THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

Glenn, S., and O. Schofield. 2009. Growing a distributed ocean observatory: Our view from the COOL Room. *Oceanography* 22(2):128–145, doi:10.5670/oceanog.2009.44.

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Growing a Distributed Ocean Observatory: Our View From the COOL Room

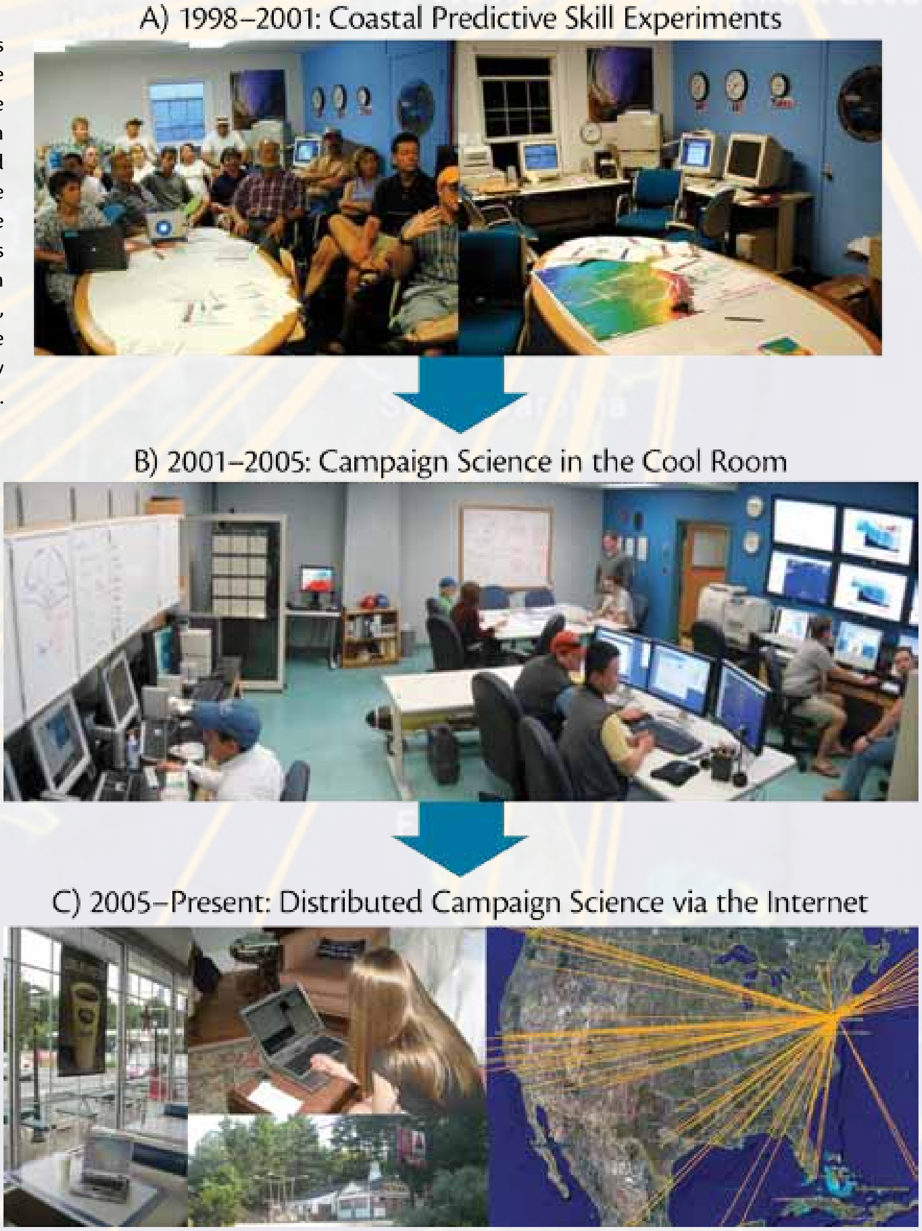

Figure 1. The evolution of the COOL operations center. (A) In the early years, science campaigns were conducted at remote field sites, such as the marine labs in Tuckerton, New Jersey. The remote location limited the duration of the experiments that could be conducted. (B) Improvements in the World Wide Web, combined with wireless technologies, allowed the operations center to be moved to the main campus of Rutgers University. (C) The most recent evolution allows experiments to be sustained remotely anywhere, anytime. Many large field deployments can now be supported from restaurants, from home, or from any location with a decent wireless connection.

ABSTRACT. The Rutgers University (RU) Coastal Ocean Observation Lab (COOL) is an enduring product of the National Oceanographic Partnership Program (NOPP). The key to its longevity is the academic, industry, and government partnerships that were formed through the NOPP process. These partnerships were galvanized by time at sea and then sustained through peer-reviewed proposals. The lab operates an advanced ocean observatory that has maintained a continuous presence on the New Jersey continental shelf since 1992. Key technologies for sustained spatial observations include locally acquired satellite infrared and ocean color imagery, a multistatic high-frequency radar array, and a fleet of autonomous underwater gliders. COOL provides a regional perspective that supports interdisciplinary process studies; provides a test bed, allowing rapid spiral development of sensors and platforms; and has anchored new "campaign" science programs where hundreds of scientists come together for intensive multi-institutional experiments. RU COOL is now a core component of the National Oceanic and Atmospheric Administration Mid-Atlantic Regional Ocean Observing System that, in 2007, began providing data for the full shelf from Cape Cod to Cape Hatteras. Looking to the future, in collaboration with partners from around the globe, the International Consortium of Ocean Observing Labs was formed to focus on improving global ocean observing. The NOPP approach was new and unique when introduced. Its philosophy of partnership among diverse groups was fundamental to the success of COOL and, we believe, will sustain international collaborations into the future.

INTRODUCTION

The Rutgers University Coastal Ocean Observation Lab (COOL) has sustained a continuous observational presence in New Jersey's coastal ocean for 16 years. Over this time, technology improvements have expanded its spatial observing capabilities. The system now provides: (a) a well-sampled region for process studies that range in size from the purview of individual principal investigators to multi-institutional science campaigns, (b) real-time and historical data sets and numerical forecasts supporting a wide variety of scientific and applied users, (c) a local test bed for new technologies, and (d) a focal point for a range of educational activities spanning K–12, undergraduate, graduate, and informal audiences, as well as in-service training. A broad portfolio of competitive grants awarded by US federal and state agencies, industry partners, private foundations, and foreign countries supports these varied activities. The diversified funding portfolio grows directly from our participation in the National Oceanographic Partnership Program (NOPP), which transformed our predominantly academic endeavors of the early 1990s into sustained academic-industry-government partnerships. NOPP provided the seed money to initiate and demonstrate the effectiveness of these approaches, and it continues to attract new partners from different disciplines.

In *Oceanography* and other publications, we have reviewed the evolution of our coastal ocean observatory and the international ocean observatory movement (Glenn et al., 2000a,b, 2004; Schofield et al., 2002, 2003, 2007; Glenn and Schofield, 2003; Schofield and Glenn, 2004). Here, we trace our progress, emphasizing developments since 2003 when our observatory operations center moved from a remote coastal location to the main campus of our research university, which is located two hours from shore (Figure 1A). The transition made the observatory an integral part of everyday campus life year round. This change also increased student involvement, most significantly at the undergraduate level. Since then, improvements in wireless technologies now allow the observatory to be controlled from any global location that has access to the World Wide Web.

