HYPERSPECTRAL REMOTE SENSING OF THE COASTAL OCEAN: ADAPTIVE SAMPLING AND FORECASTING OF NEARSHORE IN SITU OPTICAL PROPERTIES

OBJECTIVES. We propose to develop and validate an integrated adaptive sampling and modeling system for nowcasting and forecasting the 3-dimensional evolution of inherent optical properties (IOPs) in coastal waters off New Jersey. This will be accomplished by adding a bio-optical ecosystem model to a data-assimilative coastal hydrodynamic model. Specifically we propose:

● develop and deploy moored, shipboard, and autonomous bio-optical systems in the coastal ocean to ground-truth remote sensing imagery;

● quantify the physical, chemical and biological processes that define the spatial and temporal variability in the spectral IOPs for the nearshore coastal ocean;

● refine and calibrate existing hyperspectral optical models to derive IOPs from remotely sensed data using the above datasets;

● couple the radiative transfer module to the data-assimilative hydrodynamic model to 3-dimensionally forecast (horizon to horizon, surface to benthos) the impact of changing hydrography on the in situ IOPs;

● evaluate the coupled hydrodynamic-optical forecasting system by extending the Coastal Predictive Skill Experiments into the summers of 2000 and 2001 focusing on the adaptive sampling of recurrent coastal upwelling and the sub-optimal assimilation of data collected by the Long Term Ecosystem Observatory (LEO-15); and

● explore optimal assimilation schemes to generate 3-dimensional physical/biological/optical fields for dynamical analysis of key events;

RESEARCH FOCUS. Satellite ocean color data supplies a synoptic perspective on radiatively active constituents on space and time scales not possible using shipboard sampling. Remotely sensed data primarily provides data on the surface layers of the ocean. Consequently, remote sensing approaches must assume or rely upon ancillary data to estimate vertical changes in the optical properties. In the optically deep ocean (ODO), there is significant vertical variability in the concentrations of phytoplankton, colored dissolved organic matter (CDOM), suspended sediments, and detrital material which can change on the time scale of hours. This is especially true for most nearshore coastal ocean environments. This vertical heterogeneity in the IOPs thus limits the operational and predictive utility of algorithms based solely on satellite ocean color data.

Our research efforts within the New York Bight have focused on developing a relocatable data-assimilative model, which is coupled to an adaptive multi-platform sampling network. As part of the HyCODE ODO initiative, we propose to incorporate a bio-optical ecosystem model into our hydrodynamic model to provide a 3-dimensional forecasting capability for coastal optical properties. The focus will be on developing and validating an integrated system to provide nowcasts and 2-3 day forecasts of the physical/optical state of the nearshore coastal ocean. The proposed system will also allow for the continued development of adaptive sampling approaches that can characterize episodic hydrographic events. Adaptive sampling approaches are critical for sampling episodic events, since standard techniques do not adequately resolve their frequency and their disproportionately large role on the optical, biological, and chemical processes in coastal waters. The proposed nowcast/forecast system will be developed as part of a process study focused on the impact of episodic upwelling on coastal optical properties.

Upwelling in the New York Bight. Along the New Jersey coast, upwelling begins as a uniform band of cold water along the coast in response to southwesterly winds (Hicks and Miller 1980, Neuman 1996). Interactions with the bottom initially cause a 2-dimensional front to evolve into three recurrent upwelling centers located on the downstream sides of three seafloor topographic highs (Fig 1). The locations of these upwelling centers appear to be relatively fixed and have been observed during each summer over the last six years (Glenn et al. 1996, Fig. 1). Extensive CTD and surface current radar observations confirm the presence of the cyclonic eddy and the meandering coastal jet (Fig. 1). The lifetime of these transient upwelling centers can last from a few days to full month depending on the local wind conditions and/or the presence of tropical storms which can be common during the late summer in the Mid-Atlantic Bight. The upwelling enhances nutrient (nitrogen, NO_3, NO_2, NH_4) concentrations in these coastal waters, that results in phytoplankton blooms. These blooms are initially dominated by diatoms and are often succeeded by dinoflagellate blooms upon the onset of stratification (Kerkhoff et al. 1998).

