VARIABILITY IN MEASURED AND MODELED REMOTE SENSING REFLECTANCE AND COMPARISON OF SEAWIFS AND IN SITU CHLOROPHYLL A DISTRIBUTION FOR COASTAL WATERS AT LEO-15

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ABSTRACT

A data base of *in situ* bio-optical measurements and pigment samples were collected at the LEO-15 (Long-term Ecosystem Observatory) off the southern coast of New Jersey (USA). The data was used to quantify the impact of coastal upwelling on nearshore bulk apparent (AOP), inherent (IOP) optical properties and phytoplankton biomass concentration and composition. There was good qualitative agreement between the AOPs and IOPs in space and time. The measured IOPs were used as inputs to the Hydrolight radiative transfer model (RTE). Estimated spectral AOPs from the RTE were strongly correlated (generally $R^2 \geq 0.80$) to measured AOPs. If optical closure between in-water measurements was achieved then the RTE was used to construct the spectral remote sensing reflectance. The modeled remote sensing reflectances were compared to satellite derived reflectance estimates from 4 different algorithms. Quantitative agreement between the satellite-measured and in-water modeled remote sensing reflectance was good but results were variable between the different models. The strength of the correlation and spectral consistency was variable with space and time. Correlations were highest in clear offshore waters and lowest in the nearshore turbid waters. In the nearshore waters, the correlation was strongest for blue wavelengths (400-555 nm) but lower for the red wavelengths of light.

INTRODUCTION

Understanding and managing shallow coastal waters (0-30 m depth) is a high environmental priority as they represent areas of increasing economic and social significance. Despite this, studies on 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. Ocean color remote sensing will be a key component to the rapidly expanding network of ocean observatories. This will become increasingly important given the suite of new ocean color satellites to be launched in the coming decade. Currently, the ocean color satellites that will be launched by the United States include EOS AM-1 (MODIS), EOS PM-1 (MODIS), NEMO (COIS) and EO-1 (ALI & Hyperion). This will be complemented by the Japanese ADEOS-2 (GLI), the Indian IRS-P4 (OCM) and the Chinese HY-1 satellite platforms. Effective utilization of these ocean color assets will require improvements in remote sensing capabilities for optically complex coastal waters that reflect the atmospheric, freshwater/estuarine, oceanic, and anthropogenic influences all of which operate over a broad range of temporal and spatial scales.

The ONR's Hyperspectral Coupled Ocean Dynamics Experiment (HyCODE) efforts are focused on developing remote sensing techniques for optically complex coastal waters. As part of that larger effort, this study is focused on characterizing *in situ* optical variability and corresponding impacts on remote sensing reflectance and satellite-derived chlorophyll estimates.

METHODS

Field sampling

The field sampling program was focused characterizing the optical dynamics during the month of July at LEO-15. Sampling was coordinated using real-time data from ships, underwater nodes, and daily sea surface temperature imagery collected by the Advanced Very High Re*s*olution Radiometer. Results will focus on two specific days that had clear satellite imagery. The clear images provided a wide gradient of optical features reflecting variable water masses along the inshore-offshore optical gradient. The standard shipboard transects consisted of several 15-25 km cross-shelf transects. Physical surveys were conducted using an undulating guildline system equipped with a FSI CTD and Wetlabs chl a fluorometer. These physical surveys were complemented with profiles of in situ physical and optical parameters measured at discrete stations that were on spaced 1.5 km apart. At each station a vertical profile of optical and physical data were collected (see below). The profiles were measured with an integrated bio-optical package consisting of a Wetlabs (Philomath OR) a nine wavelength absorption/attenuation meter, a Falmoth Scientific Instruments CTD, a profiling OCR Satlantic spectroradiometer, a Sequoia LISST laser particle detector, a HOBI Labs six wavelength backscatter sensor, and a Sea Tech transmissometer.

The ac-9 provided in-water estimates of absorption a(λ) and attenuation c(λ) [scattering(λ) = c(λ) – a(λ)] at 412, 440, 488, 510, 555, 630, 650, 676, 715 nm. The instruments were factory calibrated prior to the summer field season. Manufacturer recommended protocols were used to track instrument calibration throughout the field season. This included clean water, temperature, and salinity calibrations. Frequent clean water calibrations were conducted; however sampling schedules did not always allow for a daily calibration. At each station, the instrument was lowered to depth to remove air bubbles and the instrument was allowed to come to temperature before the data was collected. Only data from the upcast were utilized.

