HIGH TEMPORAL RESOLUTION OPTICAL AND PHYSICAL TIME SERIES DATA: COASTAL MIXING AND OPTICS AND LEO-15

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ABSTRACT

High-resolution time series of bio-optical and physical data were obtained using moored and bottom-mounted instruments on the southern New England continental shelf in 70 m water depth during the Coastal Mixing and Optics (CMO) experiment from July 1996 through June 1997. The most prominent physical and bio-optical signals observed during the experiment were associated with seasonal variability. However, several important events interrupted the seasonal cycle. These episodic events appear to have had a great impact on biogenic and non-biogenic matter. Hurricanes and storms passed over or near the CMO site, resulting in reduced stratification of the water column, particle redistribution, and sediment resuspension. Changing hydrographic conditions that resulted from the influence of several water mass intrusions affected particle concentration on time scales of days to several weeks. The bottom boundary layer processes had a large influence on particle movement in the water column and along the seafloor, affecting the inherent optical properties and subsequently, phytoplankton biomass distributions and primary productivity in the upper water column following storms and hurricanes. The results suggest that there is considerable interannual variability in both the bio-optics and physics because of active and diverse physical forcing. This experiment sets the context for comparing our CMO results with other coastal ocean sites (LEO-15) as well as with previous open ocean findings. Time scales of optical variability (e.g., changes in phytoplankton spectral shapes of absorption) are generally shorter for the CMO coastal environment (on scales of days to weeks) as compared with open ocean optical variability (on monthly to seasonal scales). We hypothesize that time scales of optical variability at the LEO-15 site (New Jersey shelf in 15 m water depth) will be less than those found at the CMO site because of greater dynamical forcing in shallower shelf waters.

INTRODUCTION

The present study was part of the Office of Naval Research-sponsored Coastal Mixing and Optics (CMO) experiment. The CMO experiment was designed to examine the mixing of ocean water on a continental shelf and the effects of mixing and other physical processes on water column optical properties. The overall objective of our research is to determine the effects of physical forcing on particle and optical properties under various oceanic conditions on a continental shelf and to compare and contrast the CMO coastal environment with analogous LEO-15 (New Jersey shelf in 15 m water depth) coastal results and open ocean results.

We acquired an extensive set of unique observations of processes such as: internal solitary waves and their effects on bio-optics, bio-optical effects of the passage of two hurricanes [Dickey *et al.*, 1998; Chang *et al.*, 2000], several water mass intrusions, and the evolution of the seasonal cycle in hydrography and phytoplankton biomass as inferred from chlorophyll-*a* concentration. Our data are used to statistically quantify physical and biological processes and their relationships, and can be used for the development and testing of coupled physical-optical-biological, radiative transfer, and sediment resuspension and transport models [Souza *et al.*, 2000], and as inputs into data assimilation models to predict bio-optical responses to physical forcing. The present paper focuses on the description, quantification, and interpretation of temporal variability of physical processes and associated bio-optical responses on the Middle Atlantic Bight (MAB) of the southern New England continental shelf over the period of July 1996 through June 1997 [Chang and Dickey, 2000]. A comparison of our findings with those of analogous LEO-15 coastal results and open ocean results is also presented.

METHODS

The site of the CMO experiment was the "Mud Patch" of the MAB continental shelf, the southern portion of the New England shelf. The site is located about 110 km south of Martha's Vineyard, Cape Cod, Massachusetts, U.S.A. in water depth of approximately 70 m (Figure 1). Oceanographic instruments were placed on a mooring and a bottom tripod at the CMO site (roughly 40.5°N, 70.5°W) to concurrently collect high-resolution time series of physical and bio-optical data at several depths (Figure 1). Our observational study was coordinated with studies by other CMO investigators using shipboard, mooring, and satellite data sets to complement our measurements (see Dickey and Williams [2000]).

Instruments were deployed on a subsurface mooring to measure physical and bio-optical properties and currents. These instruments included temperature and salinity sensors at several depths, and an uplooking RD Instruments Acoustic Doppler Current Profiler (ADCP) at 65 m (Figure 1). Three bio-optical systems (BIOPS) were placed on a subsurface mooring at 12, 30, and 50 m depths, and one at about 2 meters above the bottom (mab) on a bottom tripod (Figure 1). BIOPS instruments measured: temperature, chlorophyll-*a* concentration (Chl-*a*; derived from fluorescence), photosynthetically available radiation (PAR), and absorption and beam attenuation at nine wavelengths (ac-9). For further instrumentation and calibration details, see Chang and Dickey [2000].