The predictable spatial locations of these upwelling centers are correlated with regions of recurrent low dissolved oxygen (Pearce et al. 1985). The depletion of oxygen can stress benthic organisms and has in the past seriously impacted New Jersey fisheries. A particularly severe example occurred in 1976 when bottom water anoxia resulted in a $550 million loss to shell fishing and related industries (Figley et al. 1979). The historic regions of recurrent low Dissolved Oxygen (DO) were originally believed to be associated with specific anthropogenically-impacted estuaries; however, recent studies show that the relationship between anthropogenic loading from estuaries and hypoxia in these coastal waters is at best ambiguous. It has been hypothesized that the recurrent upwelling centers are responsible for declines in DO. Data collected during upwelling events in 1996 and 1997 confirm enhanced concentrations of dissolved and particulate matter within these upwelling centers as indicated by increases in the AOPs and IOPs (from 1 to 8 m^{-1}, Fig. 1). Recent data suggests that the accumulation of material reflects phytoplankton growth, estuarine loading of organic matter, material scavenged from the benthic boundary layers, and resuspension of sediments in nearshore waters. The relative importance of these different sources of organic material is variable in time as minimal advective transport within the upwelling centers allow the biological and chemical properties to evolve within the upwelling center. For example, the prominence of phytoplankton pigments signatures in the blue and red wavelengths become increasingly significant in the AOPs and IOPs during an upwelling event. The subsequent remineralization of the organic material, and corresponding decline in DO, is also dependent on the transport of material to the benthos. For example, in 1993, upwelling which began in July was disrupted by persistent downwelling winds. This resulted in the shoreward transport of warm surface water, subduction of upwelled water, the capping of cooler bottom waters and declines in DO. The declines in DO suggest efficient degradation of subducted organic materials. This is consistent with other studies in the Mid-Atlantic Bight, which suggest up to 95% of the particulate matter is remineralized and/or consumed by heterotrophic processes (Biscayne et al. 1994, Falkowski et al. 1994). The DO values remained low until Hurricane Emily thoroughly mixed the region at the end of August 1993. In contrast, a similar upwelling pattern was observed in 1994; however, prevailing wind conditions prevented downwelling, and DO levels remained elevated throughout the summer.

As part of the ONR Coastal Ocean Modeling and Observation Program (COMOP) and two National Ocean Partnership Program (NOPP) awards, efforts have focused on using adaptive sampling techniques to characterize the dynamic behavior of these upwelling centers. The recurrent upwelling centers are separated from the warm offshore waters by a sharp (kilometer scale) upwelling front that is readily visible in AVHRR and SAR satellite imagery. The subsurface location of the frontal boundary is also clear in the in situ spectral signatures of the AOP and IOPs. While the upwelling centers themselves are typically about 25 km in diameter, they contain many observed features that occur at smaller scales. A strong alongshore jet (20-30 cm/sec) remains on the warm side of the upwelling front above the thermocline as it meanders around the colder upwelling center. Consistently associated with the offshore thermocline is a broad chlorophyll peak. The vorticity ridge located near the point where the jet turns onshore propagates downstream at a much slower rate than the advective velocity, consistent with vorticity conservation arguments. Near-inertial waves are observed on the warm side of the front, with intensified subsurface velocities at the thermocline similar in magnitude to the advective velocities of the jet. Currents within the upwelling center are much weaker and do not exhibit the strong inertial wave signals. A dominant feature of the upwelling center is the development of a cyclonic eddy within the northeast quadrant as winds relax. The surface circulation is divergent in the middle of the upwelling center, and is surrounded by a ring of convergent currents just within the upwelling front (Fig. 1). This suggests a secondary circulation pattern within the upwelling center consisting of cold water leaving the divergent region in the middle, travelling out towards the upwelling front and then back down as it encounters the front. The convergent currents can potentially concentrate material and may account for some of the heterogeneity of the optical patterns within the upwelling center.

These upwelling centers will provide a complex dynamic optical feature that varies on the time scales of hours to days. We propose to expand our studies of these upwelling centers by using an adaptive sampling network, guided by a data-assimilative numerical ecosystem model, to characterize the dynamic behavior of the in-water optics. A primary emphasis will be placed on utilizing the observed and modeled optical properties to characterize the evolution of the major biological and chemical features in space and time. The resulting observational database (in situ and satellite) will be used to test the proposed optical forecasting system. Hyperspectral data from AVIRIS and/or the Coastal Ocean Imaging Spectrometer (COIS) will be complemented with daily data from additional ocean color sensors, such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS). A highly instrumented multiplatform network, which currently exists, will supply near-synoptic sea truth data for these remote sensing platforms. Results from the proposed study will be used to evaluate hyperspectral techniques in the nearshore coastal ocean and to address the following scientific questions focused on the impact upwelling on in situ optics:

1) How well do hyperspectral sensors characterize the horizontal and vertical distribution of radiatively active constituents in the optically complex coastal ocean? How robust are the deconvolution models in space and time during dynamic physical events?

2) How much ancillary vertical data is required to accurately predict the nearshore coastal optical climate?

3) How accurately can coupled hydrodynamic-optical models be used to forecast biological rate processes in optically complex waters during episodic events?