THE NOPP DECADE

COOL has participated in six NOPP projects to date (Table 1). Beginning with the first round of NOPP awards, Rutgers-led projects focused on demonstrating the capabilities of an integrated ocean observing and forecast system to maintain a well-sampled 30 km x 30 km portion of the coastal ocean. The need for personnel to be moved to the coastal site to conduct these experiments, and the broad spatial coverage of these experiments, meant that they could only be sustained for about one month (Figure 1A). New sampling technologies and communications systems were required to expand the footprint in space and time. More importantly, initial partnerships formed through the NOPP process grew into a self-sustaining technology development and scientific study team. The team conducted process studies supported by the Office of Naval Research (ONR) and the National Science Foundation (NSF), and enabled

Table 1. The decade of NOPP grants in which COOL participated

TITLE	PARTICIPANTS	INSTITUTIONS	YEARS
Multi-scale model-driven sampling with autonomous systems at a national littoral laboratory	J.F. Grassle S.M. Glenn D.B. Haidvogel C.J. von Alt E.R. Levine D.E. Barrick B. Lipa J.W. Young	Rutgers University Woods Hole Oceanographic Institution National Undersea Warfare Center CODAR Ocean Sensors Ltd.	1997–1999
Demonstration of a relocatable regional ocean atmosphere modeling system with coastal autonomous sampling networks	S.M. Glenn D.B. Haidvogel R. Avissar J.F. Grassle O. Schofield C.J. von Alt E.R. Levine D.C. Webb D.E. Barrick B. Lipa J.W. Young R.P. Signell	Rutgers University Woods Hole Oceanographic Institution National Undersea Warfare Center Webb Research Corporation CODAR Ocean Sensors Ltd. Teledyne RD Instruments United States Geological Survey	1998–2000
Bringing the ocean into the precollege classroom through field investigations at a national underwater laboratory	M.P. DeLuca C.J. von Alt J.F. Grassle J. McDonnell K.A. Able S.M. Glenn O. Schofield	Rutgers University Woods Hole Oceanographic Institution	1997–1998
An integrated wireless coastal communication network	R. Nichols J. Burbank W. Kasch D.L. Porter S. Glenn O. Schofield C. Jones	The Johns Hopkins University Rutgers University Webb Research Corporation	2004–2006
Novel acoustic techniques to measure schooling in pelagic fish in the context of an operational coastal ocean observation	K. Benoit-Bird C. Jones O. Schofield S. Glenn J. Quinlan J. Condiotty	Oregon State University University of Washington Rutgers University Simrad	2005–2008
Development of fluorescent induction and relaxation systems for the measurement of biomass	O. Schofield S. Glenn P. Falkowski M. Gorbunov C. Jones S. McLean	Rutgers University Webb Research Corporation Satlantic Inc.	2005–2009

technology-development projects supported by ONR, the Department of Homeland Security (DHS), and the National Aeronautics and Space Administration (NASA).

NOPP also invested funds to develop key technologies and grow a diverse observatory community. Some NOPP efforts focused on improving communication networks for coastal observatories by enabling virtual collocation, ultimately freeing scientists from the constraints of having to move all operations to the shore lab for one-month time periods (Figure 1B, C). NOPP also supported the development of new sensors that were rapidly transitioned into the observatory for prototyping and feedback to developers. Additionally, NOPP focused on building linkages to K–12 and the education research community. We explored the concepts of using real-time ocean data in the classroom, a highly successful effort leading to the establishment of two NSF Centers for Ocean Science Education Excellence (COSEE) at Rutgers. The key lessons of our NOPP experiences are that equal partnership, rapid spiral development[1], and leveraging of resources lead to successful programs.

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[1] Spiral development was introduced in the mid 1980s by Barry Boehm of TRW Inc. as a way to reduce risk on large software projects after finding that these programs were too often designed and built with little input from end users, resulting in failure to meet objectives. Boehm's cyclical approach included early customer evaluation and identification of potential trouble spots by in-house engineers at an early stage. This approach has since been applied more generally to large projects.

Partnerships

NOPP proposals required partnerships among academic, industry, and government laboratories. Our strategy was to assemble a distributed collaborative team regardless of each partner's academic status, proximity, or congressional district. The net result was a virtual institution fueled by a shared vision. The diversity of the partners contributed new perspectives, which were assessed through the peer-review process. The participants, whether they were data providers or data users, were always considered equal partners in the project's execution. This goal-driven mode of construction was in contrast to early efforts by others who built systems based on input from external users.

Spiral Development

The NOPP process recognized that many of the sampling, communication, and modeling technologies required to provide a self-sustaining ocean observatory had not yet been developed. The fixed duration of the NOPP funding promoted a rapid spiral development cycle, which encouraged engineers to work alongside scientists in the field. Early NOPP projects focused on developing novel sampling technologies such as high-frequency [HF] radar and autonomous underwater gliders; later projects were devoted to sensor development. With no guarantee of sustained support, survival of the partnerships was contingent on producing results that would support the next round of peer review or survive the commercial marketplace. This process accelerated the pace of development.

Leveraging of Resources

NOPP was founded, in part, to allow all relevant federal agencies to address ocean observation, modeling, and data management needs jointly. As NOPP challenged scientists and engineers to cross departmental and academic-industry-government lines, the research community was challenging the federal agencies to fund efforts that often overlapped the different agencies' missions. This arrangement resulted in the development of ocean test beds that could simultaneously serve multiple needs. The cyclical support from individual agencies was merged to provide a more continuous funding stream. As the technologies matured, the test beds became more cost efficient, so that keeping an ocean observatory running 24/7/365 was not much more expensive then the cost of repeated mobilization and demobilization cycles. Addressing the scientific research problems of multiple agencies resulted in diverse scientific programs that constantly pushed the limits of available technology and improved the observatory over time.

DEVELOPMENT OF THE COOL ROOM

Our initial NOPP efforts focused on the three-dimensional topographic steering of coastal upwelling and its role in driving bottom water hypoxia/anoxia along the New Jersey coast (Glenn and Schofield, 2003; Glenn et al., 2004b; Schofield et al., 2004; Figure 2A). To study the dynamics of upwelling events, we deployed a month-long coastal observatory during July 1998–2001. The network consisted of real-time remote-sensing data from multiple satellites, aircraft, and shore-based HF radars; a cross-shelf mooring array; and numerous research vessels, autonomous underwater vehicles (AUVs), and numerical forecast models. Nearly 200 researchers from over 30 institutions participated (Schofield et al., 2002, 2004; Glenn and Schofield, 2003) as part of NOPP-supported efforts and ONR programs. Overall, the scientific results: (1) provided a physical understanding of recurrent upwelling zones, (2) defined the biological dynamics within the upwelling eddies, (3) indicated significant loading of anthropogenic materials by small, nearshore, coastal jets not resolved using traditional sampling strategies, (4) quantified the annual importance of the summer upwelling events, and (5) linked biological dynamics to bottom-water hypoxia. While successful, the need for all operations and personnel to be moved to the shore-based center was a fundamental factor limiting the experiment's duration. Thus, future efforts focused on developing an operational command location on the main Rutgers campus.

The new COOL room was established on the Rutgers campus in 2001 (Figure 1B). It was designed to operate throughout the year and integrate students into the field efforts during the academic year. The first major effort to use the campus COOL room was the NSF 2003–2005 Lagrangian Transport and Transformation Experiment (LaTTE; Figure 2B). LaTTE focused on understanding how mixing and transport in the Hudson River plume regulates biological and chemical transformations within the coastal zone. The observatory guided the multi-ship field effort to track the buoyant plume, which was highly sensitive to local wind

