Hyperspectral Remote Sensing of the Coastal Ocean: Adaptive Sampling and Forecasting of Near-Shore In Situ Optical Properties

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LONG-TERM GOALS

Water clarity is a key parameter of coastal ecology, as well as being important to some near-shore Naval operations. The clarity of the water column depends upon the depth-dependent distribution of the inherent optical properties and the geometric structure of the light field (an apparent optical property). Our long-term goal is to develop the remote sensing techniques, data analysis, and modeling capabilities to nowcast and forecast the 3-dimensional Inherent and Apparent Optical Properties (IOPs and AOPs) of the near-shore coastal environment.

OBJECTIVES

1) To develop and deploy optical systems in the coastal ocean to ground-truth remote sensing imagery.

2) Reformulate 1-dimensional Ecological Simulation 1.0 into 3-dimensional simulation of the coastal IOPs and AOPs, and couple this new code with the Regional Ocean Modeling System (ROMS) being developed at Rutgers University.

3) Develop the techniques to incorporate IOPs measured from in situ, and suggested from inversion of remote sensing data, into a 3-dimensional nowcast/forecast model of the Long-term Ecological Observatory at 15 meters (LEO-15) off the coast of New Jersey.

APPROACH

Optical properties are well suited for rapid environmental assessment, as the instrumentation to measure absorption, attenuation, and water-leaving radiance are more engineered than those to determine organism biomass or quantity. For the coastal ocean resource manager, optics could become the proxy by which the ecosystem is quantitatively described. Thus, forecasting the optical properties of the coastal zone would be a boon to environmental resource managers, as well as those Naval operations that depend upon water clarity. It would demonstrate the coupling of predictive physical and ecological models, which rely on fundamental quantitative understanding of the processes operating in the marine environment. It would also facilitate the efficient allocation of scientific resources during critical times of environmental study, i.e., adaptive sampling.

The breath of area, as well as the rapid change of the water conditions in the coastal ocean makes any sampling, optical or otherwise, very time consuming and difficult. However, the focus on optics allows us to explore remote sensing techniques that can rapidly sample large areas, either by aircraft or satellite sensors. Optical remote sensing techniques have generally relied on empirical methods to invert the water-leaving radiance signal to relative measures of optical constituents, e.g. chlorophyll a (Gordon and Morel, 1983), or apparent optical properties, e.g., diffuse attenuation coefficients (Austin and Petzold, 1981). These inversion techniques assume a homogenous optical layer and were developed mainly for open ocean conditions. Thus, they have difficulties in more turbid coastal waters. Newer techniques have been developed for coastal waters that optimize the water-leaving radiance signal over many different wavelengths (Gould and Arnone, 1998), but these techniques require in situ measurements during the collection of the remote sensing data.

We hypothesize that predictions of in situ IOPs could be used in these algorithms as a means of constraining their optimization equations. In addition, the remote sensing data would provide an ideal initialization and validation data stream with which to constrain both the physical and ecological simulations. Thus, it is clear that the future development of both optical remote sensing techniques and predictive models of IOPs would benefit by being coupled together. This project is part of a larger effort to facilitate this development. It is a collaborative effort with many of the PIs in ONR's Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE) and, in particular, is funded as part of a larger project led by O. Schofield (Rutgers University, Award N00014-99-1-0196).

WORK COMPLETED

The 2001 LE0-15 field experiment (July 21-August 3, 2001) provided a uniquely coordinated opportunity with a variety of remote sensing imagery collected simultaneous to a small fleet of vessels, moorings, and a buoy with optical ground truth measurements. Imagery was collected by satellite (SEAWIFS), high altitude aircraft (AVIRIS @ 20km), medium altitude aircraft (PHILLS2 @10km), and low altitude aircraft (PHILLS1@ 300m). To further close the loop on atmospheric correction, the Florida Environmental Research Institute along with the University of South Florida's Ocean Optics Laboratory deployed automated and handheld sun photometers along with a meteorological station. From these instruments, aerosol optical depths, downwelling irradiance, ozone, air temperature, barometric pressure, and relative humidity were monitored during the over flights at the Rutgers University Marine Field Station (RUMFS near Tuckerton, New Jersey 39.508°N, 74.323°W). The data from these sensors was analyzed and prepared for publication, as well as for use in the atmospheric correction of both satellite and aircraft imagery.

