Progress in Multi-disciplinary Sensing of the 4-Dimensional Ocean

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Abstract

Many luminaries of oceanography have articulated the problem of adequately sampling a multiplicity of interdisciplinary ocean processes. Progress has accelerated within the past two decades as societal and naval interests in monitoring and predicting the state of the ocean environment has heightened. Oceanographers are capitalizing on a host of new platform and sensing technologies. Some recent programs contributing to improved 4-dimensional open and coastal ocean multi-disciplinary observations are used to highlight the development of new integrated optical, chemical, and physical measurement systems that can be deployed from stationary and mobile platforms to telemeter data in near real-time or real-time. For example, the NOPP O-SCOPE and MOSEAN projects have developed and tested several optical and chemical sensors in deep waters off Bermuda and Hawaii, at OWS 'P' in the North Pacific Ocean, and in coastal waters off Santa Barbara and Monterey, California. Most of the testing for these projects has been conducted using moorings; however, NOPP instrumentation is also being used on mobile platforms including AUVs, profiling floats, and gliders. Progress in adequately sampling the temporal and spatial variability of selected ocean 'sampling volumes' using multi-platform, multi-disciplinary sampling is described using examples from selected recent programs.

Keywords: Platforms, sensors, scales, sampling strategies, observing systems, data assimilation

1. INTRODUCTION

The vast ocean continues to be undersampled because of several common technological challenges (e.g., summarized in Table 2 of Dickey and Bidigare, 2005). Thus, our knowledge of the science of the ocean is constrained by limited observations needed for fundamental descriptions that are required for development and testing of theories and diagnostic and predictive models. Temporal and horizontal spatial scales of known oceanographic processes span over ten orders of magnitude as depicted in (e.g., see Dickey and Bidigare, 2005). Exemplary processes encompass molecular diffusion and turbulence through global scale ocean circulation, atmosphere-ocean teleconnections, and carbon fluxes and acidification. Importantly, the coupled atmospheric and oceanic system is complicated by episodic, nonlinear, and chaotic phenomena such as hurricanes, typhoons, and cyclones, earthquakes and tsunamis, rogue waves, planktonic blooms, outbreaks of harmful algal blooms and invasive species, eutrophication, ice shelf breaking and calving, and dust outbreak events (see Table 1 of Dickey and Bidigare, 2005).

Major observational advances, which have been enabled by using *in situ* platforms, have accelerated over the past two decades in particular (e.g., Bidigare and Dickey, 2005; Dickey et al., 2003, 2006, 2008). Sensors and systems for measuring chemical, bio-optical, and bio-acoustical variables were most limited up to a decade ago. However, several new multi-disciplinary sensors and integrated systems have now been developed and have thus enabled a greatly expanded suite of multi-disciplinary measurements. Oceanographers have utilized a variety of stationary and mobile *in situ* platforms as well as airborne and space-based sensors to characterize and quantify a variety of ocean processes that bear on a host of problems. Problems of interest have included: biogeochemical fluxes related to carbon and global climate change, coastal dynamics and ecosystems, optical imaging, and heat budgets and transport along with many episodic phenomena as mentioned earlier. A comprehensive list of relevant problems is given in Dickey and Bidigare (2005). Ultimately, 4-dimensional (3 dimensions in space and one in time), multi-disciplinary observations executed in synchrony with hindcasting and predictive data assimilation models should allow oceanographers to advance interdisciplinary oceanographic sciences and to facilitate prediction and management of the ocean environment for a host of applications.

This brief report reviews 1) advances in ocean platforms, 2) development of new ocean sensors and systems, 3) examples of open ocean observing capabilities, and 4) examples of coastal ocean observing capabilities. In the spirit of the present symposium, several optically-based illustrations are given and interdisciplinary research is emphasized. Finally, a summary and some future directions are presented in conclusion. Several references to more comprehensive and in-depth reviews are cited.

2. OCEAN PLATFORMS

Observation of the ocean requires a host of platforms, some orbiting space or flying on aircraft and others sampling in the ocean itself. The need for a diversity of platforms lies in the specific capabilities and deficiencies of each type. Airborne- and satellite-based sensing provide excellent semi-synoptic, snapshot views of large portions of the ocean's surface or very near surface layer, relying upon use of either passive or active electromagnetic radiation. However, information from greater depths is limited because of the inability of electromagnetic radiation to penetrate very deeply into the ocean. Also, the numbers of chemical variables that can be sensed or inferred remotely are relatively few at this point. Nonetheless, creative uses of airborne and satellite platform data are expanding rapidly and provide critical complements for *in situ* data sets. Readers interested in the state of ocean color remote sensing are directed to a recent review paper by McClain (2009). The focus here is upon *in situ* observations and draws on more comprehensive and in-depth reviews by Dickey (2003), Dickey and Bidigare (2005), and Dickey et al. (2006) and a recent volume dedicated to autonomous and Lagrangian platforms and sensors introduced by Dickey et al. (2008). Next, brief summaries of stationary and mobile platform capabilities are outlined.

