2009

The NOPP O-SCOPE and MOSEAN Projects: Advanced Sensing for Ocean Observing Systems

Tommy Dickey
University of California

Nick Bates
Bermuda Institute of Ocean Sciences

Robert H. Byrne
University of South Florida, rhbyrne@usf.edu

Grace Chang
University of California

Francisco P. Chavez
Monterey Bay Aquarium Research Institute

See next page for additional authors

Scholar Commons Citation

Dickey, Tommy; Bates, Nick; Byrne, Robert H.; Chang, Grace; Chavez, Francisco P.; Feely, Richard A.; Hanson, Alfred K.; Karl, David M.; Manov, Derek; Moore, Casey; Sabine, Christopher L.; and Wanninkhof, Rik, "The NOPP O-SCOPE and MOSEAN Projects: Advanced Sensing for Ocean Observing Systems" (2009). *Marine Science Faculty Publications*. 1595.
https://digitalcommons.usf.edu/msc_facpub/1595

Authors

Tommy Dickey, Nick Bates, Robert H. Byrne, Grace Chang, Francisco P. Chavez, Richard A. Feely, Alfred K. Hanson, David M. Karl, Derek Manov, Casey Moore, Christopher L. Sabine, and Rik Wanninkhof

THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

Dickey, T., N. Bates, R.H. Byrne, G. Chang, F.P. Chavez, R.A. Feely, A.K. Hanson, D.M. Karl, D. Manov, C. Moore, C.L. Sabine, and R. Wanninkhof. 2009. The NOPP O-SCOPE and MOSEAN Projects: Advanced sensing for ocean observing systems. *Oceanography* 22(2):168–181, doi:10.5670/oceanog.2009.47.

THE NOPP O-SCOPE AND MOSEAN PROJECTS

ADVANCED SENSING FOR OCEAN OBSERVING SYSTEMS

BY TOMMY DICKEY, NICK BATES, ROBERT H. BYRNE,
GRACE CHANG, FRANCISCO P. CHAVEZ, RICHARD A. FEELY,
ALFRED K. HANSON, DAVID M. KARL, DEREK MANOV, CASEY MOORE,
CHRISTOPHER L. SABINE, AND RIK WANNINKHOF

ABSTRACT. The National Oceanographic Partnership Program (NOPP) consecutively sponsored the Ocean-Systems for Chemical, Optical, and Physical Experiments (O-SCOPE) and Multi-disciplinary Ocean Sensors for Environmental Analyses and Networks (MOSEAN) projects from 1998 through 2008. The O-SCOPE and MOSEAN projects focused on developing and testing new sensors and systems for autonomous, concurrent measurements of biological, chemical, optical, and physical variables from a diverse suite of stationary and mobile ocean platforms. Design considerations encompassed extended open-ocean and coastal deployments, instrument durability, biofouling mitigation, data accuracy and precision, near-real-time data telemetry, and economy—the latter being critical for widespread sensor and system utilization. The complementary O-SCOPE and MOSEAN projects increased ocean sensing and data telemetry capabilities for addressing many societally relevant problems such as global climate change, ocean carbon cycling and sequestration, acidification, eutrophication, anoxia, and ecosystem dynamics, including harmful algal blooms. NOPP support enabled O-SCOPE and MOSEAN to accelerate progress in achieving multiscale, multidisciplinary, sustained observations of the ocean environment. Importantly, both programs produced value-added scientific results, which demonstrated the utility of these new technologies. The NOPP framework fostered strong collaborations among academic, commercial, and government entities, and facilitated technology transfers to the general research community and to long-term observational and observatory programs.

INTRODUCTION

Societal problems such as global climate change, ocean carbon cycling and sequestration, acidification, eutrophication coupled with hypoxic and anoxic events, ecosystem dynamics, and harmful algal blooms (HABs) are gaining interest as the world's population continues to grow, especially in coastal areas. Increasing anthropogenic pressures on the marine environment along with episodic and extreme oceanic events (i.e., hurricanes, tsunamis) that impact human lives and marine resources require sustained monitoring and prediction (Dickey and Bidigare, 2005). Thus, a new paradigm for conducting oceanography is being defined, in which scientists, educators, managers, and the general public seek immediate feedback and predictions concerning the state and health of the ocean environment and its inhabitants. To satisfy these needs, a wide variety of measurements must be made over a broad range of temporal and spatial scales. The only way that this can be accomplished is through multiscale (spatial and temporal) networks of autonomous sensors and sensor platforms (i.e., moorings, autonomous underwater vehicles [AUVs], profiling floats, and gliders) to collect and then transmit data to laboratories in real time for validation with standardized and accurate protocols (e.g., Dickey and Bidigare, 2005; Glenn and Schofield, this issue). Other papers in this issue by Bishop et al., Eriksen et al., Glenn and Schofield, Roemmich et al., and Scholin et al., as well as an article by Dickey et al. (2008), describe progress in interdisciplinary measurements from mobile platforms. In the last decade, various ocean technologies have pushed ocean scientists closer to achieving their vision (e.g., reviews by Dickey, 1991, 2003; Daly et al., 2004; Dickey et al., 2006, 2008; Glenn and Schofield, this issue).

The accomplishments of observational oceanography have not come easily, and many challenges remain. Perhaps no challenge is more daunting than the development of sensors to autonomously sample the biology and chemistry of the ocean (e.g., see reviews in Varney, 2000; Tokar and Dickey, 2000; Daly et al., 2004). In the recent past, observations of ocean biology and chemistry were largely restricted to discrete water samples collected from ships or piers because of the limited number of in situ biological and chemical sensors and because most biological and chemical analytical systems were designed only for use in laboratories (e.g., Tokar and Dickey, 2000; Hansen and Moore, 2001). The advancement of long-term, robust, compact, lightweight, and energy efficient biological and chemical sensors has become necessary in order to fully exploit emerging autonomous in situ sampling platforms and to realize the vision of observing the global oceans using stationary and mobile instrument arrays and cabled networks (e.g., Stommel, 1989; Dickey, 1991, 2003; Glenn and Dickey, 2003; Schofield and Tivey, 2005; Dickey et al., 2006, 2008; Glenn and Schofield, this issue).

Tommy Dickey *(tommy.dickey@opl.ucsb.edu) is Professor, Ocean Physics Laboratory, Department of Geography, University of California, Santa Barbara, Santa Barbara, CA, USA.* **Nick Bates** *is Senior Research Scientist and Associate Director of Research, Bermuda Institute of Ocean Sciences, St. George's, Bermuda.* **Robert H. Byrne** *is Distinguished University Professor, College of Marine Science, University of South Florida, St. Petersburg, FL, USA.* **Grace Chang** *was Associate Researcher, Ocean Physics Laboratory, University of California, Santa Barbara, CA, USA, and is currently Senior Marine Scientist, Sea Engineering Inc., Santa Cruz, CA, USA.* **Francisco P. Chavez** *is Senior Scientist, Monterey Bay Aquarium Research Institute, Moss Landing, CA, USA.* **Richard A. Feely** *is Program Leader, Carbon Group, NOAA Pacific Marine Environmental Laboratory, Seattle, WA, USA.* **Alfred K. Hanson** *is President, SubChem Systems Inc., Narragansett, RI, USA.* **David M. Karl** *is Professor, Department of Oceanography, University of Hawaii, Honolulu, HI, USA.* **Derek Manov** *is Principal Engineer and Lab Director, Ocean Physics Laboratory, University of California, Santa Barbara, CA, USA.* **Casey Moore** *is President, WET Labs Inc., Philomath, OR, USA.* **Christopher L. Sabine** *is a scientist in the Carbon Group, NOAA Pacific Marine Environmental Laboratory, Seattle, WA, USA.* **Rik Wanninkhof** *is a scientist in the Ocean Chemistry Division, NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL, USA.*