Following the discovery of errors in the data-assimilative ROMS physical circulation simulations at the end of last year, we focused on running the simulation in a non-assimilative mode in order to test the robustness of the EcoSim/ROMS coupling. This allowed us to study the ecological response functions when driven by 3-D physical dynamics. This initial 3-D study led to some general ecological and IOP simulation successes; however, additional errors in the physical circulation model, (which were deemed too extensive to fix in the 1.8 version of ROMS) were found and these required fixing before additional ecological/optical studies could be completed. The physical modeling group has chosen to correct these errors with the soon to be release ROMS 2.0 version in order to generate physical simulations for the 2001 LEO field season. The 2.0 version of ROMS was developed for distributed parallel computering and nested model development (e.g. the high resolution LEO domain

nested into the lower resolution North Atlantic domain). This required a significant amount of recoding of the EcoSim modules (which has been completed).

RESULTS

Atmospheric Measurements
During the LEO 2001 experiment, there were two days suitable for the generation of Langley plots (instrument voltage versus airmass), July 21st and 27th. Aerosol loading on all other days (July 31st, August 1st, and 2nd) proved to be too variable or had systematic increases that skewed regression despite being visually cloud-free. The intercepts were then used to calculate the total and aerosol optical depths as well as Angstrom exponents (Figures 1).
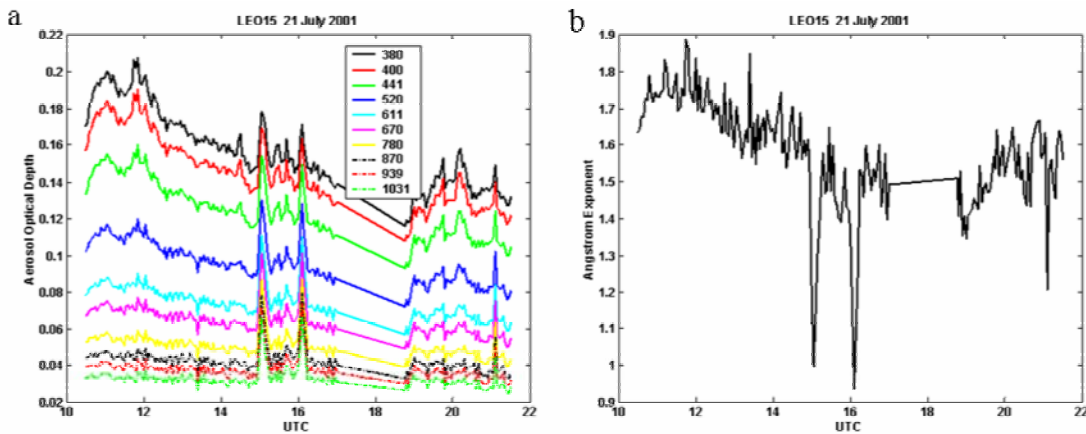

Figure 1: Aerosol Optical Depth (a) and Angstrom Exponent (b) during the July 2001 HyCODE LEO-15 experiment. July 21st and July 27th (not shown) had the most consistent airmasses during the experiment. Aerosol optical depth averaged approximately 0.035 for 1031 nm, increasing to approximately 0.16 for 380 nm. The angstrom exponent averaged approximately 1.6.

There were two distinct aerosol characteristics at LEO in response to frontal passages. Before the July 26th storm, the typical conditions were for aerosol optical depth, τ_a, on the order of 0.1-0.2 and an angstrom exponent, α, of 1.5-1.8. Immediately following the storm on the morning of July 27th, τ_a dropped to exceptionally low values of 0.07 -0.1 with α of 1.2-1.3. These were consistent throughout the day but are masked in the Automated Solar Radiometer (ASR) products by jet contrails. The larger storm event on July 29-30th produced a similarly clear atmosphere on July 31st. However, it rapidly degraded during the early morning hours. The τ_a climbed steadily throughout the next 60 hours from the lowest to highest values for the experiment, 0.07 – 0.50, and the α increased from 1 to 2, indicative of small particles typical of urban/continental aerosol models.

The first check on the ASR products was a comparison to those independently derived from other sensors on site and those derived from SeaWiFS processing. In addition to the ASR, two Microtops (one with ozone channels and the other with SeaWiFS channels) were deployed at various locations during the experiment. Two images from SeaWiFS were collected during the field experiment. Since the SeaWiFS overpass occurs close to local noon, the 7/27 image was collected after the contrails had dissipated and confirms the low aerosol concentration for the day. The 7/31 image shows that not only did the aerosol concentration increase with time, but also varied spatially.