2.1 Stationary Platforms

Mooring-based measurement systems are intended to maintain geographic location (i.e., geographically stationary), although there is necessarily some associated horizontal motion. These systems are quasi-Eulerian in nature and a plethora of well-developed time series analytical methods are readily available for data analyses. Temporal resolution and duration are key attributes of mooring-based sampling. Moorings can utilize either surface (buoy) or subsurface flotation (subsurface float). Surface buoys are useful for collecting meteorological and air sample data (i.e., for CO_2, dust, aerosols, etc.). Mooring platforms can be divided into two categories. The first typically utilizes sensors placed at several fixed depths and the second employs a single instrument package or profiler, which translates vertically at set or event responsive (on command) intervals. One of the most heavily instrumented moorings to date is the Bermuda Testbed Mooring (BTM), which was deployed approximately 80 km off Bermuda over the period of 1994-2008. This fixed-depth type of mooring and its counterpart, the Hawaii Air-sea Logging Experiment, A Long-term Oligotrophic Habitat Assessment (HALE-ALOHA, H-A) mooring located north of Oahu, Hawaii, have been used for both development and testing of new optical and chemical sensors and samplers (Dickey et al., 2009). The advantages of the fixed-depth mooring include 1) the capability of deploying multiple instrument packages, which may be relatively large, 2) high temporal resolution time series data products, and 3) data telemetry and system controls for adaptive sampling. Disadvantages lie in the need for many instruments to resolve vertical structure and susceptibility to biofouling of instruments deployed in the euphotic layer. A variety of moored profiling systems have been developed to enable increased vertical resolution. Some use winches while others take advantage of buoyancy devices and controllers on the instrument package itself. Fewer sensors can be utilized for profilers, but they can be parked at depths below the euphotic layer to minimize biofouling effects. Poorer temporal resolution is a drawback along with greater potential for catastrophic loss if the profiler accidentally goes adrift because of mooring line failure. The New Jersey coastal LEO-15 program was one of the first to demonstrate the capability of profiling moorings (e.g., Glenn et al., 2004) and several others have now proven successful. New chemical and optical sensors have been developed and tested using moorings, which often have the additional advantage of regular accessibility by ships for seatruthing and instrument and mooring hardware interchanges. Some important breakthroughs enabled by moorings include capturing events such as dust events (e.g., Sholkovitz and Sedwick, 2006), hurricane passages (e.g., Dickey et al., 2001; Black and Dickey, 2008), mesoscale eddies (e.g., Dickey et al., 1993, 2001; McNeil et al., 1999; Sakamoto et al., 2004; Jiang et al., 2008), and rapid exports of carbon and other elements to the deep sea (e.g., Conte et al., 2003; Honda et al., 2006).

2.2 Mobile Platforms

Autonomous mobile platforms include a broad group of sampling devices (e.g., Perry and Rudnick, 2003; Dickey et al., 2009). Some are designed to follow water parcels (i.e., quasi-Lagrangian) whereas others are intended to traverse the ocean using either propellers or their own buoyancy changes coupled with hydrodynamic propulsion forcing. Drifters placed at the ocean's surface and others drogued to set depths have served oceanographers for many years and the advent of GPS has increased their utility greatly. Relatively small interdisciplinary sensors can be mounted on the drifters and can enable broad spatial coverage, especially in remote regions, when deployed in large numbers. One of the major advances in drifter technology has been the measurement of CO_2 and related variables in adverse oceanic environments such as the Southern Ocean (e.g., Boutin et al., 2008). Neutrally buoyant subsurface floats have been keys to understanding ocean circulation at depth and have been tracked acoustically using hydrophone arrays. Profiling floats (e.g., Davis et al., 2001) including Argo floats (Argo Science Team, 2001; Roemmich et al., 2009) now populate the oceans in large numbers (i.e., ~3000 profiling Argo floats are now sampling in the world ocean) and provide high quality temperature and salinity as well as dissolved oxygen profile data in some cases. They have also been used to measure wind speeds and rainfall during monsoons (e.g., Riser et al., 2008). The number of interdisciplinary measurements that can be made from floats is increasing rapidly (see introductory paper by Dickey et al., 2009). For example, new optical and chemical sensors are being attached to some profiling floats as well (i.e., Bishop et al., 2002, 2009; Le Teste et al., 2009; Checkley et al., 2008; Martz et al., 2008). Studies have included particle and plankton dynamics, dissolved oxygen and net community production, and dust-induced carbon flux events.