One of the National Oceanographic Partnership Program's (NOPP's) main missions in addition to fostering federal agency partnering was to fast-track specific initiatives to quickly make breakthroughs, including developing and transitioning new oceanographic technologies, especially those of an interdisciplinary nature. With this backdrop, NOPP funded the Ocean-Systems for Chemical, Optical, and Physical Experiments (O-SCOPE) and Multi-disciplinary Ocean Sensors for Environmental Analyses and Networks (MOSEAN) projects for the periods of 1998–2003 and 2003–2008, respectively. Table 1 lists partners and investigators for each project along with their primary research foci. The general

Table 1. O-SCOPE and MOSEAN partners, investigators, their institutions, and primary research foci

Partner and Investigators	Project	Institution	Primary Foci
Tommy Dickey (Lead PI for both projects) Grace Chang Derek Manov	O-SCOPE and MOSEAN	University of California, Santa Barbara (UCSB)	Test bed moorings, data telemetry, interfacing of sensors and systems, optical sensors, anti-biofouling systems
Nick Bates	O-SCOPE	Bermuda Institute of Ocean Sciences (BIOS)	CO_2 sensors and testing, seatruthing
Robert Byrne	O-SCOPE	University of South Florida (USF)	Chemical sensors and systems, seatruthing
Francisco Chavez	O-SCOPE	Monterey Bay Aquarium Research Institute (MBARI)	Test bed moorings, data telemetry, interfacing of sensors and systems, chemical and optical sensors, seatruthing
Richard Feely	O-SCOPE	NOAA Pacific Marine Environmental Laboratory (PMEL)	CO_2 sensors and testing, seatruthing
Alfred Hanson	MOSEAN	SubChem Systems Inc.	Chemical sensors and systems
Dave Karl	MOSEAN	University of Hawaii (UH)	Water samplers, test bed moorings, seatruthing
Casey Moore	O-SCOPE and MOSEAN	WET Labs Inc.	Optical and chemical sensors and systems, data telemetry, interfacing of sensors and systems
Christopher Sabine	MOSEAN	NOAA Pacific Marine Environmental Laboratory (PMEL)	CO_2 sensors and testing, seatruthing
Rik Wanninkhof	O-SCOPE	NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML)	Dissolved oxygen sensors, water samplers, sample preservation, seatruthing

objectives of O-SCOPE and MOSEAN were to improve the variety, quality, cost-effectiveness, and availability of ocean observations using new sensors, systems, and autonomous sampling platforms. O-SCOPE and MOSEAN focused principally on developing and testing new generations of chemical and optically based biological sensors and systems that could collect and telemeter data from virtually all existing in situ sampling platforms. The projects were true partnerships, with full participation and interaction between scientists and engineers from the academic, private laboratory, governmental, and commercial sectors. In this article, we review the O-SCOPE and MOSEAN projects, including background information, methodologies, results, transitions, and the value of the various partnerships to fulfilling our objectives.

OCEAN-SYSTEMS FOR CHEMICAL, OPTICAL, AND PHYSICAL EXPERIMENTS (O-SCOPE)

The O-SCOPE program addressed the need for technologies to quantify the seasonal, interannual, and decadal, as well as high-frequency and episodic, changes in upper ocean biogeochemical and bio-optical variability as driven in part by atmospheric and oceanic dynamics. Some of the primary variables of interest for O-SCOPE were: pH, CO_2 partial pressure (pCO_2), dissolved inorganic carbon (DIC), total alkalinity, dissolved oxygen, water turbidity, chlorophyll, and optical absorption and scattering (for applications including reflectance models for remote sensing of ocean color).

O-SCOPE interdisciplinary sensor suites (e.g., pCO_2 and pH sensors, chemical analyzers, and spectral optical sensors) were tested on three deep-sea moorings: (1) the Bermuda Testbed Mooring (BTM) located about 80 km southeast of Bermuda, (2) the Monterey Bay Aquarium Research Institute (MBARI) M2 mooring in Monterey Bay, CA, and (3) the NOAA Tsunami warning buoy at Ocean Weather Station Papa (OWS "P") in the North Pacific (Figure 1).

Sensor and System Development

An autonomous, in situ instrument called the Spectrophotometric Elemental Analysis System (SEAS; see Figure 2; Byrne et al., 1999, 2002; Kaltenbacher et al., 2001) was continually improved and tested under the auspices of O-SCOPE (Robert Byrne, University of South Florida. *Note:* The names in parentheses in this article indicate principal investigators or those most responsible for the aspect of the research being

Figure 1. Photographs of buoys used during the NOPP O-SCOPE and MOSEAN programs. (Upper left) NOAA tsunami buoy deployed at Ocean Weather Station "P". (Upper right) MBARI M2 buoy off the Monterey, CA, coast. (Lower left) MOSEAN H-A buoy near the Hawaii Ocean Time-series (HOT) site north of Oahu, HI. (Lower right) Bermuda Testbed Mooring (BTM) buoy near the Bermuda Atlantic Time Series (BATS) site. (Center) MOSEAN CHARM buoy off La Conchita, CA.

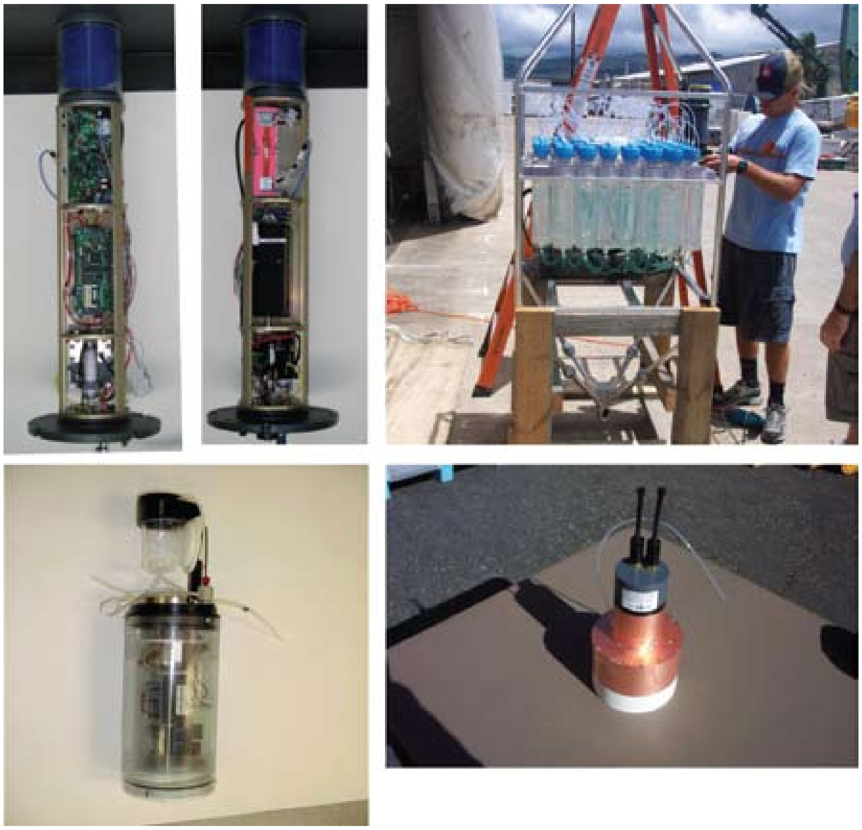

Figure 2. Chemical measurement systems used during the NOPP O-SCOPE and MOSEAN programs. (Upper left) Two views of the MAPCO$_2$ system that was deployed from the MOSEAN H-A buoy. (Upper right) The Remote Access Samplers (RAS) system deployed from the MOSEAN H-A buoy. (Lower left) The Spectrophotometric Elemental Analysis System (SEAS), which was deployed from the NOAA tsunami mooring. (Lower right) The SubChem phosphate analyzer deployed from the MOSEAN CHARM mooring.

discussed.). The current version of SEAS (SEAS II) is capable of measuring both absorbance and fluorescence. SEAS I and SEAS II have been used for in situ quantification of seawater pH (Liu et al., 2006) and nutrients (Adornato et al., 2007). The system autonomously mixes seawater and reagents, and records absorbances at user-defined wavelengths. SEAS II measurements can be obtained using liquid core waveguides or a conventional spectrophotometric cell. The use of liquid core waveguides with long path lengths provides low nanomolar detection limits for a variety of analytes (Adornato et al., 2005). SEAS pH profiles were initially obtained in the South Pacific Ocean to depths of approximately 200 m from January through March of 1996 (Waterbury et al., 1996). SEAS II sampling rates for nutrient and pH measurements are on the order of 1 Hz.