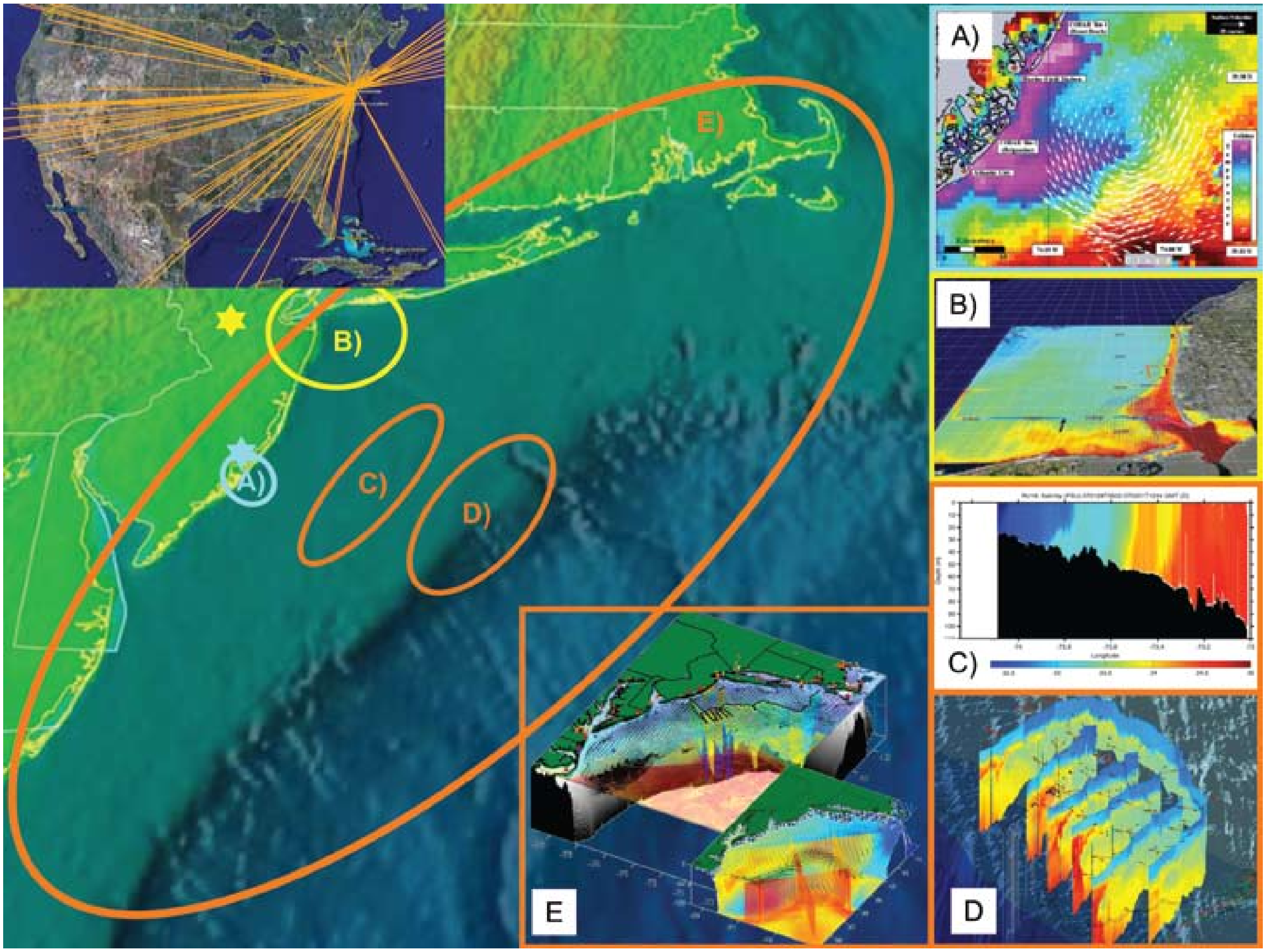

Figure 2. The experimental domains of the major COOL experiments supported by the observatory on the Mid-Atlantic Bight. Circles indicate the spatial range of the different experiments. (A) The first focus was on recurrent upwelling along the New Jersey coast and its role in driving local hypoxia/anoxia. (B) LaTTE focused on the transport and transformation of chemical and biological constituents present in the Hudson River buoyant plume. (C) Glider surveys were a critical component in efforts to resolve the physics driving front formation in Mid-Atlantic Bight waters. (D) The ONR Shallow Water 2006 joint experiment used fleets of gliders to support large mooring deployments focused on understanding the role of internal waves and the corresponding impact on acoustic uncertainty. (E) Recent work involves developing large, regional-scale observing networks to support data assimilative forecast models.

forcing. Scientists, graduate students, and undergraduates maintained the observatory with 24-hour shift rotations. Data from the Coastal Ocean Dynamics Applications Radar (CODAR) and satellites were combined with numerical forecast models to direct ship and glider operations using the wireless network available in this location (Schofield et al., 2007). The observatory-driven sampling effort provided data showing that the Hudson River recirculated in a near-shore eddy before being dispersed in an unexpected cross-shelf pathway, which represented two-thirds of the buoyant plume water being delivered to the shelf (Castelao et al., 2008; Chant et al., 2008). This unexpected cross-shore transport pathway provided a direct conduit between the urbanized watershed and the continental slope. Within the buoyant plume, phytoplankton assimilated nutrients, resulting in high rates of productivity associated with large chain-forming diatoms. The size structure of the phytoplankton mediated the accumulation of anthropogenic nutrients and contaminants in the higher trophic levels of the food web (Moline et al., 2008).

The success of the campus-based

efforts resulted in year-round offshore operations for sustained time periods (Schofield et al., 2008). For example, since late 2003, the lab's glider efforts have supported over 2300 glider days at sea spanning over 50,000 km under water (Figure 2C). Global glider efforts resulted in optimization of Iridium satellite communications, allowing a global footprint to be supported locally. The ONR Shallow Water 2006 joint experiment conducted on the outer shelf of the Mid-Atlantic Bight drove the next stage of observatory evolution (Figure 2D; Tang et al., 2007). The multi-ship and 60-mooring deployment was complemented with a fleet of Webb gliders. The efforts were supported with a daily environmental report that was delivered to the ships offshore via High Seas Net. This daily report summarized all the data for all the distributed parties. Additionally, the report provided the semblance of a social network for the large science campaign involving several hundred scientists. The daily report was coordinated through the COOL room over the three-month experiment duration; however, the lead Rutgers investigator was required to travel during the experiment for other obligations. This absence required the development of a suite of mission planning tools and Web-based products that would allow the daily report to be produced in any location with access to the Internet.

Scientific results from the glider fleet revealed four types of slope water salinity intrusions—surface, pycnocline, subpycnocline, and bottom—each appearing to be forced by different mechanisms. The extensive pycnocline intrusions were affected by stronger than usual shelf stratification due to remnants of low-density Hudson River water associated with a heavy rainfall. The new transport pathway discovered during LaTTE was observed in the CODAR surface current fields and verified with Coast Guard drifters (Castelao et al., 2008). Tropical Storm Ernesto went through an extratropical transition (the process by which a hurricane can change from a tropical cyclone to a mid-latitude depression) while transiting the region, with the transition and path well matched by an ensemble of high-resolution atmospheric forecast models that included the latest boundary-layer physics. Ernesto was observed by the gliders to resuspend significant amounts of sediment below the thermocline, which could not mix across it, motivating additional research on storms (Glenn et al., 2008).

With the success of distributed control for remote assets coordinated through COOL, the "footprint" of the observing efforts has increased significantly. Currently, ONR and NOAA are combining ocean observations and modeling dynamics to extend the limits of biological predictability using a technique called "data assimilation" (Figure 2E). Using this method requires observations at ecologically relevant scales spanning large marine ecosystems. The multiplatform observing networks provide the needed three-dimensional snapshots of water mass properties in near real time. These data are then assimilated into different models. Model uncertainties are estimated by comparing the different three-dimensional models with actual measurements. Ultimately, these models will be used to characterize regional three-dimensional water mass patterns to enable adaptive sampling.

SCIENTIFICALLY MOTIVATED TECHNOLOGY DEVELOPMENT

The expanding set of scientific problems that could be tackled by continuous data collection by our observatory resulted in an atmosphere conducive to technology development, which focused on enabling scientists to collect spatial time series. The major relevant technologies have included satellites, HF radars, gliders, and communications.

Satellites

A number of improvements have been made to observatory satellite data collection over the last five years (Figure 3). First, we set out to minimize the temporal gaps between satellite images by incorporating data from the international constellation of satellites, including Chinese and Indian ocean-color systems (Figure 3B, E). The international satellites' multiple passes per day at varying spatial and spectral resolutions provide numerous scientific and applied users with desired real-time imagery (Figure 3G). We developed customized views with input from thousands of satellite-imagery users. For example, a user could request enhanced imagery for a specific location at a specific time, allowing retrieval of the information needed without downloading a large file; this method is particularly useful for people who are working at sea with limited communication bandwidth. These real-time satellite images are complemented with a range of products developed in collaboration with the Naval Research Laboratory at Stennis Space Center, the University of Delaware, and Saint Andrews University. These collaborative efforts focused on deriving inherent optical properties from