Gliders are another new type of ocean observing platform (e.g., Davis et al., 2003; Eriksen et al., 2009). The development of gliders was anticipated in a visionary story about the mythical 'Slocum Mission' written by Henry Stommel (1989). These devices also use buoyancy changes to move vertically through the ocean at set locations and act as virtual moorings. However, control wings also enable them to translate horizontally to collect transect data (note: these are not Lagrangian measurements). New interdisciplinary optical and chemical sensors are now being tested and used for experiments with gliders (see Dickey et al., 2009). Examples of applications using gliders include studies of whale vocalizations (e.g., Baumgartner and Fratantoni, 2008), surveys of the physics and biology of coastal current systems (e.g., Davis et al., 2008), sediment resuspension events (e.g., Glenn et al., 2008), net community production and mesoscale eddies (Nicholson et al., 2008), and observations of plankton blooms in coastal regions (Perry et al., 2008) .

Autonomous underwater vehicles (AUVs) have become valuable observational tools for increasing numbers of oceanographers within the past few years as they have become easier to use and their costs have declined (e.g., Griffiths, 2003). AUVs are similar to gliders except that they are powered using energy sources. Most employ batteries, which is the limiting factor for their mission duration. However, some use solar energy, recharging batteries at the surface via solar cell light collectors. AUVs are available from very small (less than a meter in length) to large (i.e., Autosub, ~10 meters long; see Griffths, 2003) and their instrument payloads vary in rough proportion. AUVs, such as Autosub, can play major roles in exploring long distances under ice in remote regions (e.g., Nicholls et al., 2008). Examples of other important work being conducted with AUVs include: studies of high resolution ocean optics (in optical wavelengths and in space; Glenn et al., 2004), ice-ocean turbulent exchanges (e.g., Hayes and Morison, 2008), mapping of plankton and distributions of nutrient and oxygen concentrations (e.g., Johnson and Needoba, 2008), and mapping of coral reefs (e.g., Shcherbina et al., 2008) and bays (e.g., Yu et al., 2002). Deployment of large AUVs from ships at sea is difficult and may require special deck gear opposed to small AUVs, drifters, floats and gliders, some of which can be deployed from aircraft or near shore. Robotic boats are also being developed and serve similar functions as AUVs. A final type of mobile platform is the marine mammal (e.g., McCafferty et al., 1999). For example, elephant seals been used for

CTD sectional data and for studying fronts in relatively inaccessible regions such as the Drake Passage (Boehme et al., 2008).

Mobile platforms can be used to observe the global ocean, the coastal zone, or regionally for dedicated scientific experiments. Their costs are decreasing as more are produced and in some cases (e.g., gliders, robotic boats, and AUVs), they can be directed to return to a specified location, recovered, and redeployed. They are becoming more important for interdisciplinary sensing as new technologies are developed to increase the diversity of measurements and the size and power requirements of the sensors are reduced. Telemetry of data is improving (with more communications satellites, increasing bandwidth, and frequency of satellite overpasses) to the benefit of both stationary and mobile autonomous sampling platforms as well as ships.

3. OCEAN SENSORS AND SYSTEMS

The development of capable autonomous sampling platforms has been paralleled with advances in new optical, biological, chemical, acoustical, and genetic sensors which enable measurements of a broad variety of inherent and apparent optical properties, improved optical images, many more chemical elements, molecules, and compounds, and genetic matter identification. Many of the advances are direct results of advances in technologies outside of oceanography, but recognized and adapted by thoughtful oceanographers. It should be noted that some instrumentation designed originally for physical measurements has also been cleverly used by oceanographers for biological measurements. For example, the acoustic Doppler current profiler (ADCP) is being used for zooplankton studies (e.g., see Jiang et al., 2008 and references therein). Also, a recent review on genetic sensing is given by Scholin et al. (2009) and Scholin (2009). Reviews on sensors and systems published by Daly et al. (2004), Babin et al. (2008), Varney (2000), Dickey et al. (2006, 2009) go into considerable depth. In this section, a few of the recent advances in optical and chemical sensors and samplers are highlighted.