An initial deployment of SEAS I in October 1999 using the OWS “P” NOAA tsunami mooring (Figures 1 and 2) was the first ever for an in situ, autonomous spectrophotometric pH measurement system at sea (Kaltenbacher et al., 2000). Results from laboratory testing and calibration of SEAS II are consistent with a measurement precision of ± 0.001 pH units. Shipboard testing indicates that pH measurements obtained using the spectrophotometric system in both SEAS II and the University of South Florida Multiparameter Inorganic Carbon Analyzer (Wang et al., 2007) agree with conventional shipboard spectrophotometric pH measurements within approximately 0.0012 ± 0.0042 pH units.

A $p\mathrm{CO}_2$ measurement system, first introduced by Friedrich et al. (1995), was further developed and tested as part of O-SCOPE (Francisco Chavez, MBARI). The system, which utilizes a nondispersive infrared spectrometer, measures the difference in CO_2 partial pressure across the air-sea interface ($\Delta p\mathrm{CO}_2$). Major technical advances for the system concerned the development of a new controller board, a new gas inlet system for the $p\mathrm{CO}_2$ sensor, and data telemetry capability. A major breakthrough by the MBARI group was the development of a sensor suite for measuring absolute air and sea surface $p\mathrm{CO}_2$, dissolved oxygen, and nitrate concentrations (see Johnson and Coletti, 2002) in a variety of ocean environments.

Measurements of $p\mathrm{CO}_2$ and $\Delta p\mathrm{CO}_2$ were also made using traditional ship-based analyzers and compared to the MBARI CO_2 system. Other CO_2 systems tested using BTM included a Submersible Autonomous Moored Instrument-CO_2 (SAMI-CO_2; DeGrandpre et al., 2000), a commercial YSI pH sensor, and the Carbon Interface Ocean Atmosphere buoy (CARIOCA) in collaboration with Liliane Merlivat of the University of Paris (Bates et al., 2000). CARIOCA was tethered to BTM for high-temporal-resolution measurements of $p\mathrm{CO}_2$, and its $p\mathrm{CO}_2$ data were determined to be accurate to within ± 3 µatm when compared to the shipboard measurements (Nick Bates, Bermuda Institute of Ocean Sciences).

A dissolved oxygen sensor was tested at OWS "P" in the eastern North Pacific (Rik Wanninkhof, NOAA/AOML). The permeable membrane, pulsed-electrode dissolved oxygen system (Chris Langdon, Rosenstiel School of Marine and Atmospheric Science, University of Miami) was improved to enable long-term deployments in biologically productive waters. Records obtained during the deployments showed a systematic long-term drift that could be corrected by using periodic discrete O_2 samples. As part of this effort, a sample storage scheme for O_2 samples achieved successful sample storage periods of up to four months (Zhang et al., 2002). This storage scheme has been invaluable for validating samples containing dissolved oxygen (O_2) collected with probes situated on buoys and ships of opportunity.

Figure 3. (Top) Optical package used for measuring several inherent and apparent optical properties during the MOSEAN field trials. (Bottom) The WET Labs water quality monitoring (WQM) optical measurement system equipped with special anti-biofouling devices.

Another component of the O-SCOPE project focused on developing bio-optical sensors with improved stability and endurance for operational monitoring and research (Figure 3). These efforts led to the development of modular bio-optical sensor suites for long-term (months to a year or more) and sustained sampling in open and coastal ocean environments (Casey Moore, WET Labs Inc.). The sensor suite included two new open- (or flat-) faced sensors: a chlorophyll fluorometer and a multi-angle scattering sensor for measuring the volume scattering function (VSF) (Moore et al., 2000). Chlorophyll *a* is used as a proxy for phytoplankton biomass; the fluorometric measurement of chlorophyll *a* is based on excitation of the pigment in the blue to blue-green portion of the visible spectrum and the re-emission of energy at 683 nm. The optical scattering sensors were designed to measure scattering from particles at 100, 125, and 140 degrees with respect to the incident light beam's direction. The three-angle measurement provides an improved estimate of the volume scattering function between 90 and 180 degrees and subsequently improved estimates of the total backscattering coefficient. Data and derived parameters can then be used to link particle concentrations in the water to reflectance models used for remote sensing. These instruments also featured new integrated anti-biofouling shutter/wiper assemblies (discussed below) to extend the useful sampling periods (Figure 4).

A new modular servo-controlled anti-biofouling shutter system for open-faced optical sensors was developed and tested on O-SCOPE optical systems (Derek Manov and Tommy Dickey, UCSB; Chavez et al., 2000; Manov et al., 2004). Briefly, a copper shutter, or plate, is used to conceal the optical window of a sensor between sampling periods to reduce biofouling effects; copper is toxic to most microorganisms. The

Figure 4. (Top) Effects of biofouling on a MOSEAN optical package after long-term deployment off the coast of California. (Middle left) Optical sensor and copper shutter system used to mitigate the effects of biofouling. (Middle right) The WET Labs WQM system equipped with special anti-biofouling devices. (Bottom) Copper shutter systems designed and tested during the present NOPP projects to mitigate the effects of biofouling.

shutter is designed to open just prior to sampling and then re-close following measurement collection. The anti-fouling shutter technology has continued to be developed and improved and has proven effective in numerous deployments (e.g., Manov et al., 2004; Barnard, 2004), and through independent verification (Alliance of Coastal Technologies, 2005). For example, over 400 days of radiometric data have been collected in the North Pacific without appreciable biofouling effects (Manov et al., 2004; Honda et al., 2006).

Transitions

One of the central goals of O-SCOPE was to increase the number of interdisciplinary ocean observations by transitioning new technologies to the commercial sector. Project efforts served as a foundation for a product line of fluorescence and scattering sensors (WET Labs ECO series) designed for operational observations, and also for optical systems with integrated biowipers. Collectively, sales of these sensors totaled approximately 2,000 units through 2008. In addition, Satlantic Inc. incorporated the design of the modular copper shutter anti-biofouling system, developed and tested under the O-SCOPE program, into its line of spectral and hyperspectral radiometers (e.g., OCR-500 and HyperOCR series). Interestingly, hyperspectral optical systems, which permit light measurements in roughly 90 wavebands across the visible spectrum (e.g., Dickey, 2004), were developed during our two NOPP projects and utilized for some of our work. Finally, O-SCOPE and NASA support allowed us to demonstrate the concept of moorings-of-opportunity for validation of ocean color remote sensing (Kuwahara et al., 2008).