4) What are the major sources and sinks of the organic material that accumulates within the upwelling centers?

5) Do convergence zones within the upwelling centers trap organic matter and act as "depo-center" fueling potential hypoxia/anoxia events?

GOAL 1. Quantify the variability in the IOPs during episodic upwelling. We will define the dynamic behavior in the nearshore coastal optical properties using the LEO-15 observation network. Data will be used to define the relationship between the nearshore optical properties and the major radiatively active constituents during summer upwelling events. The LEO-15 network is an existing multiplatform network consisting of satellites, radar, autonomous nodes, research vessels and autonomous vehicles (Fig. 2).

Satellites. Near-real time thermal infrared (Advanced Very High Resolution Radiometer) and ocean color (SeaWiFs and MODIS) sensors will provide sea-surface temperature and chlorophyll concentration estimates, respectively, for data assimilation and model validation. This satellite capability will be greatly enhanced by hyperspectral sensor data providing high resolution spectral ocean color data which potentially allows for the characterization and quantification of diverse materials (chlorophyll, phycobiliprotein pigments, dissolved organic matter, and sediments). Preliminary algorithms to derive several of these parameters from hyperspectral data will be initially used, evaluated, and modified for the region. A SeaSonde High-Frequency Radar (CODAR) System will complement the satellite imagery. CODAR, as currently configured for the first National Ocean Partnership Program (NOPP) sponsored 1998 Coastal Predictive Skill experiment, provides real-time surface currents every hour over an approximately 32x32 grid at a fixed resolution of 1.5 km. The proposed CODAR configuration to be tested during the second NOPP sponsored Coastal Predictive Skill Experiment in 1999 will automatically switch between low resolution (3 km) large scale to high resolution (1 km) fine scale maps every half hour. This provides both high resolution and outer boundary surface currents that will be assimilated to improve model nowcasts. The remote sensing imagery will provide extensive surface data that may not reflect the physical, chemical and biological conditions at depth. Data collected by autonomous seafloor nodes, adaptive shipboard sampling, and untended autonomous vehicles will provide subsurface physical and optical data to complement the "highly-sampled" surface conditions.

Autonomous Nodes (LEO-15). The LEO-15 system consists of two robotic nodes 10 km off the central coast of New Jersey (Fig. 2). The LEO-15 nodes are connected to shore via an electrofiber-optic cable and allow for control of a vertical profiler that is outfitted with CTD/OBS/PAR/Fluorometer/oxygen probe instrument package. The LEO-15 nodes are also currently augmented with an upward looking ADCP. The LEO nodes are located in the heart of a recurrent upwelling center, which is clearly evident in the node data (Fig. 2, data represents 90 vertical profiles in a single month). As part of this HyCODE initiative we propose to add ac-9 systems (10 cm pathlength systems) into the LEO-15 instrument package to provide a temporal database for the spectral IOPs. During the HyCODE program the LEO-15 nodes will be operated autonomously at regular intervals. Rutgers divers service the nodes on a weekly basis, which in the past has been sufficient to eliminate biofouling concerns for the moored optical packages. To provide data hyperspectral reflectance we will install a battery-operated above water hyperspectral reflectance meter (Geophysical & Environmental Research Corp., 1.5 nm resolution, 350-1050 spectral range) to a weather buoy at the LEO-15 site. The GER sensor will have both downward and upward irradiance sensors and discussions are underway to have the instruments modified to retrieve data via a cellular telephone link. An equipment match by Cal-Poly will also allow one of the optical survey vessels to be outfitted with a GER sensor.

Shipboard Adaptive Sampling. The Rutgers research vessels are equipped with a surface-towed ADCP, an undulating CTD/Fluorometer/OBS system, and a suite of CTD/bio-optical submersible profiling equipment [Seabird CTD, Biospherical and TBS-OCR Satlantic spectral radiometers, Wetlabs absorption/attenuation meter (ac-9), Wetlabs spectrofluorometer (SaFire), Modular Data Acquisition System (MODAPS)]. Researchers from the University of Mississippi (see letter of support) have agreed to participate in the field exercises in the summers of 2000 and 2001 and will bring an ac-100 to provide hyperspectral measurements during scheduled NEMO and/or airplane flyovers. A Very Long Pathlength Capillary (VLPC) spectrometer (0.5 meter pathlength, nm resolution) will be integrated to one of the ship's pump systems, providing continuous maps of the near-surface absorption during ship surveys (see letter of support). During a 1997 ECOHAB cruise, Schofield and Kirkpatrick found very close agreement between the VPLC and ac-9 systems (R^2 = 0.91, Schofield unpublished data). Shipboard transects will also characterize both the vertical variability in total and dissolved IOPs. This will be accomplished by taking repetitive profiles with and without a filter (0.2 μm) on the flow tube input for all Wetlabs instrumentation. Fluorometric emission signatures will provide independent means to characterize the critical optical constituents in situ as SAFire data provides robust estimates of chl a (R^2 = 0.92), CDOM (R^2 = 0.95), and potentially phycobilin pigments (R^2 = 0.50) (Schofield unpublished data).