Discrete samples

At each station water was collected with a Niskin bottle for both the surface and bottom water. Aliquots were filtered, under low vacuum (<10 cm Hg), through GF/F (Whatman) glass-fiber filters to concentrate the particles for pigment and absorption determinations. No special effort was made to acquire a predetermined amount of particulate matter, but 500 to 750 mls were sufficient for these waters. Filters were placed into the snap top vials and quick frozen in liquid nitrogen. Samples were stored at –80 ˚C until later analysis. Photosynthetic and photoprotective pigment complements were determined using high-performance liquid chromatography (HPLC). Pigment analyses were conducted utilizing a C-18 Hypersil reverse-phase column. Chromatographic peaks were detected by a photodiode array UV-VIS detector (SPD-M6A, Shimadzu, Inc.) and identified by retention time and comparison of absorbance spectra with spectra of pigments from standard microalgae cultures.

RESULTS & DISCUSSION

Storm-induced mixing (July 17, 1999)

The LEO-15 study site during the 1999 month-long experiment was characterized by protracted periods of mild downwelling leading to strong water column stratification with high concentrations of chlorophyll that were associated with the thermocline. This downwelling phase was interrupted by a strong storm (dates) which, was sufficient to induce watercolumn mixing leading to enhanced turbidity values (Fig. 1). The storm-induced decreases in surface water temperatures did not reflect upwelling because of the immediate warming of bottom water temperatures. Associated with the mixing were enhanced concentrations of chlorophyll a as indicated by both discrete samples and satellite imagery.

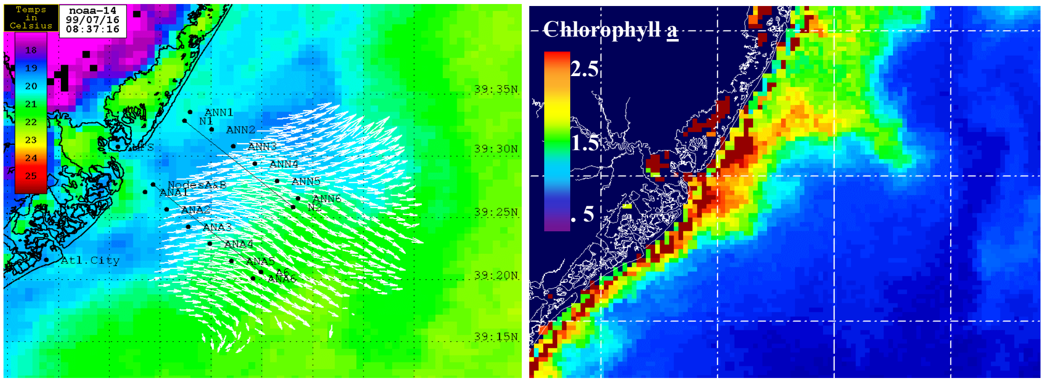
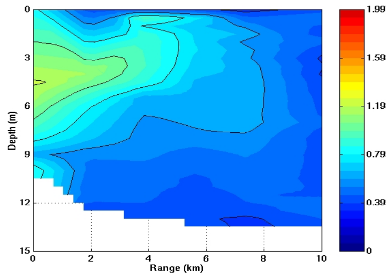


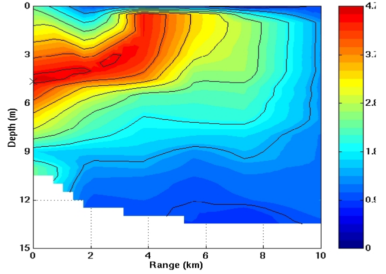
Figure 1. AVHRR sea surface temperature and SeaWiFs chlorophyll imagery for July 16, 2000.

Satellite estimates of chlorophyll a were compared to discrete HPLC measurements. All satellite chlorophyll algorithms performed poorly ($R^2 < 0.20$, $p>0.05$) in these waters with overestimated chlorophyll values by up to 75%. Consistent with the satellite imagery, the in-water optical properties showed significant cross-shelf variability. Absorption ($>1\ m^{-1}$ @ 440 nm), attenuation ($> 4\ m^{-1}$ @ 440 nm) and backscatter ($> 0.025\ m^{-1}$ @ 440 nm) showed high values in nearshore waters and decreased significantly in offshore waters. Interestingly, within the nearshore waters, there was a highly scattering water mass located about 4 kilometers offshore (Fig. 2).

