be used effectively for science and for public information, the latter being essential for predictions of extreme, episodic events such as storm surges, hurricanes and tsunamis. Credibility of ocean predictions, like atmospheric predictions, will be needed for optimizing the public's safety and welfare.

Opportunities

There are a variety of opportunities that will facilitate advances in oceanographic research and operational oceanography. The costs of obtaining oceanographic data, especially in the volumes dictated by the oceans vastness will remain substantial. Thus, it will be essential to capitalize on all available assets including those not dedicated to ocean research. Ships- and ferries-of-opportunity programs are providing some near real-time data for fundamental measurements and show significant promise for conducting increasingly sophisticated interdisciplinary measurements (e.g. Rossby, 2001). Interestingly, vacation cruise ship operators, individual boat owners, and yacht racing teams are already joining in efforts for collecting ocean data. There are hundreds of moorings in the ocean at present; however most are equipped with a relatively small number of specialized sensors (e.g. Send *et al.*, 2001); many of these could be modified to become assets for tsunami warning systems. There are a few examples of modifying mooring programs to accommodate additional interdisciplinary sensors. For example, a tsunami warning buoy has been used to measure several upper ocean chemical and bio-optical variables at Ocean Weather Station "P" in the eastern North Pacific. Another good example of opportunistic multiple-use of ocean measurement infrastructure systems involves the U.S. Navy's underwater sound and surveillance system (SOSUS), which has been used since 1993 to monitor earthquakes and animal communications and to study ocean temperature change over long distances using acoustic thermography. There are likely many other creative uses of SOSUS. Offshore platforms and piers have occasionally been similarly utilized.

It will be possible to develop autonomous instrumentation modules with telemetry; such modules could be produced in large numbers at modest cost and deployed from virtually all *in situ* platforms. High frequency radar for measuring surface currents and waves will likely provide data along a large number of coastlines around the world although siting issues need to be overcome in many cases and the interpretation of these data will require intercomparison studies. Transitioning of high frequency radar systems for some open ocean studies will be of great value as well. There are also developing programs for shoreline sample collection by volunteers; some are using genetic and other advanced analytical techniques.

Several new programs are being planned to expand upon present observational infrastructures over the next decade (i.e. NSF OOI, Schofield and Tivey, 2005). Power and data communication bandwidth capabilities will be greatly expanded using fiber-optic and electromagnetic cables and new communication satellite systems (e.g. Glenn and Dickey, 2003). Pilot projects are underway for cabled coastal and plate-scale observatories as well as for open ocean mooring platforms. These will complement developing global programs that will field about 3000 Argo profiling floats and 1000 surface drifters (e.g. Argo, 2001). Future versions of these platforms can in principle be interfaced with small, modular interdisciplinary sensor packages.

Technological progress is often so rapid that supporting infrastructure and measurement systems can quickly become obsolete, thus oceanographers will need to become more tuned into fundamental scientific breakthroughs that offer opportunities for oceanographic applications. However, partnerships with researchers and industrialists working in areas including genomics (Zengler *et al.*, 2002), nanotechnologies, material sciences, space sciences, informational technologies, and medical sciences should be used to accelerate the development, testing, and manufacturing of oceanographic sensors, systems, and platforms. Public support for ocean research and especially operational oceanography will accelerate because of growing awareness of the ocean's central role in the health and well being of planet Earth and its human and other living inhabitants. Interest in oceans and life on other planets will provide impetus for oceanographic studies and technological breakthroughs at hydrothermal vents and elsewhere.

Despite numerous challenges, the oceanographic community is poised to make major research and operational advances, in large part because of rapidly emerging technologies. In closing, it is worth noting that most predictions of technological developments underestimate the time scale of technological developments. The future is bright for the next generations of oceanographers.

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REFERENCES

Anderson, D.M. – 1989. Toxic algal blooms and red rides: a global perspective. In: T. Okaichi, D.M. Anderson, and T. Nemoto (eds.), *Red Tides: Biology, Environmental Science and Toxicology*. New York, Elsevier.

Argo Science Team, 2001. - ARGO: The global array of profiling floats, In: C.J. Koblinsky and N.R. Smith (eds.), *Observing the Ocean for Climate in the 21^{st} Century*, pp. 248-258. GODAE, Bureau of Meteorology, Melbourne.

Babin, M. and C. Roesler (eds.). – 2005. Workshop on Real-Time Systems for Observing Coastal Ecosystem Dynamics and Harmful Algal Blooms, (HABWATCH), UNESCO Publishing, in press.

Babin, S., J.A., Carton, T.D. Dickey, and J.D. Wiggert. – 2004. Satellite evidence of hurricane-induced plankton blooms in the ocean desert, *J. Geophys. Res., Vol. 109, No. C3, C03043,* doi: 1029/2003JC001938.

Bidigare, R.R., B.B. Prézelin, and R.C. Smith. – 1992. Bio-optical models and the problems of scaling, In: P.G. Falkowski and A.D. Woodhead (eds.), *Primary Productivity and Biogeochemical Cycles in the Sea*, pp. 175-212. Plenum Press, New York.