The MBARI $p\mathrm{CO}_2$ system has been adapted for use by NOAA's Pacific Marine Environmental Laboratory (Christopher Sabine, PMEL) and is being deployed as part of the NOAA sustained observations program (see Figure 2 and http://www.pmel.noaa.gov/co2/moorings/) as a contribution to the Global Ocean Observing System (GOOS). This program, in addition to the O-SCOPE OWS "P" research, marked the beginning of autonomous long-term studies of ocean acidification, carbon uptake, and ocean-atmospheric interactions (Byrne et al., 2006; Feely et al., 2006; Sabine et al., 2008). The low-power MBARI $p\mathrm{CO}_2$ sensor was also used during an NSF-sponsored iron fertilization experiment in the Southern Ocean (Coale et al., 2004) and is routinely deployed in Santa Monica Bay as part of the Southern California Coastal Ocean Observing System (SCCOOS) program. Many researchers used BTM during either or both O-SCOPE and MOSEAN for testing instrumentation and collaborative scientific research (e.g., Ed Boyle, Massachusetts Institute of Technology, trace element sampler and measurements of episodic iron elevations; Ed Sholkovitz, Woods Hole Oceanographic Institution, dust and aerosol sampler and observations of dust events; Maureen Conte, Marine Biological Laboratory and Bermuda Institute of Ocean Sciences, eddy and hurricane-related sediment fluxes). It is worth noting that several hurricanes passed over BTM during the two programs, providing demanding tests of the mooring and its new instrumentation and resulting in unique scientific reports on upper ocean physical and biological responses to tropical storms and hurricanes (e.g., Dickey et al., 2001; Zedler et al., 2002; Babin et al., 2004; Jiang et al., 2007; Black and Dickey, 2008). The value of the partnering aspects of O-SCOPE is underscored by both the advancement of ongoing and the development of new novel technologies. In addition, unexpected episodic, event-scale phenomena involving coupling of physical, biological, bio-optical, and biogeochemical processes, rarely sampled using conventional means, were revealed and quantified via both of our NOPP projects.

MULTIDISCIPLINARY OCEAN SENSORS FOR ENVIRONMENTAL ANALYSES AND NETWORKS (MOSEAN)

The NOPP MOSEAN project built upon several of the successes of the NOPP O-SCOPE project. The main goal of MOSEAN was to develop and test relatively small, lightweight optical and chemical sensors for autonomous deployment on a variety of stationary and mobile platforms. Two primary mooring sites were chosen for MOSEAN activities: (1) MOSEAN HALE-ALOHA (H-A), located in an open ocean oligotrophic environment approximately 100 km north of Oahu, HI, in the North Pacific subtropical gyre, and (2) MOSEAN Santa Barbara (SB) a coastal location in the Santa Barbara Channel. Near-real-time data telemetry system development and testing begun under the O-SCOPE project were continued during the MOSEAN project. Likewise, research to mitigate biofouling of sensors remained a priority and was especially demanding for the coastal component of MOSEAN.

Hawaii (MOSEAN H-A)

The primary MOSEAN H-A deep-sea mooring (Figure 1) was deployed north of the Island of Oahu, HI, in 4755-m water depth at Station Aloha (22°24'N, 158°W). It operated nearly continuously from August 2004 to July 2007 (David Karl, University of Hawaii, and Tommy Dickey, UCSB). Newly developed, commercially available remote access samplers (RAS; see Figure 2) were deployed on the H-A mooring for high-temporal-resolution observations of upper ocean inorganic and organic nutrient concentrations (David Karl). RAS was preprogrammed to collect a 500 mL seawater sample every three days for preservation in situ. Upon retrieval, samples were analyzed for high-sensitivity determinations of nitrate plus nitrite and orthophosphate concentrations. In addition, high-frequency dynamics in total dissolved nitrogen and total dissolved phosphorus concentrations were determined to evaluate short-term variability in inorganic and organic nitrogen and phosphorus availability and stoichiometric ratios.

With NOAA funding, a system for measuring $p\mathrm{CO}_2$ called MAPCO_2 was installed on the H-A mooring (Figures 1 and 2) throughout the deployment (Christopher Sabine, PMEL). The MAPCO_2 system was modified from the original $p\mathrm{CO}_2$ system design and transferred from MBARI to PMEL after development under the O-SCOPE project. With the availability of the H-A mooring platform, PMEL continued the development of the $p\mathrm{CO}_2$ sensor to include a calibration gas and an Iridium satellite transmission system to allow two-way communications between the instrument and the scientists on shore. The current generation of the MAPCO_2 system can be reconfigured remotely to sample a range of temporal scales at any time during the deployment, depending on the conditions observed from the near-real-time data transmissions.

Improvements have also been made in the prevention of biofouling of the

$MAPCO_2$ systems. The portion of the CO_2 sensor that normally sits in the water was originally designed to use copper to prevent biofouling. However, after a year in seawater, a significant fraction of the copper was corroded away. Therefore, new copper alloys were tested on the H-A mooring throughout the MOSEAN project. It was determined that a 70:30 Cu:Ni alloy provided sufficient biofouling protection while virtually eliminating the corrosion problem.

Monthly Hawaii Ocean Time-series (HOT) cruises provided critical seatruth data for all H-A mooring measurements as well as complementary data sets (David Karl). In addition, many other investigators used the MOSEAN H-A mooring to test sensors, systems, and platforms. Instruments tested included gas tension and oxygen sensors (Steve Emerson, University of Washington), trace element sensors (Ed Boyle, MIT), and spectral radiometers (Ricardo Letelier, Oregon State University). The deployment of gliders (Seaglider; Charles Eriksen, University of Washington; see Eriksen and Perry, this issue) during H-A mooring deployment and recovery cruises expanded the spatial coverage in the vicinity of the H-A mooring and served as a model for future integrated sampling systems and observatory initiatives. In addition, WET Labs ECO series instruments (for measurements of chlorophyll *a*, colored dissolved organic matter, and particle backscattering coefficients [ECO3]) were integrated into ProvBioB profiling floats as reported by Le Reste et al. (2009). Eight ProvBioB floats with ECO3s were deployed off Hawaii as well as in the North Atlantic and South Pacific oceans, and the Mediterranean Sea.

Scientific analyses of many of the MOSEAN H-A data are still in progress. For example, one of the events of special interest is the passage of a large, warm eddy over the H-A mooring during August 2005. Ocean color imagery indicates enhanced productivity in the region over the same time period, and the $MAPCO_2$ system recorded a drawdown in surface water pCO_2. Using their glider data sets centered on the H-A mooring, Nicholson et al. (2008) reported that Rossby waves and mesoscale eddies significantly influenced productivity in the deep euphotic layer at the H-A site as isopyncnal surfaces shoaled.

