UNIVERSITY OF CALIFORNIA
Santa Barbara

“Analyses of bio-optical variability related to physical processes on the southern New England continental shelf: July 1996 - June 1997”

A Dissertation submitted in partial satisfaction of the requirements for the degree of

Doctor of Philosophy
in
Marine Science
by
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ACKNOWLEDGEMENTS

This project could not have been completed without the assistance of others, and I would like to express my gratitude to all those people who helped and supported me.

Special thanks go to my committee members. Warmest appreciation of my advisor, Tommy Dickey, for his knowledge, friendliness, approachability, and entertainment over the years. His encouragement in giving presentations, as well as his introductions to future colleagues at major conferences is most appreciated. I'd like to thank Barbara Prezlin, Dave Siegel, and Libe Washburn for their knowledge, support, and enthusiasm towards science.

I am also greatly appreciative of the engineers, post-doctoral researchers, and staff members in our group (OPL), department (ICESS), and program (Marine Science), past and present. Thanks to Derek Manov, Dave Sigurdson, and Erin Lutrick for their technical support. This research could not have been completed without the wisdom of Joe McNeil and Xuri Yu. I'd like to thank Kathy Scheideman, Claudia Kashin, John Sanchez, Kris Duckett, Melanie Abe, and Kathleen Harris for their assistance. Special thanks to Alice Alldredge for making the Marine Science program a reality.

I would like to extend thanks to all the CMO investigators who contributed data and or ideas: Yogi Agrawal, Jack Barth, Josh Blakey, Emmanuel Boss, Tim Boyd, Paul Hill, Steve Lentz, Murray Levine, Jen MacKinnon, David Porter, Bill Shaw, Heidi Sosik, Donald Thompson, Sandy Williams, Ron Zaneveld, and especially Scott Pegau. I'd like to express my gratitude to ONR program managers Steve Ackleson, Joan Cleveland, and Lou Goodman.
I’d like to express my gratitude to my friends for their support and distractions (3-D and e-mail). Without them, I would have dropped out of grad school long ago. DeDe, Drew, Joe, Paige, Kriste, Brody (Go Vikes!), Jana, Painter, Mandy, Heidi, Junior, Colee, Tim, Steve, Neumann, Nick, Laura, Xuri, Kan, Rebecca, Val, Christy, Gabrielle, Allison, Anita, Janice, Tamara, Craig, Doug, Aaron, and others: Thanks so much, you guys!

And lastly, I’m indebted to my big brother, Jeff, for the good examples he has always set for me, and for forging the difficult paths that I simply follow. Greatest thanks to the rest of my family (mom, dad, and Carmen) for all their support and encouragement over the years.

DEDICATION

To Ebon, who thoroughly enjoyed hiking, swimming, exploring, playing ball, and the company of others. He was an inspiration to everyone to live life to its fullest.
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ABSTRACT

"Analyses of bio-optical variability related to physical processes on the southern New England continental shelf: July 1996 - June 1997"

by

Grace C. Chang

High-resolution time series of physical and bio-optical data were obtained using moored and bottom-mounted instruments during the Coastal Mixing and Optics (CMO) experiment from July 1996 - June 1997 to study the relationship between mixing and the distribution of optical properties on the southern New England continental shelf (~70 m water depth). A previously published spectral absorption model was employed with time series of spectral absorption data to separate total absorption into absorption by water, phytoplankton, detritus, and gelbstoff. Thus, temporal variability and the vertical distributions and concentrations of each component of absorption were examined. The model was validated by comparing its results against coincident \textit{in vivo} absorption coefficients derived from discrete bottle samples.