The second is often called vicarious calibration. It entails selection of atmospheric correction parameters such as aerosol/ozone/water vapor to make the remote spectra match a known or measured ground target reflectance. Most of the airborne HSI at LEO was atmospherically corrected using *Tafkaa* (Montes et al., 2001), a tabularized version of the ATREM atmospheric model (Gao and Davis, 1997; Gao et al., 2000). At two sites on 7/31, the surface reflectance was measured during the over flights by two different, well-calibrated radiometers, one a Satlantic TSRB and the other an Analytical Spectral Devices FieldspecFR. Thousands of *Tafkaa* runs were conducted, optimizing the parameters until the atmospherically-corrected AVIRIS and PHILLS2 spectra best matched the reflectance spectra measured on the water.

To demonstrate the importance of the aerosol to the atmospheric correction, a series of MODTRAN4 radiance calculations were performed using parameters appropriate for the 7/31/2001 am flight window and using the default spectral albedo for ocean. The aerosol contribution was varied from $\tau_a(550) = 0.5$ to 2.0 (or roughly a visibility range of 3 to 13 km). Figure 2 shows how the radiance at a 10 km height sensor is related to the surface reflected radiance. The large differences shown in the NIR is chief source of error in the atmospheric correction and the reason for deployment of sun photometers and the optimization schemes shown here.
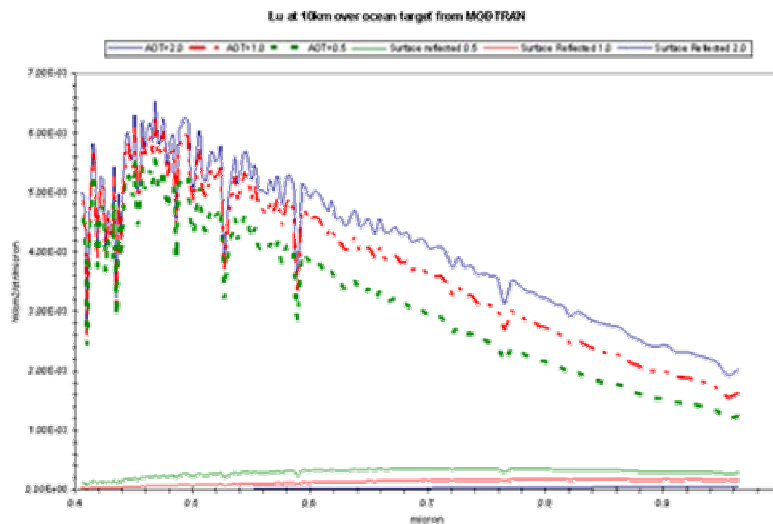

Figure 2. Upwelling radiance at 10 km altitude (upper three curves) for three different τa550 and atmospheric parameters for LEO15 on 7/31/2001 as modeled by MODTRAN4. Lower three curves are the radiance reflected from the default ocean surface in the model.

EcoSim/ROMS
There were a number of corrections to the physical code following the results of the previous simulation analysis, in part driven by errors in the assimilation scheme. The results shown here have been generated without the data assimilation scheme. This allows us to highlight the results of the coupled physical/ecological simulation without the errors in the assimilation scheme. Further physical errors are to be corrected in the ROMS/TOMS 2.0 release. The results shown are from the ROMS 1.8 release generated for the HyCODE 2001 field season and focus on August 2, 2001 (Figure 3 and 4).

Figure 3 shows the surface plots around the LEO-15 sampling grid, and Figure 4 are from the N1 sampling line (as seen in the AVHRR and SeaWiFS images in Figure 3).