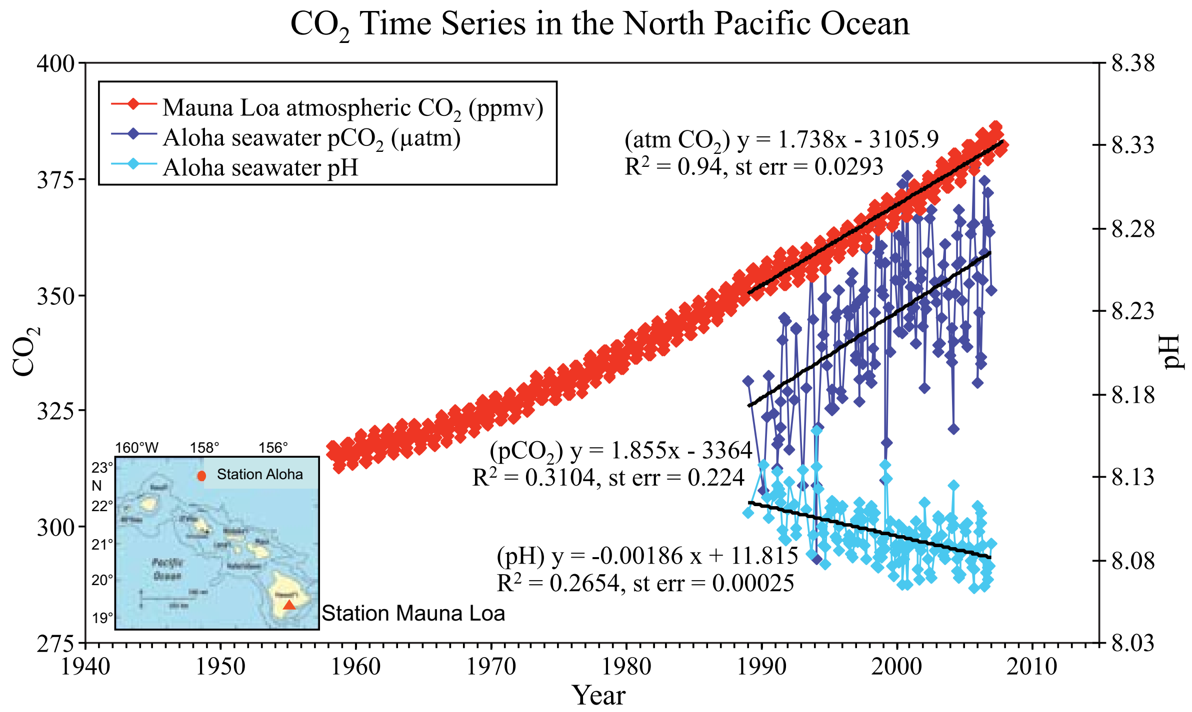

Figure 5. Time series of atmospheric CO_2 at Mauna Loa (ppmv) and surface ocean pH and pCO_2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean. Note that the increase in oceanic CO_2 over the last 17 years is consistent with the atmospheric increase within the statistical limits of the measurements. *Mauna Loa data: Pieter Tans, NOAA/ESRL (http://www.esrl.noaa.gov/gmd/ccgg/trends); HOTS/Aloha data: David Karl, University of Hawaii (http://hahana.soest.hawaii.edu); after Feely, 2008*

The H-A time-series data set has also been used to map the progress of ocean acidification in the Pacific Ocean (Feely, 2008; Doney et al., 2009). Figure 5 shows an average pH decrease of approximately 0.02 units per decade, which is a result of the oceanic uptake of carbon dioxide from fossil fuel burning and other human practices since the beginning of the Industrial Revolution. The pH of ocean surface waters has already decreased by about 0.1 units from an average of about 8.2 to 8.1. This process, which is commonly called "ocean acidification," could have profound impacts on some of the basic chemical and biological processes of the sea in coming decades.

Santa Barbara Channel (MOSEAN SB)

The coastal component of the MOSEAN project (MOSEAN SB) involved deployment of a shallow-water mooring called the CHAnnel Re-locatable Mooring (CHARM; Figure 1), which was located about 2 km offshore of La Conchita, CA, in the Santa Barbara Channel (Tommy Dickey and Grace Chang, UCSB). The site was selected for its variety of coastal ocean events, which includes HABs, storm and river (Ventura River) runoff, and sediment resuspension. The location was also well situated for line-of-sight, real-time data transfer to shore using radio frequency telemetry. Following a pilot CHARM deployment from May to October 2003, seven more deployments of up to about four months duration were completed between February 2004 and May 2007.

Multiparameter chemical and optical sensors and systems were developed through our NOPP partnering, particularly under a collaborative effort between SubChem Systems Inc. (Alfred Hanson) and WET Labs Inc. (Casey Moore), with testing by the University of California, Santa Barbara group (Dickey and Chang, UCSB) using moorings in the Santa Barbara Channel and off Los Angeles. A major impetus for technology development was the need to measure short-term, event-scale as well as longer-term variability in nutrient concentrations and bio-optical variables in the ocean. Thus, a new generation of self-contained, modular, autonomous nutrient analyzers was developed, prototyped, and tested through the MOSEAN program and other funding sources (Hanson and Moore, 2001; Hanson et al., 2006a,b; 2008). The research effort entailed both multichannel, fast-response systems and instruments designed for extended observations. The fast-response nutrient analyzer, called the Autonomous Profiling Nutrient Analyzer (APNA; Figure 6), was designed for deployment on a variety of moving platforms, including ship-deployed conductivity-temperature-depth (CTD) profilers, autonomous profilers, and AUVs. The latter efforts culminated in a production prototype sensor for long-term monitoring of phosphate in coastal and oceanic environments (Zaneveld et al., 2007). The instrument combines 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 (2008). Important steps in developing these chemical systems included reduction of size and power requirements of the electro-fluidic components to match the electro-optical detectors, extension of reagent preservation time scales to enable multimonth deployments, and development and validation of anti-biofouling strategies for multimonth deployments.

The CHARM mooring was used to test a variety of optical and chemical sensors and associated anti-biofouling approaches. Optical sensors developed and tested during the MOSEAN project included: (1) a hyperspectral absorption-attenuation meter (WET Labs Inc. ac-s) for measuring absorption, attenuation, and scattering (by difference) coefficients at ~ 4 nm wavelength resolution in the visible spectrum; (2) multispectral backscattering sensors to quantify the backscattering coefficient in situ at up to nine wavelengths; (3) a spectral excitation/emission fluorometer for measuring concentrations of chlorophyll, colored dissolved organic matter (CDOM), and phycoerythrin; (4) spectral fluorescence sensors incorporating anti-biofouling wiper technologies; and (5) stand-alone nutrient sensors for use during extended deployments.

The MOSEAN project provided a means to develop biofouling mitigation strategies beyond copper shutters. Development efforts for the biowiper, begun during the O-SCOPE project, continued to advance the technology. The newer design uses a coupled copper shutter and face plate not only to protect a flat-faced optical window but also to wipe it clean of any biofilm just prior to sampling. Other anti-biofouling strategies, including air purge and bleach injection, were developed and tested for use in flow-through optical systems. Between samples, flow-through tubes are evacuated with a pulse of oxygen gas by use of an electronic valve system