3.1 Optical sensors

Optical sensing is driven by a variety of problems including heating of the upper ocean, formation of biomass (primary productivity), ecology, imaging, organism behaviors and adaptations, biogeochemical cycling, bioluminescence, pollution, and destruction of chemical compounds. Since biology is so influential on the ocean's light field and *vice versa*, the terms bio-optical oceanography and bio-optics are commonly used in reference to ocean, marine, and hydrologic optics.

Instruments have been developed to measure inherent optical properties (IOPs), that is to quantify properties which are dependent only upon the aquatic medium itself and the wavelength of light. Since light is either absorbed or scattered (elastically or inelastically) by the aquatic medium, instruments have been developed to measure absorption and angular scattering at multiple wavelengths to characterize and quantify the light field. The total attenuation of light is defined by the total attenuation coefficient, the sum of total attenuation by absorption and scattering components. It is useful to subdivide the absorption, scattering, and attenuation into affecting constituents which include pure water, phytoplankton, detritus, and colored dissolved material. By using multispectral measurements, it is possible to attribute via empirical models percentages of absorption by the various constituents. This procedure is especially useful for many biological as well as optical problems. One of the major technological breakthroughs for optical oceanography is the development of *in situ* instruments, which can measure in roughly 90 wavebands across the visible spectrum – this is the so-called hyperspectral measurement (e.g., See Dickey, 2004 and references therein). Another is the capability of measuring scattered light at multiple angles. Together, these advances are enabling much fuller characterization of the optical properties of naturally occurring ocean waters.

In contrast to IOPs, apparent optical properties (AOPs) depend on IOPs, the angular distribution of the subsurface ambient light field, and the wavelength of light. Some of the important IOP measurements include radiance and irradiance. Radiance is defined as the radiant light flux at a specified point in a given direction per unit solid angle per unit area perpendicular to the light propagation whereas irradiance is defined as radiant flux per unit surface area. Orientation with respect to a normal to the sea surface is invoked for downward and upward irradiance; irradiance reflectance is the ratio of the upward to downward component. Spectral partitioning is often desirable and again, new instrumentation is now available for hyperspectral measurements of AOPs. Another useful optical quantity and measurement is the broadband quantity, photosynthetic available radiation or PAR. Importantly, remote sensing of ocean color from aircrafts or satellites is based on IOP measurements which are ground referenced, namely for calibration and validation (e.g., see McClain, 2009). One of the important constraints on *in situ* optical measurements is biofouling. A variety of techniques have been employed to mitigate this problem as discussed in Manov et al. (2004), Babin et al. (2008), Moore et al. (2009), and Dickey et al. (2009). Coastal environments are more problematic than their open ocean counterparts because of much higher productivity. Interestingly, open ocean optical measurements have been successfully collected for over 400 days using special anti-biofouling devices during a mooring deployment off Japan (Honda, 2006, 2009). In addition to IOP and AOP measurements, methodologies designed to capitalize on natural and artificially stimulated fluorescence and imaging have advanced considerably. It should be noted that a large number of optical sensors can be deployed from most of the stationary and mobile platforms described earlier and thus the temporal and spatial domains of sampling (in resolution, range, and duration) have been expanded to near those of their physical counterparts. Reviews by Dickey et al. (2006, 2009), Babin et al. (2008), and Moore et al. (2009) provide more detailed information on IOP and AOP measurements.

3.2 Chemical Sensors

Chemical measurements are required for a host of oceanographic problems including ocean productivity (e.g., plant nutrients), chemical pollution (e.g., oil and other environmentally toxic spills or dumps), hyperoxic and anoxic conditions causing ecosystem damage, and global climate change via greenhouse gases including carbon dioxide (e.g., see Varney, 2000 and papers and references therein, Daly et al., 2004; Dickey et al., 2009; Schuster et al., 2009). Measurements of dissolved oxygen, carbon dioxide, and pH have improved greatly and can be made from most of the platforms mentioned earlier. Plant nutrients including nitrates, nitrites, phosphates, and silicates can also be sampled, though with more difficulty at this point. Optics and colorimetry are keys to many of the measurements. For many measurements of very low concentrations of specific elements or molecules (trace amounts), water samples remain necessary. However, even these can be accomplished from moorings (e.g., see Dickey et al., 2001, 2009). As indicated earlier, several mobile and stationary platforms have collected dissolved oxygen and carbon dioxide data and some have obtained important nutrient measurements necessary for understanding processes such as productivity and fluxes associated with mesoscale eddies. Another important time series has also been initiated for measuring changing ocean water pH and acidity using moorings in the North Pacific at Ocean Weather Station P (e.g., see Dickey et al., 2009 and references therein).

