The evolution of a nearshore coastal observatory and the establishment of the New Jersey Shelf Observing System

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"*The very few existing time-series stations paint a compelling picture of important oceanic changes in physics, chemistry and biology. Yet these stations capture the time domain at only a single point. New strategies for observing the appropriate spatial correlation are required.*"
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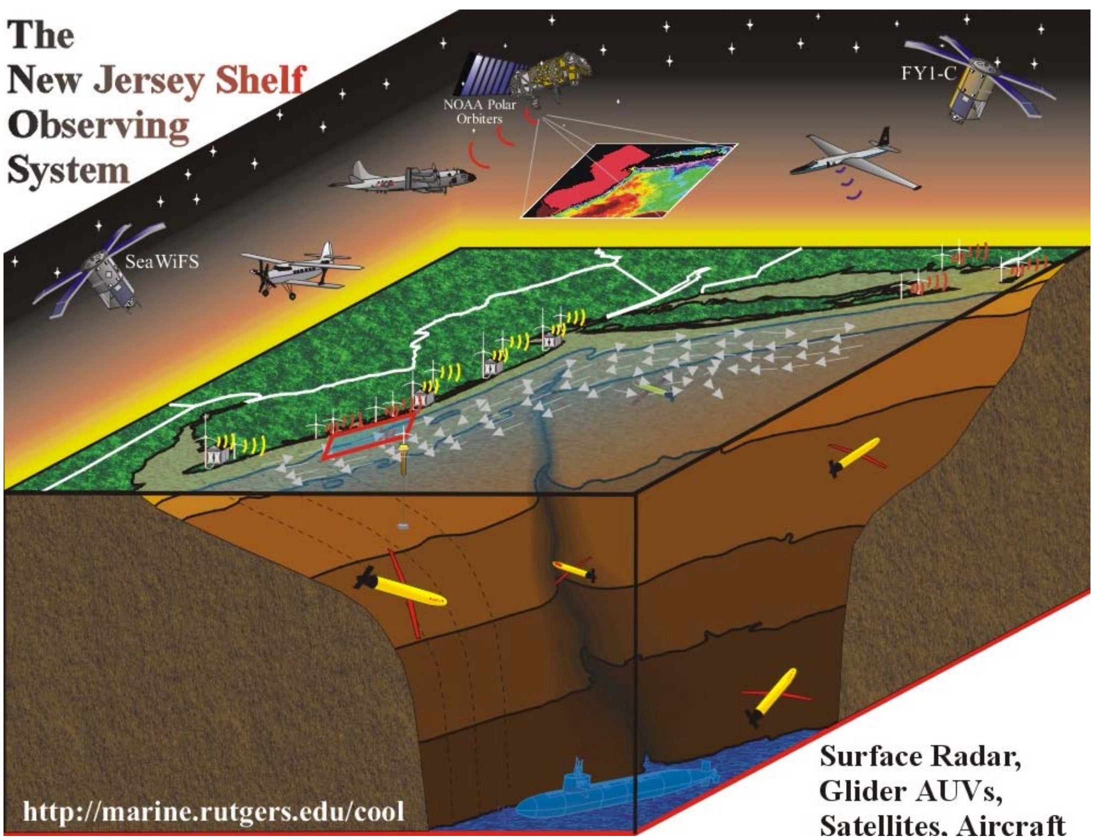


Figure 1. The Coastal Ocean Observation Laboratory (COOL) is constructing the New Jersey Shelf Observing System (NJSOS) in the New York Bight. The goal is to provide a synoptic 3-D picture of the biogeochemical cycling elements on a broad continental shelf.

