New Sensors Monitor Bio-Optical/ Biogeochemical Ocean Changes

NOPP O-SCOPE Project Develops Systems for Long-Term Research and Monitoring for the Oceanographic Community

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There is increasing interest in obtaining nearly continuous interdisciplinary observations of the ocean on regional to global scales.[1] The infrastructures for such observations are developing rapidly and will include dedicated ocean observatories and ocean observing systems that will capitalize on moorings, autonomous underwater vehicles, gliders, drifters, profiling floats, fiber optic and electromagnetic cables, and satellites to facilitate studies of high-frequency, episodic, seasonal, interannual, decadal and climate scale phenomena on several spatial scales.[2] These infrastructures will rely heavily on the ability to sense and observe the ocean using these advanced assets.

The Ocean-Systems for Chemical, Optical and Physical Experiment (O-SCOPE) project, sponsored by the National Oceanographic Partnership Program (NOPP), was conceived to develop and test advanced interdisciplinary ocean sensors that will be utilized on a variety of ocean platforms that will be elements of oceanographic observing systems[3] and thus contribute to ocean infrastructures such as those recently described by Koblinsky and Smith[4] and Clark.[2] O-SCOPE researchers and engineers from academic institutions, government agencies and private companies formed a partnership in 1997 to specifically address the need for autonomous real-time interdisciplinary long-term time series measurements in critical regions of the world oceans.

(Above) Bermuda Testbed Mooring buoy.

(Right) Tsunami warning buoy (PMEL) used for NOPP O-SCOPE.

For example, coastal ocean environments are well known to be under increasing stress. Monitoring of the state of coastal waters requires measurements of key indicators of ocean water quality. Bio-optical sensors show great promise for measuring some of these parameters to indicate occurrences of increasing water turbidity, eutrophication, harmful algal blooms (red tides) and near-surface trapping of heat.[5] Biogeochemical sensors are also becoming highly valued as they are needed, along with bio-optical sensors, to monitor causes and effects of global climate change and the ocean's capability to act as a sink for CO_2 and other greenhouse gases and heat.[6-9]

At present, high temporal resolution ocean measurements of important bio-optical and biogeochemical variables relevant to coastal water quality and global climate change are being made only sporadically, except at a very few sites. There exists a critical need to systematically obtain high-resolution, long-term, interdisciplinary oceanographic data analogous to current atmospheric studies such as the Mauna Loa atmospheric CO_2 time series.[10] In particular, autonomous measurements of CO_2, bio-optical and biogeochemical variables are required to observe ocean processes that span over 10 orders of magnitude in time and space.[6,7] Such measurements will ultimately be required from a variety of oceanographic platforms including ships, moorings, drifters, profiling floats, autonomous underwater vehicles (AUVs), gliders and satellites.[11]

The general objective of O-SCOPE was to improve the variety, quantity, quality and cost-effectiveness of interdisciplinary observations[3] in anticipation of a global ocean observing network of strategically placed moorings and other platforms.[7,12] Basic program goals were to:

- identify key variables to be measured, determine capabilities and limitations of available sensors, and define specifications for next-generation sensors
- design, develop and test integrated interdisciplinary sampling systems and technologies for biogeochemical, bio-optical and physical measurements (e.g., low-cost, easily deployed, reliable, robust)
- design a testbed mooring program (e.g., deployment scheduling, sampling rates, instrument placement depths)
- deploy next-generation interdisciplinary instrument suites on three testbed moorings
- evaluate the performances of new instrumentation and telemetry systems.

Related scientific goals to the development of the proposed technologies included quantifying trends in biogeochemical and bio-optical variables which could be caused by major changes in the ocean's thermohaline circulation and seasonal, interannual and decadal changes in upper ocean bio-optical and biogeochemical variables including carbon fluxes and monitoring trends in ocean health in the form of chemical, biological and optical indicators.

Instrument Development Effort

Within the project, the four primary instrumentation development and testing activities included:

- next-generation biogeochemical sensors (e.g., CO_2 and dissolved O_2)
- a long-path spectrophotometer for determination of pH and several other biogeochemical parameters
- a miniaturized bio-optical sensor and sensor suites
- methods for reducing the adverse effects of biofouling on instrumentation.

The instrumentation resulting from these efforts was tested using three primary moorings: the Bermuda Testbed Mooring (BTM) located 80 kilometers off Bermuda at 32N, 64W (4,530 meters depth), the National Oceanic and Atmospheric Administration (NOAA) Tsunami Warning Mooring at Ocean Weather Station P (OWS P) in the North Pacific at 50N 145W (4,020 meters depth) and the Monterey Bay Aquarium Research Institute (MBARI) M1 Mooring in Monterey Bay at 37N 122W.[3] Over the course of the project, extensive sea-truthing and other sensor verification efforts were conducted by NOPP investigators at each of these sites.