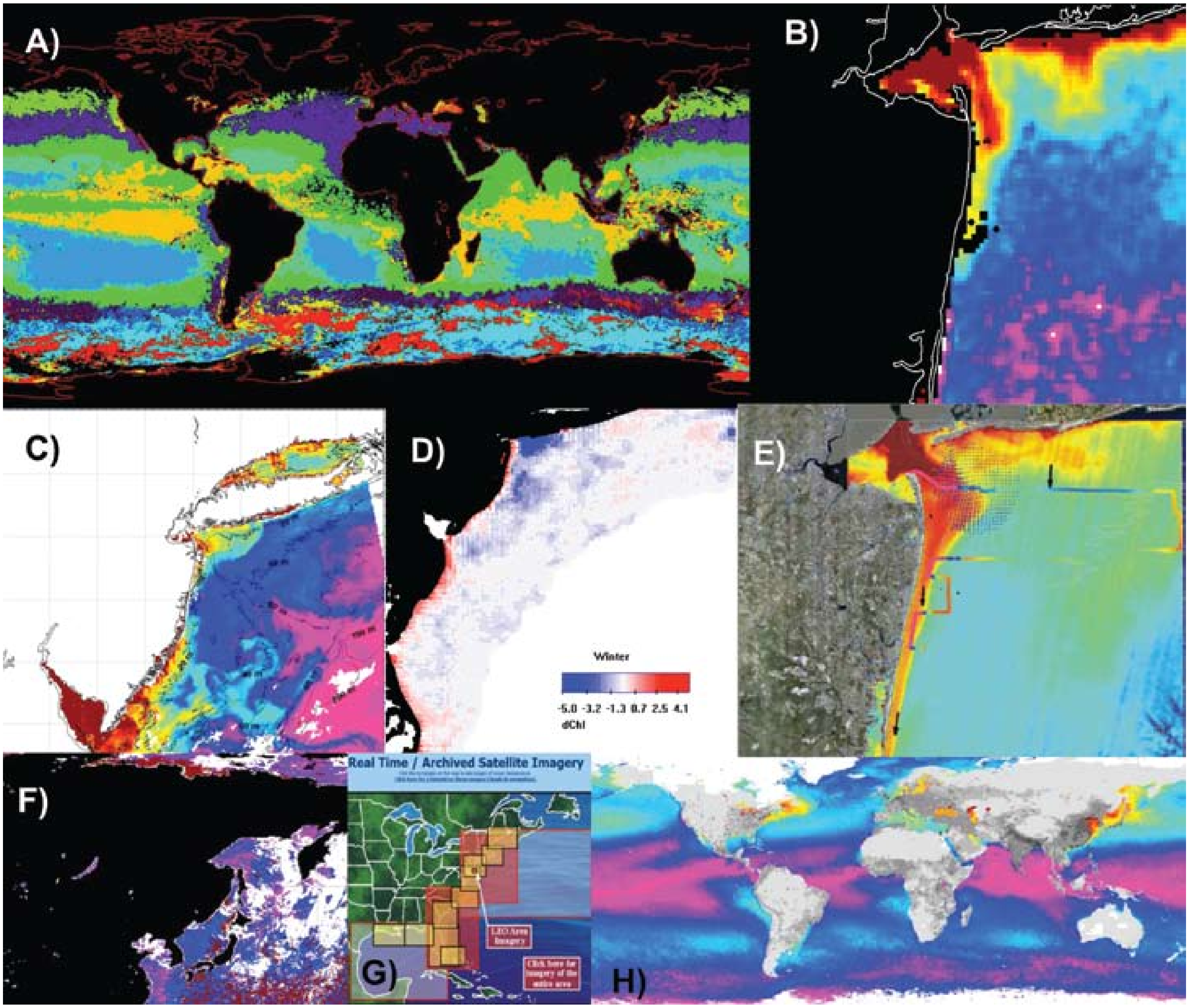

Figure 3. The major efforts in developing the capabilities of ocean remote sensing over the last decade. (A) A map of the major water masses delineated using objective bio-informatic approaches applied to satellite imagery. (B) The Hudson River plume visualized with the Chinese Fung Yen-1D polar-orbiting ocean color satellite. (C) A satellite image of the inherent optical properties (here, phytoplankton absorption) measured using ocean color satellite imagery. (D) The decadal change in the winter-season chlorophyll estimated by comparing imagery measured with the Coastal Zone Color Scanner and the SeaWIFs systems. (E) An ocean color image of the Hudson River plume visualized using the Ocean Colour Monitor on the Indian Remote Sensing Satellite. (F) Water mass classification approaches for delineating the presence of river plumes. (G) Customized satellite maps developed at the request of users who constantly access the COOL Web site. (H) The maximum annual temperature change in sea surface temperature.

space and validating the satellite estimates in the coastal ocean.

Another goal was to develop water mass classification procedures using satellite imagery. Computer algorithms were developed to identify on the satellite images the spatial extent of waters containing highly colored, dissolved organic matter associated with river inputs (Figure 3F). Because these initial algorithms were locally tuned, our recent efforts focused on developing methods that might have wider utility to the community. Instead of using subjective expert decisions (Longhurst, 1998; Devred, 2007), we used objective classification techniques that combine multiple satellite data sources to generate regional maps (Oliver et al., 2004). These objective mapping tools have been validated over a range of spatial and temporal scales and permit quick identification of water masses with particular characteristics. We also explored decadal changes in winter-season chlorophyll by comparing imagery from the Coastal Zone Color Scanner (operational from the late 1970s to the mid 1980s) with current SeaWIFs imagery. (Schofield et al., 2008; Figure 3D). Finally, there has been improvement in estimates of inherent optical properties (IOPs) from ocean color imagery (Figure 3C). IOPs are optical parameters that provide information on all materials that have color (phytoplankton, detritus, colored dissolved organic matter) and scattered light (organic and inorganic particles), and that are easier to interpret than traditional radiometry measurements. This attribute makes these optical parameters ideal for enhancing biological models. For example, photosynthetic rates are a function of total light absorption of the phytoplankton and the efficiency with which the absorbed radiation is converted into organic carbon.

HF Radar

The Rutgers CODAR HF radar network was reconfigured for LaTTE into a nested, multifrequency current mapping system that covered the New Jersey continental shelf and then focused in at higher resolution on New York Harbor and the Hudson River plume (Figure 4A). A 5-MHz network (Figure 4B) covers the shelf at 6-km resolution, a 13-MHz system covers the approaches to New York Harbor at 3-km resolution, and a 25-MHz inner nest covers the harbor entrance and the inside of the harbor at 1.5-km resolution (Figure 4 C,D). Similar nested networks were set up by other universities to cover the major bays to our south and the sounds to our east. NOAA-owned transportable HF radars designed for quick deployments from trailers were used temporarily to locally enhance coverage and for rapid response tests of simulated oil spills in remote locations (Figure 4E). Radial current data from each group participating in what came to be known as the Mid-Atlantic HF Radar Consortium (MAHFRC) was aggregated as part of the NOAA-sponsored HF radar national network server demonstration. The resulting regional array (Figure 4A) runs along ~ 1000 km of coastline, extending from Cape Hatteras to Cape Cod, though coverage at any given time remained subject to the research grant support available to each radar's host institution. The Coast Guard has conducted field tests using surface drifters to quantify improvements to search and rescue planning enabled by real-time CODAR surface currents. Similarly, NOAA was interested in validating the CODAR HF radar nearshore wave and current parameters to support rip current forecasting for lifeguards. These results were used to develop a three-phase plan to transition the current mapping network to sustained operations.

Beyond the development and demonstration of a regional current mapping capability, research on new CODAR hardware, processing algorithms, and products continued. The most significant hardware improvement was CODAR's addition of GPS timing to each radar. GPS timing enables multiple radars in close proximity to share the same frequency without interference, thus minimizing the network's footprint on the broadcast frequency spectrum. GPS timing also enables coordinated, multistatic operation of radars that are within range of one another. Standard monostatic radars, whose transmitters and receivers are collocated, operate in backscatter mode only. In multistatic operations, each receiver can acquire scattered signals from any radar transmitter within range. The result is that N monostatic radars are transformed into a multistatic network with N^2 look angles. Beyond construction of the land-based multistatic network, new bistatic transmitters were developed for stand-alone operation as either land-based systems (Figure 4B–D) or for offshore deployments on fixed platforms (Figure 4I) and buoys (Figure 4J). The network of fixed shore-based receivers acquires scattered signals from the bistatic transmitters.

Tests of the multistatic HF radar network capability were first funded by ONR for vessel-tracking experiments. The research question asked whether an HF radar network could detect and track surface ships. The positive outcome resulted in efforts to increase the range of over-the-horizon vessel detection without increasing the broadcast power of the radars. These efforts focused on improving the methodologies for enhancing signals acquired by land-based receivers, including test deployments of a super-directive multistatic receiver antenna (Figure 4F). Complementary strategies were undertaken to increase the offshore range by placing bistatic HF radar transmitters on offshore buoys, thus decreasing the distance from transmitter to target. The two approaches, both tested in the