Partnerships among academic, government laboratories, and private companies have proven especially valuable for development, testing, and transitioning of optical and chemical sensors (e.g., Dickey et al., 2009). One of the systems developed in part under National Oceanographic Partnership Program funding (O-SCOPE project) is an autonomous *in situ* instrument called the Spectrophotometric Elemental Analysis System (SEAS; see Figure 6; Byrne et al., 1999, 2002; Kaltenbacher et al., 2001). One version of the *in situ* SEAS (SEAS II) instrument is capable of both absorbance and fluorescence measurements. It has been used for *in situ* quantification of seawater pH (Liu et al., 2006) and nutrients (Adornato et al., 2007). SEAS II autonomously mixes seawater and reagents, and records absorbances at user-defined wavelengths. Its measurements are made with liquid core waveguides. Liquid core waveguides with long pathlengths provides low nanomolar detection limits for many different analytes (Adornato et al. 2005). An initial deployment of SEAS I in October 1999 using the OWS "P" NOAA Tsunami mooring was the first ever for an *in situ*, autonomous spectrophotometric pH measurement system at sea (Kaltenbacher et al., 2000). Also developed under partial funding by the NOPP O-SCOPE project, a pCO_2 measurement system, first introduced by Friedrich et al. (1995), was further developed and tested. The system utilizes a non-dispersive infrared spectrometer and measures the difference in CO_2 partial pressure across the air-sea interface. A derivative of this system is being used for several pCO_2 time series measurements from buoys by Chris Sabine (NOAA PMEL) as described in Dickey et al. (2009). A recent review on sensors and instruments for oceanic dissolved carbon measurements has been presented by Schuster et al (2009).

As part of another NOPP project, MOSEAN, a self-contained, modular, autonomous nutrient analyzer was developed, prototyped, and tested (Hanson and Moore, 2001; Dickey et al., 2009). The research effort utilized multi-channel, fast-response systems and instruments designed for extended observations. The fast-response nutrient analyzer, or the Autonomous Profiling Nutrient Analyzer (APNA), was designed for deployment on a variety of moving platforms including ship deployed-CTD profilers, autonomous moored profilers, and AUVs. These efforts culminated in a production prototype sensor for long-term monitoring of phosphate in coastal and oceanic environments (Zaneveld et al., 2007). The instrument takes advantage of a custom optical sensor with reagent delivery fluidics to perform stop-flow analyses of natural water. This sensor has been tested in various environments and its performance has been demonstrated and evaluated by the Alliance of Coastal Technologies, ACT, (2008). The MOSEAN CHARM mooring, which was located in the Santa Barbara Channel, was used to test a variety of optical and chemical sensors and associated anti-biofouling approaches. It should also be noted that new chemical sensors including an osmoanalyzer (e.g., Jannasch et al., 1994) and an *in situ* ultraviolet spectrophotometer (Johnson and Needoba. 2008) have been successfully deployed in oligotrophic waters, with both capturing nutrient injection events associated with mesoscale eddies (e.g., see McNeil et al., 1999 and Sakomoto et al., 2004). The aforementioned examples represent only a few of the new sensors and systems and applications.

4. OPEN OCEAN OBSERVATIONAL CAPABILITIES

4.1 Background

Observing the global ocean is a formidable task requiring all of the platforms described earlier along with numerical models which can be used to assimilate data under constraints of the laws and empirical constraints of physics, chemistry, and biology (Oceanography, 2004). Observational synopticity at nearly global-scales for the surface ocean has advanced with the launching of numerous satellites. Importantly, the number of variables are growing beyond sea surface temperature, sea surface elevation, and color. On the horizon are sea surface salinity, color-derived variables such as colored dissolved organic matter, and others. Importantly, atmospheric forcing of the ocean is better known as several meteorological satellites now provide key momentum, radiation, cloud, aerosol, and heat flux data sets.

