Operational Observation Networks for Ports, a Large Estuary and an Open Shelf

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Introduction

This paper describes the goals, capabilities and accomplishments of three operational coastal ocean observation networks. In the companion paper in this volume, the authors discuss reasons for the rapid proliferation of coastal ocean observation networks. Any attempt to discuss the goals, capabilities and accomplishments of the many established and emerging sites is well beyond the scope of this paper. Because many observation networks are local, the goals are often local. Because they are not static, but are constantly being improved, upgraded, and used, the capabilities and accomplishments are also constantly changing and are often several years ahead of descriptions and results available in the published literature. It therefore would be a disservice for the authors to attempt to accurately portray the current state of an observation system in which we were not directly involved.

Rather than limit our discussions to generalities, the authors instead chose to highlight here three specific observation systems that span the scales from ports, to a large estuary, and on to the open coast. The Physical Oceanographic Real-Time System (PORTS) is operated by the NOAA National Ocean Service in five of the busiest U.S. harbors. The Chesapeake Bay Observing System (CBOS), operated by the University of Maryland, covers the entire Chesapeake Bay. The Long-term Ecosystem Observatory (LEO-15) is operated by Rutgers University on the open coast offshore of Tuckerton, New Jersey. Each system is considered representative of the state of the art for its application region. The systems share many common qualities. They all have long-term goals, but real-time applications seem to be paying most of the bills. They observe on relatively local scales, while recognizing the need to expand regionally. They all strive to make their data accessible over the World Wide Web to the general public as well as the scientific community. They have all benefited from partnerships between university researchers, government agencies and commercial enterprises through programs such as the National Ocean Partnership Program (NOPP).

The Physical Oceanographic Real-Time System (PORTS) is a centralized data acquisition and dissemination system that provides real-time observations . . . from numerous locations around a bay or harbor.

An Observation Network for Harbors—PORTS

Setting

The Physical Oceanographic Real-Time System (PORTS) is a centralized data acquisition and dissemination system that provides real-time observations (updated every 6 minutes) of water levels, currents, water temperature and salinity, wind speed and direction, and atmospheric pressure from numerous locations around a bay or harbor (Figure 1). Nowcasts and 24-hour forecasts of these parameters from numerical oceanographic models driven by real-time data and forecast meteorological fields from weather models are also being implemented.

PORTS systems were designed and installed by NOAA's National Ocean Service (NOS) and are operated in partnership with the local marine community for each bay or harbor. Full PORTS systems are presently operating in the Tampa Bay (5 locations, 15

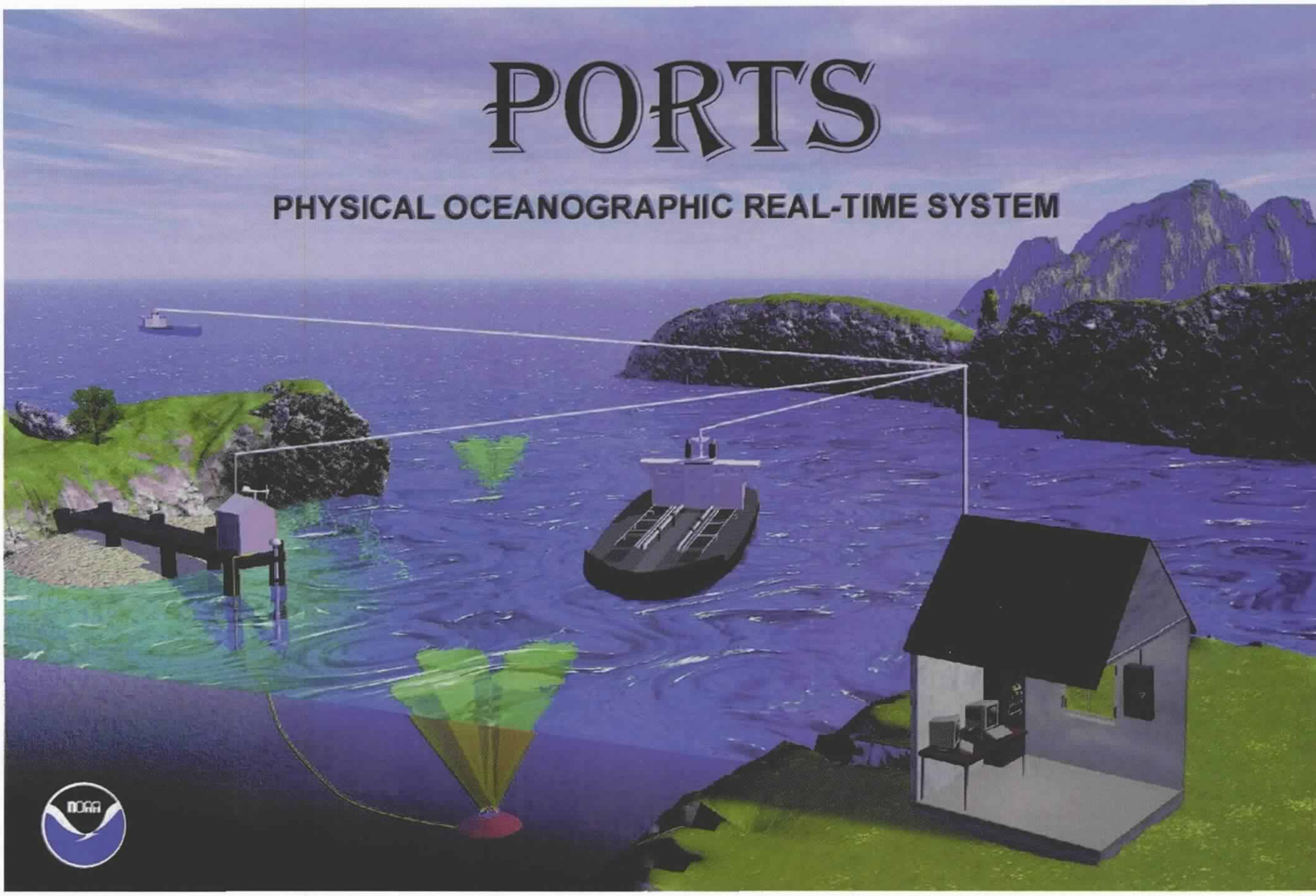

Figure 1: The Physical Oceanographic Real-Time System (PORTS) operated in Tampa, San Francisco, Galveston and Chesapeake Bays, and in the Port of New York/New Jersey.

instruments), the Port of New York and New Jersey (4 locations, 14 instruments), San Francisco Bay (9 locations, 38 instruments), Galveston Bay (5 locations, 26 instruments), and Chesapeake Bay (5 locations, 22 instruments), with plans to install similar systems in several other ports around the U.S. Systems with only a single water level gauge and several meteorological instruments ("PORTS Lite") are installed at Anchorage and Nikiski, Alaska, and Seattle and Tacoma, Washington. In addition, individual stations of the National Water Level Observation Network (NWLON) are also accessible in real-time (but are updated every 3 hours). Quasi-operational nowcast/forecast model systems developed by the Coast Survey Development Laboratory in NOS are running daily (with output on restricted Websites) for three PORTS locations: Chesapeake Bay, The Port of New York and New Jersey; and Galveston Bay. A USGS developed model is being run in a similar capacity for San Francisco Bay. The University of South Florida is developing a nowcast/forecast model system for Tampa Bay.