The most prominent physical and bio-optical signals observed during the experiment were associated with the 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 Edouard and Hortense passed near the CMO site, resulting in reduced stratification of the water column, particle redistribution, and sediment resuspension. The sediment resuspension processes associated with the two hurricanes are shown to differ primarily because of the separation distances
between the eyes of the hurricanes and the observational site. The sediment resuspension processes were tested using a one-dimensional turbulence closure model with a simple suspended particulate matter (SPM) module. Changing hydrographic conditions that resulted from the influence of several water mass intrusions greatly affected particle concentration on time scales of days to several weeks. The bottom boundary layer had an influence on particle movement in the water column and along the seafloor. The results suggest that there is likely considerable interannual variability in both the physics and biophysical processes because of active and diverse physical forcing. This experiment also sets the context for comparing our coastal ocean results with previous open ocean findings. Important differences arise because of coastal bottom boundary layer effects, large-scale water mass intrusions, and the relatively greater role of tides on the shelf. Time scales of optical variability are thus shorter for the coastal environment.
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CHAPTER 1
General Introduction

The mixing of ocean water on the southern New England continental shelf and the effects of mixing and other physical processes on water column optical properties were examined during the Office of Naval Research-sponsored Coastal Mixing and Optics (CMO; see Appendix A for abbreviations) experiment from July 1996 to June 1997. To date, observations have been employed to describe: air-sea interaction, wind mixing, surface and internal gravity wave motion, tides, current and wave-induced sediment resuspension and transport (storms, hurricanes, etc.) [Wright et al., 1986; Madsen et al., 1993; Wright et al., 1994; Dickey et al., 1998a; Chang et al., 1999]. as well as eddy-induced mixing, and turbulent mixing associated with internal solitary waves [Colosi et al., 1999; Wang et al., 1999]. The coupling between these physical processes and optical properties (e.g., light absorption, scattering, and attenuation) of the water column were examined in an effort to assess the seasonal dynamics of phytoplankton and sediment [Biscaye et al., 1988; Nittouer and Wright, 1994] in these coastal waters. Results improve understanding of the movement and distribution of micro-organisms, sediment, and contaminants in the water column and along the ocean bottom [Cacchione and Drake, 1990]. Given particulate motion influences organic matter and primary production. the results also have value in assessing various aspects of the global carbon budget [Bacon et al., 1994].

The study of the propagation of light through the water column is important in many aspects of oceanography. For instance, sunlight drives global heating of the surface of the ocean. The penetration of light, which is modulated by organic and inorganic particulate and dissolved substances, affects near surface
heating rates and stratification (e.g., Dickey [1991]). Light also supplies essential energy for the growth of photosynthetic organisms in the ocean (e.g., Kirk [1994]). Optical properties, whether measured directly or remotely, can be used to estimate phytoplankton biomass and primary productivity rates, and to derive particle characteristics and reflectance of light from the ocean (e.g., Kirk [1994]; Mobley [1994]; Esaias [1995]). Optics, combined with photophysics and photoecology, promises many beneficial “windows” into mechanistic understanding of ocean dynamics.

**Background on the experimental site**

The site for the Coastal Mixing and Optics experiment is the “Mud Patch” (named for its fine-textured bottom sediment), located about 110 km south of Martha’s Vineyard, Cape Cod, Massachusetts, U.S.A. (Figure 1.1). The site is located on a broad continental shelf in the Middle Atlantic Bight (MAB), on the southern portion of the New England shelf, in approximately 70 m of water. Tripod, mooring, shipboard, and sediment-trap measurements were made previously at or near the CMO site to determine the frequency and direction of bottom sediment movement, to identify the major processes that develop sufficient bottom stress to resuspend sediment (e.g., Butman et al. [1979]; Madsen et al. [1993]; Wright et al. [1994]), and to determine the fate of biogenic and non-biogenic particulate matter (SEEP I and II: Biscaye et al. [1988]; Biscaye [1994]; Biscaye et al. [1994]). These measurements provided data that confirmed the importance of tides, and wind- and storm-induced currents and waves in intermittent movement of bottom sediment. Advection and biological processes were found to have an influence on sediment motion during relatively tranquil periods (e.g., summer) [Butman et al., 1979]. Storm-
Figure 1.1: Geographic map of experimental site. Locations of National Data Buoy Center buoys 44008 and 44028 are indicated.
associated bottom currents and waves produced sufficient bottom shear stresses to resuspend and transport sediments (e.g., Wright et al. [1994]). Trawling of fishing gear over the central and outer New England shelf was also found to result in a substantial concentration of suspended sediments [Churchill, 1989]. Slope sedimentation was found to result from the vertical flux of particles from the near-surface waters of the slope, and from downslope transport of fresh biogenic particulate matter and resuspended sediments originating from the shelf and upper slope. Short-term variability in slope sediment accumulation was caused by local biological and resuspension events (e.g., blooms and storms). The findings of these and several other related experiments at or near the Mud Patch (e.g., Backus [1987]) in part provided motivation for the CMO experiment.