We are constructing a shelf-wide ocean observatory (NJSOS) to characterize the physical forcing of continental shelf primary productivity in the New York Bight (NYB) (Fig. 1). This will expand the existing 30 x 30 km research space of Rutgers Long-term Ecosystem Observatory (LEO) to 300 x 300 km to characterize relevant spatial and temporal biogeochemical scales. The system will be a central component of the NorthEast Observing System (NEOS), a consortium of the major academic oceanographic institutions from Virginia to Maine. The shelf observatory will consist of (1) a nested grid of standard and long-range surface current radar systems, (2) the international constellation of ocean color satellites, (3) long-duration, glider-type, autonomous underwater vehicles. These assets will provide the maps of data to be assimilated into the new generation physical-biological ocean models for hindcast and real-time continental shelf predictive skill experiments. Operation of the observatory will be through a centralized computer network dedicated to receiving, processing and visualizing the real-time data and then disseminating results to both field scientists and ocean forecasters over the World Wide Web. Specifically we intend to use the NJ-SOS system to:

- Define the relative importance of episodic physical features in driving small-scale microbial blooms in the annual productivity and biogeochemical budgets on a broad continental shelf.
- Understand the sources, sinks and transformation of organic carbon and nitrogen from land to the continental shelf on seasonal time scales.
- Quantify the importance of topographic variability in driving the observed spatial variability of biological communities by characterizing the dynamics of surface and subsurface convergence fields.
- Utilize the observatory as a magnet for engineering/modeling students, both undergraduate and graduate, including a developing new emphasis on Masters-level operational oceanographers.
- Provide critical real-time data over the World Wide Web to multiple users, including the Navy, U.S. Coast Guard and National Weather Service.

The NJSOS represents an ambitious expansion of the successful Long-term Ecosystem Observatory (LEO) (Glenn et al., 2000) which already serves as one prototype for the regional observatories of the future. Our LEO experience demonstrated that a rich fertile scientific environment thrives with the development of an *in situ* collaboratory (Figure 2). The historical core of the LEO system is a cabled observatory designed to maintain a near-permanent presence on the ocean floor. Installed offshore Tuckerton, NJ in 1996, the observatory provides power and high-bandwidth two-way communications for suites of standard and guest sensors

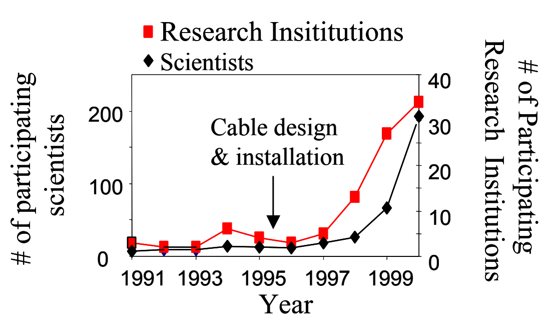


Figure 2. The collaborative atmosphere at the Long Term Ecosystem Observatory in the 1990's.

attached to a bottom-mounted junction box or “node”. The intensive time series measurements were expanded spatially to study the physics and the biological implications of the three recurrent coastal upwelling centers that develop each summer along the southern New Jersey coast.

An approximately 30 km x 30 km research space spanning the 3 m- 30 m isobaths was established to completely surround the Tuckerton upwelling center. Precision earth-location, modified cloud removal, and new compositing techniques were developed and applied to the coastal ocean to determine the spatial structure of coastal upwelling features. CODAR High Frequency (HF) Radar sites were established north and south of Tuckerton to provide vector surface current coverage of the upwelling centers and the associated alongshore jet (Kohut et al., 1999). To routinely acquire subsurface current and density data below the more spatially extensive remote sensing surface data, Remote Environmental Measuring UnitS (REMUS) Autonomous Underwater Vehicles (AUVs) were developed (REMUS) The REMUS AUVs were built to carry an ADCP, CTD, and bio-optical sensor payloads a design range of 40 km – 80 km, allowing the vehicle to be deployed nearshore in the morning, fly survey lines out and back across the upwelling center, and then be recovered nearshore before nightfall. This well-sampled research space became the site of an annual series of summer month-long Coastal Predictive Skill Experiments (CPSE) (Glenn et al, 1999) beginning in July 1998 through 2001. The CPSE focused on improving model nowcast accuracy via data assimilation and improved boundary forcing, characterizing the spatial/temporal scales of variability in inherent optical properties and developing alternative turbulent closure schemes for shallow coastal waters. These improvements were used to hone rapid environmental assessment techniques in a 30 km x 30 km space for physical/bio-optical adaptive sampling in order to calibrate the new ocean color sensors being developed by the international remote sensing community.