A large set of discrete samples will be collected during physical/optical ship surveys (Table 1). Discrete water samples will be collected and analyzed for nutrients, dissolved organic carbon, and phytoplankton load. These phytoplankton samples will also be characterized using unlabeled and ^{14}C-radiolabelled HPLC techniques allowing phytoplankton biomass, community composition, and growth to be determined. Samples will also be collected to validate the in situ optical data. Aliquots will be analyzed for particulate, dissolved, and detrital absorption on a customized DW-2a spectrophotometer. Fluorescence excitation/emission matrices will be determined for the dissolved fractions of the discrete samples on a quantum-corrected AB2 Luminescence Spectrometer. This fluorescence data will be used to validate in situ data collected by the SAFire and to delineate the relative contribution of terrestrially and/or marine-derived CDOM (Donard et al. 1989, Coble et al. 1990). The resulting dataset from these shipboard surveys will 1) provide a calibration database for the satellites and in-water instrumentation, and 2) describe the dynamic evolution of the physics, chemistry and biology during upwelling events. Specific shipboard sampling strategies are outlined below.

Untended Autonomous Vehicles. The in-water spatial heterogeneity of optical/physical parameters will also be characterized using an existing network of Remote Environmental Measuring UnitS (REMUS). These surveys will provide high-resolution vertically resolved maps of critical physical and optical parameters. The REMUS systems are currently outfitted with CTDs, ADCPs and sidescan sonar. An optical REMUS will be developed as part of this proposal to provide data on the in-water light environment. The REMUS, which is equipped with an ADCP, will be outfitted with sensors for upward and downward irradiance (Satlantic) and a Wetlabs fluorometer. The REMUS systems navigate relative to seafloor transponders, allowing for both linear and ladder surveys. The ladder surveys will allow for subsurface maps of the AOPs and reflectance to be determined (continuos above water light will be provided using the shipboard surface and buoy mounted GER reflectance sensors). Currently the REMUS vehicles have successfully completed 3-hour untended surveys. In 1997, REMUS vehicles successfully completed a series of 3-hour duration surveys at LEO-15 on rechargeable batteries. During the first NOPP experiment, we propose to test both a docking port for rechargeable REMUS vehicles, and longer duration (12-18 hour) REMUS surveys with single-use lithium batteries. These efforts will be further refined in 1999 during the second NOPP experiment in which we hope to fly more operational docking and long-duration missions.

Observational Sampling Strategy. A major goal of this project is to develop an optical forecasting system (see below); therefore observation data is key for both data assimilation and forecast validation. While 3-dimensional model resolution is adjustable, the observational capabilities to synoptically address the questions above will require coordinated sampling of the different various in situ platforms. Real-time AVHRR (4 daily passes, 1.1 km resolution) and SeaWiFs (1 daily pass, 1 km resolution) will be augmented with high-resolution hyperspectral imagery (COIS, 2.5 average repeat day orbit, 30-60 m resolution, AVIRIS 30 m). The satellite imagery will provide 1) spatial pictures of the major in-water optical constituents and 2) surface data for initialization and validation of the forecasting system. This imagery will be complemented with continuous surface current information from the CODAR and moored optical observations at the LEO nodes. The LEO nodes will profile automatically throughout the study period providing a high-resolution vertical picture of the IOPs. The satellite and LEO observational data will be used to adjust the sampling pattern of the Rutgers research vessels and AUV vehicles.