The ac-9 data was used to initialize Hydrolight 4.0. Outputs of Hydrolight were compared to independent optical measurements in order to assess to what degree optical closure between the inherent and apparent optical properties could be achieved in these waters. In general the predicted values agreed within 20% of measured Kd values across the spectrum. The R^2 between measured and predicted Kd was generally high (>0.70) in the blue wavelengths and at the chlorophyll red peak; however values were lower at 555, 620, and 705 nm. More importantly the slope between the measured and modeled Kd showed spectral variability with peak values in the blue to green wavelengths of light (490 and 510 nm) and low values in the red wavelengths of light (620-705 nm). Interestingly, the general shape of the slope between the measured and predicted Kd values were consistent with the scattering cross-section for minerogenic particles.



a 440 nm



c 440 nm

Figure 2. Absorption and scattering properties for a crosshelf transect on July 16, 1999.

Comparison of the remote sensing reflectance derived from Hydrolight and as measured by the SeaWiFs satellite showed that measured reflectances were in general higher then would be predicted by Hydrolight 4.0. The magnitude of the overestimate increased with the magnitude of scattering present in the waters. Thus offshore waters showed the close agreement between modeled and measured reflectance. The most dramatic mismatches between the satellite and measured reflectance were at 705 and 555nm. The mismatch at 555 nm varied with the water mass. For nearshore waters satellite reflectance was significantly higher then modeled reflectance. In contrast, satellite reflectance was 20% lower then modeled reflectance in the highly scattering plume. The agreement at 555 nm was good in offshore clear waters. The enhanced scattering in the plume had a spectral signature consistent with minerogenics (Fig. 4a). The backscatter coefficient was not coincident with the

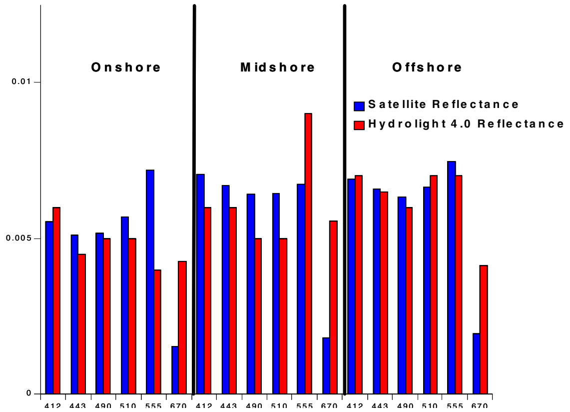


Figure 3. Comparison of satellite and modeled remote sensing reflectance for July 16, 1999. The reflectance was using Hydrolight 4.0 and ac-9 data. The default Hydrolight volume scattering functions were used.

high scattering load which, could indicate the presence of large particles leading to enhanced forward light scatter. The net result we hypothesize is a pathlength amplification resulting in depressed reflectance values.

Upwelling (July 30, 1999)

Upwelling was induced by southwest winds that resulted on July 30th cold bottom water breaking the surface. Subsurface current observations acquired by both the AUVs (equipped with ADCPs) and towed SWATH vehicles on the cross-shelf transects indicated that the northward-flowing upwelling jet on the offshore side is confined to the upper water column above the thermocline, and a highly turbid southward-flowing, subsurface jet in the nearshore waters.

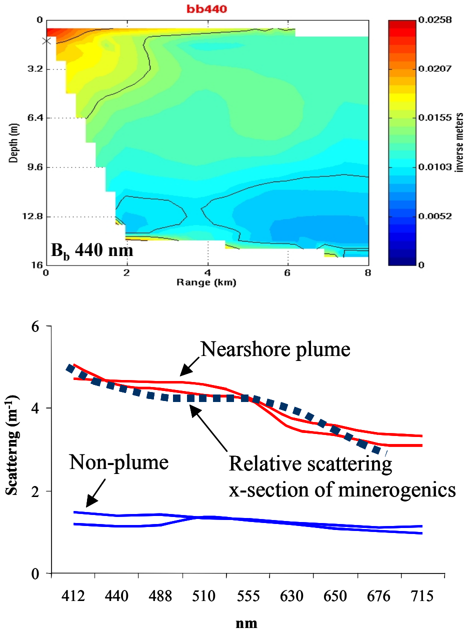


Figure 4. Scattering characteristics of the turbid plume for July 16, 1999 A) backscatter as measured with a OBI Labs HS-6. B) spectral chacteristics of scattering from an ac-9.