While successful, the observational footprint was too small to address many of the biogeochemical questions for the Mid-Atlantic Bight and efforts focused on developing the enabling technologies to expand the observational capacity to ecologically relevant scales. The goal is to address fundamental questions not resolvable with traditional field expeditions or sparsely distributed ocean moorings. Also, efforts to develop the observational network should grow hand-in-hand with the new generation of global ocean and regional nowcast/forecast models. This will hopefully provide an integrated coupled system allowing global, regional, and local scale questions to be addressed. The proposed NJSOS is now a possibility due to four enabling technologies, which are ready for preoperational demonstration projects. The enabling technologies include:

(a) high-resolution imagery from the growing constellation of satellites,
(b) a nested grid High-Frequency (HF) Radars capable of resolving the horizontal variability in the surface current fields,
(c) in-water vehicles capable of long duration (weekly) deployments, and
(d) new generation physical-biological data assimilative ocean forecast models.

COMPONENTS OF THE NJSOS

High-Resolution Ocean Color Satellite Imagery

The operational success of remote sensing to oceanographers is unmatched and has revolutionized our global understanding of the fundamental physical and biological processes in the ocean. While these efforts continue, historically the scientific community has only had access to a single platform at any given time; this however is no longer the case with the expanding number of ocean color satellites. The international constellation of satellites now offers researchers an unprecedented data bonanza, with the major advantage that any location will have multiple satellite passes. The available constellation will be one cornerstone to NJSOS. The imagery will provide real-time data for adaptive sampling by ships and AUVs. Data distribution to the science community and general public is key and will be provided over the World Wide Web via two websites, http://marine.rutgers.edu/cool designed for the scientific community, and www.thecoolroom.org designed for the general public. Web access peaks during the summer, averaging 64,000 hits per day with about 70% coming from the general public.

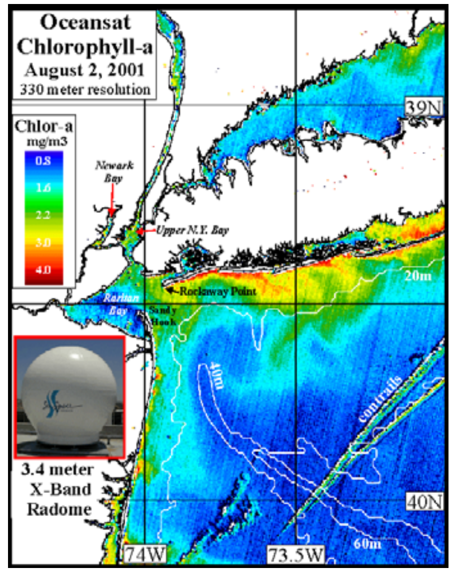


Figure 3: Oceansat Algal Blooms

Also notable is the new generation of Earth Observing Satellites, designed for the first decade of this century, have begun operations and offer higher spatial (down to 30 meters) and spectral resolutions. The higher spatial resolutions enable coastal/harbor/estuarine work not possible before, and the higher spectral resolutions provide the data required to develop new algorithms capable of detecting the presence of numerous in-water constituents (algae, harmful algal blooms, sediments, oil slicks). An example of such a new, and under utilized, sensor is the Indian OceanSat system (Figure 3). The OceanSat data clearly shows phytoplankton blooms extending across the northern side of Lower New York Harbor and along the south coast of Long Island with a higher spatial resolution than the American SeaWiFs system. The influence of ocean currents flowing up the Hudson Shelf Valley (seen in the 20 m isobath) is clearly observed in the resulting phytoplankton distributions. Figure 4 illustrates an even higher resolution image of sediment-plankton plumes observed offshore Atlantic City New Jersey with an aircraft