Shipboard sampling will begin as biweekly surveys in late May or early June to provide a baseline of nearshore optical properties and alongshore flow prior to the initiation of the summer upwelling. Upon the beginning of the upwelling event, rapid response shipboard surveys will be initiated using two vessels. The length and coastal orientation of the transects will be adjusted depending on daily satellite and CODAR imagery. As in past years, ships will be used daily during an intensive month-long survey. Local weather conditions often limit ship surveys to 4-5 days/week. The two Rutgers research vessels (R.V. Caleta and Arabella) will be used. One vessel will be outfitted with the towed and undulating instrumentation. This vessel will sample the developing upwelling center in a series of radials extending from LEO-15 (Fig. 3). The radials will extend beyond the outer edges of the upwelling front. This survey strategy will provide high-resolution maps of velocity, density and chlorophyll a structure. This vessel will also be outfitted with the pumped VPLC spectrometer providing a detailed surface map of both total and dissolved spectral absorption. Differential GPS navigation will allow for accurate placement of these maps with other datasets, allowing us to address upwelling feature validation issues. Mass balances will be calculated by integrating vertical current profiles and allow for determination of phytoplankton transport within the upwelling centers. The second vessel will be outfitted with profiling instrumentation. The vessel will conduct 2 cross-shelf transects through the upwelling center each day occupying 8 stations along the three legs to provide a more detailed optical characterization of the upwelling center (Fig. X). Discrete water samples will be collected at 3-5 depths depending on water depth (water depth ranges from 5 to 30 m). This will provide around 1500 discrete samples for a single month of sampling during the summer upwelling season. In total, this provides 6 cross-shelf transects through the upwelling on a daily basis. This is similar to the sampling regime to be used in the Coastal Predictive Skill Experiments in the summers of 1998 and 1999.

Shipboard surveys will be complemented by cross-shelf surveys by the REMUS vehicles (Fig. 3). The REMUS flightpaths across the upwelling should take close to 3-4 hours (typical speed, 4 knots) and multiple ladder flights will be conducted in a single day. The ADCP/optical REMUS vehicles will be used during summer upwelling surveys. Combined with shipboard transects this provides up to eight cross-shelf transects on a single sampling day. These high-resolution maps will 1) provide estimates for inertial motion which can be significant during upwelling and, 2) allow small-scale optical features associated with convergence zones to be mapped. These cross-shelf surveys will be used to define the relative importance of the convergence zones and assess how well the high-resolution COIS imagery can detect the small km-scale features.

GOAL 2. Develop and validate an optical nowcasting and forecasting system. We propose to couple an optical ecosystem module to an existing hydrodynamic data assimilation model. The coupled model will be used to 3-dimensionally forecast (horizon to horizon, surface to benthos) the impact of changing hydrography on the in situ IOPs. Development of the nowcasting/forecasting system will require modification of an existing optical model for use in the nearshore coastal water. The models and their evaluation strategies are discussed below.

Optical model. We will utilize a derivative of Ecological Simulation 1.0 model. EcoSim 1.0, originally developed for open ocean conditions, simulates the hyperspectral bio-optical properties of the water column via a size-fractionated phytoplankton community while including the optical constituents of CDOM (Bissett et al. 1998a,b). The model allows for estimates of the IOPs. As bio-optical signatures of the coastal regime are more complex then in open ocean waters, this project will convert EcoSim 1.0 into a coastal model of NYB by including coastal phytoplankton signatures and the optical signal of suspended sediments. In addition to the prediction of inherent optical properties (IOPs) of the water column, the optics of EcoSim will be further enhanced to predict water-leaving radiance. This will allow direct comparisons of hyperspectral remotely-sensed radiometric data with model output, i.e., predicted Rrs(440) to remotely-sensed Rrs(440), as well as the comparison of optical constituents with derived hyperspectral products, i.e., predicted chlorophyll a with remotely sensed chlorophyll a. Model estimates of the IOPs and derived products (phytoplankton, CDOM, sediments) will be evaluated by direct measurement. Efforts will focus on modeling and validating the remote sensing reflectance observed by buoys, ships, AUV's and satellites. The evolution of the optical properties over time in the upwelling center will test the ability of EcoSim to predict dynamic events in the coastal ocean.

Regional data assimilation model. The regional circulation model is based on the latest version of the S-Coordinate Rutgers University Model (SCRUM). The model is equipped with 1) a coupled surface boundary layer model and 2) a coupled Bottom Boundary Layer Model (BBLM) for inclusion of wave and sediment transport effects on bottom friction. The present version of the model incorporates extensive restructuring for sustained performance on SMP-class parallel-computing platforms and quasi-monotone algorithms for tracer advection. A recently awarded NOPP grant will significantly expand the SCRUM model by coupling it to a Regional Atmospheric Model (RAMS, in collaboration with Dr. Avissar, Rutgers University). This will result in a state-of-the-art regional circulation model with dynamically realistic air-sea and bottom boundary layer interactions. Wind inputs can be provided through a combination of local Improved METeorological (IMET sensors), offshore Coastal Environmental Systems WEATHERPAK-2000 buoys, and/or low resolution NORAPS data that is available over the Internet. Currently, data assimilation capabilities are based upon optimal interpolation (OI) and the reduced-state Kalman filter (KF); however proposal activities at Scripps Institute Oceanography (SIO) call for SCRUM to be outfitted with an an adjoint-based assimilation module. Many real-time atmospheric and oceanic forecasting systems (ex. RAMS) use sub-optimal assimilation schemes (ex. OI, reduced state Kalman filter) because fast turn-around times are required. Optimal assimilation schemes, like the SCRUM adjoint proposed by SIO, are often run in hindcast mode to generate 3-dimensional model fields for dynamical analysis that are, in some sense, in best agreement with the data. Sub-optimal data assimilation methods will be used for real-time forecasting and adaptive sampling tasks in the initial field years of the proposed program. As the optimal assimilation schemes become available, they will be used in the later years, mostly in hindcast mode, to generate 3-d fields for dynamical interpretation. Currently data assimilation experiments demonstrate that SCRUM model can qualitatively predict the formation of the coastal upwelling eddy (Fig. 3).