PORTS was originally implemented to serve the commercial navigation community, whose large deep-draft ships required more accurate water level information (than could be provided by astronomical tide tables) in order to safely enter and leave depth-limited U.S. ports. However, these data have many non-navigational uses and are finding a growing user community.

Goals

The primary goals of the PORTS program are to: promote navigation safety, improve the efficiency of U.S. ports and harbors, and ensure the protection of coastal marine resources. PORTS (used in combination with nautical charts and GPS) provides ship masters and pilots with accurate real-time information required to avoid groundings and collisions. PORTS installations in U.S. harbors have the potential to save the maritime insurance industry from multi-million dollar claims resulting from shipping accidents. Access to accurate real-time water level information and 24-hour forecasts allows U.S. port authorities and maritime shippers to make sound decisions regarding loading of tonnage (based on available bottom clearance), maximizing loads and limiting passage times without compromising safety. PORTS is important to environmental protection, since marine accidents can lead to hazardous material spills that can destroy a bay's

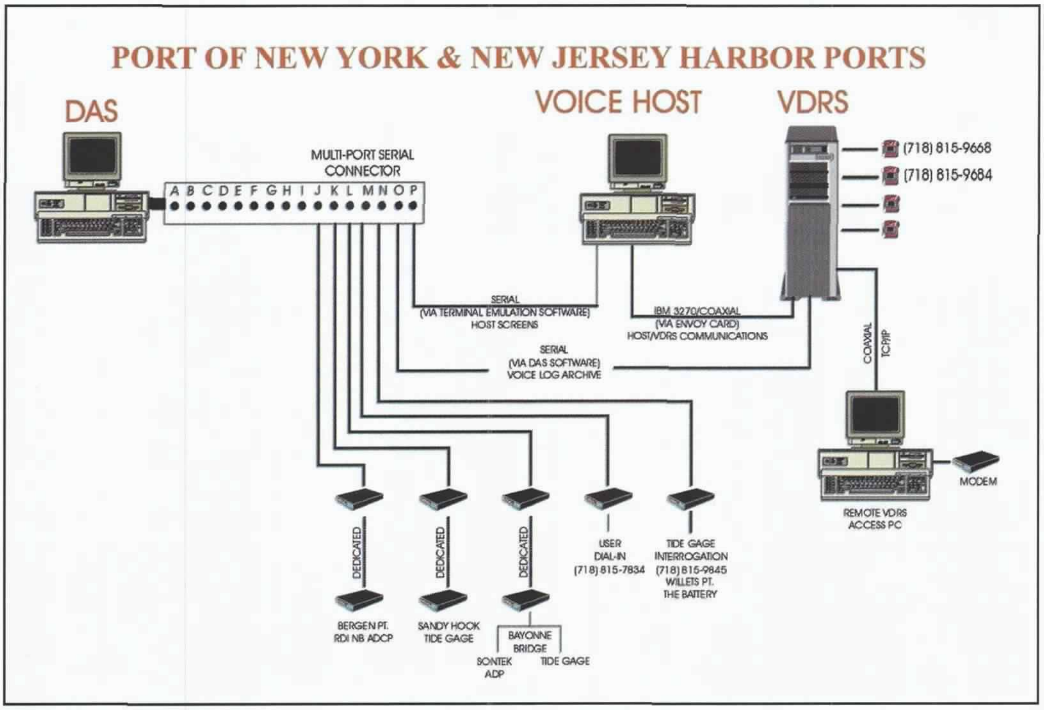

Figure 2: Schematic of the operational PORTS system for the Port of New York/New Jersey.

ecosystem and the tourism, fishing, and other industries that depend on it. Real-time and forecast circulation information from PORTS is also used to better predict the movement of hazardous spills from marine accidents, thus making cleanup more efficient.

Capabilities

PORTS uses some of the latest developments in telecommunication and oceanographic sensor technology. Data and information from a PORTS site can be accessed via: (1) Internet website [www.co-ops.nos.noaa.gov], which provides various graphical displays of not only the latest values but also of data from the previous three days; (2) touch tone phone (including cellular phone) dial up to a voice data response system (that translates the most recent data into words); and (3) phone dial up with computer and modem (to obtain a text screen of the latest values). PORTS data will also be pulled into vessel traffic services (VTS) systems, "smart bridge" systems on commercial ships, and Electronic Chart and Display Information Systems (ECDIS).

Data transmission from the remote data collection sites to the PORTS Data Acquisition System (DAS) (Figure 2) is accomplished in several ways: (1) utilizing high-speed dedicated data lines (T-1), including those used by the U.S. Coast Guard (asynchronous data interfaces are used to interface PORTS equipment with T-1 line multiplexers.); (2) line-of-site radio modems as well as wire line communication, which allow point-to-point applications with simple 3-wire RD232 interface connections; and (3) standard telephone lines installed at each water level station to allow administrative communication and backup transmission to the DAS. The DAS receives remote data, determines data type, initiates the appropriate program for that data type, performs quality control tasks, archives the data, and formats the data for output. Data transmission from each PORTS DAS to NOS headquarters in Silver Spring, Maryland (where the Web pages are maintained) is over an intranet using the MCI Network. A Continuously Operational Real-time Monitoring System (CORMS) has been developed to provide a national centralized quality control system, which determines data quality, evaluates system performance, identifies invalid or suspect data to users, and provides information needed by maintenance crews to repair PORTS systems.

Water levels at each location are measured using a downward-looking air acoustic sensor, which is referenced to ten tidal bench marks, which in turn are referenced via GPS to the National Spatial Reference System. An acoustic pulse is sent through a sounding tube from the transducer down to the water surface and back. The two-way travel time is measured for the reflected signal, from both the water surface and a calibration point in the tube. The calibration signal provides the sensor with a means of correcting each water level measurement for variations in air speed in the column due to changes in temperature or humidity. Six-minute values are obtained from one-second sampled data. Backup water level measurements are made at each location using an electronic pressure transducer integrated into a dry-purge "bubbler" system, where nitrogen gas is regulated to slowly purge through an open orifice mounted below the water surface; the transducer senses pressure change in the system as the water level changes. In addition to these data being disseminated via the PORTS system, they are also transmitted via GOES satellite every 3 hours to NOS headquarters for archiving and further quality control.

Vertical profiles of currents are measured using acoustic Doppler current profiler (ADCP) systems. Each ADCP is generally placed on the bottom in an upward-looking configuration using a low-profile platform.