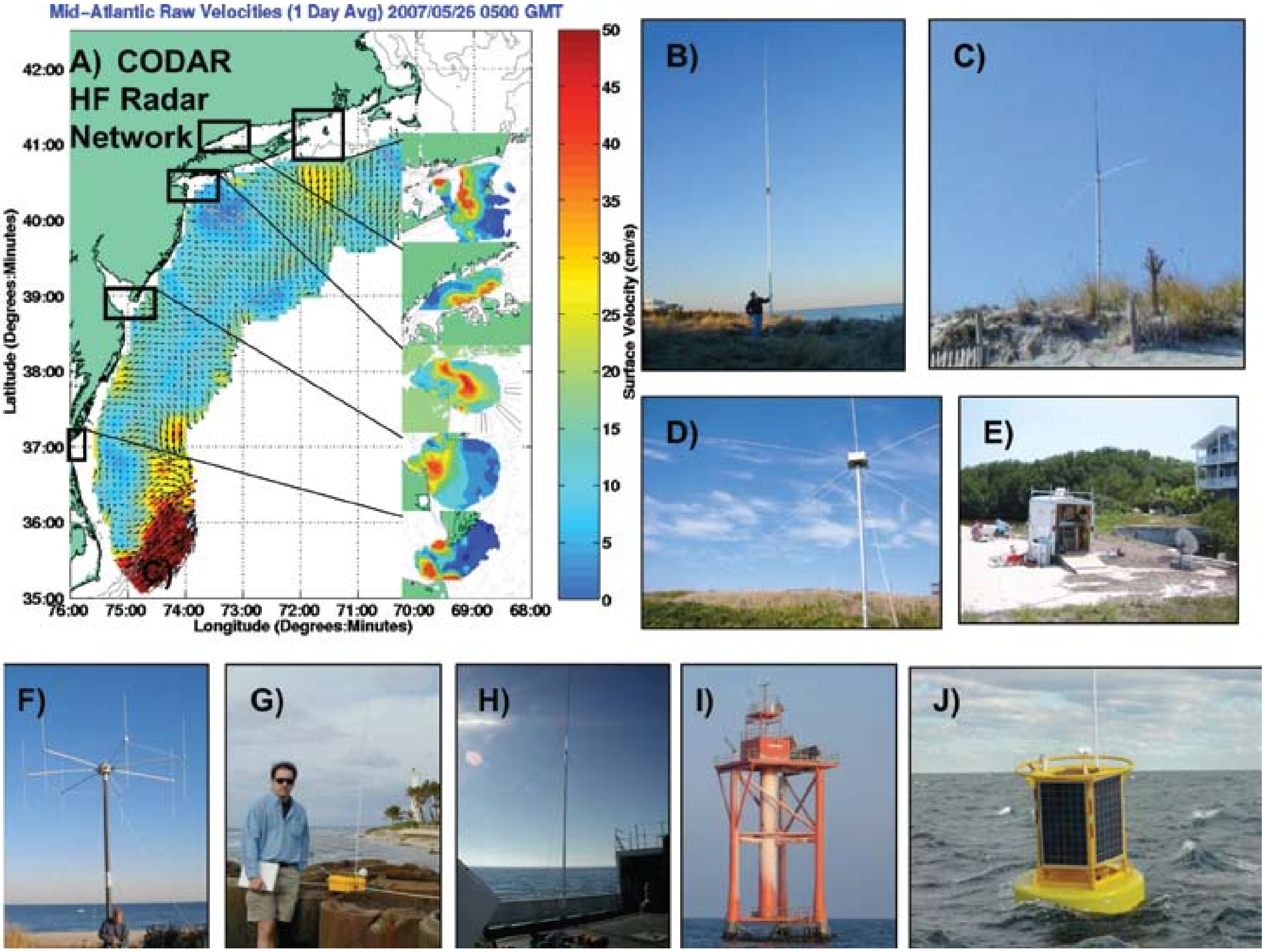

Figure 4. (A) The nested Mid-Atlantic HF radar network as currently supported by US IOOS through NOAA. Components include (B) transmitters for long-range systems (5 MHz), (C) transmitters for medium (13 MHz) and short (25 MHz) systems, (D) common receivers for all three, (E) NOAA mobile CODARs for temporary deployments and fast response, (F) superdirective receivers to increase the signal-to-noise ratio, and a series of bistatic transmitters that include (G) shore-based portable systems, (H) long-range systems deployed on ships, (I), short-range systems deployed on offshore platforms, and (J) medium-range systems deployed on buoys.

Mid-Atlantic HF radar test bed, led to improvements to the Coast Guard mapping capabilities.

Gliders

Mobile platforms are developing quickly and are transitioning into observational tools (Rudnick and Perry, 2003). One autonomous platform that is rapidly becoming indispensable is the underwater glider (Figure 5). Publicized in 1989 by Henry Stommel's view of a futuristic smart fleet of mobile, long-duration sensor platforms (Stommel, 1989), gliders are steadily earning their reputation for efficiency and endurance. A number of different gliders have been developed (Davis et al., 2003) but our group uses the Slocum glider developed by Webb Research Corporation (now Teledyne Webb Research). Gliders are a robust technology capable of anchoring large field campaigns and providing a sustained presence in the ocean (Schofield et al., 2007). Our efforts have focused on enhancing glider capabilities as part of a long-term NOPP-style partnership with Teledyne Webb Research by improving glider hardware, software, and increasing the sensors carried onboard these platforms (Figure 5).

Steady improvements in hardware and software over the last five years have

Figure 5. The success of Webb gliders deployed by Rutgers since late autumn 2003. (A) The global deployment map of the Rutgers Webb Glider fleet. (B) Hardware improvements developed under a Teledyne Webb Research/Rutgers partnership include extended glider payload bays, command/control and visualization software, pick points on the gliders, new more powerful computers inserted into the glider science bay, lithium battery packs to increase glider duration, and the new robust digi-fin. (C) Many instruments have been carried on Rutgers gliders over the last five years, including (starting at the top left panel) oxygen sensors, passive acoustic sensors, attenuation sensors, chlorophyll/colored dissolved organic flourometers, turbulence sensors, fish bioacoustic sensors, scattering and backscattering sensor packages, spectral backscatter sensors, radiometer sensors, video imaging components, acoustic Doppler current meters, fast-repetition-rate flourometers, and hyperspectral absorption sensors.

included simple features such as pick-up points to enable glider deployment/recovery from large ships, extended body forms for carrying larger sensors or extra battery packs, robust tail fins, command/control and visualization software, and improved onboard science computers (Figure 5B). The hardware improvements have extended glider duration and performance. Additionally, a wide range of new sensors has been incorporated into the gliders. Measurements presently being made by gliders include physical (temperature, salinity, turbulence), acoustic (active and passive), optical (spectral radiometry, backscatter, attenuation scattering, absorption, video imagery), fluorescence (chlorophyll *a*, colored dissolved organic fluorescence, fast repetition rate fluorometry), and dissolved gas (oxygen) (Figure 5C).

Communication Networks

During the 1998–2001 Coastal Predictive Skill Experiments, lack of communication capabilities necessitated removal of the entire shore-based team from the Rutgers main campus to a coastal site. The camaraderie stimulated by collocating personnel at one shore-based control center was similar to that of going to sea, but the multiple ships and shore crews involved in the experiment still required a means to communicate. During this time period, virtual collocation was enabled with radio modems that connected ships and aircraft to the shore-based science crew. This mode of communication was complemented by shore-based Web broadcasts of live video and radio chatter in an effort to involve the outside community. For these communication efforts, the physical range was limited to line of sight (~ 30 km). In 2003, the range changed with our participation in the Ocean.US Iridium Pioneers program. The ability to communicate globally using Iridium SIM cards was transformational.

During LaTTE programs from 2003–2005, we worked with a commercial vendor to expand communication regionally using higher-bandwidth cell phone modems. During the ONR Shallow Water 2006 experiments, which required coordination for three months and a virtual presence for COOL, all data sets were available via the World Wide Web. These changes in the mode by which the field teams communicated allowed science planning to be conducted from another research lab, from restaurants, or even from our living rooms via wireless Internet connections (Figure 1C). Global access to the observatory through WiFi hotspots remains in constant use today. Observatory assets can be accessed, systems checked, data visualized, and adaptive sampling plans adjusted on a sustained basis from any location in the world as part of normal life activities. Daily achievements are documented on public blog sites, enabling anyone—from collaborating scientists to the general public—to follow along on missions of discovery.

DEVELOPMENT OF A SUSTAINED REGIONAL TEST BED

The first long-range 5-MHz CODAR HF radar was deployed on the East Coast in the summer of 2000 during the third ONR/NOPP Coastal Predictive Skill Experiment. The 200+ km range of the radial current field covered the full cross-shelf distance to the shelf break. It solidified plans for developing a regional observatory spanning the Large Marine Ecosystem (#7) of the Northeast US Continental Shelf (see http://www.lme.noaa.gov/ for more information on the 64 Large Marine Ecosystems designated worldwide). The regional network would be anchored by a nested, multistatic HF radar network. Initial attempts focused on combining our existing subregional ocean-observing assets into a loose federation that we called the North East Observing System (NEOS). Building on the strength of the NOPP partnership approach, NEOS consisted of academic observatories, government backbone observatories, and industry networks collaborating with instrument developers. At that time, NEOS partners believed the observatory should be based on the best science available to improve coupled forecast models.

The NOAA regional network developed in the Mid-Atlantic Bight (MAB) is the foundation of the developing NEOS network (Figure 6). In 2007, NOAA funded the Mid Atlantic Regional Coastal Ocean Observing System (MARCOOS), which revolved around two regional themes. Theme 1, Maritime Safety, would provide maps of nowcasts and forecasts of regional surface currents to improve search and rescue and hazardous material spill response, as well as nearshore products to improve rip current forecasting. Theme 2, Ecosystem Decision Support, would provide regional three-dimensional temperature and circulation data, nowcasts, and forecasts of the ocean, extending from Cape Cod to Cape Hatteras, for the recreational, commercial, and fishery management communities. To generate the nowcasts and forecasts, an extensive array of existing observational data, data management, and modeling assets required coordination (Figure 6).