Bishop, D., P. Gammel and C.R. Giles. – 2001. The little machines that are making it big, *Physics Today*, 54: 38-44.

Bishop, J.K.B., R.E. Davis and J.T. Sherman. – 2002. Robotic observations of dust storm enhancement of carbon biomass in the North Pacific, *Science,* 298: 817-821.

Chang, G.C. and T.D. Dickey. – 2005. Interdisciplinary sampling strategies for detection and characterization of harmful algal blooms, *Workshop on Real-Time Systems for Observing Coastal Ecosystem Dynamics and Harmful Algal Blooms, (HABWATCH)*, eds. M. Babin and C. Roesler, UNESCO Publishing, in press.

Chang, G., K. Mahoney, A. Briggs, D. Kohler, M. Lewis, C. Mobley, M. Moline, E. Boss, M. Moline, E. Boss, M. Kim, W. Philpot and T. Dickey. – 2004. The new age of hyperspectral oceanography, *Oceanography*, 17(2): 16-23.

DeLong, E.F., L.T. Taylor, T.L. Marsh and C.M. Preston. – 1999. Visualization and enumeration of marine planktonic archaea and bacteria by using polyribonucleotide probes and fluorescent *in situ* hybridization, *Appl. Environ. Microbiol.,* 65: 5554-5563.

Dickey, T. – 2001. The role of new technology in advancing ocean biogeochemical research, *Oceanography*, 14(4): 108-120.

Dickey, T. – 2002. A vision of oceanographic instrumentation and technology in the early 21^{st} century. In: J.G. Field, G. Hempl, and C.P. Summerhayes (eds.), *Oceans 2020: Science for Future Needs*, pp. 209-254. Island Press, Washington, DC.

Dickey, T., 2003. - Emerging ocean observations for interdisciplinary data assimilation systems, *J. Mar. Syst.*, 40-41: 5-48.

Dickey, T. – 2004. Exploration of biogeochemical temporal variability, NATO Advanced Study Institute Series. In: T. Oguz and M. Follows (eds.), *The Ocean Carbon Cycle and Climate*, pp. 149-188. Kluwer Academic Publishers, The Netherlands.

Dickey, T. and G. Chang. – 2001. Recent advances and future visions: temporal variability of optical and bio-optical properties of the ocean, *Oceanography*, 14(3): 15-29.

Dickey, T. and P. Falkowski. – 2001. Solar energy and its biological-physical interactions in the sea. In: A. Robinson, J. McCarthy, and B. Rothschild (eds.), *The Sea*, Vol. 12, pp. 401-440. John Wiley and Sons.

Davis, R. E., J. T. Sherman, and J. Dufour. – 2001. Profiling ALACEs and other advances in autonomous subsurface floats, *J. Atmos. Ocean. Tech.*, 18, 982-993.

Eriksen, C.C., T.J. Osse, R.D. Light, T. Wen, T.W. Lehman, P.L. Sabin, J.W. Ballard and A.M. Chiodi. – 2001. Seaglider: a long range autonomous underwater vehicle for oceanographic research, *IEEE J. Oceanic Eng.*

Glenn, S. and T. Dickey (eds.). – 2003. *Scientifc Cabled Observatories for Time Series (SCOTS) Report*, National Science Foundation Report, published by Consortium for Oceanographic Research and Education.

Glenn, S.M., T.D. Dickey, B. Parker and W. Boicourt. – 2000. Long-term real-time coastal ocean observation networks, *Oceanography*, 13: 24-34.

Griffiths, G., R. Davis, C. Eriksen, D. Frye, P. Marchand, and T. Dickey. – 2001. Towards new platform technology for sustained observations, In: C.J. Koblinsky and N.R. Smith (eds.), *Observing the Ocean for Climate in the 21^{st} Century*, pp. 324-338. GODAE, Bureau of Meteorology, Australia, Melbourne.

Hallegraeff, G.M. – 1993. A review of harmful algal blooms and their apparent global increase, *Phycologia*, 32: 79-99.

Hallegraeff, G.M. and C.J. Bolch. – 1992. Transport of diatom and dinoflagellate resting spores via ship's ballast water: Implications for plankton biogeography and aquaculture, *J. Plankton Res.*, 14: 1067-1084.

Hofmann, E.E. and M.A.M. Friedrichs. – 2001. Biogeochemical data assimilation. In: J.H. Steele, S. Thorpe, and K. Turekian (eds.), *Encyclopedia of Ocean Sciences*, pp. 302-308. Academic Press, London.

Jaffe, J.S., K.D. Moore, J. McLean, and M.P. Strand. – 2001. Underwater bio-optical imaging: status and prospects, *Oceanography*, 14(3): 64-75.

Kaku, M. – 1997. *Visions: How Science Will Revolutionize the 21^{st} Century*, Anchor Books Doubleday, New York.

Koblinsky, C.J. and N. R. Smith. – 2001. *Observing the Ocean for Climate in the 21^{st} Century*, GODAE, Bureau of Meteorology, Australia, Melbourne.

Kurzweil, R. – 1999. *The Age of Spiritual Machines*, Penguin Books, New York.

