The LEO-15 Coastal Cabled Observatory – Phase II For the Next Evolutionary Decade of Oceanography

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Abstract – The Long term cabled Ecosystem Observatory at 15 meters (LEO-15) deployed in 1996 has served the scientific community well for over a decade. Simultaneously, methods to acquire spatial datasets that were difficult to sustain in the 1990s have evolved to the point where sustained operation over ecologically relevant regional scales is a reality. Rutgers University, with four industry partners, has developed a sustained regional coastal observatory for the Mid-Atlantic continental shelf. The observation network includes remote sensing systems (satellite imagery and HF radar) providing spatial data for the surface ocean and two long-duration subsurface sampling systems (autonomous gliders and cabled observatories). The network is controlled in an operations center located on Rutgers main campus so that it is both sustainable and readily accessible for research and teaching. The cabled network has been undergoing extensive upgrades after decade at sea, and those upgrades improving the integration the LEO-15 Coastal Cabled Observatory into the broader ocean observing network are described.

The world's continental shelves cover only 10% of the surface of the globe but account for most of the world's primary productivity and are home to most of the world's fish species. The coastal oceans throughout the world are undergoing profound transformations due to a massive increase in the flux of nutrients, fishing pressures, and introduction of exotic species that result directly from the inevitable population growth of humans. For example. coastal eutrophication alters microbial community diversity and metabolism, leading to a long-term change in the chemistry of continental shelves. The change in chemistry is often catastrophic to humans, leading to massive losses of fisheries, the production of extremely potent green house gases, altered food webs, and potentially permanent loss of marine biodiversity (extinction). These changes are driven by human-induced at both local pressures and global changes to the ocean-climate system. Therefore it is not surprising that the U.S. Commission on Ocean Policy, stated the need for "sound science for wise decisions" to ensure the sustainable use of our coastal oceans for this and future generations. The Commission also highlighted the need for, "a robust infrastructure of cutting edge technology forms the backbone of modern ocean and coastal science and effective resource management and enforcement". It was against this backdrop, the Rutgers Coastal Ocean Observing Laboratory (COOL) evolved. Here we describe Rutgers history and present status in its long term effort to bring new observational technologies to the field of coastal oceanography. We will also highlight how it fulfills many of the needs highlighted by the U.S. Commission on Ocean Policy.

LEO-15 Coastal Cabled Observatory In the early 1990's Fred Grassle (Rutgers University, RU) and Chris von Alt (Woods Hole Oceanographic Institution, WHOI) designed a visionary cabled observatory system for the sea floor [1]. Their 1993 proposal to NSF (Figure 1) was funded before the World Wide Web was even considered useful by the scientific community. The Long-term Ecosystem Observatory (LEO-15) was constructed at WHOI, a 10 km long electro-fiber optic cable connected to the Rutgers Marine Field Station (RUMFS) near Tuckerton, New Jersey was buried in the seabed, and, in 1996, science Nodes A and B were deployed in 15 m of water, located 8.1 and 9.6 km, respectively, offshore [2].

Table 1. The Desired Goals for LEO-15 in the 1990's.

1) Continuous observations at frequencies from seconds to decades,
2) Spatial scales of measurement from millimeters to kilometers,
3) Practically unlimited power and broad bandwidth, two-way transmission of data and commands,
4) An ability to operate during storms,
5) An ability to plug in any type of new sensor and to operate them over the Internet,
6) Bottom mounted winches cycling instruments up and down in the water, either automatically or on command,
7) Docking stations for a new generation of autonomous (robotic) underwater vehicles (AUVs),
8) An ability to assimilate node data into models and make three-dimensional forecasts for the oceanic environment,
9) Means for making the data available in real-time to schools and the public over the Internet, and
10) Low cost relative to the cost of building and maintaining manned above- and below-water systems.

Through NOAA support for research, operations and maintenance, the LEO-15 system has served the scientific community well for over a decade [3-6], with most of the initial goals achieved (Table 1). The general public, and pre-collegiate educational programs, have also utilized the data [7-8]. In the process, many lessons have been learned [9].