The site of LEO-15 (Long-Term Ecological Observatory at a 15 m water depth) is the New Jersey shelf, approximately 4 miles off the coast of Great Bay, New Jersey, in 15 m water depth. Bio-optical, physical, chemical, acoustic and laser sensors and systems are deployed *in situ* from moorings, bottom tripods, drifters, floats, autonomous underwater vehicles (AUVs), offshore platforms, aircraft, satellites, and ships using towed and profiled packages (see *http://marine.rutgers.edu/cool/LEO15.html*). Data discussed here are from instruments (e.g., temperature, salinity, ADCP, ac-9, and fluorometer) deployed on a mooring, bottom tripod, and two underwater nodes.

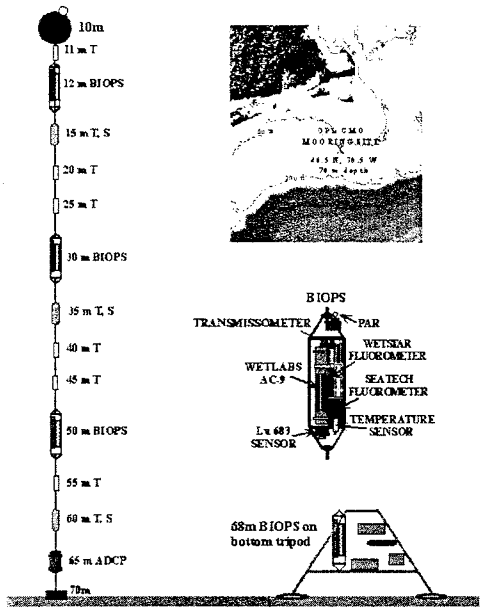

Figure 1: Coastal Mixing and Optics site map. A red "X" marks the location of the mooring and tripod used for this study. Also shown are schematic diagrams of the instrumentation, mooring array, and bottom tripod.

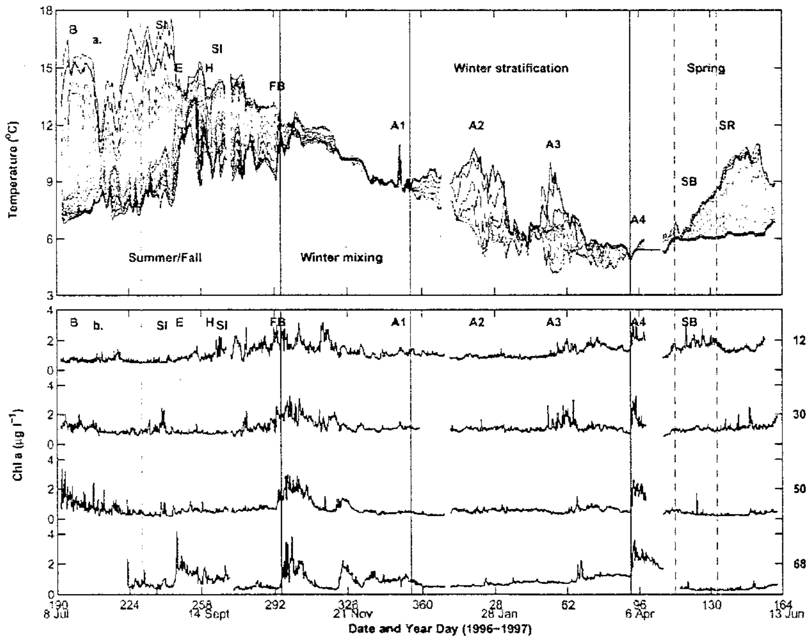

Figure 2: Time series stackplots of 36-hour averaged a) temperature (measured every ~3 meters between 11 m [red] and 68 m [blue]), and b) Chl-a at 12, 30, 50, and 68 m. Decimal year day convention = 0 h UTC January 1 is day 1.0. Events: "B, E, and H" = Hurricanes Bertha, Edouard, and Hortense, respectively; "SI" = high salinity water mass intrusions; "FB and SB" = fall and spring bloom, respectively; "A1, A2, and A3" = slope-water advection events; and "SR" = spring runoff. Hydrographic seasons are separated by black vertical lines and labeled. The green vertical dashed lines indicate the time periods when complementary profile data were obtained.