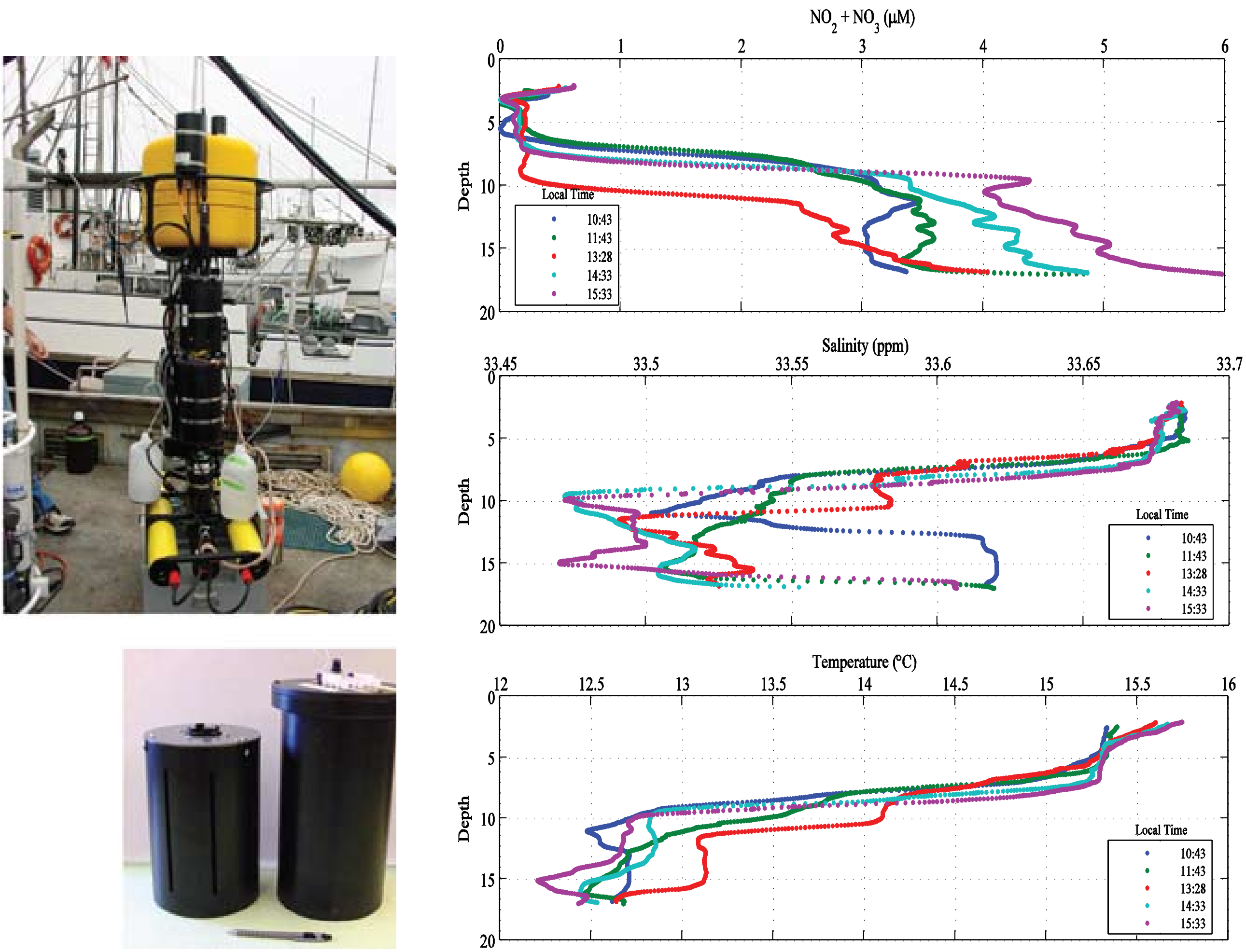

Figure 6. The APNA nutrient analyzer payload (lower left) ready for deployment on the University of Rhode Island (URI) profiler (both developed with NOPP funding) in Monterey Bay (upper left) from R/V *Shana Rae* and examples of hourly profiles for nitrate (top right), salinity (middle right), and temperature (lower right) that were obtained autonomously with the system in Monterey Bay. The URI instrument is an autonomous, battery-operated, moored profiler that can be deployed in the coastal ocean for weeks at a time. It contains a full suite of instruments and sensors for monitoring the physical, optical, biological, and chemical properties of the water. The profiler can be programmed to make repeated profiles from the bottom to the surface on a pre-set time schedule, to send the multiparametric results by radio telemetry to a shore- or ship-based receiver station, and then to return to the bottom to await the start time for the next profile.

or injected with a low concentration of bleach to retard biological growth. The bleach injection system is now routinely used for the WET Labs Inc. water quality monitoring (WQM) sensor system (Figures 3 and 4). A prototype SubChem phosphate analyzer (Figure 2) was also tested using the CHARM mooring. Many of the chemical and bio-optical sensors and systems developed through MOSEAN are now commercially available and are enabling researchers and managers to utilize the new technologies to address scientific and societal problems. Partnering between the commercial and academic elements was critical to the success of this aspect of MOSEAN.

In addition to offering an invaluable test bed platform for advancing sensor technologies for coastal applications, the CHARM mooring provided a base for other observational efforts. Scientific problems of interest for the CHARM site have included: (1) optical and chemical detection and characterization of HABs, (2) quantifying particulate dynamics through optics, and (3) determining effects of physical processes on chemical and bio-optical properties. Several significant HAB events occurred during the MOSEAN CHARM experiment. For example, there were multiple *Pseudo-nitzschia australis* blooms accompanied by toxic domoic acid events and sea lion and dolphin beachings, and bioluminescent red tides of *Lingulodinium polyedra* that resulted in anoxia and a massive fish kill in Ventura Harbor. Hyperspectral optical property measurements and analyses indicate that *P. australis* is virtually indistinguishable from other phytoplankton communities using satellite ocean color data. However, *L. polyedra* exhibits a distinctive remote-sensing signal, which could be used to synoptically monitor red tide events off the southern California coast.

Relationships among and variability of bio-optical properties at the MOSEAN CHARM site were investigated. It was determined that water masses were biogeochemically complex and highly variable; optical water types changed rapidly from relatively clear and dominated by biogenic particles to extremely turbid with high concentrations of inorganic particles (Chang et al., 2006). The complexity of coastal regions such as the CHARM site limits the use of traditional remote-sensing algorithms to synoptically monitor particle and ecosystem dynamics. However, recent work by author Chang and Amanda Whitmire, Oregon State University, shows that accurate remote-sensing inversions used to derive information about ocean biogeochemistry are highly dependent on in situ particle type and size and that marked improvements to remote derivations are possible. For example, a priori knowledge of the backscattering and/or diffuse attenuation coefficient at one wavelength can improve estimates of absorption and backscattering by more than 50%. Additionally, an optical water-type classification method, the spectral angle mapper, was successfully employed to distinguish turbid, inorganic waters from ambient conditions (Chang et al., 2006). Finally, Chang and Whitmire (2009) used CHARM data to model the effects of bulk particle scattering characteristics on backscattering and optical closure. These collective methods and results should be useful for improving interpretation, application, and modeling of ocean color remote-sensing data in complex coastal waters.

SUMMARY

The NOPP-sponsored O-SCOPE and MOSEAN projects built upon previous and ongoing technological work. Some aspects of these projects resulted in modest extensions of existing technologies whereas others resulted in clear breakthroughs. Sensor and system testing was an essential element of both projects and several scientific advances were enabled by the studies, thanks to the novel measurements acquired. To summarize, O-SCOPE and MOSEAN achieved the following:

1. These projects were used to successfully develop and test new compact, energy-efficient sensors and systems for autonomous measurements of biological, chemical, and optical parameters. In particular, O-SCOPE and MOSEAN chemical sensors and systems included water samplers as well as spectrophotometric elemental, pulsed-membrane, colorimetric, and microfluidic/fluorometric technologies. Optical technologies developed as part of the NOPP programs included fluorescence and turbidity meters, multispectral and multi-angle scattering and backscattering sensors, a hyperspectral absorption-attenuation meter, and spectral fluorescence sensors. These advances, along with improved water storage and validation techniques, enable accurate in situ and remote observations and estimates of a wide variety of biogeochemical parameters, for example, inorganic and organic particles such as phytoplankton and HABs.
2. New technologies were developed to effectively mitigate biofouling of optical and chemical sensors to enable long-term coastal and open-ocean deployments. In particular, copper shutters and biowipers are now commercially available for a number of open- or flat-faced optical sensors, and bleach injection systems are used for the commercialized WQM (WET Labs Inc.). O-SCOPE and MOSEAN systems were deployed and tested for several months to a year on moorings in a wide variety of environmental conditions, thereby ensuring robust hardware and high data integrity.
3. Several of the O-SCOPE and MOSEAN systems have now been used on moorings, AUVs, gliders, and profiling floats as evidenced in other NOPP papers in this issue. Near-real-time data telemetry systems were developed, tested, and effectively used during our field studies in both open-ocean and coastal waters.
4. The concept of "moorings of opportunity" was validated using a NOAA tsunami warning mooring at OWS "P"; in addition, this effort resulted in the first high-temporal-resolution time-series measurements relevant to the problem of ocean acidification. This work has been continued by a separate group, led by Steve Emerson, University of Washington, through a subsequent National Science Foundation-sponsored effort at the same site.

5. Importantly, several of the measurement and anti-biofouling systems have been transitioned to the commercial, government, and academic sectors, and numerous oceanographic researchers, including NOPP-funded scientists, have already benefited from the sensors and systems originated or advanced by the O-SCOPE and MOSEAN projects.

Both programs also produced important value-added scientific results that demonstrate the utility of these new technologies. The NOPP framework fostered strong collaborations among academic, commercial, and government entities, and accelerated technology transfers to the general research community and long-term observational and observatory programs. Thanks to NOPP and other similar programs, oceanographers are closer to realizing the dream of multiscale, multidisciplinary, sustained observations of the ocean environment.