Coastal Predictive Skill Experiments at LEO. In a program initiated by the National Ocean Partnership Program (NOPP) and further supported by ONR, NSF and NOAA, Rutgers University led a series of month long Coastal Predictive Skill Experiments (CPSEs) each summer from 1998-2001 in the vicinity of the Long-term Ecosystem Observatory. Scientific motivation was provided by the need to understand 3-D coastal upwelling and its interaction with alongshore topographic variations, its effect on phytoplankton distributions, and its relation to dissolved oxygen. To achieve the goals of the CPSEs (Table 2), a spatially-extensive coastal ocean observatory was operated for one month duration each summer [Figure 2]. The LEO CPSE network included remote

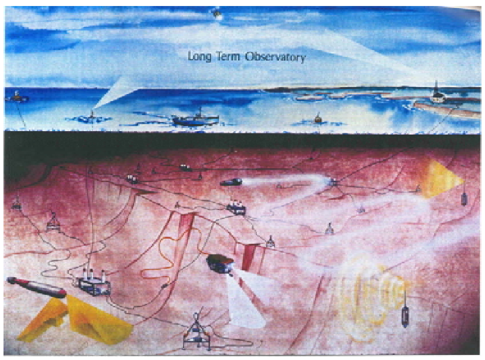

Figure 1. Artist conception of LEO from the original proposal funding LEO.

sensing data from satellites, aircraft and shore based HF Radars, a cross-shelf mooring array, and numerous research vessels and autonomous underwater vehicles. Nearly 200 researchers from over 30 institutions participated [2, 9]. Operation of the system required radical collocation of scientists and technicians to the RUMFS coastal facility, making the system difficult to sustain for prolonged periods. Scientific results are

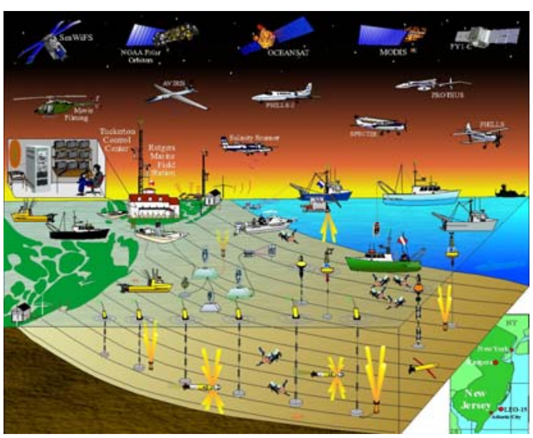

Figure 2. LEO during the CPSE efforts.

summarized in a special Coastal Observatories section of JGR [10]. The success demonstrated the value of the NOPP partnership model for the rapid transition of new observational technologies into widespread use by the scientific community and beyond.

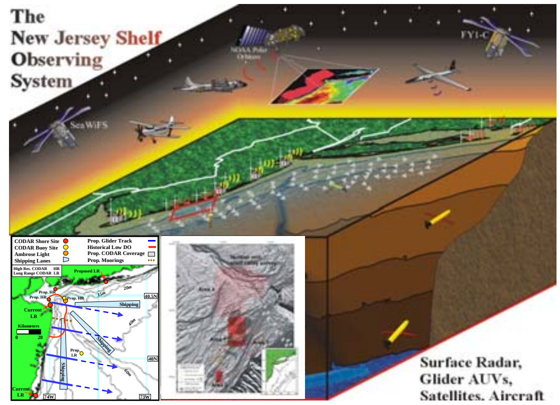

Figure 3. The shelf wide COOL observatory. The insets show to process study experiments within the observatory, LaTTE (NSF) and SW06 (ONR).

Table 2: General goals of the LEO Coastal Predictive Skill Experiments, 1998-2001.

1) Build a distributed observation network using modern remote sensing, *in situ* and meteorological instrumentation,
2) develop an ability to process, visualize and combine diverse datasets in real-time to generate data-based nowcasts of the 3-dimensional ocean structure,
3) development of a new coastal ocean circulation model with multiple turbulence closure schemes and improved boundary conditions obtained through coupling to atmospheric models, large-scale ocean models, and surface wave models,
4) The ability to assimilate multivariate datasets into the ocean model in real time to generate nowcasts and forecasts of the three-dimensional ocean structure,
5) The development of adaptive sampling strategies that use the nowcasts and forecasts to guide ship-towed and autonomous underwater vehicle sampling for interdisciplinary applications,
6) The development of an open access database management system for wide-spread distribution of the data, nowcasts and forecasts, and
7) To provide scientists a user-friendly data-rich environment in which to conduct focused research experiments.