OBSERVATIONS AND DISCUSSION

Statistical analyses were used to establish the relationships between physical and bio-optical processes at several time scales at the CMO site (see Chang and Dickey [2000] for details regarding statistical analyses). The most dominant signal was the seasonal evolution, including stratification, mixing, and re-stratification of hydrographic properties, and associated blooms and death of phytoplankton (inferred from Chl-*a*; Figure 2). The semi-diurnal tidal period was prominent in current speed data (Figure 3), sometimes resulting in the generation of internal solitary waves (ISWs), which have the potential to mix nutrients and phytoplankton. However, phytoplankton was apparently only temporarily vertically displaced past our instruments on the CMO mooring during the passage of ISWs in summer/fall (Figure 4). This led to significant coherence between PAR and Chl-*a* at high frequencies during highly stratified conditions (summer/fall).

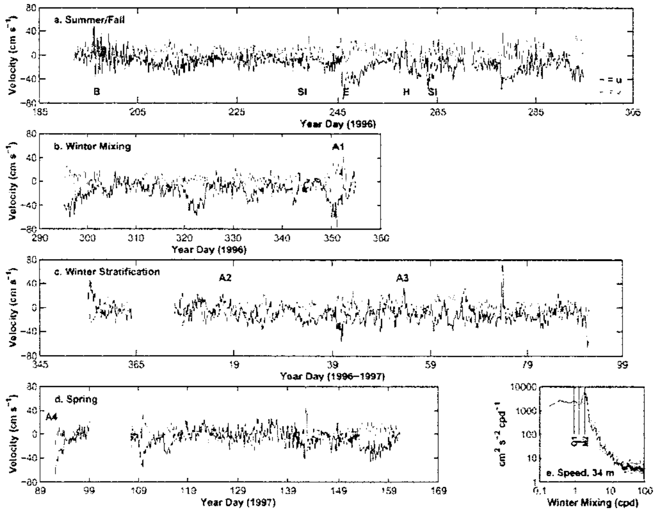

Figure 3: Time series of 6-hr averaged 10 m east (u) and north (v) component current velocity during a) summer/fall, b) winter mixing, c) winter stratification, d) spring; and e) current speed autospectra versus frequency (cycles per day) during winter mixing at 34 m (pink lines indicate 95% confidence intervals). The M2 semi-diurnal tidal frequency (12.42 hours), O1 diurnal tidal frequency (25.82 hours), and inertial period at the observational site ("I"; ~18.5 hours) are labeled.

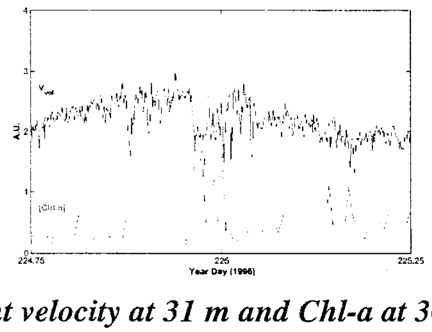

Figure 4: North-component velocity at 31 m and Chl-a at 30 m between periods of year day 224.75 and 225.25. Arrows indicate when internal solitary wave and response in Chl-a were observed at the experimental site. Data are plotted in arbitrary units.

At the CMO site, light and nutrient conditions were greatly affected by episodic events that were observed throughout the 11-month time series record: storms, hurricanes, and water mass intrusions induced by mesoscale variability. Mesoscale variability, in particular shelf-slope frontal intrusions and Gulf Stream eddies (Figure 5), caused advection of high concentrations of nutrients and possibly high biomass waters past the CMO site. These intrusions occurred at time scales as short as one-day to as long as 45 days resulting in high coherence between temperature and Chl-*a* at the near-bottom depths. The advected water masses often resulted in increased Chl-*a* and changes in the shape of phytoplankton spectral absorption [Chang and Dickey, 1999]. Intense atmospheric forcing during storms and hurricanes at time scales of ~3 days mixed the water column and particles, bringing nutrients up from the ocean bottom into the euphotic layer, as well as resuspended sediments and relict pigments, increasing the attenuation of light (Figure 6) [Dickey *et al.*, 1998; Chang *et al.*, 2000]. This is evidenced in the significant coherence between beam attenuation at 660 nm (beam c) and Chl-*a* at 68 m during periods of intense storms, partitioned spectral absorption [Chang and Dickey, 1999], as well as in the scatter plots of Chl-*a* versus beam c (Figure 6). Therefore, bottom boundary layer processes were very important to bio-optical properties. Inertial periods did not appear to be important at the CMO site, except perhaps following major storms or hurricanes ("B" in Figure 3).