For this proposal we propose to couple SCRUM to a coastal version of EcoSim model (Eco-SCRUM). This model system will assimilate observational data providing a nowcast that will serve to initialize the model run. Forecasting efforts require specification of the 3-dimensional initial conditions (ICs) and the future boundary conditions (BCs) to forecast forward in time. The initial conditions (nowcasts) will be developed via data-assimilation of (1) spatially extensive surface data acquired by remote sensing platforms and (2) spatially limited sub-surface data acquired by stationary observing systems, moveable ships and AUVS (see below). The RAMS model will provide forcing conditions at the sea surface. As the spatial and temporal variability in the IOPs during upwelling is strongly dependent on local hydrographic forcing, modeling forecasts will be based upon the transported optical constituents in space and time. The standing stock of materials will be determined by local transport, growth, sinking and resuspensions rates.

Model Forecast Evaluation Procedures. Project participants have a long history of hydrodynamic model evaluation including regional Gulf Stream models (Glenn and Robinson, 1995), coastal hurricane models (Keen and Glenn, 1996) and North Atlantic Basin scale models (Haidvogel et al., 1998). These evaluation procedures include both qualitative evaluations of the model's ability to reproduce observed events and quantitative skill scores for the hydrographic features. As part of COMOP, Drs. Glenn, Haidvogel and Schofield adopted a similar multi-level approach to evaluate the hydrodynamic coastal circulation model at LEO-15 for its ability to reproduce the observed location and structure of upwelling fronts, and for its ability to predict the advective transports and dynamical balances. In each category, several questions that can be answered by both models and observations were proposed to serve as a basis for model/data comparison and characterization. A similar approach will be adopted for the bio-optical components of the system proposed here. During the HyCODE study, forecast validation of in-water optical properties (IOPs, AOPs, chl a, CDOM, etc) will be based on both (1) a qualitative assessment of the model's ability to reproduce observed optical features within the upwelling centers over time and (2) a quantitative assessment based on the offset between observed and predicted optical fronts associated with the boundaries of the upwelling center as measured simultaneously by satellites and in situ instruments. This procedure will allow an evaluation of forecast sensitivity to model configuration (grid size, number of levels, spectral complexity of optical module), initial conditions, and predicted parameters (water-leaving radiance, IOPs, chlorophyll a, dissolved organic matter, etc). The specific optical features, which can be addressed by both the models and observations, which will serve as a basis of comparison include:

General Spatial/Temporal Behavior of Upwelling Features. We expect the model to reproduce the general optical features associated with the upwelling events; therefore we will address specific questions focused on the biological and chemical features present during an upwelling event. During the evolution of an upwelling center, what is the rate of accumulation of matter within an upwelling center? Can this accumulation be accounted for by phytoplankton growth or does it reflect material transported from local estuaries and/or the benthic boundaries of the shallow continental shelf? Are phytoplankton growth rates enhanced within the upwelling center or does biomass accumulation reflect the retarded advective transport of phytoplankton by alongshore coastal jets? Do the enhanced growth rates correlate with enhanced nutrient availability as typically observed for open ocean and deep coastal systems? How do the major optically active constituents vary with depth inside and outside of the upwelling center and do materials accumulate in the convergence zones within the upwelling center? Does significant deposition occur throughout an upwelling event or does transport to the benthos largely result from downwelling conditions?

Spectral Properties of the Upwelling Centers. The composition of the organic matter will obviously impact the optical properties within and outside the upwelling centers. The spectral properties of the upwelling events will be characterized using both in situ and satellite ocean color data. We also expect a gradient in the composition of the matter present based on the proximity to local estuaries due to the loading of terrestrial CDOM. What is the significance of terrestrial and marine CDOM to the nearshore optical properties in these waters? What is the corresponding impact of upwelling on the relative importance of CDOM and phytoplankton to water leaving radiance? Do the spectral properties within the upwelling centers significantly change during phytoplankton successional events? What is the impact of sediment resuspension on water leaving radiance in the shallow waters?