The Rutgers University (R.U.) Coastal Ocean Observation Lab (COOL) developed a plan to implement the New Jersey Shelf Observing System (NJSOS) in the late 1990s (Figure 3). The concept can be considered a coastal implementation of Stommel's fictional 1980's Slocum Mission and Munk's 1+1=3 scenario [11] for a well sampled ocean. In Munk's scenario, the combination of remote sensing surface data with extensive subsurface sampling is required to elevate ocean science beyond the 1900's "Century of Undersampling".
The objective was to develop and transition the technologies tested at LEO during the CPSEs into a shelf-wide observatory capable of sustained year-round operations. Long-term academic-industry partnerships were forged with SeaSpace for satellite imagery, CODAR

Ocean Sensors for HF Radar mapping, Webb Research Corporation for long-duration autonomous underwater gliders, and WETSAT for cabled observatory operations to develop these four targeted technologies into a regional network. The envisioned observatory would provide interdisciplinary scientists sustained spatial datasets at ecologically relevant scales. The sustainability requirement drove the need away from an operational model based on traditional radical collocation to a relatively untested virtual collocation model. Implementation began with the installation and testing of the first U.S. east coast long-range CODAR HF radar system in 2000. Additional key milestones include the development of reliable global Iridium satellite communications with the Webb Slocum Gliders in 2003, the installation of a new SeaSpace X-Band satellite receiver in 2003, and the upgrade of the LEO coastal cabled observatory that began in 2005. Most critical was the 2005 establishment by Rutgers' Cook College of a cost-center featuring a centralized observatory control room on Rutger's main campus known as the COOL Operations Center.

COOL Operations Center The COOL Operations Center maintains the world's most advanced coastal ocean observatory that it controls in a facility popularly known as the COOLroom (Figure 4). Start-of-the-art sampling capabilities are continuously upgraded as new technologies developed and demonstrated by the research group are immediately transitioned into the operational setting of the Center. The mission of the center is to sustain operations of key observing technologies for

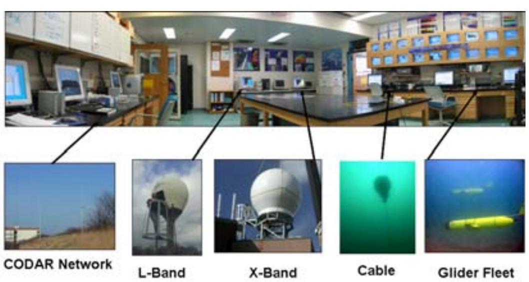

Figure 4. The COOL Operations Center.

scientific research, technology development, and education/outreach. Under the leadership of a director, the group consists of staff members who oversee the hardware (responsible for maintaining the instrument platforms, sensors, communications and telemetry, insuring data makes it from the field to the lab in real-time) and software (responsible for processing acquired data, generating real-time visualizations for the web, establishing and implementing QA/QC procedures, maintaining quality controlled archived, and systems control software for mission control).

Cost-effective sustained spatial sampling of the coastal ocean is accomplished with a variety of new platforms and sensors that include: (1) the local acquisition of satellite imagery from the international constellation of thermal infrared and ocean color sensors, (2) a triple-nested multi-static HF radar network for surface current mapping and waves, (3) a fleet of long-duration autonomous underwater gliders equipped with physical and optical sensors, and (4) a cabled observatory for water column time series. Raw datasets are shared with a variety of super-users throughout the U.S. for real-time backups, data archiving, and advanced product generation. Each of these technologies provides long-term, synoptic scale data that are an invaluable asset for researchers conducting process studies within the observing system region. Operational data products are produced in real time and displayed on the World Wide Web for use by scientists, educators, decision-makers and the general public. Website access peaks in the summer, averaging over 140,000 hits/day in 2004.

SeaSpace Satellite Acquisition Systems. COOL has continuously operated an L-Band satellite tracking and data acquisition system since 1992 and a larger X-Band system since 2003. Both systems enable local real-time access to the full resolution direct-broadcast imagery from an international constellation of polar orbiting satellites. The L-Band system currently tracks the NOAA Polar Orbiting Environmental Satellites (POES) and China's FY1-D. Products include the operational Sea Surface Temperature (SST), visible and simple ocean color. The X-Band system is used to acquire data from more recent satellites featuring higher spatial and spectral resolution. This currently includes the NASA MODIS (both Terra and Aqua) satellites and India's OceanSat (Figure 5). Tracking multiple satellites, including those operated by other countries, decreases revisit intervals, providing multiple overflights of rapidly evolving coastal features at different times of day. Missed data due to groundstation downtime is minimized through an automated real-time backup system with the University of Maine where either system can write recently acquired raw data to the other's pass disk if it senses a disruption, enabling the downstream data flow to continue uninterrupted at either location.