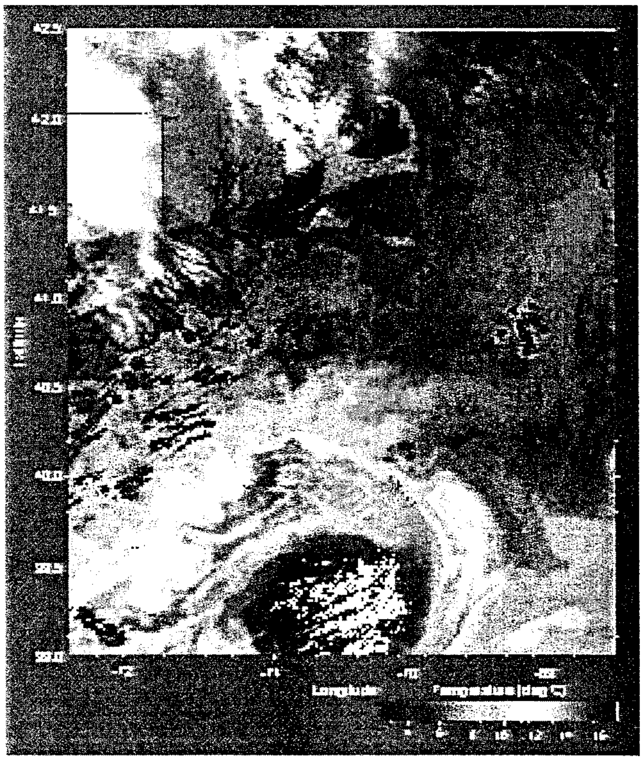

Figure 5: Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST) image of the Mud Patch region showing a Gulf Stream eddy at the shelf-break and subsequent slope-water intrusions onto the continental shelf on 18 February at 1742 GMT. The site of the CMO experiment is labeled with a white "X".

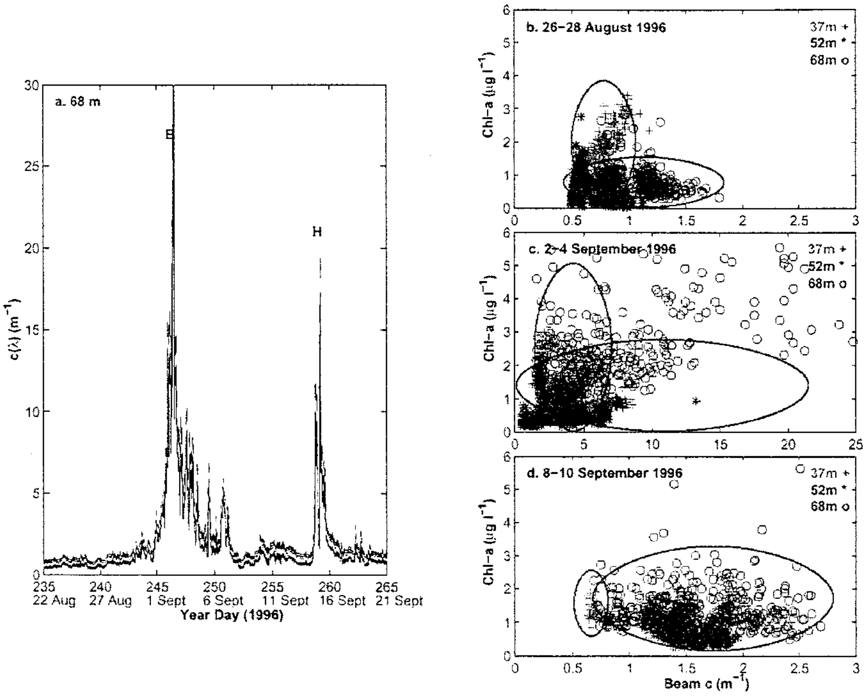

Figure 6: a) Hourly averaged time series of beam attenuation at nine wavelengths (between 412 and 715 nm) at 68 m, "E" and "H" indicates sediment resuspension during the passage of Hurricanes Edouard and Hortense, respectively; and Chl-a plotted versus beam c (both 6-hr averaged) at 37 (+), 52 (*), and 68 m (o) depths over the period of b) 26-28 August, c) 2-4 September, and d) 8-10 September 1996. Light signals indicative of biogenic and detrital matter are shown as vertical and horizontal ellipses, respectively.