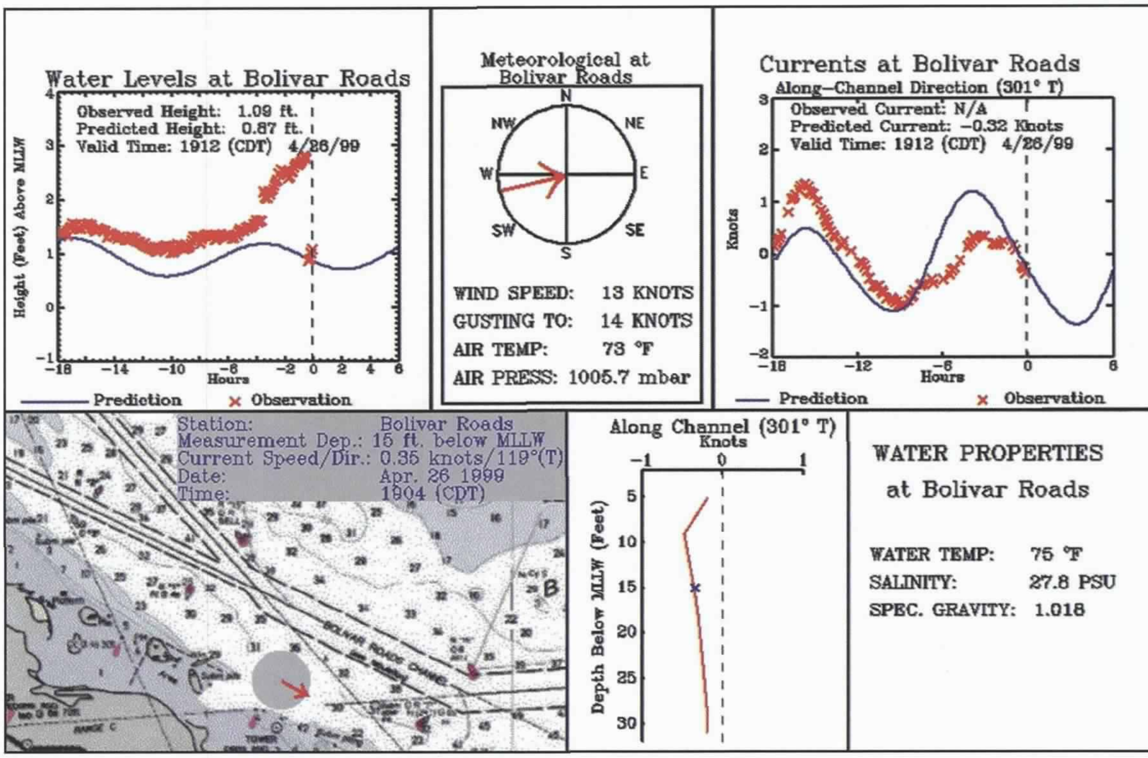

Figure 3: Real-time water levels, winds, currents and water properties reported at the Bolivar Roads site through the Galveston Bay PORTS system.

Water temperature, conductivity, wind speed and direction, wind gusts, atmospheric pressure, and air temperature are regularly measured with a variety of the off-the-shelf sensors, with other sensors such as visibility and rainfall added when required.

The nowcast/forecast model system being incorporated into each PORTS relies on real-time and forecast information from other sources besides the real-time information from each PORTS installation (described briefly above), including meteorological data and forecasts from NWS and other sources, and hydrological data from USGS (Figure 3). A map-based prototype Website has been implemented for the Chesapeake Bay area to provide other users with a central source for all these real-time data. Communication mechanisms for obtaining these data for the models presently rely heavily on the Internet, but will eventually include NWS's NOAAPORT and other mechanisms. The Chesapeake Bay nowcast/forecast model system is presently the most elaborate of the four model systems. Forecasts rely on forecast entrance boundary conditions provided by a coastal forecast model for the U.S. East Coast, which is driven by forecast fields of winds, pressure, and other meteorological parameters from an NWS weather model, as well as wind fields over the Bay from a high-resolution mesoscale weather model, whose boundary conditions come from the same large scale weather model and which is initialized by meteorological fields from LAPS (Local Analysis and Prediction System). Nowcasts, updated hourly, are driven with real-time oceanographic data and meteorological fields from LAPS, with data assimilation techniques being developed to improve the model prediction skill. These nowcasts provide the initial conditions for 24-hour forecast runs.

On several occasions real-time currents from PORTS have been used to help predict the trajectories of oil spills.

Accomplishments

Real-time information from 5 full PORTS systems, 4 PORTS Lite systems, and dozens of NWLON systems are presently used every day to insure safe navigation of U.S. waterways, especially by oil tankers, cargo ship, and container ships. On several occasions real-time currents from PORTS have been used to help predict the trajectories of oil spills. The first stages of the CORMS quality control system is operational. An Ocean Systems Test & Evaluation Facility (OSTEF) is being established for evaluating new instrument technology and for developing and applying oceanographic measurement quality assurance (QA) processes. Nowcast/forecast model systems have been developed for four PORTS locations and are running daily in a quasi-operational mode. These model systems are driven by real-time data and forecasts from weather models and a coastal ocean forecast system. A NOPP-funded project is underway to improve the technical skill of the Chesapeake Bay and East Coast model systems and to integrate a variety of real-time data and forecast products for evaluation by a dozen user groups. This project includes seven NOAA partners (in NOS, NWS, OAR), the University of Maryland, Princeton University, the University of Rhode Island, TASC, Inc., WSI, Inc., and the Navy.

An Observation Network for Estuaries and Coastal Embayments—CBOS

Setting

Estuaries, with their strong inputs from both land and sea into confined basins, resemble continuous reactors, where fresh water and ocean waters mix, and where nutrients derived from the land are efficiently converted to harvestable resources. These productive reactors are vulnerable to the accelerating additional uses man has made of these water bodies, including maritime commerce, recreation, and the disposal of wastes. With the increase in the population living near the coast has come the urban estuary the Hudson-Raritan, Baltimore Harbor, Tampa Bay, Mobile Bay, Galveston Bay, San Francisco Bay, and Puget Sound. Of primary concern for many estuaries is the introduction of excess nutrients from point sources (municipal sewers) and from diffuse sources such as runoff from agricultural lands, with the resulting overenrichment and environmental degradation. Unfortunately, in the face of accelerating stresses, the ability to assess trends in the health of estuaries has been woefully inadequate, and almost always, retrospective. Furthermore, as scientists reveal more complexity in the myriad interacting components of these systems, the task of detecting trends, much less predicting future conditions, has seemed increasingly daunting. We are learning that man's impacts do not always appear as sudden, obvious jumps in easily detected signals, but are typically subtle, creeping changes in sometimes unexpected indicators, slowly manifest over many decades. An example is the summertime depletion of oxygen in the lower layers of Chesapeake Bay or in the offing of the Mississippi River, which is likely the result of increasing nutrient inputs from land. Detection of these trends has been made difficult, not only by the sparseness of historical records, but also by the masking of these low, slowly varying signals by the noise of large shorter-term natural variations in the ecosystem. Although the effect of regular, short-term fluctuations can be isolated from the continuum, more worrisome are sporadic events such as phytoplankton blooms, river-flow surges, floods, and major storms that can profoundly shift the estuarine ecosystem for decades.

We are learning that man's impacts do not always appear as sudden, obvious jumps in easily detected signals . . .

As the recognition of environmental degradation of estuaries has emerged, shipboard-based monitoring programs have been instituted to guide and assess proposed actions to restore and protect these valuable resources. But both efforts labor under the challenge that the actions promise success with sufficient certainty to warrant society's expenditure of sometimes painfully large resources toward these ends. Unfortunately, shipboard surveys seldom resolve either the higher-frequency fluctuations or the rapid shifts in the ecosystem. Furthermore, they seldom measure the circulation of water, despite the strong influence that it exerts on the biology of the estuary.

Goals

The first estuarine real-time monitoring system was designed to address these deficiencies in the largest U.S. estuary, the Chesapeake Bay, which extends 200 miles seaward from the Susquehanna River mouth at the northern end, to the Virginia Capes which form the Bay's entrance. The Chesapeake Bay Observing System (CBOS) was inaugurated in 1989 by the University of Maryland Center for Environmental Science (Figure 4). From the outset, it was intended as a cooperative program among academic, governmental, military, industrial, and environmental partners. The initial goals were aimed at both ends of the variability spectrum, but were also related: (a) to examine long-term ecosystem change, and (b) to aid short-term process research.