The ecological interactions between the phytoplankton groups yield differences between the accumulation of pigments and carbon biomass. The differences result primarily because of the differences in the carbon to chlorophyll ratios of each functional group. The total chlorophyll a associated with diatoms, cyanobacteria, and dinoflagellates are similar to that estimated by HPLC analysis, and most of the chlorophyll split between diatoms and cyanobacteria. Carbon biomass, however, is weighted between the functional groups differently, with cyanobacteria dominating the total carbon biomass. This has significant implication for remote sensing algorithms and prediction of water-leaving radiance. Absorption is most closely associated with total pigment concentration; however, scattering is more of a function of species and total carbon biomass (Stramski et al., 1999). Algorithms designed to detect types of phytoplankton, i.e., Harmful Algal Blooms, may have to resolve the difference between absorption and scattering at the species level. Once the physical issues are resolved in ROMS, the IOPs from this simulation will be used to drive predictions of water-leaving radiance using Ecolight (See Bissett ONR Progress Report, N000140110456, and Mobley ONR Progress Report, N0001400D01610002). These will be directly compared to remote sensing upwelling irradiance measurements collected by PHILLS1, PHILLS2, AVIRIS, SeaWiFS, and MODIS sensors.
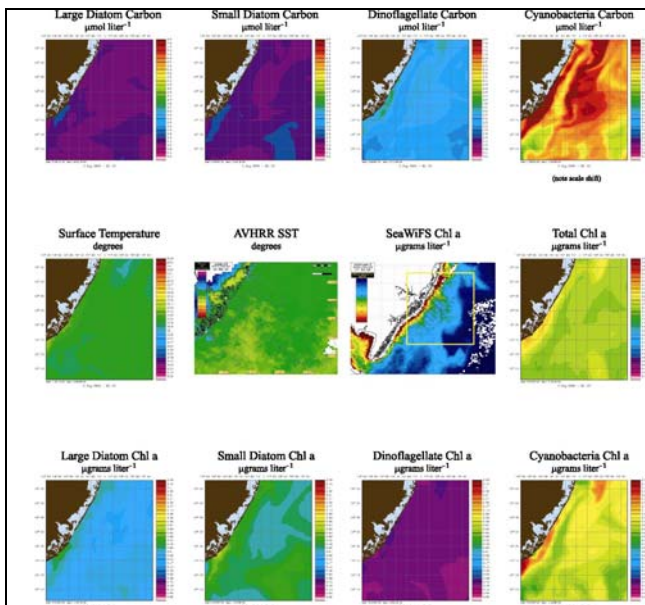
Figure 3: Surface distribution of simulated carbon biomass per functional group (top row); simulated SST, AVHRR SST, SeaWiFS Total Chlorophyll, and simulated Total Chlorophyll (middle row); and simulated chlorophyll a per functional group (bottom row) at the LEO 15 field site August 2nd during HyCODE 2001 experiment.
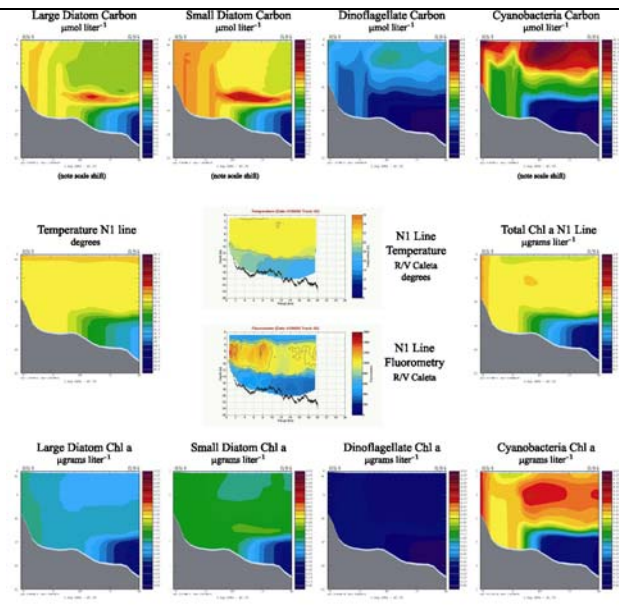
Figure 4: Vertical distribution along N1 Sampling Line of simulated carbon biomass per functional group (top row); simulated temperature, measured temperature, measured chlorophyll fluorometry, and simulated Total Chlorophyll (middle row); and simulated chlorophyll a per functional group (bottom row) at the LEO 15 field site on August 2nd during HyCODE 2001 experiment.

IMPACTS/APPLICATIONS

The short- and long-term prediction of IOP distribution in the coastal ocean requires the ecological simulation of the time-dependent change of color, as well as the accurate advection of color and color causing materials (i.e. nutrients -> phytoplankton -> absorption and scattering). Validated forecasts of ocean color will allow for the accurate performance prediction modeling of in-water and above-water active and passive optical systems, such as MCM laser line scanners and UAV imaging spectrometers. In addition, nowcast/forecast system may supply IOP estimates for areas where remote sensing data is unavailable, i.e. cloud or smoke cover, to provide adequate data streams in access denied areas.

RELATED PROJECTS

The list of HyCODE PI's is extensive and can be found at http://www.opl.ucsb.edu/hycode.html.

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HONORS/AWARDS/PRIZES

2003 Small Business of the Year, Semi-Finalist, Florida Environmental Research Institute, W. Paul Bissett, Ph.D., Executive Director, Greater Tampa Chamber of Commerce.