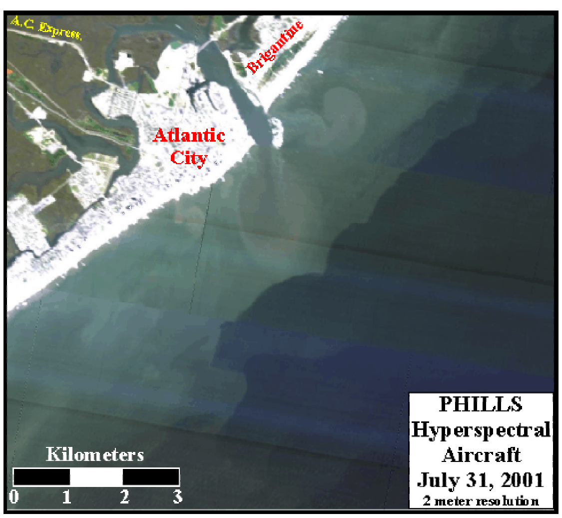


Figure 4: PHILLS Sediment Plumes

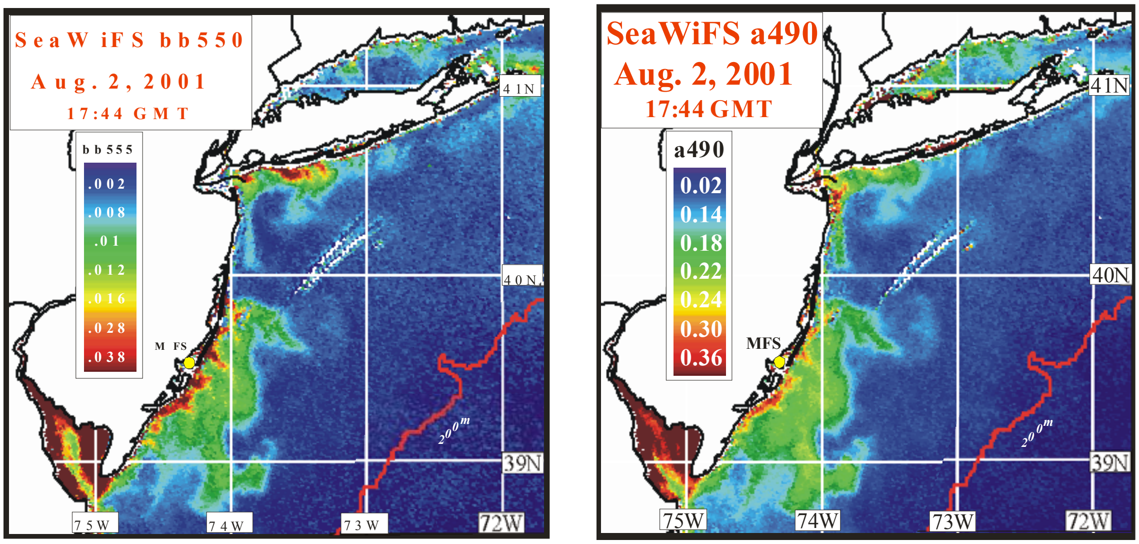


Figure 5. Maps of the inherent optical properties derived from SeaWiFs

mounted hyperspectral sensor. The sensor is similar to future hyperspectral satellite systems with spatial resolutions of up to 30 meters. Hyperspectral data is the key to developing new ocean color algorithms. A promising strategy that will be developed at NJSOS is to partition the reflectance into the component inherent optical properties (backscatter and absorption, Figure 5). The advantage of using the inherent properties is that they depend only on the medium and are independent of the ambient light field, thereby making them easier to interpret and allows for the partitioning of bulk optical properties into the individual components (e.g. water, dissolved organic matter, phytoplankton, detritus, sediment, etc.). If robust, this should provide a mechanistic means, which can be applied from optically-simple to optically-complex waters.