TIMELINE

Year 1. Modeling efforts in first year will be focused on modifying EcoSim for use in coastal waters. EcoSim efforts will initially focus on 1-dimensional model studies of upwelling/non-upwelling events on both sides of the upwelling fronts. Modifications to SCRUM include integrating the RAMS model. Before integrating EcoSim to SCRUM, the optical model will be adjusted for use in coastal waters and modified to provide spectral estimates of the IOPs and water leaving radiance. Techniques to efficiently acquire, process, and deliver available satellite data will be developed, and in appropriate cases, automated. Existing algorithms to derive inherent optical properties and geophysical parameters from ocean color data will be compiled and evaluated. Modification for use in coastal waters requires the absorption characteristics for typical coastal phytoplankton assemblages and resuspended sediments to be added to the model. These spectra will be collected during the summer field season in 1999. The field efforts in 1999, funded by the COMOP and NOPP programs, will collect discrete samples which will be analyzed for total particulate, dissolved and phytoplankton absorption. The particulate and phytoplankton absorption will be determined for 3 size fractions (>5 μm, 5 to 1 μm, 1 to 0.2 μm) using the filter pad technique. Absorption of sediments can be difficult to determine due to high scattering; therefore, size-fractionated samples will be analyzed on a Dw-2000 Aminco spectrophotometer at the University of California at Santa Barbara. The system at Santa Barbara is equipped with an integrating sphere with an internal sample holder allowing for accurate absorption spectra for even highly scattering solutions (Nelson and Prezelin, 1993). The instrumental efforts in Year 1 include development of an optical REMUS, installation of ac-9 sensors to the LEO-15 nodes, and the installation of WeatherPAK buoys with the GER reflectance sensors.

Years 2 and 3. The second and third year represent the major field efforts for the HyCODE program. During year 2, the 3-dimensional model of EcoSim will be fused to SCRUM. Data from LEO-15 will be collected during the entire year but major field efforts will begin in late May and early June prior to the summer upwelling season and will last into August. Collection, processing, and delivery of satellite data will continue. The field efforts will include hyperspectral satellite imagery, ship and AUV surveys. The priority in year 3 will be using the Eco-SCRUM model to provide physically forced 3-dimensional nowcasts and 2-3 day forecasts of the in situ bio-optical properties. The nowcasts will provide guidance to shipboard and REMUS surveys. Other efforts include remote sensing algorithm development and validation.

Years 4 and 5. If renewed, years 4 and 5 are reserved for data synthesis, model and assimilation evaluation, visualization and dynamical analysis of the resulting 3-dimensional fields, publication and dissemination. Optimal assimilation schemes will be run in hindcast mode to generate 3-dimensional model fields for dynamical analyses.

PROGRAM & DATA MANAGEMENT.

Program Management. This project represents a group effort from several research institutions. Table 2 lists responsibilities and data products of the individual research partners. Data products will be maintained in a data management system being developed at IMCS (see below).

Institution	Roles and Tasks	Data Products
Rutgers University (Schofield, Glenn, Haidvogel, Grassle)	1) Project Coordinators 2) Integrate physical/bio-optical submodels and provide forecasts during field programs 3) Upgrade and deploy physical/bio-optical adaptive sampling network during field years 4) Develop 3-d fields of key events for dynamical analysis and interpretation	*Field data*. AVHRR, SeaWiFs, CODAR, LEO-15 nodes (CTD, Fluorometer, OBS, ac-9, ADCP), Meteorological sensors (Coastal Met tower, Coastal SODAR, Offshore Met Buoy), Shipboard instrumentation (surface towed ADCP, undulating CTD & Fluorometer, ac-9, ac-100, Safire, VLPC spectrometer, Biospherical and Satlantic radiometers) *Model*. Eco-SCRUM
Navy Research Laboratory (Bissett)	1) Upgrade and calibrate EcoSim model 2) Evaluate bio-optical forecasts during field years	*Model*. Eco-SCRUM

Cal-Poly (Moline)	1) Mounting of hyperspectral reflectance sensors to LEO-15 2) Laboratory analysis of discrete samples	*Field data*. GER reflectance sensors, in situ nutrients, oxygen, HPLC pigments, phytoplankton growth rates, size fractionated absorption spectra
NOAA-NESDIS (Brown)	1) Continuous satellite coverage 2) Satellite algorithm development	*Field data*. SeaWiFs, MODIS, AVHRR, RADAR-SAT[1]
WHOI (von Alt)	1) Integrate optical sensors on REMUS 2) Integrate optical sensors on LEO-15 node 2) Operate REMUS during field years	*Field data.* REMUS surveys with ADCP, CTD, Fluorecence, and upward radiance & downward irradiance