Martin, S. – 2004. *An Introduction to Ocean Remote Sensing*, Cambridge University Press.

National Research Council. – 1999. *From Monsoons to Microbes: Understanding the Ocean's Role in Human Health*, Washington, DC: National Academy Press.

National Research Council. – 2000. *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science Committee on Seafloor Observatories: Challenges and Opportunities*, Ocean Studies Board, Washington, DC: National Academy Press.

National Research Council. – 2002. *Marine Biotechnology in the Twenty-first Century: Problems, Promise, and Products*. Washington, DC: National Academy Press.

Oceanography. – 2000. volume 13(1), Special Issue: Coastal Ocean Observing Systems.

Oceanography. – 2001. volume 14(4), Special Issue: JGOFS.

Oceanography. – 2003. volume 16(4), Special Issue: Ocean Observatories.

Oceanography. – 2004. volume 17(2), Special Issue: Coastal Ocean Optics and Dynamics.

Pace, N.R. – 1997. A molecular view of microbial diversity and the biosphere, *Science* 276: 734-740.

Perry, M.J. and D.L. Rudnick. – 2003. Observing the oceans with autonomous and Lagrangian platforms and sensors: the role of ALPS in sustained ocean observing systems, *Oceanography*, 16(4): 31-36.

Pinardi, N., E. Arneri, A. Crise, M. Ravaioli, and M. Zavatarelli. – 2005. The physical, sedimentary, and ecological structure and variability of shelf areas in the Mediterranean Sea, *The Sea*, Vol. 14, Harvard University Press, in press.

Robinson, I.S. – 2004. *Measuring the Oceans from Space: The Principles and Methods of Satellite Oceanography*, Springer-Praxis.

Robinson, A.R. and P.F. J. Lermusiaux. – 2002. Data assimilation for modeling and predicting coupled physical-biological interactions in the sea. In: A.R. Robinson, J.J. McCarthy, and B.J. Rothschild, *The Sea*, Volume 12, pp. 475-536. John Wiley and Sons.

Rossby, T. – 2001. Sustained ocean observations from merchant vessels, *Mar. Technol. Soc. J.*, 35: 38-42.

Russell, S.J. and P. Norvig. – 2002. *Artificial Intelligence: A Modern Approach*, 2^{nd} edition, Prentice-Hall.

Schmidt, T.M., E.F. DeLong and N.R. Pace. – 1991. Analysis of a marine picoplankton community by 16S rRNA gene cloning and sequencing, *J. Bacteriol.*, 173: 4371-4378.

Schofield, O. and M.K. Tivey. – 2005. *ORION: Ocean research Initiative Observatory Networks*, A Report of the Workshop Held January4-8, 2004, San Juan, Puerto Rico.

Send, U., B. Weller, S. Cunningham, C. Eriksen, T. Dickey, M. Kawabe, R. Lukas, M. McCartney and S. Osterhus. – 2001. *Oceanographic Timeseries Observatories, for Climate in the 21^{st} Century*, C.J. Koblinsky and N.R. Smith (eds.), pp. 376-390. GODAE, Bureau of Meteorology, Melbourne.

Stahl, D.A. and J.M. Tiedje. – 2002. *Microbial Ecology and Genomics: A Crossroads of Opportunity*, Report from the American Academy of Microbiology, Washington, D.C.

Stein, J., T.L. Marsh, K.Y. Wu, H. Shizuya and E.F. DeLong. –

1996. Characterization of uncultivated marine prokaryotes: Isolation and analysis of a 40 kilobase genome fragment from a planktonic marine Crenarchaeote, *J. Bact*., 178: 591-599.

Stommel, H. – 1989. The Slocum mission, *Oceanography*, 2: 22-25.

Tokar, J. and T. Dickey. – 2000. Chemical sensor technology – current and future applications, In: *Chemical Sensors in Oceanography*, pp. 303-329. Gordon Breach Scientific Publishers, Amsterdam.

Varney, M. – 2000. *Chemical Sensors in Oceanography*. Gordon and Breach Scientific Publishers, Amsterdam.

Wilson, S. – 2000. Launching the ARGO armada, *Oceanus*, 42: 17-19.

Yoder, J.A., J.K. Moore, and R.N. Swift. – 2001. Putting together the big picture: remote-sensing observations of ocean color, *Oceanography*, 14(4): 33-40.

Yu, X., T. Dickey, J. Bellingham, D. Manov, and K. Streilein. – 2002. The application of autonomous underwater vehicles for interdisciplinary measurements in Massachusetts and Cape Cod Bays, *Cont. Shelf Res*., 22: 2225-2245.

Zehr, J.P. and W.D. Hiorns. – 1998. Molecular approaches for studying the activities of marine organisms. In: K.E. Cooksey (ed.), *Molecular Approaches to the Study of the Ocean*, pp. 91-112. Chapman and Hall.

Zengler K., G. Toledo, M. Rappé, J. Elkins, E.J. Mathur, J.M. Short and M. Keller. – 2002. Cultivating the uncultured, *PNAS*, 99: 15681-15686.