Figure 5. Oceansat RGB image showing the sediment plumes exiting the Hudson River Estuary.

CODAR HF Radar Network. CODARs are compact HF radar systems that provide a current mapping, wave monitoring and vessel tracking capability. COOL has continuously operated CODAR HF radars since 1999. COOL currently owns and operates over a dozen individual CODAR HF radars deployed in three nested multi-static networks in the New York Bight. Traditional HF radars operate in a mono-static backscatter mode, where the transmitter and receiver are collocated. Multi-static operation, enabled by GPS-based synchronization, allows a radar receiver to acquire signals from any radar transmitter within range. This transforms N individual mono-static radars are into a network of N^2 multi-static radars, increasing both the coverage area and the accuracy of the derived current fields. Nesting is achieved by operating at different frequencies, in our case 5 MHz, 13 MHz and 25 MHz. Higher frequencies result in higher

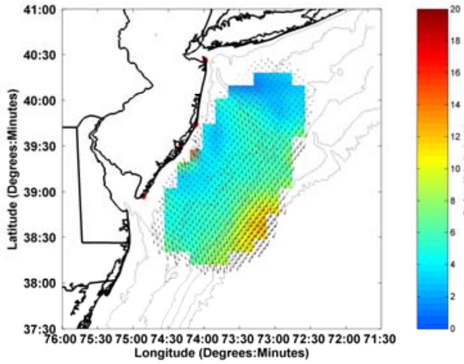

Figure 6. Four year mean CODAR surface currents (years 2002 through 2005).

resolution but over shorter ranges. The long range 5 MHz network is deployed on the New Jersey coast and the island of Nantucket, providing coverage of the continental shelf out beyond the shelf break (Figure 6). The intermediate 13 MHz network is deployed around the entrance to New York Harbor. The high-resolution 25 MHz network is deployed at the entrance to and within New York Harbor. In addition to the usual shore based systems, COOL operates the only two buoy-based bi-static transmitters, a larger spar buoy for 5 MHz and a smaller surface buoy for 25 MHz. The transmitter is bi-statically paired with an onshore receiver, extending coverage offshore and improving the accuracy of total vector currents nearshore. A new upgrade for 2005 is the installation of a compact super-directive receiver at 13 MHz that will increase range and directivity, and in 2006, the construction of a 13 MHz bistatic transmitter buoy.

Webb Slocum Glider Fleet. Slocum Gliders are autonomous underwater vehicles that propel themselves through the water by changing their buoyancy and using their wings to glide in a sawtooth pattern through the water column along a subsurface transect. At user specified intervals, the glider surfaces, transmits its data to shore via the Iridium satellite system, and checks its email boxes for new directions or missions. The Slocum Gliders have been operated jointly by COOL scientists and Webb Research Corporation engineers in science experiments since 1999, transitioning to sustained deployments by the COOL Operations Center in 2003. Since then, the Gliders have logged over 15,000 km of sampling in the New York Bight, offshore Massachusetts, Virginia and Florida, Sargasso Sea, Baltic Sea, Irish Sea, the Mediterranean and offshore Australia (Figure 7). Sensors on the gliders currently include a SeaBird CTD and a payload bay capable of carrying one of several optical sensors, including a hydroscat, a Scattering Attenuation Meter (SAM), and optical pucks. A mission control center monitors glider progress on current missions and alerts operators of any problems. Artificial intelligence is being added to the mission control center using an Agent oriented programming approach similar to NASA's approach for intelligent spacecraft. Reactive Agents are currently used to make many of the yes/no control decisions while Planning Agents are being developed to adjust flight paths to optimize sampling for specific goals.

WetSat Coastal Cabled Observatory. Based on the successful academic/industry partnership model for satellites, CODAR and gliders, Rutgers formed a partnership with WetSat to rebuild the LEO cabled observatory to address key needs (Table 3).