The project objectives placed a common set of requirements upon all of the sensor developmental groups. The sensors and sensor suites needed to be capable of being installed on existing mooring platforms with minimum interference with other instrumentation, operate autonomously for at least three to six months per deployment with sampling intervals of less than one hour, provide stable measurements over several months without experiencing measurement data quality degradation and operate in the ocean environment with minimal fouling or other environmentally related degradation.

MBARI CO_2 Analyzer. A partial pressure of CO_2 (pCO_2) measurement system that was developed by Gernot Friederich and Francisco Chavez prior to this effort[13] was redesigned and upgraded to meet some of the challenges for the deployments during O-SCOPE. Major technical advances included the development of a new controller board, a new gas inlet system for the pCO_2 sensor and data telemetry capability. Analyses of data collected with these systems have demonstrated their effectiveness under a variety of oceanic conditions. In particular, the most recent testing at the BTM site has led to results suggesting that the usual summertime sea surface CO_2 supersaturation was interrupted during most of July 2000 when pCO_2 returned to near-atmospheric values. The pCO_2 decrease may have been coupled with a regional cooling event. In autumn, temperature and pCO_2 decreased concurrently. The instruments functioned for the full duration of both BTM deployments, and the results from the MBARI M1 site demonstrate that a service interval of one year can be achieved routinely for this apparatus. While these instruments were deployed, development of a new low-power, low-cost pCO_2 instrument was initiated. The MBARI group also contributed to the development of new O-SCOPE anti-biofouling mechanisms.


Monterey Bay Aquarium Research Institute buoy.

USF SEAS. An autonomous *in-situ* Spectrophotometric Elemental Analysis System (SEAS) for measurement of seawater pH and other variables from ocean moorings was developed by Bob Byrne and Eric Kalten-bacher.[14,15] Seawater pH and pCO_2 are closely linked, and pH can be used to quantitatively relate pCO_2, dissolved inorganic carbon (DIC) and total alkalinity. SEAS is configured for measurements of seawater pH using pH-sensitive indicator dyes. The system autonomously mixes seawater and indicator dye, records absorbances within the liquid core waveguide at three wavelengths and, through external electronics, communicates to shore-based facilities via the Geo-stationary Operational Environmental Satellite (GOES) system. Prior to deployment at sea, laboratory pH comparisons involving SEAS and conventional spectrometers indicated agreement to within 0.008 pH units.

"The NOPP O-SCOPE project and associated development efforts resulted in several transitions leading to broader use of bio-optical and biogeochemical measurements."

The deployment of the SEAS sensor on the NOPP OWS P mooring was the first deployment of an autonomous spectrophotometric pH measurement system at sea.[16] Subsequent to the OWS P mooring deployment, technical advances, including improved lamp intensity at short wavelengths and continuous monitoring of spectrophotometer dark currents, have substantially improved the precision and accuracy of SEAS pH measurements. Comparisons between SEAS and conventional spectrophotometric pH measurements are approaching agreement to within 0.001 pH units.

AOML Dissolved Oxygen Sensor. A second-generation permeable membrane pulsed electrode dissolved O_2 system built by Chris Langdon (LDEO) was utilized and tested by O-SCOPE partner, Rik Wannikhof. Dissolved O_2 measurements require high sampling frequency; however, problems of instrument drift and storage and calibration of oxygen samples have long plagued researchers. Attributes of the new sensor enabled longer-term deployments in biologically productive waters. New probes were tested on the BTM and during cruises using a shipboard system. Results showed excellent agreement between the BTM and ship-based data sets. For complementary O_2 sensor testing, a new sample storage scheme was also developed with successful storage periods of up to four months. An autonomous water sampler (36 samples) was also tested and used to evaluate the stability of CO_2, O_2 and nutrient samples.

UCSB/WET Labs Optical Sensor Package. Tommy Dickey and Derek Manov teamed with Casey Moore and WET Labs Inc. engineers to develop new bio-optical sensors and sensor suites. WET Labs developed a modular sensor suite for bio-optical sampling for extended deployments. These include two new sensors a chlorophyll fluorometer and a multi-angle scattering (volume scattering function or VSF) sensor. The instruments also featured new integrated anti-biofouling shutters for use in long-term deployments. The fluorometer enables the user to monitor chlorophyll fluorescence, which can subsequently be used to model changes in primary biological productivity. The optical scattering sensor concurrently measures scattering from particles at 100°, 125° and 140° with respect to the incident light beam. Through interpolation, specific angles of scattering can then be matched to reflectance models used for remote sensing of ocean color. UCSB incorporated the WET Labs sensors with radiometers developed by Satlantic Ltd. into novel integrated optical sensor systems for mooring deployments. An external copper shutter design for biofouling protection was developed by UCSB as part of O-SCOPE; the system was inspired by one described by Chavez et al.[17] The new servo-controlled copper anti-biofouling shutters were engineered for the radiometers and successfully tested at two of the NOPP sites. The first suite of sensors was deployed at the NOPP OWS P site in October 1999. A three-wavelength surface radiometer and another deployed at seven-meters depth were sampled once per hour; a digital data stream was stored in memory. The radiometer systems were connected by cable to the NOPP buoy's data loggers. Once per day the radiometer sensor system was successfully interrogated by the PMEL surface data telemetry system for subsequent data transmission by the GOES satellite system. A near real-time data archive was then generated for the O-SCOPE and PMEL websites. An identical sensor suite and logging system was deployed at 15 meters. Using the BTM, UCSB deployed systems to measure surface irradiance and radiance at seven meters and 15 meters along with WET Labs fluorometers and three-angle backscatter sensors. The final 120-day O-SCOPE BTM deployment, and a more recent 400-day deployment of the bio-optical sensor suite from a mooring off Japan both indicate high fidelity and little signal degradation due to biofouling.