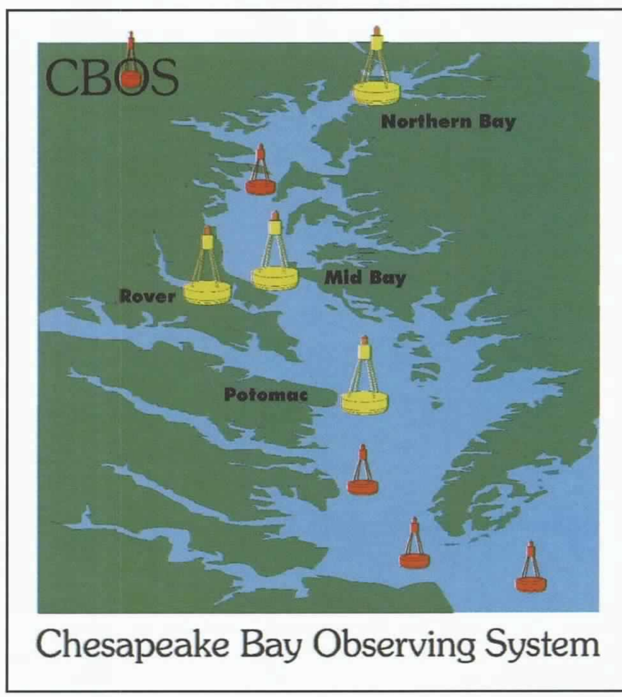

Figure 4: Chesapeake Bay Observing System. Permanent Monitoring Stations are arrayed along the central axis of the Main-Stem Bay, with four existing (yellow) and four planned (red) platforms. Rover Buoys are dedicated to research and monitoring the rivers that drain into the Bay. All buoys have individual telemetry towers on land, which communicate via the Internet to the Data Management Center at UMCES Horn Point Laboratory. Monitoring information is then processed, visualized, and released via the web (www.cbos.org).

Long-term records provide information on not only the slowly varying component of coastal ocean processes, but also provide many realizations of episodic and high-frequency fluctuations. These realizations help researchers develop a more accurate description of these processes, and ultimately improve the detectability and understanding of long-term ecosystem change. A major technique enabling this improvement is the reduction in signal-to-noise ratio by extracting the higher-frequency process signals from the lower-level, slowly varying signal.

Even with these scientific and environmental goals, there was a recognition at the outset of CBOS that an expensive and committed observing system could benefit from a wider purpose. The off-the-shelf feasibility of real-time communication opened the door for a variety of uses that are more dependent on rapid return of information than scientific analysis. One of these uses is maritime commerce. The dominant subtidal variability in water level and currents in Chesapeake Bay is caused by a quarter-wave seiche, with period of approximately 2 days, and with an amplitude of up to 1 m. The astronomical tide in Baltimore Harbor is of the order 0.5 m, so that these variations can create significant uncertainty in navigation of deep-draft vessels entering the port, where below-keel clearances are often minimal in the dredged channels. In the early days of CBOS, the expectation was that, with an accurate numerical model of the circulation of the Bay, real-time information on winds, tides, and currents in the Bay could be assimilated along with wind predictions to provide forecasts of water level in the Port of Baltimore. Although tides and currents are important for this determination, the primary need from CBOS is real-time information on winds over the Bay, which often differ significantly in both magnitude and direction from winds over land.

The excitement of real-time information is a substantial asset in education, whether in the K-12 or university classroom, or in the education of the public at large, who need to be sufficiently engaged to support the large costs of restoring the Bay.

Another use for a model fed with real-time data from CBOS is the forecasting of oil-spill trajectories. Chesapeake Bay's enclosed geometry not only enhances biological productivity, but it also renders its productivity especially vulnerable to hazardous material spills. With the improved technology for oil-spill containment and remediation, real-time information from CBOS could be crucial in directing resources during a spill. Even prior to the delivery of improved marine forecasts, real-time information on over-water winds and sea conditions is also of significant value for boating and fishing, which are of substantial economic value to the region. Commercial charter boats routinely check CBOS information prior to leaving port for the day's fishing activity.

One aspect of real-time systems that is harder to document but has real consequences is the excitement of fresh information in both science and education. Scientific ideas are often generated when new data are at hand, and before speculation is fettered by more sober analysis. The excitement of real-time information is a substantial asset in education, whether in the K-12 or university classroom, or in the education of the public at large, who need to be sufficiently engaged to support the large costs of restoring the Bay. The education process is helped by having teaching materials available online for manipulation, visualization, and interpretation of the information.

Capabilities

As originally envisioned, the Chesapeake Bay Observing System was designed as a series of 6-8 moored platforms arrayed down the axis of the Bay. As is typical of estuaries, the strong inputs of fresh water and salt combined with the Bay's topography create regional structures in circulation, property distributions, and biological resources that require a minimum number of platforms to properly represent conditions along its 200 mile axis. The intent was to maintain these platforms as Permanent Monitoring Stations, providing continuous information throughout the year and far into the future. To complement this permanent array, a series of rapidly deployable Rover Buoys was planned to provide higher-resolution information in regions of topical interest for shorter time scales. Rover Buoys could be deployed in response to events such as fish spawning, oil spills, harmful algal blooms, or process research to augment the larger Monitoring Station array. The first Permanent Monitoring Stations were launched in 1989 in the northern and middle reaches of Chesapeake Bay. The first Rover Buoys were launched in the Patuxent River, a western shore tributary, in 1993. An additional Permanent Monitoring Station was added in 1998.

The large nutrient inputs to the Bay create both high productivity and a severe depletion of oxygen in the Bay's lower depths during summer. Biofouling and anoxia degrade all underwater sensors, but especially chemical and optical sensors, requiring short service intervals during the summer. However, even during the winter, underwater sensors must be turned around within 6 weeks. Such a service schedule would be prohibitively expensive if the large Monitoring Station buoys were replaced at this frequency because they require a larger, more expensive vessel that has sufficiently heavy deck gear to handle the buoy and mooring tackle. Instead, buoys are deployed for a year and underwater sensors are mounted on a separate taut-wire mooring with subsurface floatation, and the data are relayed to the surface buoy by acoustic telemetry. These adjacent moorings can then be serviced with smaller, less-expensive vessels.