ACKNOWLEDGEMENTS

Support by NOPP (award numbers N00014-98-1-0803, N00014-02-1-0941, and OCE-0338434 to TDD) is gratefully acknowledged. Tommy Dickey also received support through a Secretary of the Navy/Chief of Naval Operations Chair in Oceanographic Science and from the National Science Foundation, Office of Naval Research, and the National Aeronautic and Space Administration for his interdisciplinary mooring activities. Additional support for David Karl's work was provided by the Gordon and Betty Moore Foundation. We wish to thank the following program managers for their assistance and support during O-SCOPE and MOSEAN: Reginald Beach, Kandace Binkley, Cynthia Decker, Jim Eckman, Alexandra Isern, and Jerry Miller. Many thanks to the crews of R/Vs *Ron Brown*, *Kaimikai-O-Kanaloa*, *Kilo Moana*, *Robert Gordon Sproul*, and *Weatherbird II*. Special thanks to the many individuals who contributed to the technical and scientific successes of our projects: Amanda Ashe, Andrew Barnard, Robert Bidigare, Ed Boyle, James Case, Robert Castle, Matt Church, Cathy Cosca, Maureen Conte, Alex Derr, Andrew Dickson, Scott Doney, Jim Dunn, Peter Egli, Steve Emerson, Charlie Eriksen, Gernot Friedrich, Songnian Jiang, Cyril Johnson, Erik Kaltenbacher, John Kemp, Victor Kuwahara, Matt Levin, Ricardo Letelier, Jeff Lord, Stacy Maenner, Jason Masters, Mike McPhaden, Scott McLean, Hugh Milburn, Francesco Nencioli, Cristina Orrico, Esa Peltola, Dave Romanko, Jim Ryder, Dan Sadler, Jorge Sarmiento, Wesley Strubhar, Ed Sholkovitz, Frank Spada, Charles Stump, Chantal Swan, Blake Watkins, Amanda Whitmire, John Ye, and Ron Zaneveld. Two anonymous reviewers and the editors of this issue are thanked for their efforts in improving this contribution.

REFERENCES

Adornato, L.R., E.A. Kaltenbacher, D.R. Greenhow, and R.H. Byrne. 2007. High-resolution in situ analysis of nitrate and phosphate in the oligotrophic ocean. *Environmental Science and Technology* 41:4,045–4,052.

Adornato, L.R., E.A. Kaltenbacher, T.A. Villareal, and R.H. Byrne. 2005. Continuous in situ determinations of nitrite at nanomolar concentrations. *Deep-Sea Research I* 52:543–551.

Alliance of Coastal Technologies (ACT). 2005. Detailed testing protocols for verifying the performance of in situ chlorophyll fluorometers. *Alliance of Coastal Technologies*. Available online at: http://www.act-us.info/evaluation_reports.php (accessed March 7, 2009).

Alliance of Coastal Technologies (ACT). 2008. Performance demonstration WET Labs Cycle-P nutrient analyzer, ACT TD08-03. Available online at: http://www.act-us.info/evaluation_reports.php (accessed March 7, 2009).

Babin, S.M., J.A. Carton, T.D. Dickey, and J.D. Wiggert. 2004. Satellite evidence of hurricane-induced plankton blooms in the ocean desert. *Journal of Geophysical Research* 109(C3):C03043, doi:1029/2003JC001938.

Barnard, A. 2004. Biofouling prevention of bio-optical sensors: Data from long-term ocean deployments. *Eos, Transactions, American Geophysical Union* 84(52), Fall Meeting Supplement, Abstract OS32E-03.

Bates, N.R., L. Merlivat, L. Beaumont, and C. Peguinet. 2000. Intercomparison of shipboard and moored CARIOCA buoy seawater fCO_2 measurements in the Sargasso Sea. *Marine Chemistry* 72:239–255.

Black, W.J., and T.D. Dickey. 2008. Observations and analyses of upper ocean responses to tropical storms and hurricanes in the vicinity of Bermuda. *Journal of Geophysical Research*, doi:10.1029/2007JC004358.

Byrne, R.H., X. Liu, E.A. Kaltenbacher, and K. Sell. 2002. Spectrophotometric measurement of total inorganic carbon in aqueous solutions using a liquid core waveguide. *Analytica Chimica Acta* 451:221–229.

Byrne, R.H., E. Kaltenbacher, and R. Waterbury. 1999. Autonomous in-situ analysis of the upper ocean. *Sea Technology* 40(2):4.

Byrne, R.H., X. Liu, S. Mecking, and R.A. Feely. 2006. Acidification of the North Pacific Ocean: Direct observations of pH in 1991 and 2006. *Eos, Transactions, American Geophysical Union* 87(52), Fall Meet. Suppl., Abstract OS21C-1598.

Chang, G., and A.L. Whitmire. 2009. Effects of bulk particle characteristics on backscattering and optical closure. *Optics Express* 17(4):2,132–2,142.

Chang, G.C., A.H. Barnard, S. McLean, P.J. Egli, C. Moore, J.R.V. Zaneveld, T.D. Dickey, and A. Hanson. 2006. *In situ* optical variability and relationships in the Santa Barbara Channel: Implications for remote sensing. *Applied Optics* 45:3,593–3,604.

Chavez, F.P., D. Wright, R. Herlien, M. Kelley, F. Shane, and P.G. Strutton. 2000. A device for protecting moored spectroradiometers from bio-fouling. *Journal of Atmospheric and Oceanic Technology* 17:215–219.

Coale, K.H., K.S. Johnson, F.P. Chavez, K.O. Buesseler, R.T. Barber, M.A. Brzezinski, W.P. Cochlan, F.J. Millero, P.G. Falkowski, J.E. Bauer, and others. 2004. Southern Ocean iron enrichment experiment: Carbon cycling in high- and low-Si waters. *Science* 304:408–414.

Daly, K.L., R.H. Byrne, A.G. Dickson, S.M. Gallager, M.J. Perry, and M.K. Tivey. 2004. Chemical and biological sensors for time-series research: Current status and new directions. *Marine Technology Society Journal* 38(2):121–139.

DeGrandpre, M.D., M.M. Baehr, and T.R. Hamma. 2000. Development of an optical chemical sensor for oceanographic applications: The submersible autonomous moored instrument for seawater CO_2. Pp. 123–141 in *Chemical Sensors in Oceanography*. M.S. Varney, ed., Gordon and Breach Publishers.

Dickey, T. 1991. The emergence of concurrent high resolution physical and bio-optical measurements in the upper ocean and their applications. *Reviews of Geophysics* 29:383–413.

Dickey, T. 2003. Emerging ocean observations for interdisciplinary data assimilation systems. *Journal of Marine Systems* 40–41:5–48.

Dickey, T. 2004. Studies of coastal ocean dynamics and processes using emerging optical technologies. *Oceanography* 17(2):9–13.

Dickey, T.D., and R.R. Bidigare. 2005. Interdisciplinary oceanographic observations: The wave of the future. *Scientia Marina* 69(Suppl. 1):23–42.

Dickey, T.D., E.C. Itsweire, M. Moline, and M.J. Perry. 2008. Introduction to the special issue on Autonomous and Lagrangian Platforms and Sensors (ALPS). *Limnology and Oceanography* 53:2,057–2,061.

Dickey, T.D., M.R. Lewis, and G.C. Chang. 2006. Optical oceanography: Recent advances and future directions using global remote sensing and *in situ* observations. *Reviews of Geophysics* 44: RG 1001, doi:10.1029/2003RG000148.

Dickey, T., S. Zedler, D. Frye, H. Jannasch, D. Manov, D. Sigurdson, J.D. McNeil, L. Dobeck, X. Yu, T. Gilboy, and others. 2001. Physical and biogeochemical variability from hours to years at the Bermuda Testbed Mooring site: June 1994–March 1998. *Deep-Sea Research II* 48:2,105–2,140.

Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas. 2009. Ocean acidification: The other CO_2 problem. *Annual Review of Marine Science* 1:169–192, doi:10.1146/annurev.marine.010908.163834.