The relatively short time scales of variability (~5 days) associated with wind and current speeds at all depths and time periods were expected in autocovariance analyses. Variability in wind speed was primarily associated with passing atmospheric pressure systems, and current speed variability was generally the result of atmospheric forcing, surface and internal waves, tides, and mesoscale advection events. Beam c exhibited relatively short temporal lag as well (<10 days) at 12, 30, and 68 m depths. High variability existed in beam c due to fluctuations in all components of attenuation (phytoplankton, detritus, and dissolved matter). Relatively low concentrations of phytoplankton and dissolved matter at 50 m likely resulted in longer temporal lag or less variability in beam c seen at this depth. Autocovariance spectra for temperature were generally similar at each depth; the temporal decorrelation scale was relatively long (>20 days). Temperature decorrelation time scales were dependent on mixing, advection, and water mass movements through mesoscale activity. Chlorophyll-*a* concentration autocovariance, a result of biological processes, was highly variable with depth and season (Figure 2b).

Our results allow us to compare important mixing processes (wind mixing, surface and internal gravity waves, tides, storms, hurricanes, eddy-induced advection and mixing, and turbulent mixing associated with internal solitary waves) relevant to bio-optical variability at the CMO site versus those observed at the LEO-15 site and in the open ocean.

The lower frequency time scales of variability (e.g., seasonal cycle, tidal frequencies) at LEO-15 are comparable to those found during the CMO experiment. The dominant signal on the New Jersey shelf is the seasonal cycle, which is frequently interrupted by episodic events such as storms and mesoscale activity in the form of coastal jets and eddies (discussed below). Frequency autospectra of currents show that the semi-diurnal, and to a lesser extent, the diurnal tidal frequencies are also important at the LEO-15 site (Figure 7). Higher frequency currents appear to be more important at LEO-15 (Figures 3e and 7) than at the CMO site. ISWs have not been observed at LEO-15, most likely due to dissipation of the waves offshore of the 15 m nodes.

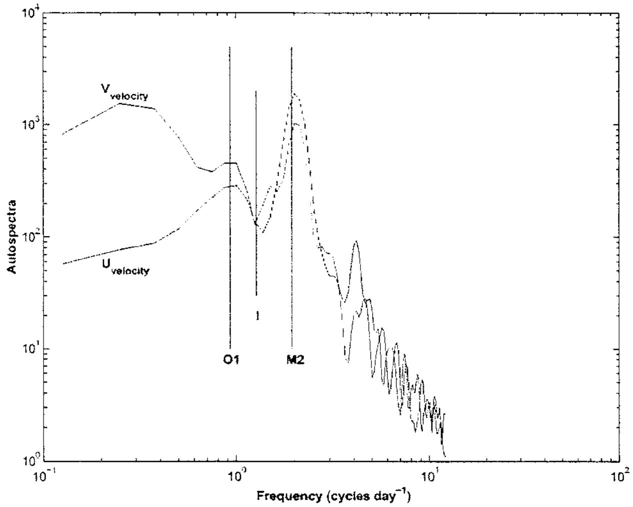

Figure 7: East ($U_{velocity}$; blue) and north ($V_{velocity}$; red) component current velocity autospectra versus frequency (cycles per day) at 5 m depth. The M2 semi-diurnal tidal frequency (12.42 hours), O1 diurnal tidal frequency (25.82 hours), and inertial period at the observational site ("I"; ~18.9 hours) are labeled.

Hydrographic variability and mesoscale activity differ from those found at the CMO site due to more dynamical forcing on the relatively shallower shelf waters of the LEO-15 site. The time scales of decorrelation for hydrographic properties at LEO-15 are on the order of 2-5 days, whereas temporal lag of CMO hydrographic properties is about 20 days. This difference is likely due to greater influence by winds, waves, and diurnal heating on the LEO-15 shallow shelf waters. At LEO-15, shelf water is oftentimes advected onto the slope, rather than slope water intruding into the LEO-15 site. It has been observed that strong southerly winds are responsible for newly formed upwelling fronts to move offshore. After the winds relax to light and variable for several days, explosive growth of the upwelling center with an embedded cyclonic eddy occurs and continues to move offshore (Figure 8). It is hypothesized that this eddy carries "optically loaded" water, eventually displacing the relatively clear shelf water to the continental slope with turbid, high biomass coastal frontal waters.