It is now known that the Mud Patch region can be spatially characterized by: 1) strong horizontal gradients due to the presence of a persistent, but spatially varying shelf-slope front just offshore from our observational site (e.g., Barth et al. [1998]; Linder and Gawarkiewicz [1998]); 2) strong vertical variability in water column currents and physical and bio-optical properties; and 3) mesoscale variability forced by advection of warm core eddies, jets, filaments, meanders, etc. onto the shelf (e.g., Pickart et al. [1999]). Temporal characteristics include: 1) distinct seasonal cycles in hydrography [Flagg, 1987] and primary productivity [O'Reilly et al., 1987]; 2) a prominent semi-diurnal tidal cycle [Brown and Moody, 1987]; 3) internal gravity waves and small-scale mixing events associated with internal solitary waves [Colosi et al., 1999; Wang et al., 1999], high current shear, and atmospheric forcing; 4) episodic frontal movements [Pickart et al., 1999]; and 5) strong wind forcing associated with storms (e.g., Wright et al. [1986]; Madsen et al. [1993]; and
Wright et al. [1994]) and hurricanes [Dickey et al., 1998a; Chang et al., 1999; Williams et al., 1999].

**Hydrography**

The water at the CMO site is primarily a mixture of Georges Bank Water (GBW) and Maine Surface Water (MSW). Georges Bank Water is distinguished by its vertical and horizontal homogeneity and a distinct seasonal cycle with temperature and salinity changing from 16°C and 32.2 psu in summer to 3°C and 33.0 psu in winter [Flagg, 1987]. Warming takes about five months from March through August, whereas cooling trends last seven months from September through March. Maine Surface Water is the surface layer of Gulf of Maine waters, characterized as a heterogeneous mixture of local river and low-salinity water from the Scotian Shelf. Maine Surface Water has a temperature and salinity range of 1-17°C and 31.6-33.2 psu respectively. Lower salinities are associated with coastal waters.

A persistent yet spatially varying shelf-slope front exists near the CMO site that separates the shelf waters from more stratified, warmer, more saline, and nutrient-rich water from the upper continental slope of the North American east coast. The shelf-slope front exhibits strong horizontal temperature and salinity gradients lasting throughout the year. Cross-shelf advection of shelf-slope front waters occurs through jets, meanders, filaments, or the detachment of eddies [Pickart et al., 1999]. A detailed review of the hydrographic structure of New England shelf and slope waters can be found in Flagg [1987].
Circulation

It is convenient to separate currents at the CMO site into mean (without tides), tidal, high-frequency, and low-frequency currents [Butman et al., 1987]. The mean currents in the area are typically 10-15 cm s$^{-1}$ [Twichell et al., 1987; Brink et al., 1987]. The current transport direction is generally from the east to west, parallel to bathymetry. The two important tidal components on the southern New England continental shelf are the M2 semi-diurnal and the less prominent O1 diurnal [Brown and Moody, 1987]. Tidal currents are relatively strong to the northeast (on Georges Bank: ~60 cm s$^{-1}$), decreasing in speed (to <10 cm s$^{-1}$) over the Mud Patch, with bottom tidal currents approximately half of those at the surface [Twichell et al., 1987]. High-frequency currents are associated with surface and internal waves and can lead to strong shear and vertical mixing which act to redistribute biogenic and non-biogenic particles. Typical surface waves are caused by local and remote winds over the MAB. Northeasterly storms and hurricanes are relatively common in the area, and can lead to extreme wave conditions. The coastline and topography of the MAB also convert trapped Kelvin waves into a variety of surface and internal waves [Butman and Beardsley, 1987]. Superposition of these waves leads to a distortion in the tides, which in turn, can also lead to mixing on the shelf. Internal gravity waves often form along isopycnals and can lead to vertical mixing on the shelf. Shoreward propagating continental shelf internal tides can evolve into internal bores with high-frequency soliton-like internal waves, which are oftentimes highly energetic [Colosi et al., 1999; Wang et al., 1999]. Current fluctuations, which occur on time scales of about 36-hr to 30 days, are considered low-frequency currents. These currents can be caused by translating wind and atmospheric-pressure systems and oceanic mesoscale

6
activity in the form of frontal movements, meanders, eddies, and jets (e.g., Brink et al. [1987]).