In situ observations of the open ocean, which are critical for 4-D characterizations and predictive models of the ocean have advanced with the development of platforms described earlier. However, *in situ* global-scale sensing of the ocean remains a major challenge with acoustical methods being perhaps the best option for many problems because of the relative opacity of seawaters to electromagnetic radiation. However, the scales of interest for much interdisciplinary research require *in situ* platforms collecting data locally. Thus, the advantages of different sampling platforms and sensors need to be capitalized upon for reasonably comprehensive interdisciplinary data sets to be realized. The number of ocean locations that can be intensely sampled are limited because of costs and accessibility. The Argo array of ~3000 profiling floats, complemented with drifters, gliders and ships of opportunity, offers hope for improved spatial coverage for interdisciplinary data as new sensors and systems become available for integration.

Time series using moored systems in the open ocean have proved especially important for processes including mesoscale eddies, tropical instability waves, ENSO, monsoons, intense storms including hurricanes, typhoons, and cyclones, and dust-driven planktonic blooms. The NOAA array of moorings in the equatorial Pacific has been particularly effective (McPhaden et al., 1998). Within the past two decades, optical and chemical systems have been deployed from some of the moorings in this array to significant advantage for atmospheric and oceanographic research and predictions (e.g., Foley et al., 1997; Chavez et al., 1999; Chris Sabine pers. comm.). The examples presented thus far have goals of quantifying temporal changes in atmospheric conditions and physical oceanography on large horizontal scales for the most part. Next, an example of an open ocean testbed mooring complemented with a variety of other observational platforms is described.

4.2 Bermuda Time Series Observational Programs

Plans are being made to implement open ocean time series observatories at key sites in the world ocean (e.g., OceanSITES, see Send et al., 2001). The atmospheric analog is the CO_2 time series collected from Mauna Loa on the Big Island of Hawaii. The oceanic time scales of interest range from minutes to decades. The Bermuda Testbed Mooring (BTM) and its counterpart, the Hawaii Air-sea Logging Experiment, A Long-term Oligotrophic Habitat Assessment (HALE-ALOHA, H-A) mooring have served in many ways as proto-types for OceanSITES. The BTM, which operated from 1994-2008, 80 km southeast of Bermuda (BATS site), and the HALE-ALOHA (H-A) mooring, which was positioned about

80 km north of Hawaii (HOT site), collected data from 1997-2000 and 2004-2008. Both resided in waters of more than 4500 m depth and provided fundamental measurements of meteorological, physical, biogeochemical, biological, and optical variables. These programs served as magnets for oceanographers for testing new technologies and sensors, for satellite sensor calibration and validation (cal/val), and for scientific measurements used for novel analyses and model development and testing. For brevity, we focus here on the BTM, however many of the discussion point apply to the H-A program as well. Several references are available for both programs (e.g., see Dickey et al., 2006 and references therein).

The Bermuda Testbed Mooring (BTM) program had four major objectives. These included: 1) Development and testing of new deep-sea technologies, interdisciplinary sensors, anti-biofouling techniques and hardware, and data telemetry systems. For example, a new BTM interdisciplinary surface buoy design is now being used extensively at other sites. Representative instrumentation tested using the BTM included: an atmospheric dust and aerosol sampler, several different multi-wavelength optical sensors, chemical samplers and sensors (i.e., for macro- and micro-nutrients, carbon dioxide, oxygen, nitrogen, and noble gases), an *in situ* primary production device, and acoustic Doppler current meters used for currents as well as zooplankton distributions. 2) Facilitation of scientific studies requiring high frequency, sustained interdisciplinary data. Complementary ship-based (e.g., Steinberg et al., 2004), sediment trap mooring (e.g., Conte et al., 2003), AUV, and satellite data sets were used along with BTM data to expand the utility of several regional scientific research efforts. The BTM mooring proved its value in detecting and observing extreme and episodic processes that cannot be captured with ship- or satellite-based sampling. For example, BTM data were collected during direct hits by two hurricanes and one tropical storm as well as near passes by several other major storms along with several mesoscale eddies. 3) Providing data for developing and testing interdisciplinary models. BTM data sets were and continue to be used to develop and test improved models of several upper ocean processes during and in the wakes of extreme wind forcing events and nutrient injections, and plankton blooms, ecological shifts associated with eddies. 4) Validation of satellite-derived ocean observations. Ocean color measurements were the primary focus here. Moving toward the use of autonomously sampling vehicles, the Autosub AUV and gliders have operated in the vicinities of the BTM and H-A mooring sites, enabling calibration and validation of the mobile measurement systems and expansion of observations in time and space scales.