Feely, R.A. 2008. Ocean acidification. Pp. S58 in *State of the Climate in 2007*. D.H. Levinson and J.H. Lawrimore, eds., *Bulletin of the American Meteorological Society* 89(7). Available online at: http://www.ncdc.noaa.gov/oa/climate/research/2007/ann/bams/chapter-3-oceans.pdf (accessed March 7, 2009).

Feely, R.A., C.L. Sabine, R.H. Byrne, and D. Greeley. 2006. Direct evidence for ocean acidification of the North Pacific Ocean. *Eos, Transactions, American Geophysical Union* 87(52), Fall Meeting Supplement, Abstract OS12B-04.

Friedrich, G.E., P.G. Brewer, R. Herlien, and F.P. Chavez. 1995. Measurement of sea surface partial pressure of CO_2 from a moored buoy. *Deep-Sea Research I* 42:1,175–1,186.

Glenn, S., and T. Dickey, eds. 2003. *SCOTS: Scientific Cabled Observatories for Time Series*. NSF Ocean Observatories Initiative Workshop Report, Portsmouth, VA, 80 pp. Available online at: http://www.geo-prose.com/pdfs/scots_rpt.pdf (accessed March 24, 2009).

Hanson, A.K., and C. Moore. 2001. Real-time nutrient surveys in coastal waters. *Sea Technology* 42:10–14.

Hanson, A., E. Morin, S. Veitch, P. Egli, P. Donaghay, C. Moore, and R. Arrieta. 2006. Transitioning submersible chemical analyzer technologies for sustained, autonomous observations from profiling moorings, gliders and other AUVs. *Eos, Transactions, American Geophysical Union* 87(36), Fall Meeting Supplement, Abstract OS54A-02.

Hanson, A., P. Egli, R. Sweetman, D. Katz, and P. Donaghay. 2006. The role of nutrient gradients in the episodic formation of thin plankton layers in Monterey Bay, CA. *Eos, Transactions, American Geophysical Union* 87(36), Fall Meeting Supplement, Abstract OS34M-01.

Hanson, A., P. Egli, R. Sweetman, S. Veitch, and P. Donaghay. 2008. The role of nutrient gradients in the episodic formation of thin plankton layers in Monterey Bay, CA. Pp. 152–153 in *2008 Ocean Sciences Meeting Abstracts*. Available online at: http://www.aslo.org/orlando2008/files.html (accessed March 19, 2009).

Honda, M.C., H. Kawakami, K. Sasaoka, S. Watanabe, and T. Dickey. 2006. Quick transport of primary produced organic carbon to the ocean interior. *Geophysical Research Letters* 33:L166603, doi:10.1029/2006GL026466.

Jiang, S., T. Dickey, D. Steinberg, and L. Madin. 2007. Temporal variability of zooplankton biomass from ADCP backscatter time series data at the Bermuda Testbed Mooring Site. *Deep Sea Research I* 54:608–636.

Johnson, K.S., and L.J. Coletti. 2002. In situ ultraviolet spectrophotometry for high resolution and long term monitoring of nitrate, bromide, and bisulfide in the ocean. *Deep-Sea Research I* 49:1,291–1,305.

Kaltenbacher, E.A., R.H. Byrne, and E.T. Steimle. 2001. Design and application of a chemical sensor compatible with autonomous ocean-sampling networks. *IEEE Journal of Oceanic Engineering* 26(4):667–670.

Kaltenbacher, E., E.T. Steimle, and R.H. Byrne. 2000. A compact, in-situ spectrophotometric sensor for aqueous environments: Design and applications. Pp. 41–45 in *Proceedings of Underwater Technology.* May 23–26, Tokyo, Japan.

Kuwahara V., G. Chang, X. Zheng, T. Dickey, and S. Jiang. 2008. Optical moorings-of-opportunity for validation of ocean color satellites. *Journal of Oceanography* 64:691–703.

Le Reste, S., X. Andre, H. Claustre, F. D'Ortenzio, and A. Poteau. 2009. First success of ProvBio floats. *Coriolis* no. 5, January 2009: 6–8. Available online at: http://www.ifremer.fr/coriolis/ (accessed March 19, 2009).

Liu, X., Z. Wang, R.H. Byrne, E.A. Kaltenbacher, and R.E. Bernstein. 2006. Spectrophotometric measurements of pH *in-situ*: Laboratory and field evaluations of instrumental performance. *Environmental Science and Technology* 40:5,036–5,044.

Manov, D.V., G.C. Chang, and T.D. Dickey. 2004. Methods for reducing biofouling of moored optical sensors. *Journal of Atmospheric and Oceanic Technology* 21:958–968.

Moore, C., M.S. Twardowski, and J.R.V. Zaneveld. 2000. The ECO VSF—A multi-angle scattering sensor for determination of the volume scattering function in the backward direction. In *Proceedings of Ocean Optics XV*. October 16–20, Monaco.

Nicholson, D., S. Emerson, and C.C. Eriksen. 2008. Net community production in the deep euphotic of the subtropical North Pacific gyre from glider surveys. *Limnology and Oceanography* 53:2,226–2,236.

Sabine, C.L., R.A. Feely, F.J. Millero, A.G. Dickson, C. Langdon, S. Mecking, and D. Greeley. 2008. Decadal changes in Pacific carbon. *Journal of Geophysical Research* 113, C07021, doi:10.1029/2007JC004577.

Schofield, O., and M.K. Tivey. 2004. Building a window to the sea: Ocean Research Interactive Observing Networks (ORION). *Oceanography* 17(2):105–111. Available online at http://www.tos.org/oceanography/issues/issue_archive/17_2.html (accessed March 7, 2009).

Stommel, H. 1989. The Slocum mission. *Oceanography* 2(1):22–25. Available online at: http://www.tos.org/oceanography/issues/issue_archive/2_1.html (accessed March 7, 2009).

Tokar, J.M., and T.D. Dickey. 2000. Chemical sensor technology in current and future applications. Pp. 303–329 in *Chemical Sensors in Oceanography*. M.S. Varney, ed., Gordon and Breach Publishers, Amsterdam.

Varney, M.S., ed. 2000. *Chemical Sensors in Oceanography*. Gordon and Breach Publishers, Amsterdam.

Wang, A.W., X. Liu, R.H. Byrne, R. Wanninkhof, R.E. Bernstein, E.A. Kaltenbacher, and J. Patten. 2007. Simultaneous spectrophotometric flow-through measurements of pH, carbon dioxide fugacity, and total inorganic carbon in seawater. *Analytica Chimica Acta* 596:23–36.

Waterbury, R.D., R.H. Byrne, J. Kelly, B. Leader, S. McElligott, and R. Russell. 1996. Development of an underwater in-situ spectrophotometric sensor for seawater pH. Pp. 170–177 in *SPIE—The International Society for Optical Engineering; Proceedings Volume 2836.* Denver, Colorado; August 1996.

Zaneveld, J.R.V., M. Levin, A. Barnard, J. Koegler, I. Walsh, C. Moore, A. Hanson, P. Egli, T.K. Gregory, and R. Morrison, 2007. An underwater reagent based sensor for long-term deployments. Paper presented at ASLO 2007 Aquatic Sciences Meeting, February 4–9, 2007, Santa Fe, NM.

Zedler, S.E., T.D. Dickey, S.C. Doney, J.F. Price, X. Yu, and G.L. Mellor. 2002. Analysis and simulations of the upper ocean's response to Hurricane Felix at the Bermuda Testbed Mooring site: August 13-23, 1995. *Journal of Geophysical Research* 107(12), doi:10.1029/2001JC00969,2002.

Zhang, J.-Z., G. Berberian, and R. Wanninkhof. 2002. Long-term storage of natural water samples for dissolved oxygen determination. *Water Research* 36/16:4,001–4,004.