On this day, satellite estimates of chlorophyll a were highly correlated ($R^2 > 0.95$, $p < 0.001$) with the discrete chlorophyll measurements. All algorithms (Carder, Stumpf, Arnone, and Morel [1,2,3]) showed a strong positive linear correlations with measured chlorophyll. The slopes between the satellite and measured chlorophyll values varied by 20-50%. The Carder chlorophyll a algorithm provided the best quantitative agreement with the measured values. Similar as July 16, 2000 the nearshore waters were more turbid then offshore waters. The derived apparent optical properties from the Hydrolight runs, using the ac-9 data, showed a closer and more robust agreement with independent measurements then on July 16, 2000. The R^2 between modeled and measured Kd ranged between 0.8 and 0.95 across the spectrum. In contrast to July 16 1999, the slope showed no significant spectral variability.

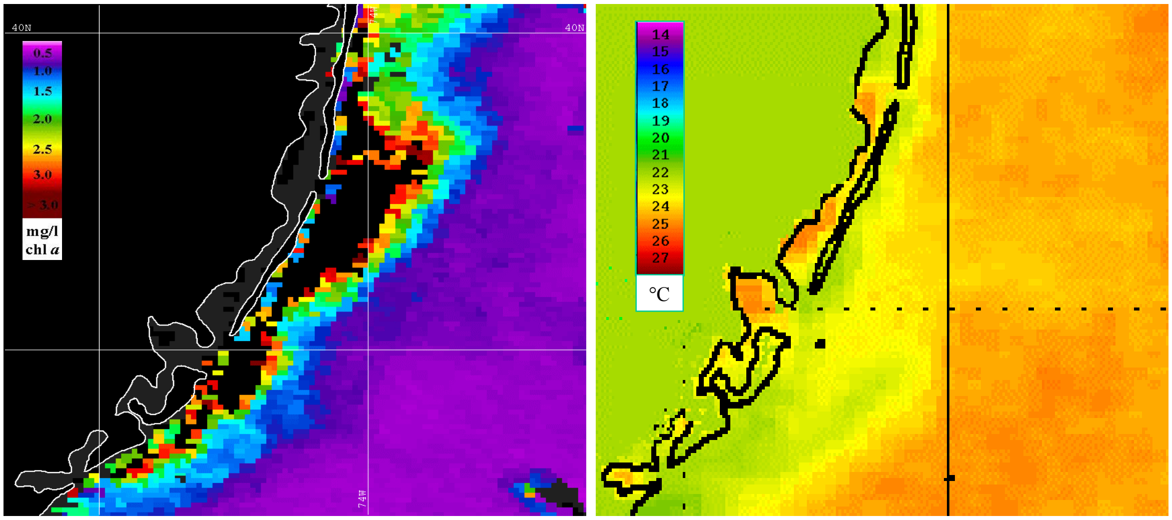


Figure 5. Upwelling event of July 20, 2000. Increases in ocean turbidity were immediately coincident with the cool water temperature.

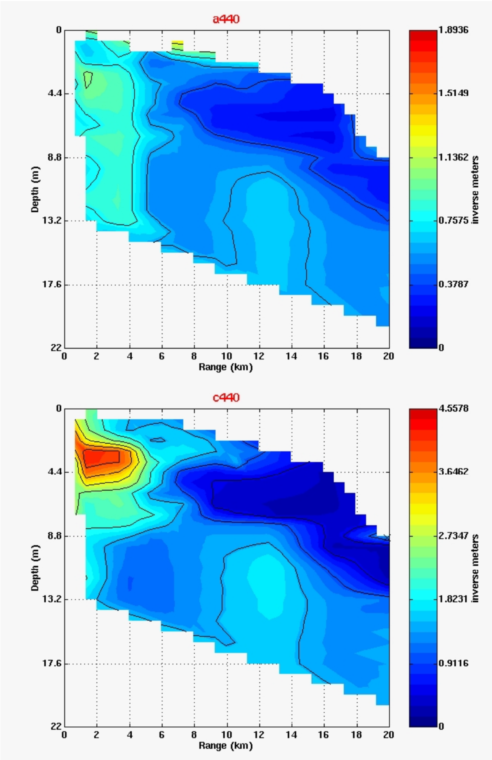


Figure 6. Optical properties for an upwelling event observed on July 30, 1999.

CONCLUSIONS

Satellite estimates of chlorophyll were compromised by a storm that resulted in enhanced concentrations of particles. These particles were most likely minerogenics as indicated by the spectrally skewed scattering spectra. Within these particle-dominated waters, closure between in-water measurements was also compromised. These problems were only associated with the highly scattering plume water as optical closure and robust pigment estimates were observed in offshore and turbid upwelling waters.