CODAR HF Surface Radar. A nested grid of Coastal Ocean Dynamics Applications Radar (CODAR) HF Radar systems is currently being operated in the New York Bight as NJSOS. Each shore-based site consists of a FCC-licensed radio transmitter antenna and a receiver antenna deployed along the beach. Similar to atmospheric Doppler Weather Radars, each site can measure the component of the surface currents traveling toward it or away from it. By combining data from two or more of the shore-based Radar sites, vector maps of the spatially varying current field can be produced. Currently, four long-range (5 MHz) and two standard (25 MHz) sites are broadcasting along the New Jersey

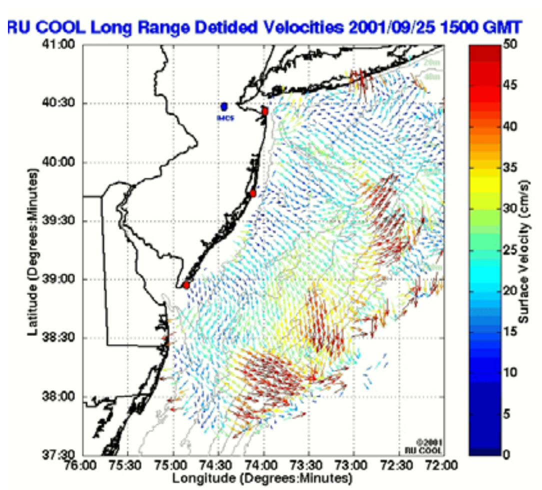


Figure 6. NJSOS Long-range HF Radar Coverage in the New York Bight

coast. The four long-range sites provide hourly surface current vector maps (Figure 6) for most of the New Jersey shelf at 6 km resolution. The two standard HF Radar sites produce higher resolution (1.5 km) hourly surface current maps offshore of Tuckerton for scientific use at LEO. These systems are complemented by a recently tested BiStatic CODAR system. This technology modifies the existing monostatic systems by separating the transmitter from the receiver, this converts the monostatic backscatter system into a bistatic forward-scatter system (see Kohut et al. this issue). These monostatic and BiStatic CODAR systems will form the backbone of the NEOS confederation of ocean observatories (Figure 7). The emphasis on CODAR technology is due to their successful 3 year deployment and their central importance to the Coastal Predictive Skill Experiments at LEO. During the CPSE, CODAR currents were used directly to determine present conditions and they were assimilated into numerical models to predict future conditions.

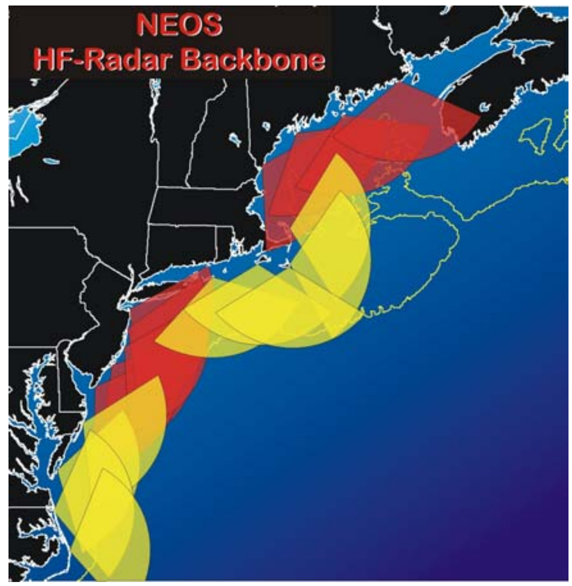


Figure 7. Long Range HF radar arrays planned for the northeast United States. Red shaded areas are already funded. Yellow shaded areas are proposed CODAR

Underwater Autonomous Gliders. Autonomous gliders have been demonstrated in field experiments on both the east and west coasts in the recent years. The Gliders can be programmed to patrol the subsurface for weeks at a time, surfacing to transmit their data to shore while downloading new instructions at regular intervals at a tremendous cost savings compared to traditional surface ships. The small relative cost and the ability to operate multiple vehicles with minimal personnel and infrastructure will enable small fleets of Gliders to study and map the ever-changing (in space and time) features of our subsurface coastal waters around-the-clock and calendar. The challenge ahead is to determine how best to operate a Glider fleet given cues from coupled