Several new discoveries and results have been obtained off Bermuda using the BTM. Recent work has also shown the influence of mesoscale features on primary production and their relation with deep ocean sediment flux events (e.g., Conte et al., 2003; Jiang et al., 2007). As another example, the dynamics and biological responses of the upper ocean have been observed at the BTM site during passages of hurricanes and other intense storms (e.g., Babin et al., 2004; Black and Dickey, 2008). The hurricane observations are unique and are enabling development and testing of models (e.g., Zedler et al. 2002).

5. COASTAL OCEAN OBSERVATIONAL SYSTEMS

5.1 Background

In some ways, systematic observations of select coastal areas are clearly less formidable of a task than comparable sampling of global basins or the entire world ocean because of the spatial advantage (Oceanography, 2000). Also, some measurements can be made from shore or with pier- or shore-based instrumentation (e.g., high frequency (HF) radar for ocean currents and waves). And generally, these regions are more accessible with ships or deployed AUVs and gliders, which can be deployed near the shore. However, coastal regions present more formidable challenges in several other ways. For example, fouling of instrumentation is more problematic because of greater biological productivity and river and coastal runoff. There is also more human activity in the form of fishing, boat and ship traffic, and oil drilling. In addition, there are often significant regulatory statutes that must be honored. Over the past two decades, major advances in well-integrated, multi-disciplinary coastal ocean observing systems intended to sample in 4-dimensions have been made. New instrumentation as described earlier has been developed and tested in both the open and coastal ocean with each benefitting from the other. In the following subsection, some examples of such systems are reviewed and finally a very recent coastal experiment devoted to waves and optics is introduced.

5.2 Examples of Coastal Ocean Observatories

Three examples of coastal ocean observing systems, which have utilized optical sensors and systems, are briefly discussed here (see Dickey et al., 2006 and references therein for more details). The Long-term Ecological Observatory site (LEO-15) is located off Tuckerton, New Jersey (e.g., see Glenn et al., 2000, 2004). A profiling mooring with a fiber optic cable link to shore for high bandwidth data transmission, fixed-depth moorings, AUVs, gliders, shore-based HF radar and meteorological tower, and ships have been used to observe a variety of physical, geological, chemical, biological, and optical phenomena with high temporal and spatial resolution. These *in situ* resources have been complemented with aircraft overflight and satellite-based ocean color sensing data. LEO-15 was one of three sites used for the Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE); other sites were located off the west Florida coast and off Lee Stocking Island in the Bahamas (the latter is called trhe CoBOP program). HyCODE's goals included development of operational ocean color algorithms and radiative transfer models for both shallow and deep ocean environments, understanding of water column visibility, establishing relationships among optical, physical, geological, and chemical variables, retrieval of ocean bathymetry, and characterization of bottom materials using hyperspectral remote sensing (see introductory article by Dickey, 2004). New technological tools, including high spectral resolution optical sensors and scanners, were central to HyCODE. These devices were deployed both *in situ* and from aircraft for the first time and enabled the development of new remote sensing algorithms with much greater capabilities than those of previous multi-wavelength (typically 7-9 wavebands) optical sensors used for observations of the marine environment. New multi-angle instruments were also employed to better characterize and quantify the distributions of scattered light as well as absorption and thus enabled better estimates of optical closure. Other optical systems were used to quantify particle size distributions, CDOM, and fluorescence. In addition, most of the data were recorded and telemetered in real-time or near real-time. These data were inspected in an experiment control room and numerical models were run to enable forecasts and to direct *in situ* sampling platforms to optimal locations of interest (e.g., to fronts, jets, sites of active upwelling and mixing, sediment resuspension events, phytoplankton blooms including harmful algal blooms, HABS).

Other coastal observatories have been developed for the Gulf of Maine (GoMOOS) and along most of the other coastal regions of the United States; these are described elsewhere (see http://hpl.umces.edu/projects/wrkrpt.pdf, Oceanography, 2000, and Schofield et al., 2009). Two Canadian coastal interdisciplinary observing systems have deployed in Lunenberg Bay, Nova Scotia and in the northern Gulf of St. Lawrence in Bonne Bay, Newfoundland. Both utilize hyperspectral optical sensors and real-time or near real-time data telemetry systems and include predictive modeling components. The latter site employs an elecro-optical cable for powering and data transmission for its profiling mooring system.