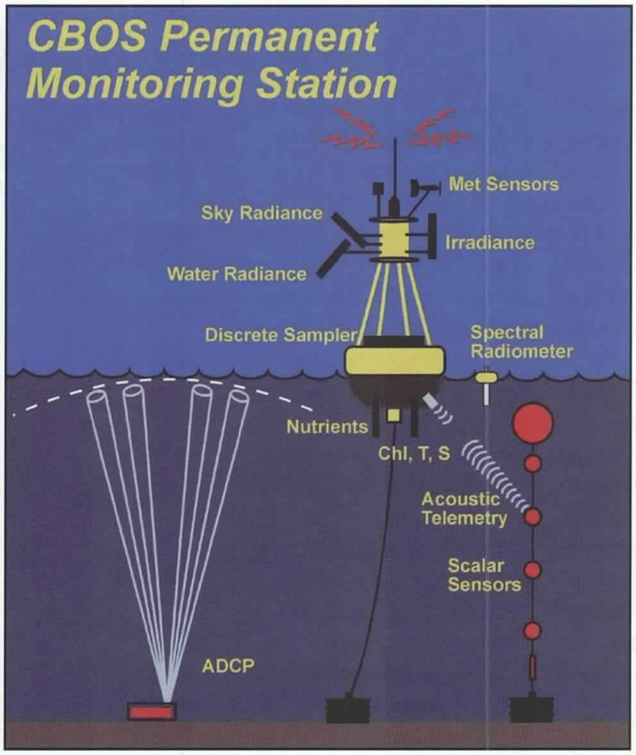

Figure 5: Schematic diagram of a CBOS Permanent Monitoring Station, showing the full sensor suite and the configuration of the underwater sensor array. The surface buoy was designed sufficiently large to remain on station for one year, to allow onboard access to electronics, and to provide space for shorter-term sensor experiments. Biofouling and summer anoxia require servicing of underwater sensors at intervals of less than 4 weeks. For this reason, a separate taut-wire mooring is deployed adjacent to the surface buoy, and data are communicated via acoustic telemetry.

The size and design of the Monitoring Station buoys has evolved, with the early buoys having discus, or surface-following hulls designed for wave measurements. More recent buoys (Figure 5) have a more hemispherical hull shape, with longer instrument wells and a 1-ton counterweight. These hulls are more a heave-buoy design, with the intent of stiffening the rolling moment to improve meteorological and optical measurements. Hulls are Surlyn ionomer foam, which has proved durable and protective of the onboard processors. The two original hulls have been used for 10 years, and are still deployed annually.

At the outset of CBOS, UHF and VHF radio linked line-of-sight to shore stations was chosen for telemetry. Satellite links were significantly more expensive, and sometimes encountered substantial delays in data transmission. When cellular phone coverage became broad enough to cover the Bay, and the new and less costly data-packet cellular technology was introduced, this method of communication was considered. Uncertainty in the reliability of cellular-phone telemetry in the Bay region has led to the postponement of this conversion. In the meantime, the need for higher bandwidth for additional sensors led to the incorporation of Spread-Spectrum radios for two new CBOS buoys.

Once the data are received at shore stations, they are transmitted via the Internet to a central server at UMCES Horn Point Laboratory in Cambridge, Maryland for processing and visualization, and then delivered to the public by the Web (Figure 6). A real-time data-base engine called AutoMate was built to handle the entire procedure, from acquisition through visualization and downloadable archiving on the Web.

In 2000, an additional Permanent Monitoring Station and two additional Rover Buoys will be added to CBOS. As these buoys have come online, there will be an expansion of the sensor suite, to obtain full vertical profiles of currents, temperature, and salinity. At present, the additional cost and effort to maintain biological and chemical sensors, such as oxygen, chlorophyll, nutrients and turbidity, has limited deployment intervals to as short as two weeks. For this reason, record lengths of multiple deployments of biological sensors are seldom longer than one or two seasons. Various biofouling reduction techniques have been explored with the aim of extending deployments to sufficient length and to eventually move these sensors to operational status. Optical sensors for incoming irradiance and water-leaving radiance have been outfitted on a stationary tower

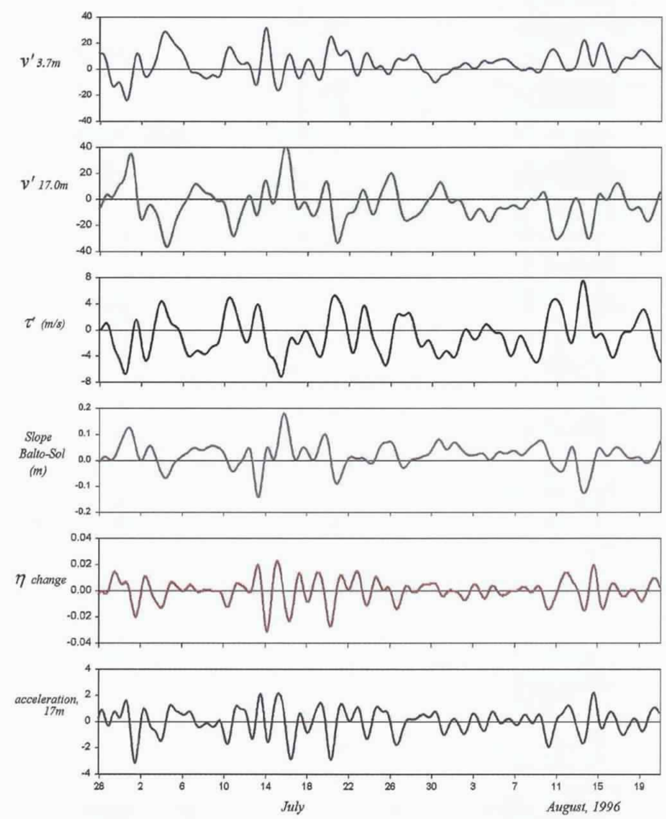

Figure 6: Subtidal axial currents from Acoustic Doppler Current Profiler (v', in cm/sec, at 3.7m and 17.0m), northward component of wind (τ' in m/sec), surface slope between Baltimore and Solomons Island, change in water level (η), and acceleration in lower layer currents at 17m at Mid-Bay CBOS Permanent Monitoring Station in summer 1996. Current and water-level fluctuations are primarily wind-driven, with the upper-layer directly forced and the lower layer responding at a lag of 12 hours to the resulting tilt of the sea surface.

and CBOS buoy to develop techniques for obtaining continuous measurements of ocean color and chlorophyll in support of aircraft and satellite overflights.

Accomplishments

In the early days of CBOS, system development required sufficient focus that occasionally the primary goals of both long-term ecosystem change and short-term process research were neglected in the fray. Over the last few years, as more science programs have para the last few years, as more science programs have participated in CBOS and come to depend on the system to provide a temporal and physical context for shorter- term research, the initial design has begun to come to fruition. As scientific papers and graduate theses using CBOS data have been produced, a wider audience has considered the system as a resource for research on the Bay. The National Science Foundation Land Margin Ecosystem Research Program on Chesapeake Bay has relied heavily on CBOS data. In addition, new scientific programs have taken advantage of CBOS platforms and data telemetry to install new sensors for biology and chemistry. Furthermore, additional sensors have been added to provide input to operational models of sound propagation for military installations, for which artillery concussions and sonic booms are the primary environmental problems. The NOAA Air Resources Laboratory have installed sensors for monitoring the atmospheric deposition of nutrients, which are the primary pollutant entering Chesapeake Bay. The NOAA Center for Coastal Ecosystem Health is considering establishing a Sensor Testbed Facility on the Chesapeake Bay, and CBOS would provide platforms and telemetry infrastructure to aid in this effort.

Real-time CBOS data will be assimilated in a numerical model to improve these forecasts of winds and water levels over the Chesapeake Bay region as part of the same NOPP project discussed under PORTS. As wave sensors are added to the CBOS suite, a real-time wave forecasting model will be put in place. Eventually, an oil spill model assimilating CBOS data will be constructed to guide containment and cleanup efforts. To realize the promise of CBOS for education, K-12 teachers have been incorporated into the program as summer fellows, developing teaching materials and activity modules. With these aids, science teachers will be able to have their students access CBOS online, and then download and analyze the data for a variety of scientific lessons.