**Bottom Sediment**

The bottom sediment on the MAB shelf and slope is mainly fine-textured, containing more than 30% poorly sorted silt plus clay [Churchill, 1989]. As much as 90% silt plus clay is found in the Mud Patch [Churchill, 1989]. Coring surveys have shown that the Mud Patch is actually a 2-14 m thick deposit of uniform fine-grained material which overlays coarser sand-sized sediment [Twichell et al., 1987]. Primary mineral constituents of the sediments found in this area are more than 90% quartz and feldspar, less than 2% heavy minerals (amphibole and mica), and less than 5% carbonate (benthonic foraminifera fragments) [Twichell et al., 1987]. Unlike the rest of the MAB, rock fragments are absent from the Mud Patch. Sediment deposition rates in the Mud Patch have been estimated to be 20-30 cm/1000 yr based on geochemical evidence [Bothner et al., 1981]. Radiocarbon dating has indicated that the fine-grained sediment started accumulating 8,000-9,000 years ago [Bothner et al., 1981]. Studies have not yet revealed the reason for sediment accumulation in this region. It has been hypothesized that a westward decrease in tidal current amplitude from Georges Bank to the Mud Patch, along with the mean westward flow, results in deposition of sediment [Twichell et al., 1981; Butman, 1987].

**Contaminants**

Previous studies have revealed that high concentrations of contaminants are deposited in the Mud Patch. Extremely high levels of lead have been found.
with concentrations of about 15 mg kg\(^{-1}\) higher than mean concentrations observed in crustal rocks (12.5 mg kg\(^{-1}\)) [O’Connor, 1996]. High values of plutonium (48.32 dpm kg\(^{-1}\)), cesium (103.33 dpm kg\(^{-1}\)), and iron (700.44 dpm kg\(^{-1}\); all averaged over a depth of 0-32 cm) are present to depths of at least 32 cm [Cochran and Livingston, 1987]. Sewage dumping and effluents, industrial effluents in river discharge, and fallout of air-borne chemicals are sources of pollutant organic compounds (e.g., Farrington and Boehm [1987]; Fry and Butman [1991]; Bothner et al. [1994]; Takada et al. [1994]). Several thousand synthetic organic compounds are produced and used in coastal areas and have the potential to be released and transported into the coastal ocean. High concentrations of dichlorodiphenyltrichloroethane (DDT), and polychlorinated biphenyls (PCBs) have been found in the Mud Patch [Farrington and Boehm, 1987]. Some effects of these contaminants should they enter the food web include decreases in the amount of eggs of fish and shellfish, weight of eggs, and percent of eggs fertilized, increases in the occurrences of mutations, and increases in tumors and skin lesions in fish (flounder) [O’Connor, 1996].

*Primary Productivity*

The rate of primary productivity over the MAB continental shelf is extremely high compared to the rest of the world’s oceans. It is three times the mean of the world’s continental shelves, and ten times the rate of that of the open ocean [Bourne and Yentsch, 1987]. Sherman et al. [1996] reported an annual total primary production of 310 g C m\(^{-2}\) yr\(^{-1}\) for the Mud Patch. Spring blooms (mainly of diatoms) usually occur between March and April, tending to decline in late April or early May, then giving way to summer stratification, when nutrients become limited in the eutrophic layer. In September, surface layers begin to cool. The cycle continues with more vigorous wind forcing and
thermal inversion of the water column, leading to vertical mixing and the replenishment of nutrients from below, oftentimes resulting in a fall bloom. In winter, daily averaged light levels diminish significantly due to shorter daylengths, decreased light intensities, and increased cloud cover. Primary productivity is at its lowest during the winter. Cell abundance during the spring bloom (about 300,000 cells L$^{-1}$) is about an order of magnitude greater than cell abundance during summer, and up to two orders of magnitude greater than cell abundance during winter [Cura, 1987]. Shallow shelf waters, high light availability, and high nutrient availability all contribute to the high concentrations of chlorophyll, phytoplankton, nanoplanckton, and those organisms higher in the food chain [O'Reilly et al., 1987]. Intense vertical mixing in addition to horizontal mixing from frontal activity also promotes high primary productivity.