WETSAT's new node design (Figure 8a) was able to accomplish all of the above goals within the extremely limited NOAA operations budget available for the upgrade. Testing of the 10 km long electro-fiber optic cable revealed no degradation in the optical properties since its installation. Using the existing cable termination and power transformer box, the full node control electronics suite was replaced inside the exiting pressure housing with WETSAT's RU COOL Scientific Instrument Interface Module (SIIM, Figure 8b). The

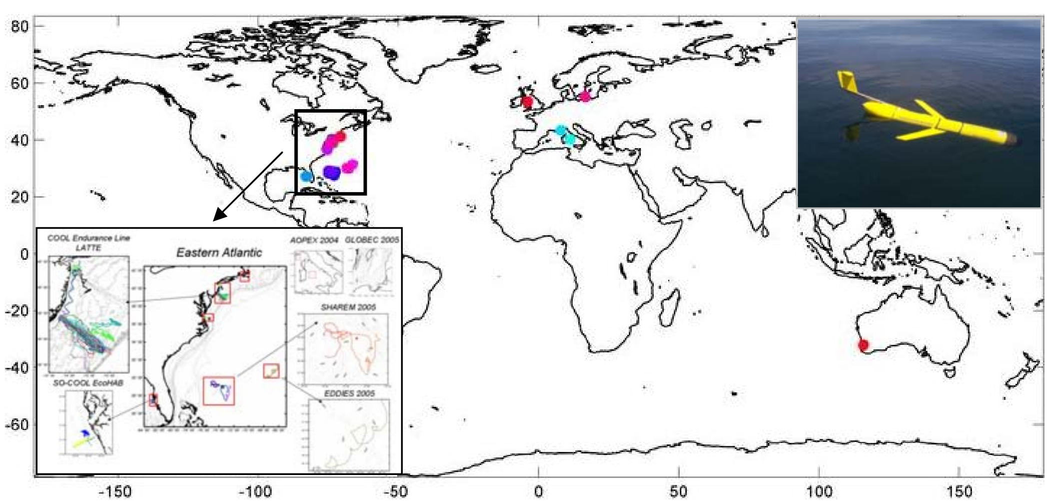

Figure 7. World-wide deployment locations for glider operations between 2003-2005. The inset shows the projects and deployments along the US East Coast.

SIIM is connected to the existing junction box which was upgraded to now include 15 science interfaces (11 serial, one winch, two 10/100 BASE-TX Ethernet, and one experimental 1000BASE-TX) and 6 video interfaces (two stationary, two pan/tilt, and two lamp). The Ethernet connections allow for additional SIIMs to be connected in the future if required. The new communication system is implemented as a local area network using Internet Protocols (IP) over 1000BASE-TX gigabit Ethernet. The new power system includes isolated and regulated power busses after the transformer box to reduce the effects of summer shore voltage brownouts, and all the SIIM power ports are independently and dynamically configurable without affecting other ports. The DACNet R4 ocean observatory operating system was installed to control and monitor node infrastructure and instruments. DACNet provides remote access over the Internet of control functions, monitoring functions, and telemetry data from any secure web browser, providing full remote control capabilities at a Network Operations Center (NOC), which in our case is the COOLroom located 150 km north on Rutgers New Brunswick campus. Finally, an observatory port simulator (OPS, Figure 8d) replicates the SIIM serial and Ethernet science ports for testing scientific instruments for observatory compatibility in the lab before deployment. The upgraded Node A was redeployed on the seafloor on January 12, 2006 for its initial sea-trial.

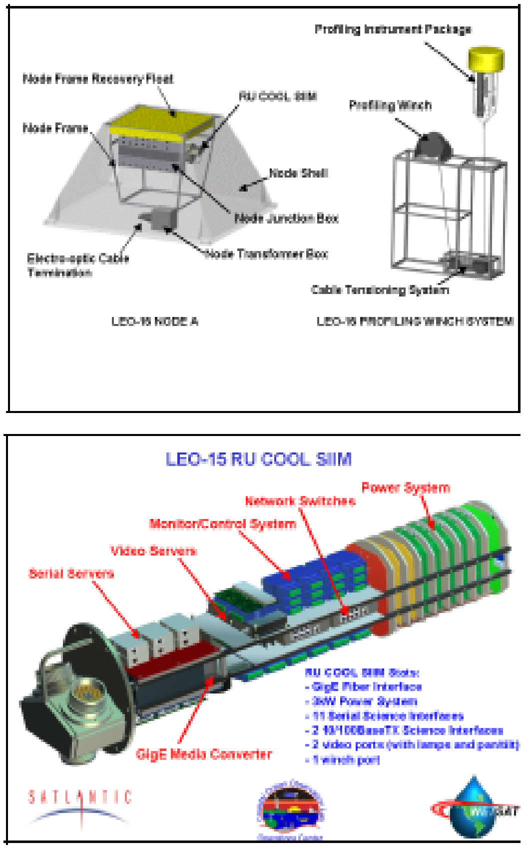

Figure 8. (a) LEO-15 Node A layout, and (c) the SIIM assembly of the node upgrade.