An Observation Network for the Open Coast—LEO-15

Setting

The Rutgers University Long-term Ecosystem Observatory at the 15 m isobath (LEO-15) is an instrumented natural littoral laboratory located offshore Tuckerton, New Jersey. According to Brink (1997) at the NSF sponsored APROPOS Workshop, "shelf waters deeper than about 3 m and shallower than about 30 m have often been ignored in the past because of the very difficult operating conditions and the complex dynamics, where the water is effectively filled with turbulent boundary layers". LEO is designed to span the 3 m to 30 m water depths with an approximately 30 km x 30 km well-sampled research space (Figure 7). The LEO observation network includes multiple remote sensing, shipboard, autonomous and moored sensor systems that surround a pair of instrument platforms or nodes secured to the ocean floor.

Goals

Specific goals for the LEO-15 nodes are (Grassle et al., 1998):

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,

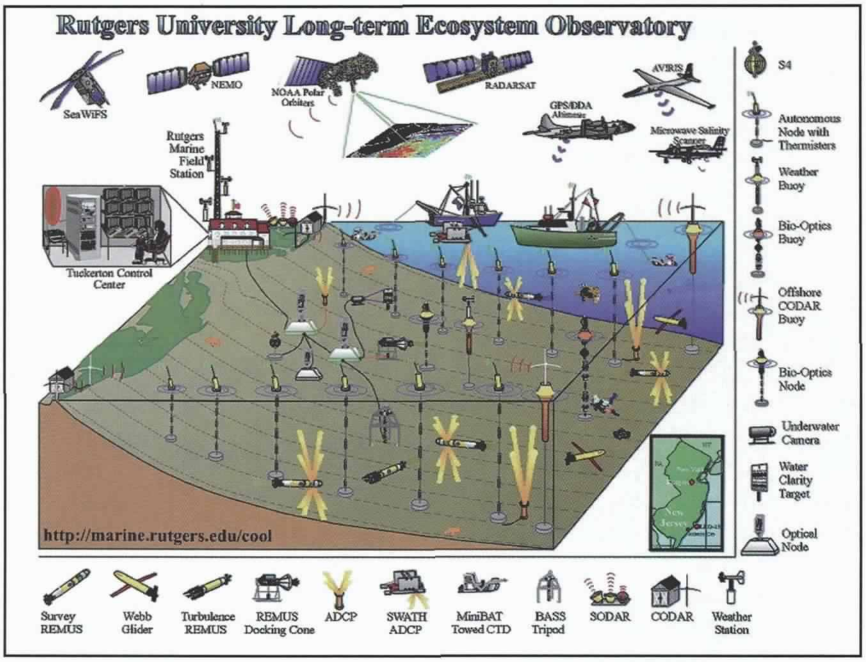

Figure 7: LEO observation network operated offshore of Tuckerton, New Jersey. Instruments shown include those used during the peak summer sampling periods.

5. an ability to plug in any type of new sensor, including cameras, acoustic imaging systems, and chemical sensors 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) to download data and repower batteries,
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.

General goals for the LEO observation network include:
1. the construction of a distributed observation network using modern remote sensing, in situ and meteorological instrumentation,
2. an ability to process, visualize and combine diverse datasets in real-time to generate data-based nowcasts of the 3-dimensional ocean structure,
3. the 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 3-dimensional ocean structure,
5. the development of new 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 LEO data, and
7. to provide scientists a user-friendly data-rich environment in which to conduct focused research experiments.

Capabilities

The two LEO nodes were installed on the ocean floor in 1996 about 10 km offshore in about 15 m of water. A buried electro-fiber optic cable links the nodes to the Rutgers University Marine Field Station (RUMFS), which provides power and access to the Internet. The cable transmits continuous power for instrumentation, and provides bi-directional communication and video links over three optical fibers. To allow for periodic servicing, the complete electronics/mechanical package from each node is recoverable by boat. Except during the busy summer season when demand is high, one node is often out of the water being serviced or upgraded while the other node maintains the long-term dataset.

Each node is equipped with an internal winch that moves a profiler vertically through the water column. The winch can be controlled by an onshore computer to automatically profile at specified intervals, or it can be manually controlled, either directly from the RUMFS shore base, or remotely over the Internet. The profiling package is typically equipped with pressure, temperature, conductivity, optical backscatter, light, chlorophyll, and oxygen sensors. The nodes are further equipped with several bottom-mounted systems, including a pressure sensor (for waves, tides and storm surge), an ADCP (for current profiles), a hydrophone, a fixed video camera, and a pan-and-tilt video camera. In addition, 8 guest ports provide power and Internet communications to additional sensors deployed by other investigators. Guest sensors have typically included tripods equipped with current meters, sediment size distribution sensors and fluorometers for resuspension and transport studies.

An autonomous underwater vehicle (AUV) docking port was installed on one of the LEO nodes during July 1998. On numerous occasions during this initial test phase, a Remote Environmental Measuring UnitS (REMUS) AUV (von Alt et al., 1997) successfully docked and was redeployed with a new mission profile downloaded from the shorebase over the fiber-optic cable. A third optical node was deployed on the sea bottom during the summer of 1999 and attached to the same fiber-optic cable. The optical node contains a winch operated profiler with a suite of sensors designed to provide data on inherent optical properties, particle size distributions, and fluorescence.

The network of observation systems surrounding the LEO nodes include satellite, aircraft and shore-based remote sensing systems to provide broad spatial coverage of surface properties, meteorological systems to provide forcing information, autonomous nodes to spatially extend the permanent LEO nodes during selected periods, and multiple shipboard and AUV systems for subsurface adaptive sampling. Satellite datasets include real-time sea-surface temperature and ocean color derived from locally-acquired direct broadcast transmissions from the AVHRR and SeaWiFS sensors, delay mode surface roughness data acquired from RADARSAT through NOAA, and delay mode hyperspectral data from the NEMO satellite scheduled for launch in 2000. Surface current data are updated hourly by a pair of CODAR HF-Radar stations located on the barrier islands to the north and south of LEO.

Local meteorological data currently are collected on a 64-meter tower located at the RUMFS. Recent upgrades include an atmospheric profiler onshore and a weather/optics buoy offshore. A single line of 6 autonomous nodes was deployed on a cross-shelf line during the summer of 1998 to act as a navigation network for the REMUS AUVs. RF-modem communications via a repeater located at the top of the meteorological tower allowed real-time tracking of the AUV survey missions. Twelve autonomous nodes were redeployed along 2 cross-shelf lines in 1999, with each node further equipped with 8 thermistors.

Two coastal research vessels are equipped for physical and bio-optical subsurface adaptive sampling. The physical survey vessel tows a Small Water Area Twin Hull (SWATH) vehicle with an ADCP off the starboard side, and a winged undulating vehicle with a CTD/OBS/Fluorometer system off the stern. A shipboard local area network with a RF Ethernet bridge to shore is used to display and transmit the high resolution physical data to shore as it is collected. The bio-optical survey vessel is equipped with multiple profilers for both apparent and inherent optical properties. An RF Ethernet bridge is used on this vessel to access and display the numerous real-time datasets to guide scientists deciding where and when to stop the boat for profiling.