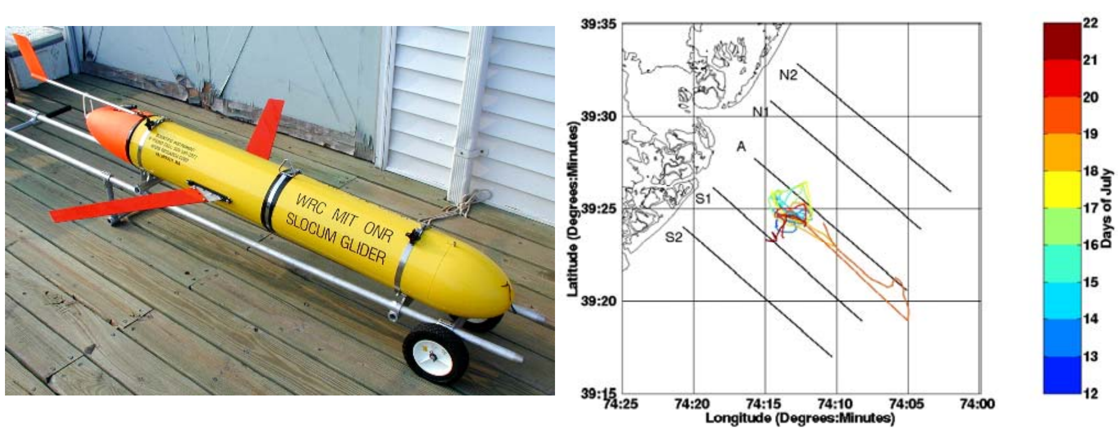


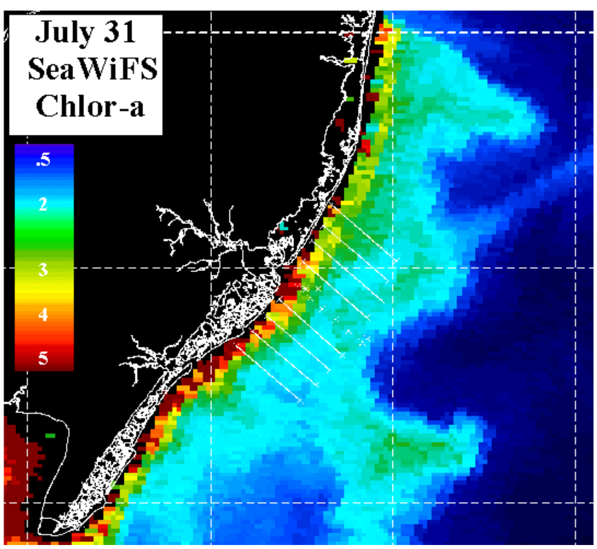
Fig. 8. Picture and flight track of the slocum glider from the summer 2000 experiment