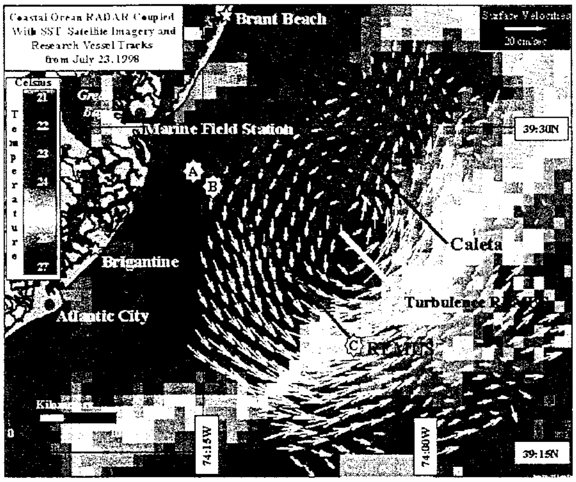

Figure 8: AVHRR-derived sea surface temperatures and CODAR-derived surface currents depicting an upwelling center with an embedded cyclonic eddy at the LEO-15 site on July 23, 1998. The location of the nodes are labeled "A" and "B". Research vessel tracks are also labeled.

Analogous measurements of physical and bio-optical variability in the Sargasso Sea, the subarctic North Atlantic Ocean, and the Arabian Sea have been reported by Dickey *et al.* [1993 and 1998b], Dickey *et al.* [1994], and Dickey *et al.* [1998c], respectively. Some time scales of mixing that are important to bio-optics in the open ocean are similar to those of the coastal ocean (seasonal, tidal, and episodic), except for the inertial period, which was less important at the CMO site than reported by open ocean studies. Mixing processes important to bio-optics in the open ocean include inertial, eddies, storms and hurricanes, and shear instabilities. Other than storms and hurricanes, these mixing processes are quite different from the results of the CMO experiment; water mass variability (except eddies), advection, frontal gradients, and internal solitary waves are less relevant mixing processes in the open than the coastal ocean. The bottom boundary layer and associated processes (resuspension of sediments and nutrients) are not at all important in the open ocean. Sosik *et al.* [2000] report that more diverse assemblages of optically important material are present on and near continental shelves, as compared to the open ocean. Differences in biological processes between the open and coastal ocean are well known [Mann and Lazier, 1991], e.g., light levels and attenuation, and mixing of nutrients versus recycling.

CONCLUSIONS

The CMO experiment was unique in that an extensive data set of concurrent high-frequency temporal resolution physical and bio-optical parameters was collected with oceanographic instruments on a mooring and a bottom tripod, and our study was coordinated with studies by other CMO investigators to complement our measurements. We identified several processes that were important to bio-optics on the southern New England continental shelf during the CMO experiment. The most prominent physical and bio-optical signals observed during the experiment were associated with the seasonal variability. However, several important episodic events interrupted the seasonal cycle. These episodic events (e.g., hurricanes, storms, water mass intrusions) appear to have had a great impact on biogenic and non-biogenic matter. Because of these major transient events, there is likely considerable interannual variability in the seasonal cycles of the physical and bio-optical properties on the MAB continental shelf. In addition to episodic events, the semi-diurnal, and to a lesser extent, the diurnal tides were significant for the bio-optical as well as physical time series signals. The inertial period appeared to have been important only following major storms and hurricanes. The bottom boundary layer processes had a great influence on particle movement in the water column and along the seafloor, affecting the inherent optical properties, and subsequently, phytoplankton biomass distributions and primary productivity in the upper water column following storms and hurricanes (further discussed in Chang and Dickey [1999]; Chang *et al.* [2000]).

This experiment also set the context for comparing our unique CMO coastal ocean results with other coastal sites and with previous open ocean findings. Important differences arise because of large-scale water mass intrusions, coastal bottom boundary layer effects, and the relatively greater role of tides on the shelf. Time scales of optical variability are thus generally shorter for the coastal environment. Finally, these data are being used with interdisciplinary models (e.g., physical-bio-optical and sediment resuspension) to establish and possibly predict relationships between physical, optical, and biological processes in a coastal environment.

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