**Objectives**

The overall objective of my research thesis was to characterize how particles and optical properties respond to physical forcing under various oceanic conditions during the Coastal Mixing and Optics experiment. More specific objectives were to: 1) quantify the variability of optical and physical properties at time scales as short as a few minutes; 2) relate physical processes (listed above) to optical variability [Chang and Dickey, 1999a]; 3) determine the relationships between vertical fluxes of particles and optical properties with respect to the physical environmental conditions such as shear and stratification; 4) make general distinctions among particle types and to partition their origins [Chang and Dickey, 1999b]; and 5) relate optical and
particle variability near the ocean bottom to physical processes affecting sediment resuspension [Dickey et al., 1998a; Chang et al., 1999].

My thesis addresses these objectives by analyzing a data set, which quantified temporal variability of bio-optical parameters associated with physical processes on the southern New England continental shelf from July 1996 through June 1997. A description of the methods and instrumentation from the Coastal Mixing and Optics experiment is found in Chapter 2. The partitioning of total spectral absorption to determine the origin of material in the water column and along the seafloor is discussed in chapter 3. Chapter 4 describes temporal variability of physical processes and associated bio-optical responses from July 1996 to June 1997. Sediment resuspension and water column characteristics as a result of the passages of two hurricanes near the CMO site during the fall of 1996 is presented in chapter 5. Chapter 6 summarizes the findings of this study. The results from these studies can be used to statistically quantify physical and biological processes and their relationships, as well as for the development and testing of coupled physical-optical-biological, radiative transfer, and sediment resuspension and transport models, and as inputs into data assimilation models to predict bio-optical responses to physical forcing.
CHAPTER 2

Methods

Newly developed oceanographic instruments were placed on a mooring and a bottom tripod at the CMO site (roughly 40.5°N, 70.5°W; 70 m water depth) to concurrently collect high resolution time series of physical and bio-optical data at several depths (Tables 2.1, 2.2, and 2.3; Figure 2.1). Four mooring deployments were conducted from 8 July 1996 through 11 June 1997. The tripod was deployed approximately 400 m southeast of the mooring from 9 August 1996 through 11 June 1997. Mooring and tripod turnarounds were approximately every 3 months with 1-7 day breaks for mooring and tripod recovery and redeployment. The first mooring deployment period was 8 July to 26 September 1996. The tripod was first deployed from 9 August to 26 September 1996. The second and third mooring and tripod deployments were from 27 September 1996 to 3 January 1997 and 6 January to 9 April 1997, respectively. The last mooring and tripod deployment period was 16 April to 11 June 1997. This observational study was coordinated with studies by other CMO investigators using shipboard, tripod, mooring, buoy, tracers, and satellite data sets. which complement the University of California, Santa Barbara (UCSB) mooring and tripod measurements (see Dickey and Williams [1999]). The data obtained during the mooring and tripod deployments were compared to profile and discrete bottle sample data taken from ships near the CMO mooring site (within ~200 m) during the first and fourth deployments as well as before and after each mooring turnaround.
Table 2.1: Subsurface mooring instrumentation. first deployment: 8 July – 26 September 1996

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Measurement</th>
<th>Manufacturer(^a,^b)</th>
<th>Accuracy</th>
<th>Sample Interval</th>
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<tbody>
<tr>
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<td>Temperature, Salinity</td>
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<td>2 min</td>
</tr>
<tr>
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<td></td>
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<td>BIOPS(^a)</td>
<td>BIOPS(^a)</td>
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</tr>
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<td></td>
<td>PMEL</td>
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<td></td>
</tr>
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<td>2 min</td>
</tr>
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</table>

\(^a\)See Table 2.3 for BIOPS instrumentation.