This NOAA investment will be augmented by other agencies. Currently, NSF proposes to build the Ocean Observatories Initiative (OOI), which calls for a robotic array to be placed on the MAB shelf south of Cape Cod near the shelf break. Research funded by ONR, while designed to support the Navy in forward deployed areas, often uses the same region as a test bed for instrument development and scientific process studies. Although there is no substitute for actually going to sea in specific regions of interest, the cost of foreign deployments exceeds the cost of local deployments by an order of magnitude. Local surrogate test beds for regions of interest are cost effective for development and training of operational Navy personnel. DHS is interested in the over-the-horizon capabilities of HF radar for maritime domain awareness. Leveraging the existing network was one cornerstone for a recently formed DHS Center of Excellence for

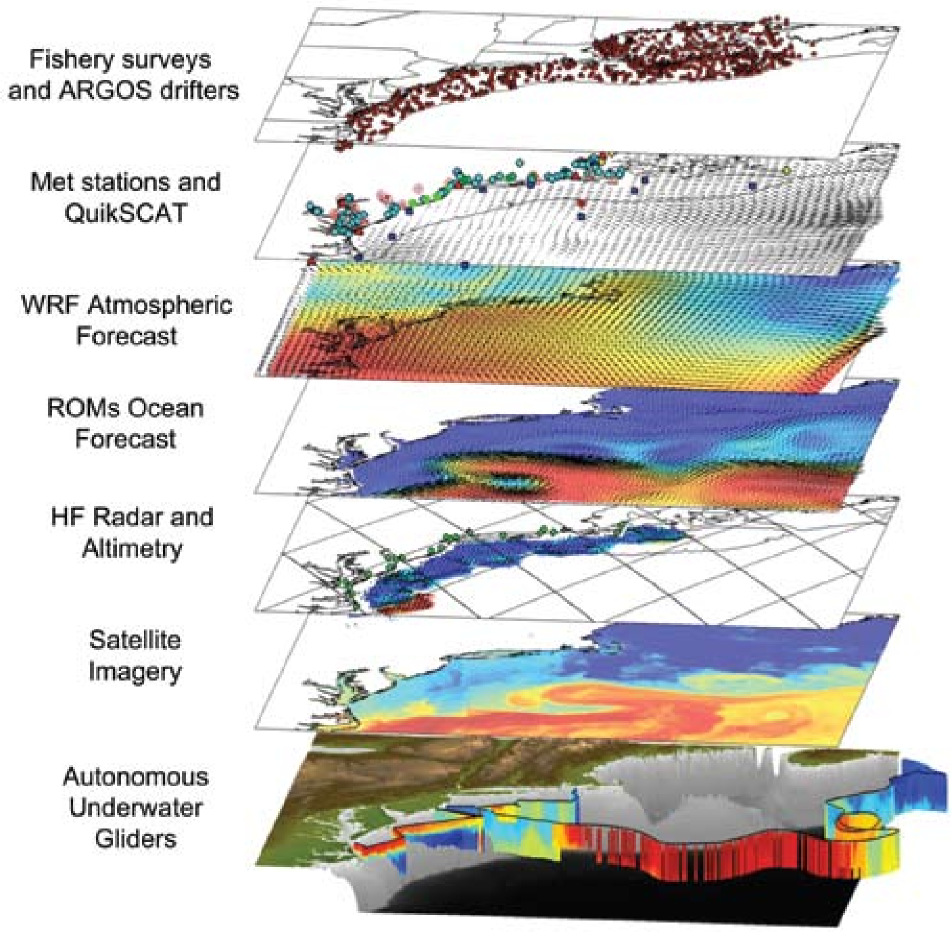

Figure 6. The current status of the North East Observing System (NEOS) showing the numerous data streams being compiled by the distributed academic-federal-commercial team.

Port Security. Additionally, there is rapidly expanding interest from the energy industry. Public Service Electric & Gas (PSE&G) funded high-resolution weather forecasts to pre-position service trucks during storms to reduce response time to power outages. Offshore wind energy companies provide support to enhance the observing network in the vicinity of proposed offshore wind farms. Offshore wave power companies are investing money to enhance offshore platforms in the region, using it as a test bed for energy harvesting systems.

Funding for the observatory emphasized commonalities. Development of new enabling technologies was central to all observatory users. All benefited from investments of others and all required access to real-time data and forecasts for operational decisions, ranging from adaptive scientific sampling with autonomous vehicles to adaptive response to storms by repair vehicles. All desired access to historical data to study specific events of interest in order to improve future responses. All required a sustained data stream to identify long-term trends that could affect their event-based responses. The result is a wide variety of observatory users that also happen to be observatory funders, spanning eight federal agencies and industry.

Collaboration and leveraging is evident throughout. Glider operations run by several universities in the region are supported by ONR, NOAA, and NSF. Satellite ground stations at Rutgers, University of Maine, and The Johns Hopkins University Applied Physics Laboratory each acquire the real-time direct broadcast data and provide a back-up data source in case one station goes down. Academic institutions mostly own the HF radars, with support now provided by NOAA for the US Integrated Ocean Observing System (IOOS). As with the gliders, ONR, NOAA, and NSF support the regional ocean models typically run by multiple academic institutions, while the Navy and NOAA operate the basin-scale models. Local NOAA Weather Service Offices, academics, and industrial partners run the ensemble of atmospheric models. NOAA operates the main regional fisheries cruises on agency vessels, while academics cover the supplemental surveys with fishing industry vessels.

DEVELOPMENT OF AN INTERNATIONAL COLLABORATORY

IOOS is the US contribution to the Global Ocean Observing System (GOOS), which, in turn, is the international oceanographic community's contribution to the Global Earth Observing System of Systems (GEOSS). The structure provides an international forum for governments to collaborate on the critical need for observing the world ocean in an era of human-induced climate change and population growth. Still, it is unclear how the practicing scientist contributes to the global expansion of the already difficult task of making observations in an often hostile ocean environment.

The 2005 Oceanography Society meeting in Paris was one turning point in the promotion of international collaborations in the spirit of NOPP. Discussion focused on how best to collaborate, share data, and begin to form a coherent network. This coalescing collaboration was reminiscent of the atmospheric observing community in the early 1900s when the telegraph first connected individual weather forecasters from different countries independent of official government organizations. It became clear there was much to be gained by sharing expertise and limited observational assets. Although enabling technologies continue to be demonstrated locally or even regionally in many places around the world, we remain capacity limited if we try to address the challenges of globalization.

Seeing the collaborative spirit at the Paris meeting as a way forward for the working scientist, at a Paris sidewalk café, John Cullen from Dalhousie University initiated the International Consortium of Ocean Observing Labs (I-COOL). Plans for the first collaborative I-COOL deployment followed the next morning with John Howarth from the Liverpool Bay Observatory proposing a glider mission coordinated with his ongoing shipboard cruises. Collaborations continue today, fueled by the need to sample the ocean with new satellite, HF radar, glider, and AUV-based technologies. Our objective is to distribute the technologies developed locally in the Northeast regional test bed to the global marketplace.

Currently, I-COOL has three main themes. One is to provide platforms and expertise that enable local scientists to demonstrate success and hence fuel local funding for programs that contribute to the larger I-COOL effort. There have already been many successful collaborations with European, Australian, and Caribbean scientists. For example, CODAR HF radars are being deployed in Norway, with gliders and AUVs to follow with support from the Norwegian government, which is interested in the environmental impacts of climate change.

The second I-COOL theme uses these novel technologies to explore extreme environments. Targeted environments include the poles, severe storms, urbanized ports, and developed coastlines, all of which are often avoided by scientists because of hazardous operating conditions. Now, gliders are being deployed along the West Antarctic Peninsula for climate change research as part of NSF's Palmer Station Long-term Ecological Research study in collaboration with British scientists. Because observing networks are robust, they are allowing scientists to safely study severe storm processes in real time without having to curtail operations, for example, glider operations on the New Jersey shelf that continued unperturbed and yielded to insights into shelf-water processes during a very stormy period in fall 2003 (Glenn et al., 2008). The natural and anthropogenic forcing at work in urbanized ports often result in extremely dynamic environments whose turbulence and spatial complexity are difficult to sample using traditional technologies; observing networks will help overcome the difficulties of conducting research in these heavily used environments.

The third I-COOL theme is to extend the limits of long-duration underwater glider flights by developing new power and control systems. The long-duration studies are powerful magnets that get undergraduates interested in science (see Box 1) and have the potential to increase the visibility of ocean exploration to the general public. Currently, efforts are underway to re-occupy the many legs of the 1872–1876 HMS *Challenger* voyage using a global fleet of long-duration gliders and to compare modern and historical physical and biological characteristics. This effort will require a global collaboration of scientists and students over the Internet. We hope to include developing nations in this project, but must overcome the lack of infrastructure in these countries, which have the fastest growing human coastal populations and thus a great need for ocean observing applications such as for fisheries management.