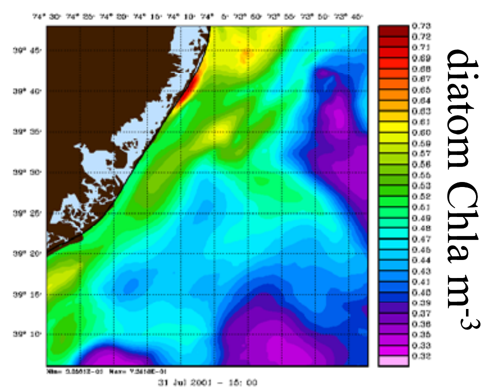
atmosphere/ocean forecast models, from the other backbone components of a regional observation network, or from adaptive sampling platforms that include ships and other AUVs working within the regional network. Webb Research Corporation has developed the Slocum Coastal Electric Glider AUV pictured in Figure 7. The first untethered open ocean flight of the Slocum Glider was conducted at LEO in July 2000 (Figure 8). The Glider's nominal mission profile consisted of a series of 2.5-minute undulations with a surfacing interval of 45 minutes. During the surface interval, a new GPS position was collected, data were transferred to shore, and new mission profiles were downloaded with a freewave radio modem. Over the 10-day deployment period, the Glider collected and transmitted 5,190 CTD casts without ever returning to the dock. Although the Gliders are not equipped with a current meter, their observed drift between surface intervals can be used to infer depth-averaged velocities. Glider-derived average velocity estimates are based on the differences between the actual GPS position and the expected position based on dead reckoning every time the Glider surfaces. Whenever the Glider was within 2 km of a LEO ADCP during the July deployment, the Glider depth time series was used to average together the corresponding ADCP velocities. For comparison purposes, the top bin of the ADCP (about 3 m below surface) and the CODAR surface velocities are also plotted. The RMS differences between Glider and averaged ADCP are less than the RMS differences between the CODAR and the top bin of the ADCP. The CODAR/ADCP RMS difference is similar to the RMS difference between the ADCP bins 3 m and 6 m below the surface, and between two other LEO ADCPs located 4 km offshore and onshore, indicating that a good part of the observed differences may be associated with natural variability. For the NJSOS, 4 gliders have been purchased and efforts in the coming summer are focused on coordinated sampling of multiple gliders.

Currently these efforts focus on developing a flexible, autonomous and a responsive software tool to coordinate the Glider Fleet. The coordinating software design is based on a Decision Theoretic Expert System. The field of Decision Analysis studies the application of Decision Theory to solve actual decision problems. The advantage of using Decision Theory over other approaches is its ability to incorporate uncertainty in the environment and taking into account the value of information before making decision. The system will make optimal decisions based on available ocean observations from satellites or CODAR. This software will be both adaptable and adaptive. Simulations on data from past Glider missions has demonstrated that the software was able to change the instruction set for the Gliders without human intervention providing some evidence of adaptibility.

Data Assimilative Models. The NJ SOS will be complemented by an extensive suite of atmospheric, ocean, and biological nowcast/forecast models being developed through funding by the Office of Naval Research and the National Ocean Partnership Program. The ensemble of forecasts are generated by the Regional Ocean Modeling System (ROMS) developed by Rutgers and UCLA. Selected components of the Princeton Ocean Model (POM) are currently being merged with ROMS to form a generalized Terrain-following Ocean Modeling System (TOMS) as part of ONR's Navy Expert System program. ROMS is typically forced by both Navy-generated (COAMPS) and locally-generated (RAMS) atmospheric forecasts, contains options for two different internal turbulent closure schemes, and has options for a range of bottom boundary layer interactions with a moveable sediment bed. Data assimilation in forecast mode has been through simpler nudging and Optimal Interpolation (OI) schemes. Past experience at LEO has indicated that the CODAR surface current fields are one of the most significant assimilation datasets for improving ocean nowcasts. But assimilation of the CODAR surface currents requires information on the vertical structure of the current field below the surface. Some of the simplest approaches first estimate the depth of the thermocline and then specify that the currents above are well correlated and the currents below are poorly correlated with the CODAR data. A fleet of Gliders operating beneath the long-range CODAR network will significantly improve this approach. The Gliders can return the actual observed depth of the thermocline, and by undulating either above or below, use the Glider drift velocities to determine the subsurface structure and its relation to the CODAR surface currents. Model error fields can be used to direct Gliders into regions where they are most needed.

The Terrain-following Ocean Modeling System (TOMS) is being coupled with a full bio-optical ecosystem model. We are using a derivative of the Ecological Simulation 1.0 model, which was originally developed and validated for open ocean conditions. The model simulates the hyperspectral bio-optical properties of the water column via a size-fractionated phytoplankton community while including the optical constituents of labeled and recalcitrant colored dissolved organic matter (Bissett et al 1998a,b). EcoSim utilizes the spectral distribution of light energy, along with temperature and nutrients, to drive the





Measured total chlorophyll a and simulated diatom chlorophyll a for a summer upwelling off New Jersey in summer 2001.