Beyond the REMUS Docking Vehicle, three other REMUS AUVs were used operationally at LEO in 1998 and 1999. A REMUS Survey Vehicle equipped with upward/downward looking ADCPs and a CTD completed 15 cross-shelf survey sections in 1998 and 18 more in 1999, including a 72 km, 12 hour duration mission. A REMUS Turbulence Vehicle further equipped with fast response CTDs, shear probes and thermistors completed 4 missions in 1998 and 11 missions in 1999 to observe turbulent fluctuations at the millimeter scale. A REMUS Bioluminescence Vehicle completed its first night operations at LEO in 1999.

The Webb Coastal Electric Glider conducted its first sea-trials at LEO in 1999 with two successful deployments. These Glider AUVs are equipped with a CTD/Fluorometer. By cycling their buoyancy between positive and negative, they fly in a sawtooth pattern, potentially collecting upwards of 200 CTD casts per day for several weeks without being recovered. At regular intervals, the Glider is programmed to fly to within RF-Modem range, upload its data via the RF-repeater on the meteorological tower, then download a new mission profile for the next interval.

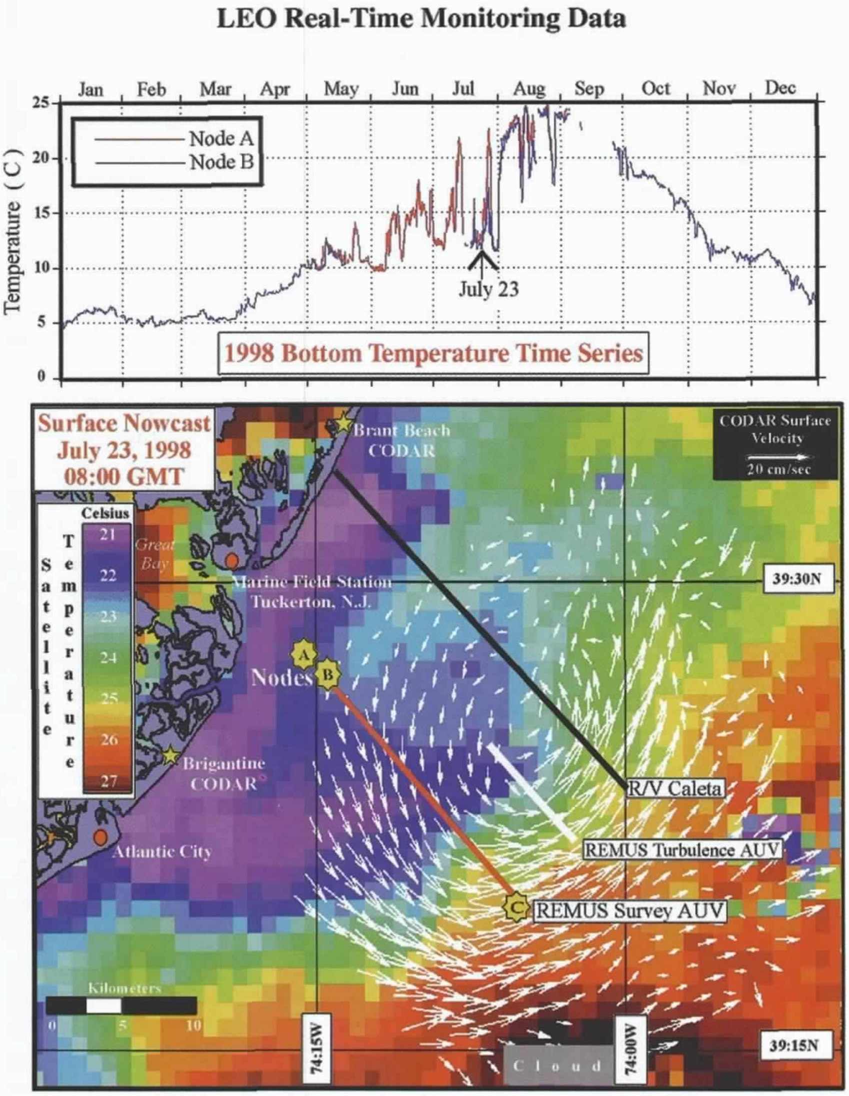

Figure 8. LEO real-time monitoring data. Top: 1998 Bottom Temperature Time Series from LEO Node A (red) and Node B (blue).
Bottom: July 23, 1998 sea surface temperature and surface current nowcast of a fully-developed upwelling center derived by detiding and low-pass filtering the combined CODAR vector velocities. Lines indicate the locations of the three cross-shelf repeat transects chosen for subsurface shipboard (black) and AUV (red, white) sampling.

Accomplishments

Extensive infrastructure and an open data policy have fostered broad participation in LEO-15 research projects by the scientific community. Over 60 researchers from over 25 institutions are currently funded for LEO-15 related research projects. NOPP partners include Woods Hole Oceanographic Institution, Naval Undersea Warfare Center, CODAR Ocean Sensors, RD Instruments, Webb Research Corporation and the US Geological Survey. The largest research programs are associated with studies of coastal upwelling and its optical, biological and chemical implications in the summer, and sediment transport in the fall. Figures 8 and 9 illustrate typical monitoring and adaptive sampling data acquired during the summer 1998 coastal upwelling experiment.

Figure 8 (top) shows the yearly cycle of warming and cooling observed in the 1998 bottom temperatures collected by the LEO-15 nodes. The largest variations in the seasonal cycle are caused by the summertime upwelling events, such as the one entering a relaxation phase on

July 23. The surface current and temperature real-time data for July 23 (Figure 8, bottom) indicated that the upwelling jet was meandering around a cyclonic eddy embedded within the cold upwelling center. This data-based nowcast, the model forecast for continued relaxation of the upwelling, and sensitivity runs showing a dependence on turbulent closure on the cold side of the front, were used to define three cross-shelf sampling transects. A ship-towed SWATH ADCP and an undulating CTD/Fluorometer (Creed et al., 1998) were sent to patrol the transect just north of the eddy center, and a REMUS Survey Vehicle was sent to patrol the transect just south. The REMUS Turbulence Vehicle was sent directly into the eddy center to observe the changing turbulence characteristics as the vehicle drove out of the eddy and crossed the upwelling front. The alongshore current component (Figure 9a, color contours) acquired by the REMUS Survey Vehicles not only indicates that the northward-flowing upwelling jet on the offshore side is confined to the upper water column, it also reveals a southward-flowing, subsurface jet on the nearshore side. The systems towed along the northern transect uncovered a similar velocity structure (Figure 9b). The offshore jet was confined to the warm water above the thermocline (Figure 9c), and the nearshore jet was found within the cold water of the upwelling center. The corresponding fluorometer section (Figure 9d) indicates that the highest phytoplankton concentrations of the season were located within the subsurface jet, leading to the hypothesis that phytoplankton concentration increases within the upwelling center may be dominated by advection from the north.

When spatially-extensive, rapidly-updated, real-time data are available, forecasters can compare the developing trends in their model generated forecast with the developing trends in the observations to see where the model is staying on track, and where it is drifting off.