LESSONS LEARNED

Glenn and Schofield (2003) outlined concerns, lessons learned, and conclusions based on initial construction of the New Jersey shelf-wide observatory. Some of those lessons still apply, including the necessity of coalescing scientific and societal goals, the importance of iterative development supported by peer-reviewed grants, and the need to train a new workforce that currently does not exist. Other concerns have evolved, in particular those surrounding sustained funding. In 2003, entrance into the IOOS family of observatories was best obtained through congressional earmarking. The change to a scientific peer-review system in 2007 made it particularly painful for those systems that had not diversified their funding base through spiral development.

Observatories Inspire Young Scientists

In the 1990s, senior-level scientists warned us that our work on ocean observatories would negatively impact our scientific careers. We may have heeded that advice if not for the tenure system and the nine months of university salary support we received for teaching, research, and service activities. Thus, while NOPP enabled new partnerships, institutional support was critical in allowing those partnerships to mature. In 2003, we also warned young, untenured faculty that building and operating an ocean observatory was not a prudent choice at that early stage of their careers. This view was based on our experience with the excessive grant and management pressures required to sustain an observatory outside of the scientific mainstream. Our concern was that the required work would come at the expense of manuscript preparation, which is, and will remain, the central currency for earning tenure. We were not alone in sounding this alarm. In 2003, with the primary investment in observatories coming through congressional earmarks, faculty who did participate were required to focus on demonstrating accountability through political visibility rather than professional development. The end result was a missing generation of young, hardworking scientists supporting the ocean observatory movement.

In the last five years, we have seen dramatic changes. Observatories exist, they will continue to evolve, and in some form or another, they are here to stay. Young faculty members who access the observatories find they have a platform that provides them a competitive advantage. The existing infrastructure allows them to propose ambitious experiments that take advantage of the 24/7/365 spatial view of the ocean. Rather than having to raise all the money for expensive infrastructure themselves, young faculty can use existing observatory capabilities to meet many of their sampling needs, paying only for the incremental costs of pursuing their specific research problems. Two recent examples of multi-institutional research programs designed and led by untenured Rutgers COOL faculty are the NSF-supported LaTTE (Robert Chant) and Mid-Shelf Front Experiment (Josh Kohut) programs. Additionally, universities find that an environmental observation network serves the needs of multiple departments. The on-campus COOL control center provides an academic nexus that has enhanced collaborations spanning marine science, geological science, environmental science, microbiology, computer science, engineering, education, and economics. New joint faculty appointments among the Marine Science Department and the School of Engineering, the Graduate School of Education, and the Agricultural Experiment Station are growing the number of faculty interested in using or improving ocean observatories. These collaborations provide a means to unite diverse faculty interests while simultaneously accessing a wider range of sponsors. Our own Rutgers University Vice President for Research and Graduate and Professional Education, in a 2008 speech to incoming tenure-track faculty, warned that single-author papers are not enough anymore, and that collaborations, especially interdisciplinary, are highly valued by tenure reviewers. Observatories are an effective means for young faculty to conduct interdisciplinary research.

> “THE LESSONS LEARNED THROUGH THE NOPP EXPERIENCE DEMONSTRATED THE VALUE OF PARTNERSHIPS, THE ROLE OF RAPID SPIRAL DEVELOPMENT, AND THE VALUE OF LEVERAGING THE SUPPORT OF MULTIPLE FEDERAL AGENCIES.”

Partnerships That Result in Diversification

In 2003, when congressional earmarks for ocean observatories were on the upswing, observatory management was being pushed away from the already successful NOPP model of equal partnerships. In the user-driven model that the earmarks encouraged, the scientist's role was undervalued. Data providers were made subservient to data users, and management did not understand the difficulties of operating in a hostile ocean environment. Narrow definitions of the users that were expected to drive this system, and the refusal of management to

Box 1. Transforming Undergraduate Education through Ocean Observatories

BY SCOTT GLENN, DAKOTA GOLDINGER, ETHAN HANDEL, SHANNON HARRISON, DANIELLE HOLDEN, JOSH KOHUT, ANTHONY LUND, JANICE MCDONNELL, EVAN RANDALL-GOODWIN, EMILY ROGALSKY, JUSTIN SHAPIRO, ERIC VOWINKLE, AND OSCAR SCHOFIELD

The Coastal Ocean Observation Lab is developing new initiatives as part of a university-wide effort to transform undergraduate education at Rutgers. Enabled by an ocean observatory operations center purposely located on the main campus of a major research university, the lab has established a program featuring hands-on, team-based research projects that complement course work and are specifically designed to engage undergraduates in science. The program encourages students to become involved as early as the freshman year, remaining in contact with many of the same students and professors for their full four years at Rutgers. A series of Introduction to Oceanography courses with significant freshman participation, and a variety of small seminars for first-semester freshmen, serve as the feeder courses. Interested students join faculty in the lab during their second semester, either through one-credit research courses or work-study programs. The students are organized into a NOPP-style research team, and given a task reflecting the core NOPP values —collaboration between scientists and engineers from multiple disciplines, rapid spiral development cycles that work toward achieving a long-term goal, and leveraging the support of multiple groups from around the world. The initial task supported by the undergraduate team—to be the first to fly an autonomous underwater glider from Tuckerton, New Jersey, to Halifax, Nova Scotia—was accomplished during spring 2008 with RU15. Their second task, still ongoing, is to fly the first glider across the Atlantic from New Jersey to Spain.

These long-duration underwater robotic flights are made possible through the convergence of research, engineering, and educational projects from multiple agencies. Slocum gliders are now being delivered with the new DigiFin, an improved design that requires testing by ONR to meet Navy needs. NOAA initiated testing of lithium primary batteries for the new higher-powered sensors proposed for a NOPP instrument development project. NSF required testing of an extended payload bay to enable additional batteries to be carried for flights between the United States and British bases in Antarctica. Still, the main purpose of the long-duration flights remains educational. Rutgers alumni donated a glider for use as the primary platform to engage undergraduates in projects related to ocean observatories. NSF provided a summer intern from its Research Internships in Ocean Sciences (RIOS) program, in this case, an aeronautical engineer from the University of Maryland. Qualitas, a Spanish company installing and operating the national HF radar network for Spain, contributed an internship for a student with a dual major in marine science and Spanish. Glider training courses, developed and delivered for NOAA-sponsored IOOS projects and used extensively by the operational Navy, NATO, and the European Glider Association, were used to spin students up in every aspect of glider operations over the winter break.

Each student on the team was responsible for a specific aspect of the long-duration flights. Two freshmen worked alongside the three glider technicians to help with construction and testing of the actual glider, RU17. At the end of their spring semester, they returned to their high school, giving talks to their science teacher's class and the high school robotics team at Marine Academy of Technology and Environmental Science, in Manahawkin, New Jersey, on what they accomplished at Rutgers in their freshman year. Two juniors worked on the flight characteristics of RU17, optimizing the flight controls and providing feedback to the manufacturer. Two freshmen worked on the NOAA-sponsored IOOS Mid-Atlantic HF radar network as the launch zone for these two flights, while a junior worked on HF radar in Spain to help prepare