Data Telemetry and Distribution

Most of the systems described above have data telemetry capabilities. Some of the data sets were distributed in near real-time using a website (www.pmel.noaa.gov/oscope/) developed by Dick Feely and Cathy Cosca; other O-SCOPE and complementary data were accessible through this website. The NOPP data were combined with historical data to determine the increase of DIC over time. The DIC increase in the mixed layer near OWS P is consistent with the atmospheric increase over the same region.

Field Verification Activities

The focus of the present report is upon the new sensors and systems developed during O-SCOPE. However, field verification of resulting data sets was essential at each of the three sites.[3] Shipboard intercomparative sampling was done for variables sampled autonomously from the moorings, and multiple moored sampling systems were utilized in some cases. Remote sensing data sets were also used to provide spatial context and intercomparisons with *in-situ* ocean color measurements.

Transitioning of Technologies

The NOPP O-SCOPE project and associated development efforts resulted in several transitions leading to broader use of bio-optical and biogeochemical measurements. These included:

- Newly developed instrumentation were deployed on the NOAA Tsunami Warning System Mooring located at OWS P in the Pacific and two NOAA Tropical Atmosphere-Ocean (TAO) moorings in the equatorial Pacific as part of the NOAA Global Carbon Cycle Program.
- O-SCOPE sensors have been used for other NOPP projects (e.g., miniature interdisciplinary sensors for gliders).
- Bio-optical systems developed under O-SCOPE were used for the Office of Naval Research (ONR) HyCODE study at the LEO-15 site off the New Jersey coast and are being used at present for a Japanese biogeochemical mooring program and a Mexico-U.S. study in the Gulf of California.
- The O-SCOPE program led to the commercialization of new optical instruments by WET Labs, which have already sold over 200 miniature optical sensors (for multi-angle scattering and fluorescence). In addition, the UCSB anti-biofouling copper shutter design was adopted by Satlantic Inc. for its BioShutter that is used with its OCR-500 radiometer line of instrumentation. These instruments are

widely used for autonomous marine environmental observations and satellite ocean color validation applications.

• The development of a new low-power pCO_2 sensor that was started during O-SCOPE resulted in a drifter-based instrument that was successfully deployed during a recent Southern Ocean iron fertilization experiment.

O-SCOPE Accomplishments

The O-SCOPE project facilitated the formation of a successful partnership among academic, government and industrial partners who developed, tested and transitioned requisite next-generation technologies to the oceanographic community for long-term measurements and research of biogeochemical and bio-optical, as well as physical, processes.

Several new biogeochemical and bio-optical systems for moorings (and other platforms) have been developed and tested at three mooring sites: BTM, MBARI and OWS P in the North Pacific. The O-SCOPE project significantly accelerated interdisciplinary ocean measurement technology capabilities by increasing data, in terms of raw numbers and the variety, which can be collected autonomously; improving the robustness and reliability of interdisciplinary sampling systems; reducing adverse biofouling effects on bio-optical and chemical systems; developing a system for near real-time telemetering and dissemination of data via the Internet; and enabling the commercialization and broad distribution of new bio-optical systems.

The O-SCOPE activity represents one of the early coordinated efforts to advance autonomous interdisciplinary sensor and system technologies. A new NOPP project, Multidisciplinary Ocean Systems for Environmental Analysis and Networks (MOSEAN) will build on the O-SCOPE activity and ultilize new testbed moorings in the deep ocean off Hawaii and in shallow waters in the Santa Barbara Channel.

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References

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Tommy Dickey has taught oceanography at the university level for over 25 years. His research has centered on interdisciplinary studies, as well as autonomous sampling technologies. Study topics have included air-sea interaction, upper ocean dynamics, turbulence, internal gravity waves, biogeochemistry, ecosystems, bio-optics and pollution. Dickey's field activities have taken place in coastal and open ocean setttings, and he serves on several international committees concerning the development of the global ocean observing system.

Casey Moore has over 20 years' experience in the design and development of optically based sensors and systems. In 1992, he founded WET Labs Inc., a developer and manufacturer of in-water analytical instrumentation. Moore currently serves as president of the firm and still remains actively engaged in the company's ongoing research and development efforts.