1. In collaboration with Dr. Colon

Data Management. All data will be maintained in a project-driven data management scheme being developed by IMCS. Data is managed at three distinct levels. Level 1 is the archived raw data downloaded from individual instruments stored off-line. Level 2 is a series of on-line directories containing calibrated and processed data generated by the individual investigators in a flexible ASCII or Binary format. Level 3 is a second set of on-line directories containing composite data sets and model results in NetCDF format for advanced applications (Rew and Davis 1990). The data sets are maintained on a UNIX disk server controlling a large, multi-stage archiving system. Online access to Level 2 and 3 data is provided over the Internet via World Wide Web or anonymous ftp, where local users can log directly in with read-only access. For mission planning, preliminary real-time versions of many of the Level 2 datasets are available on our web site (http://marine.rutgers.edu/mrs), which is currently peaking at over 20,000 hits per day. A dedicated data manager (Dr. Yunquing Zhang) has recently been hired by IMCS and will ensure data is available in a timely manner.

RELATION TO EXISTING PROGRAMS. This proposed program benefit from several ongoing projects at LEO-15. Currently, ONR's COMOP program is developing adaptive sampling networks for the nearshore coastal ocean. The COMOP program provides a significant portion of the salary costs associated with Rutgers personnel through 2001. Also two individual NOPP awards are focused at LEO-15. These awards are developing autonomous forecasting networks for local circulation patterns, coupling an advanced atmospheric model to SCRUM, and demonstrating the relocatability of these forecasting approaches as part of the Gulf of Maine EcoHAB program (Dr. Anderson, lead PI). These NOPP awards have substantially improved the computer visualization capabilities at Rutgers, and expanded the observation infrastructure at LEO (WeatherPak buoys, modified REMUS packages, fluorometers for undulating systems). The COMOP and NOPP awards provide 90% of the funding for the field efforts in 1999. Significant ship costs and the majority of the LEO-15 maintenance is provided by the Mid-Atlantic National Undersea Research Center (NURC). Since its establishment in 1992, the NOAA Middle Atlantic Bight (MAB) NURC has provided and average of $1,000,000 annually in peer-reviewed support for LEO-15 research and technology development projects and infrastructure support for the LEO-15 system. Technology projects initially funded by the MAB NURC include the initial engineering designs of the LEO-15 underwater nodes, the REMUS AUVs, and a new chemi-luminscent fiber-optic dissolved oxygen sensors. Research projects initially funded by the MAB NURC include a series of multi-institutional bottom boundary layer/sediment transport studies (Rutgers, WHOI, Sequoia, USM) that led to the development of the new BBLM to be coupled to the shelf circulation model as part of NOPP, and the initial studies of coastal upwelling, leading to three $1 million summer field programs sponsored by NSF (1996), NOPP (1998, 1999). Over 50 researchers from nearly 20 institutions have worked at or used data from LEO-15. We will also coordinate our efforts to assist other potential HyCODE projects at LEO-15 (Trowbridge and Agrawal). They currently plan to deploy LIST systems during the summer and fall to characterize the impact upwelling and storm events on sediment resuspension and the subsequent impact the in situ optical properties. We view interactions with Trowbridge and Agrawal as a unique opportunity as the SCRUM is already outfitted with the BBLM. Dr. Agrawal has already conducted three bottom boundary layer/sediment transport experiments at LEO-15 with Scott Glenn. Drs. Agrawal and Glenn have a fourth joint sediment transport deployment scheduled for fall of 1998 to provide further calibration data for the new BBLM. We will provide in situ optical data and logistical support whenever possible.

DELIVERABLES An integrated system for predicting the 3-dimensional structure of coastal currents, water density and in-water optical properties on the time scales of days is essential to numerous naval operations such as mine counter measures, special forces operations, amphibious landings, and shallow water anti-submarine warfare. The NEMO satellite provides hyperspectral ocean color data for mapping in-water constituents in areas of high naval interest. This program will benefit the HyCODE program by providing an extensive sea-truth database collected at a highly-instrumented field site, refined optical deconvolution models, a hydrodynamic/optical forecasting system and optical REMUS AUV technology. Another key deliverable for the Navy are the forecasting and REMUS systems which are relocatable assets for future naval operations. Development of forecasting systems for phytoplankton blooms is a key civilian deliverable. Early generation biological forecasting systems are a key focus of the EcoHAB program. We are already working with the regional EcoHAB in the Gulf of Maine. Drs. Schofield, Bissett, and Kirkpatrick also are directly involved in the Gulf of Mexico EcoHAB program, which is focused on developing *Gymnodinium breve* forecasting networks. Comparisons of the forecasting strategies and relative success for these disparate waters will be informative.

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