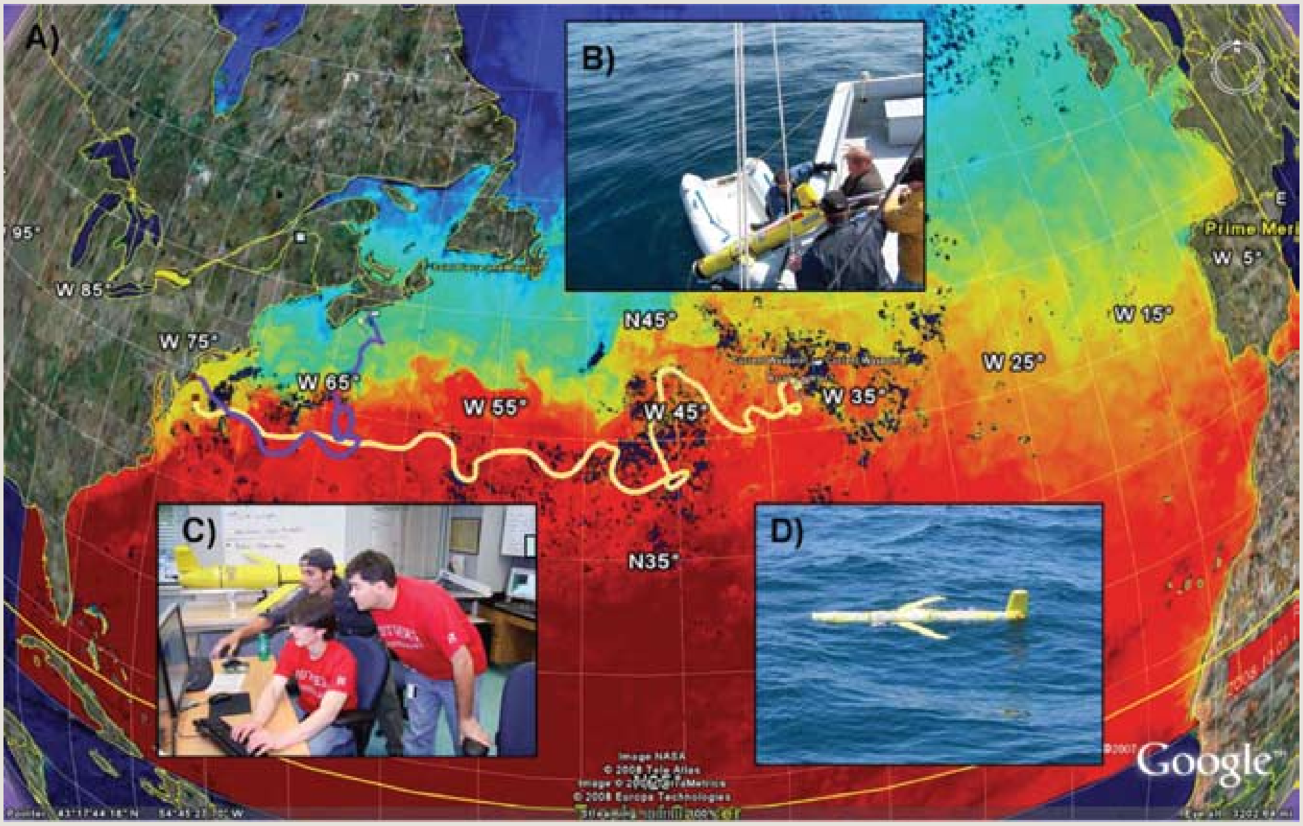

Figure B1. (A) Glider tracks overlain on a weekly composite satellite sea surface temperature image displayed in the Google Earth interface for the Halifax (RU15; blue) and Trans-Atlantic (RU17; yellow) missions. After setting the world record for distance traveled, communication with RU17 was lost just 220 miles shy of the Azores. Following our philosophy of rapid spiral development, lessons learned from the flight of RU17 are incorporated for the transatlantic mission of RU27, scheduled to begin its journey in April 2009. (B) Recovery of RU15 in Halifax, Nova Scotia, by NOPP partners at Satlantic Inc. (C) Undergraduates and a faculty member retasking RU17 to a new waypoint based on environmental data collected in the COOL room. (D) RU17 deployed off New Jersey prior to the start of its record-breaking journey.

the landing zone. Two seniors worked on path planning, Web site development, and the Google Earth interface that has been used in three Navy exercises, and is part of our Mid-Atlantic control center.

Our objective is to attract and retain students in lab activities for their full undergraduate careers. The on-campus operations center draws students from a variety of majors, and the excitement of the hands-on projects keeps them coming back semester after semester, and summer after summer. The students follow the cognitive apprenticeship learning model, which we reduce to the simple three-step teaching philosophy of "watch one, do one, teach one." They begin in freshman year with a lot of watching, often shadowing full-time research staff. By their sophomore and junior years, they know their way around the lab and are contributing key components to a variety of projects. By senior year, they are concluding their work, and passing their knowledge on to others by helping train the incoming freshmen. An NSF-sponsored education course, Communicating Ocean Sciences to Informal Audiences, is provided to the seniors so they can develop the teaching skills they will use in their last semester at Rutgers and beyond. The end result is a cluster of students that have demonstrated their ability to work together on a team for years, contributing to cutting-edge projects and building bonds they will remember as they pursue their careers.

upgrade technologies, limited the range of the data's applicability (Pettigrew et al., 2008). Ultimately, many of these observatories proved unsustainable due to overreliance on a single source of funding.

We have seen this increase in interest over the last five years as COOL continues to transition additional sampling and forecasting technologies from supporting discrete science experiments, government exercises, or industrial tests, to year-round operations. The transitions were coordinated with a growing number of academic, industry, and government partners that together sought federal, state, and foreign support as well as funding from industry and private foundations. We found that in many cases, the data users were also data providers regardless of their academic, industry, or government homes. We found that the NOPP concept of partnerships, focused on specific targeted and funded goals, moves observatories forward faster than general support for a wide range of observational parameters. Most users we ask will insist that they want the best science to support the decision-making process. In many cases, operational decisions are based on forecasts and their uncertainties rather than static historical data. Just as new technologies provide new data sets as a product of the observatory, new science that enables new forecast models is also a valued product.

Exploration and Discovery Enhances Education

The ocean is still a great unknown, far from being fully explored and understood. It is a difficult, exciting, and sometimes dangerous environment in which to work. These concepts are generally not taught in school. A common misconception is that everything is already understood. Daily difficulties that must be overcome to make progress typically go unshared, and dead ends encountered along the way go unreported. The public view is that science is conducted behind closed doors and that results are only shared when the scientist has already developed a complete story. This view contributes to a science culture that is risk adverse, where failure is viewed as a negative as opposed to a regular and common feature of scientific exploration and discovery. Additionally, the public does not see the ongoing process of science, and thus often has an incomplete perspective of how science is conducted and, therefore, how exhilarating the scientific process can be.

The committee appointed by the National Research Council identified the need to entrain the wider society to increase science and technical literacy of the United States by inspiring the next generation of scientists (National Academies, 2007). In oceanography, past discovery often involved unexpected events on the deck of a ship, far away and disconnected from the public we are trying to engage. Yet, the challenges of working in an extreme environment provide a great vehicle for capturing the public imagination. Observatories have developed the initial means to broadcast these adventures widely. Our experience indicates the audience that is excited to follow these adventures is much larger than our community might expect. Developing the means to broadcast our stories and thus entrain the wider community in our science requires effort prior to an experiment; the scientist must be prepared to be in public view through the full discovery process, including failures. Oceanography is fun, exciting, and suspenseful. It requires passion, blood, and sweat. Sometimes experiments don't work, but when they do, the excitement of discovery is indescribable. Therefore, we believe it is time to include wider society in the scientific "thrill of victory and the agony of defeat."

CONCLUSIONS

The lessons learned through the NOPP experience demonstrated the value of partnerships, the role of rapid spiral development, and the value of leveraging the support of multiple federal agencies. We have learned that partnerships are made by the hard work and dedication of the people involved based on the strengths of individuals and their belief in the synergies achievable through teamwork. New technologies born of the partnership model have enabled the evolution of our observatory with a diverse funding base in the Northeast United States at the scale of the Large Marine Ecosystem. Based on the same partnership model, we have expanded internationally, first with scientific partners around the world, followed by the exploration of extreme environments, and now the challenges of long-duration underwater flight. We have seen young faculty become involved and succeed through new science and new applications, and we have seen enabling technologies produce new data sets, and the science produce new forecast models. Public exploration of the ocean is attracting the next generation of scientists by involving undergraduates in the daily operation of an ocean observatory.

This is a unique time in the maturing of our field of oceanography. The world ocean is vastly under-sampled and presents a challenging work environment. Our generation of ocean scientists, originally trained only within our own core disciplines, is growing more collaborative as we tackle interdisciplinary problems. And federal funding agencies are growing more collaborative in their search for dual-use technologies, new science, local development test beds, and leveraging opportunities. People from academia, industry, and government are forming virtual communities for collaboration independent of their home institutions. The definition of an oceanographer continues to expand as we attract new people to the field and make it easier to spend time at sea. It is a great time to be an oceanographer.

ACKNOWLEDGEMENTS

The Rutgers University Coastal Ocean Observation Lab acknowledges the broad support of the oceanographic community. We are especially grateful for the friendships established with our long-term industry partners, including SeaSpace, CODAR Ocean Sensors, Teledyne Webb Research, Teledyne RD Instruments, Satlantic, WET Labs, Ocean Power Technologies, Deepwater Wind, and Public Service Electric & Gas. Our growing list of international colleagues, representing over ten different countries, is too long to list here. Finally, we acknowledge the daily support of COOL faculty, research staff, and students who work alongside us. The combined efforts of this diverse group are transforming ocean observing capabilities globally at a critical time for the unselfish benefit of generations to come. Thank you all for providing the inspiration that keeps us moving forward.

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