\(^b\)PMEL = Pacific Marine Environmental Laboratories; Alpha-Omega = Alpha Omega Computer Systems.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Measurement</th>
<th>Manufacturer</th>
<th>Accuracy</th>
<th>Sample Interval</th>
</tr>
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<tr>
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<td>24 min</td>
</tr>
<tr>
<td>65</td>
<td>Currents</td>
<td>RD Instruments</td>
<td>±2.0%</td>
<td>3.75 min</td>
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</table>

\(^a\)See Table 2.3 for BIOPS instrumentation.
<table>
<thead>
<tr>
<th>Instrument(^b)</th>
<th>Manufacturer</th>
<th>Accuracy(^c)</th>
<th>Sample Interval</th>
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</thead>
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<tr>
<td>Lu683</td>
<td>Biospherical Instruments, Inc.</td>
<td>Not reported</td>
<td>7.5 min</td>
</tr>
<tr>
<td>Chlorophyll fluorescence Temperature</td>
<td>WET Labs. Inc. and Sea Tech, Inc.</td>
<td>~±0.09</td>
<td>7.5 min</td>
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<td>Temperature</td>
<td>Sea-Bird Electronics, Inc.</td>
<td>Not reported</td>
<td>7.5 min</td>
</tr>
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<td>Beam c (660 nm)</td>
<td>Sea Tech. Inc.</td>
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<td>7.5 min</td>
</tr>
<tr>
<td>ac-9</td>
<td>WET Labs. Inc.</td>
<td>±0.001 m(^{-1})</td>
<td>60 min</td>
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</tbody>
</table>

\(^a\)BIOPS = bio-optical systems.

\(^b\)PAR = Photosynthetically available radiation. Lu683 = upwelling radiation at 683 nm. beam c = beam attenuation coefficient at 660 nm. ac-9 = absorption and attenuation coefficient at nine wavelengths.

\(^c\)Accuracy of PAR stated as noise level; accuracy of WET Labs. Inc. fluorometer stated as stability over one hour. actually dependent on calibration.
Figure 2.1: Schematic diagrams of sub-surface mooring, physical and optical tripods, and BIOPS instrumentation. The depths of mooring instruments are labeled (see Tables 2.1 and 2.2). BIOPS=bio-optical systems, TPOD=temperature pod, SEACAT=temperature and conductivity sensors, ADCP=acoustic doppler current profiler. mab=meters above the bottom.
Instrumentation

Subsurface Mooring Physical Instrumentation

Several instruments were deployed on the subsurface mooring (Figure 2.1) to measure physical properties and currents during the first deployment by Murray Levine and Tim Boyd (Oregon State University (OSU)) (Table 2.1). These instruments included: 1) Pacific Marine Environmental Laboratory (PMEL) MTR temperature sensors at 14, 28, 32, 35, 42, 48, 57, and 65 m; 2) Alpha-Omega Computer Systems temperature sensors (9102) at 20, 24, 30, 36, 45, 51, and 60 m; 3) Alpha-Omega Computer Systems temperature sensors (9311) at 22 m (with pressure sensor) and 29 m; 4) Alpha-Omega Computer Systems temperature and velocity sensors (9407) at 16 (with pressure sensor) and 66 m; 5) Sea-Bird Electronics, Inc. temperature and conductivity sensors (SBE-16) at 12, 18, 26, 39, and 54 m (with pressure sensor); and 6) an uplooking RD Instruments Acoustic Doppler Current Profiler (ADCP: 300 kHz RDI Workhorse) at 65 m for currents binned every 4 m. The sampling rate for the Alpha-Omega 9407 at 16 m was once every eight min and the 9407 at 66 m sampled once every four min. The Alpha-Omega 9311 sensors at 22 and 29 m sampled at an interval of one and 0.5 min, respectively. The sampling rate for the 54 m Sea-Bird Electronics, Inc. SBE-16 was every four min (temperature and salinity: eight min for the pressure sensor). All other sensors sampled once every two min. A summary of sampling rates (intervals) is given in Table 2.1. For further instrumentation details, see Boyd et al. [1997].

The UCSB group deployed similar physical instruments on the subsurface mooring during the remaining three deployments of the CMO experiment.
(Table 2.2; Figure 2.1). Sea-Bird, Inc. SBE-16 temperature and conductivity sensors were deployed at 15, 35, and 60 m. Temperature was also measured by TSKA TPODs and Onset Computer Corp. Tidbit temperature sensors at 10, 11, 20, 25, 30, 40, 45, 50, 55, and 65 m. An uplooking RD Instruments ADCP (300 kHz RDI Workhorse) was deployed at 65 m to measure water column currents binned every 2 m. These instruments sampled once every 3.75 min, except for the Tidbit temperature sensors, which sampled once every 24 min. Sampling rates (intervals) are summarized in Table 2.2.