Table 3: Key needs identified for the LEO-15 Coastal Cabled Observatory upgrade.

1) upgrade a single LEO node allowing the second LEO node to keep running on the old system, making use of as much of the existing infrastructure,

2) modularize hardware to improve reliability and serviceability

3) separate the winched system as an independent and easily recoverable, serviceable and ultimately replaceable unit

4) update the communication standards to a post-WWW environment,

5) improve power control to individual sensors and systems

6) provide a larger number of simpler interfaces between new sensors and the permanent infrastructure,

7) increase the video capabilities to allow for more cameras and improved control and recording,

8) provide upgradeable control software with a support group

9) provide a means for moving the cable control interface from the cable landing site to an offsite control center

10) provide a shore-based simulator to test sensors before deployment.

New Masters Degree in Oceanographic Technologies. Given the advances in ocean technology, who will run this and other ocean networks, given the small available trained workforce? A new Masters degree in Oceanographic Technologies was recently established at Rutgers University. The purpose of the new degree is to produce Masters-level students in oceanography with background technology training and hands-on experience in a modern integrated and sustained research observatory. The program will generate the type of graduates required to operate the rapidly expanding network of research and applied observatories currently being constructed. Duration of the program is that of a standard Masters degree, typically 2-3 years depending on the time required for the Masters thesis. An important feature of the program is direct participation in ongoing research programs. Students will have numerous hands-on training opportunities in the collaborative environment of the R.U. COOL Operations Center. It is anticipated that a small cohort of 3-6 students will enter the program each year. Interacting as peers, they will learn from each other in a team oriented environment. The program was developed in collaboration with a similar evolving Masters program in Operational Oceanography at the University of Bergen in Norway. The U.S. side of this collaboration is currently being supported by the G. Unger Vetlesen Foundation.

Education and Outreach. The mission of the Institute of Marine and Coastal Sciences Education and Outreach (E&O) group is to promote ocean literacy through the development of a broad range of products and services that use the unique scientific resources and assets of IMCS. The group's serves a variety of clients including K-12, community college, universities, the private sector, local-regional-state-national-international government agencies, non profit organizations, news media, and the general public. Under the leadership of a director the group consists of staff members who oversee the communications (website management and correspondence for projects and intitatives) and science education (linking scientists and their programs to the K-12 education community and bringing ocean education to the classroom).

The education and outreach group delivers approximately 3-4 professional development workshops/institutes for K12 educators (> 3 day programs), 20-30 one day in-service professional development programs or consultations, or coastal decision maker workshops for municipal officials, 4-8 public/family science programs, 1-2 outreach events, and 3-6 print products annually. In addition, the group consults and assists in the writing of 15-25 broader impact statements" annually, either serving the programmatic needs of the scientists directly or "brokering" the service to a partner in the informal or formal education community.

As both the E&O group and Operations Center have matured, it has determined that a joint appointment would provide the ability to improve data products, visualizations, and delivery mechanisms for the data products. A Data Translator was hired to work with the leads from the data acquisition and data processing teams to develop relevant visualizations for a range of user groups (anyone from a scientist, to K12 educator, to the media). This position allows fosters collaboration between the two groups, ensuring the operations group is aware of the visualization needs of E&O efforts, and provides the E&O group with access to upcoming data products and research findings for story development. Additionally, the data translator is currently assisting the data processing team in the development of a data management system and new operational visualizations to ensure smooth an efficient collaboration between data archiving, retrieval, and data product delivery to relevant user groups.

Conclusions. The field of oceanography and the tools oceanographers use are maturing, prompting and enabling more collaborative and interdisciplinary science as well as economically vital applications. As this process continues, policy decisions on the safe and sustainable use of our coastal oceans will increasingly depend on scientific knowledge of the environment to improve both its prediction and our understanding of the downstream consequences. Improved predictions for decision making requires sustained observations to continuously update the present state of the environment, and continued scientific research to improve our understanding of the processes that control how that environment will evolve in the future. Universities already are very good at producing research oceanographers. As the field continues to mature, additional effort will be required to train the new technology proficient operational oceanographers to sustain the observatories, and to educate the broader public on the linkages between the ocean and the global environment to effect policy.

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