Figure 9. Comparison of a hindcast simulation using the coupled ROMS and EcoSim model to a SeaWiFs image for a phytoplankton bloom during the Summer 2001 CPSE.

growth of phytoplankton functional groups representing broad classes of the phytoplankton species. The inter-cellular chlorophyll a stocks of each functional group are allowed to vary as a function of the light history and nutrient status of the group. Each phytoplankton species chromatically adapts to changes in total photon flux and intercellular nutrient status, via changes in its carbon to chlorophyll a ratio. Changes in carbon to chl a ratios, in turn, lead to changes in accessory pigment concentrations. The time rate of change of the carbon to chl a ratio is a function of the growth rate of the individual phytoplankton groups. The advantage of the EcoSim model is that it allows for estimates of the inherent optical properties (IOPs) so it can be initialized using the satellite-derived IOP estimates. The goal is to begin to run ensemble biological forecasts, which can be validated using the real-time data from the field assets. This will be used to guide the evolution of the biological model. Initialization of the model will be based on satellite estimates and glider measurements of the inherent optical properties. The maps of the inherent optical properties are deconvolved into constituent end members using the algorithms, developed through the ONR's HyCODE program, providing fields for phytoplankton, dissolved organics, detritus and sediments. By partitioning the overall optical fields into constituent end members appropriate transport rates can then be applied for the model simulations (Figure 9). Model results show good spatial correlations, and efforts are now focusing on a full quantitative hindcast analysis.

Observations and Models. In the typically under-sampled ocean, ocean forecast errors are often dominated by uncertainties in the model initialization; therefore ensemble forecasts with differing initial conditions are used to identify regions in which additional data are required. Hence the models provide insight into what has not been sampled and guidance for field efforts. With recent advances in our observational capabilities, we are no longer consigned to operate in an under-sampled environment. Ocean observation networks using multiple platforms, including remote (satellites, aircraft and shore-based), stationary (surface and subsurface), moveable (ships and AUVs), and drifting (surface or vertically mobile) systems, can provide spatially extensive observational updates on time scales of an hour or better (Glenn et al 2000). This rapid environmental assessment capability changes the entire paradigm for adaptive sampling and nowcast/forecast modeling. In the well-sampled ocean, forecast errors may now be dominated by uncertainties in the model formulations or boundary conditions, and ensemble forecasts with differing model parameterizations can be used to identify regions in which additional data can be used to keep a model on track. In the time it takes to prepare the ensemble of forecasts for the well-sampled ocean, additional data has arrived, and on-the-fly model-data metrics can be used to quantify which forecast in the ensemble is most accurate. Thus in the well-sampled ocean, the observations are used to improve our understanding of errors associated with model assumptions.

Conclusions. In conclusion, the recent development of remote sensing technology, surface current radar, and AUV technology make the development of a synoptic scale ocean observatories a possibility. As the proposed regional networks unite this will form a basis for a national ocean observation system. These networks combined with the data assimaltive models will provide a nested observational capacity for conducting process studies over biogeochemically relevant scales. This will provide information aiding water quality managers, industry, the navy and coast guard authorities. The data will also be of public interest. The new observational paradigms for the well-sampled ocean will be especially important to improving our ability to describe biological dynamics in coastal ecosystems (Schofield et al. 1999). Current biogeochemical models describe seasonal changes usually in terms of bulk phytoplankton biomass or nutrient fields. A well-sampled ocean provides the means to run ensemble biogeochemical forecasts, which can then validated by real-time data on time scales allowing field assets to be diverted to regions where additional data is required. The ensemble biogeochemical forecasts can represent models of varying food web complexity, which is critical in regulating biogeochemical fluxes (Walsh et al. 1999) and characterize how the past and present conditions define the physiological profile of individual species. A whole host of physiological models, which describe biological responses to changes in incident light or nutrient fields have been developed with varying degrees of complexity. Choosing the appropriate models requires understanding of the processes that occur over different scales of time, space, and organizational complexity (Levin 1992). The new ocean observatories not only provide the observational capacity to study the scaling problem, but also a means to assess which of an ensemble of model forecasts best describes reality.

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