5.3 Radiance in a Dynamic Ocean (RaDyO) Experiment

The Office of Naval Research (ONR)-sponsored Radiance in a Dynamic Ocean (RaDyO) builds upon progress made during HyCODE. RaDyO, which was initiated in 2005, is a 5-year project devoted to the topic of light propagation and imaging across the air-sea interface and within the ocean's surface boundary layer (SBL) as affected by the physics and chemistry of the upper ocean and atmospheric forcing (see www.opl.ucsb.edu/radyo/). This topic bears not only upon optical imaging, but also on the use of light field measurements for characterizing and quantifying surface waves, phytoplankton physiology and productivity, near surface thermodynamics, natural and man-made surfactants, bubbles, and gas exchange across the air-sea interface. Several aspects of RaDyO also bear on the problem of constraining global carbon budgets. The primary goals of the ONR-sponsored Radiance in a Dynamic Ocean (RaDyO) program are to: (1) Examine time-dependent oceanic radiance distribution in relation to dynamic surface boundary layer (SBL) processes. (2) Construct a radiance-based SBL model. (3) Validate the model with field observations. (4) Investigate the feasibility of inverting the model to yield SBL conditions.

RaDyO problems are being approached through three field experiments: Scripps Pier Experiment (instrument testing and observations in nearshore conditions, January 6-28, 2008), Benign conditions (Santa Barbara Channel moderate wind conditions, September 7-28, 2008), and High Sea State conditions (south of the Big Island of Hawaii, planned for August 23-September 14, 2009). The first phase of RaDyO emphasized the testing of newly developed optical and wave sensing instrumentation from the Scripps Institution of Oceanography pier in January, 2008. In September 2008, RaDyO investigators came to the

Santa Barbara Channel for the first of two major field experiments. The Santa Barbara Channel site was selected because of its relatively benign wind and sea state conditions as well as its varied optical properties. The multi-platform, interdisciplinary experiment was designed to observe extremely high temporal and spatial resolution optical data and included several specialize meteorological, wvae, and optical instruments. RaDyO instrumentation was deployed from the Research Platform (R/P) FLIP, the research vessel R/V Kilo Moana, two AUVs, a small platform for collecting surfactants at the ocean surface (dubbed Lil Kilo Moana for obvious reasons – see picture of Big and Lil Kilo Moana together), and a small airplane. R/P FLIP and the twin-hulled SWATH vessel R/V Kilo Moana were selected because of their exceptional stability characteristics, which are required to satisfy stringent sampling constraints for proper measurements of small waves and their effects on light fields. These collective platforms measured a host of ocean processes related to the fundamental problem of light propagation as affected by waves, turbulence, bubbles, surfactants, and the optical properties of near surface seawater. The Scripps Pier and Santa Barbara Channel data sets are being analyzed at present. In the summer of 2009, the final RaDyO field experiment will be executed south of the Big Island of Hawaii. This site was chosen to contrast the conditions of the Santa Barbara Channel because of its relatively high and steady wind and wave-state conditions and clear waters.

6. SUMMARY AND FUTURE DIRECTIONS

6.1 Summary

A major goal of oceanography is to sample a multiplicity of variables on a continuum of temporal and spatial scales so that diverse and interacting oceanographic processes may be described, understood, and modeled. There is increasing societal pressure to achieve these demanding goals because of environmental concerns for humans and marine life in general. Progress has accelerated as oceanographers are now able to capitalize on a host of new platform and sensing technologies. Some recent programs contributing to improved 4-dimensional coastal and open ocean observations have been used to highlight the development of new integrated optical, chemical, and physical measurement systems. These are now being deployed from stationary and mobile platforms and can telemeter data in real-time or near real-time and many incorporate data assimilation modeling for adaptive sampling and predictions. Several examples have been presented here.

6.2 Future Directions

Oceanographers need to continue to draw upon new breakthrough technologies in other fields. Miniaturization of sensors and systems is needed to increase the volume of measurements, which can be made from a host of platforms. Advances and commercialization in the area of microelectromechanical systems (MEMS), nanotechnologies, and genetic sampling are clearly ripe for transition. Needs continue for more interdisciplinary measurements in general, but especially in adverse environments with ice cover being a good example. Finally, predictive models of the 4-dimensinal ocean will require increased computing capabilities along with data collected from more economical and robust sensors and autonomous sampling platforms coupled with satellite-based sensors.

ACKNOWLEDGEMENTS

Support for this work was provided by ONR, NOPP, NSF, and NASA. I also wish to acknowledge the special support of my Secretary of the Navy/Chief of Naval Operations Chair in Oceanographic Science.

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