The above example illustrates how adaptive sampling strategies are transformed in a well-sampled ocean. When spatially-extensive, rapidly-updated, real-time data are available, forecasters can compare the developing trends in their model generated forecast with the developing trends in the observations to see where the model is staying on track, and where it is drifting off. Adaptive sampling is no longer guided solely by the model results, but instead by data-based nowcasts and model-generated forecasts. The goal of adaptive sampling also changes. In under-sampled regions, errors in model generated forecasts are usually dominated by errors in an under-resolved initial condition. In a well-sampled region, errors in the ocean forecast may instead be dominated by imperfect model physics, such as unparameterized turbulent mixing mechanisms, or by imperfect forecasts of the atmospheric forcing. Instead of focusing on improving model initializations, adaptive systems can shift their focus to sampling regions where the physics is poorly understood and the results are sensitive to changes in their numerical parameterizations. The adaptive sampling data sets can be used for model verification, to help improve model physics, or for assimilation, to help keep the model on track despite the imperfect physics.

Observations like those illustrated above are displayed on the LEO Website

LEO Adaptive Sampling Data

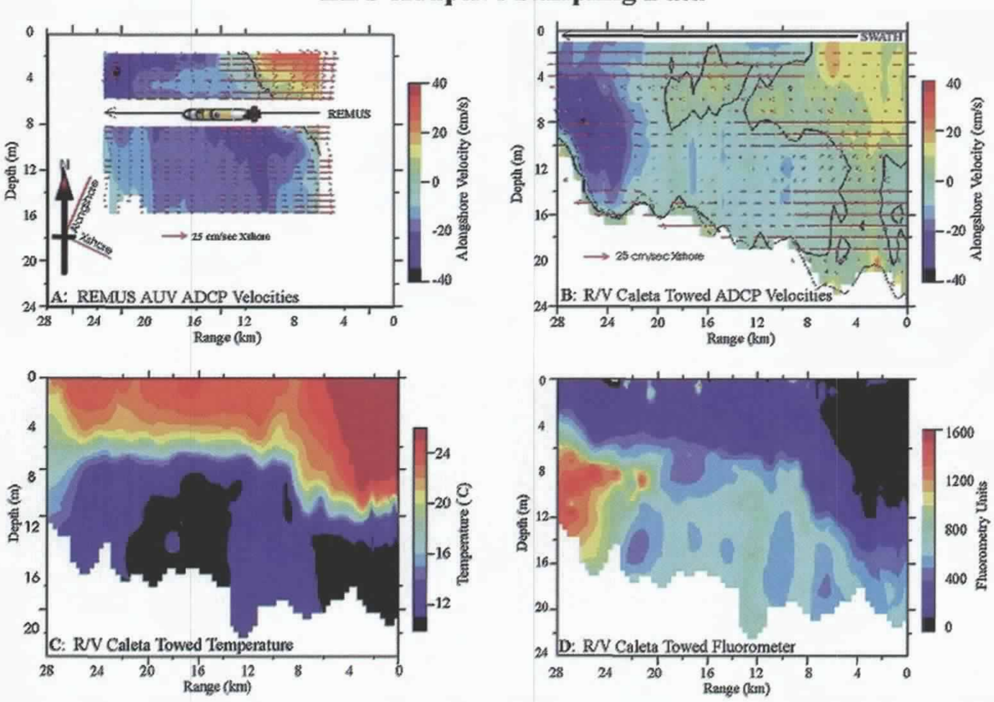

Figure 9: LEO adaptive sampling data. Top: (a & b) Alongshore (color contours) and cross-shore (arrows) velocity components derived from the upward and downward looking ADCPs on the REMUS Survey AUV (a) and the downward looking ADCP on the surface-towed SWATH (b). A northward flowing surface jet is observed offshore, and a southward flowing subsurface jet is observed inshore.
Bottom: Temperature (c) and Fluorometer (d) sections obtained from the towed undulator. The offshore jet is located in the warm, clear water above the thermocline, and the nearshore jet is located in the cold, phytoplankton rich water below the thermocline.

(http://marine.rutgers.edu/cool) in real-time. Selected historical datasets also can be downloaded from the Website using the Rutgers Ocean Data Access Network (RODAN). Access to the LEO Website has been continuously tracked since 1995. It currently averages over 5,000 accesses and over 22,000 hits per day, with over 70% of the Web hits from commercial Internet service providers (as opposed to government and educational institutions). One of the most important users outside of the research community is the Project Tomorrow K-12 educational outreach program. Through Project Tomorrow, thousands of teachers have been introduced to LEO-15, with over 600 participating in training sessions lasting up to a week. Over 45 teachers have participated in the design of Web based lesson plans that use the LEO-15 data. This year, over 12,000 students will be using the LEO Website through the Marine Activities Resources & Education (MARE) program.

LEO-15 has emerged as a valuable validation site for new instrumentation, in particular AUVs and remote sensing systems. Many of the initial operational missions for the REMUS Docking, Survey, Bioluminesence and Turbulence Vehicles were conducted at LEO, along with the first sea-trials for the Coastal Electric Glider. LEO was chosen as one NOAA site for the validation of RADARSAT surface roughness imagery, and is one of three Navy validation sites for the hyperspectral NEMO satellite scheduled for launch in 2000. Several aircraft are scheduled for overflights, including two hyperspectral sensors (AVIRIS and PHYLS) as part of the ONR HyCODE program, the microwave salinity mapper (SLFMR), and the Bistatic GPS altimeter. Additional systems proposing to use LEO as their first test site include a second aircraft altimeter (the Delay Doppler) and the floating bistatic CODAR HF-Radar systems (Kohut et al., 1999).

Summary

Over the last decade we have witnessed the emergence and rapid expansion of coastal ocean observation networks at numerous sites throughout the U.S. and the world. Three mature operational networks, PORTS, CBOS, and LEO-15, were described here in terms of their system specific goals, their current capabilities, and their recent accomplishments. Each of the networks was constructed through partnerships between scientists and engineers from universities, industry and government. Each has a proven track record of supporting scientific studies, real-time operational needs, and long-term trend analyses. Their observational datasets have been used by the academic community including K-12 educators, commercial enterprises, and the general public. Their long-term value is well recognized and their support has been maintained even though operational funding sources at times are scarce. The challenges ahead remain the linking of the multitude of locally operated systems into regional, national and international networks. During the next decade we will witness the development of these linkages, where datasets are shared between networks, and local networks respond to observations reported in other locations. Support of this process, and the widespread distribution of the resulting datasets, will facilitate the safe, efficient and effective use of the coastal zone.

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REFERENCES

Brink, K.H., 1997: Observational coastal oceanography, Advances and Primary Research Opportunities in Physical Oceanography Studies (APROPOS) Workshop, NSF-sponsored workshop on the Future of Physical Oceanography, 15-17 December, 1997. http://www.joss.ucar.edu/joss_psg/project/oce_workshop/apropos/presentations/brink.html

Creed, E.L., S.M. Glenn and R. Chant, 1998: Adaptive sampling experiment at LEO-15. *OCC '98 Proceedings, Marine Technology Society,* November, pp. 576-579.

Grassle, J.F., S.M. Glenn and C. von Alt, 1998: Ocean observing systems for marine habitats. *OCC '98 Proceedings, Marine Technology Society,* November, 567-570.

Kohut, J.T., S.M. Glenn and D.E. Barrick, 1999: SeaSonde is integral to coastal flow model development. *Hydro International,* April, pp. 32-35.

von Alt, C.J., M.P. De Luca, S.M. Glenn, J.F. Grassle and D.B. Haidvogel, 1997: LEO-15: Monitoring & managing coastal resources. *Sea Technology,* 38, (8), pp. 10-16.