Bio-optical Systems (BIOPS)

Three bio-optical systems (BIOPS) were placed on the subsurface mooring at 12, 30, and 50 m depths, and one at about 2 m above the bottom (mab) on the bottom tripod (Figure 2.1). BIOPS utilize the following instruments: 1) Biospherical Instruments, Inc. photosynthetically available radiation (PAR) scalar irradiance sensors (400-700 nm; QSP-200: [Booth, 1976]); 2) Biospherical Instruments, Inc. upwelling radiance (683 nm) sensors (MRP-200); 3) Sea Tech, Inc. stimulated fluorometers [Bartz et al., 1988]; 4) WET Labs, Inc. WETStar stimulated fluorometers; 5) Sea Tech, Inc. transmissometers (660 nm) [Bartz et al., 1978]; 6) Sea-Bird Electronics, Inc. temperature sensors (SBE-3); and 7) WET Labs, Inc. absorption and attenuation meters (ac-9; Moore et al., [1992]). The sampling rate for the ac-9 was once per hour and the sampling rate for all other sensors was once every 7.5 min. Subsurface mooring and tripod instrument depths, sampling rates (intervals), and accuracy estimates are summarized in Tables 2.1, 2.2, and 2.3.
Optical Tripod

Characteristics of near bottom particles were measured using instruments mounted on an optical bottom tripod, deployed approximately 400 m from the mooring in 70 m water depth. A BIOPS (as described above) was placed about 2 m ab. In addition, Yogi Agrawal and Chuck Pottsmith (Sequoia Scientific, Inc.) deployed particle size analyzers (LISST-100, LISST-ST, and MSCAT) and Paul Hill (Dalhousie University) deployed a photographic camera on the tripod (Figure 2.1). The LISST-100 measured true volumetric concentration from size distribution for particles between 5-500 μm. It was mounted 1.6 m ab and sampled every 15 min, starting on the hour. The LISST-ST, at about 1 m ab, measured size-dependent settling velocity distribution (also for particles between 5-500 μm) by capturing a sample at midnight and letting the particles settle for the 24 hr duration. The MSCAT measured the response of the seabed to friction by currents and waves. It sampled every 6 hr, in a 128 sec long burst at 1 Hz at roughly 0.15 mab. These instruments have previously been described in Agrawal and Pottsmith [1994]. The camera system, similar to one described in Syvitski et al. [1991], was located about 1 mab and used to monitor size distributions of particles larger than 500 μm in the bottom boundary layer. Photographs were taken every 8 hr by a Nikon F4 camera for a viewing area of 10 cm by 16 cm, with focal plane at 76 cm from the camera.

Physical Tripod

An additional bottom tripod that measured physical parameters was deployed by Sandy Williams, III (WHOI) within 400 m of the subsurface mooring in approximately 70 m water depth. Benthic Acoustic Stress Sensors (BASS) current meters [Williams et al., 1987; Williams et al., 1997] mounted on the
tripod recorded vector velocities at 0.38, 0.74, 1.1, 2.2, 3.3, 5.4, and 7.0 mab. These data at the above-mentioned measurement depths were burst sampled at 1.2 Hz for 28 min and 49 sec every hour and the half-hour after the even hour. The average vector current direction and speed were computed from each half-hour recording of BASS current meter data. Bottom shear (shb), subtidal current bottom shear stress (τc), subtidal current dissipation rate (εc), wave orbital velocity (uω), combined current and wave bottom shear stress (τc+ω), and current-wave dissipation rate (εc−ω) were calculated from the east (uex) and north (uey) components of velocity derived from BASS current meter data to investigate sediment resuspension during the CMO experiment.

Bottom shear was calculated between each depth of the BASS current meters and between the bottom and 0.38 mab using the following equation:

\[ shb = \sqrt{(du_ex/dz)^2 + (du_ey/dz)^2} \]  

(2.1)

A no-slip condition was assumed for the bottom boundary. Subtidal plus tidal current bottom shear stress was computed using the “law of the wall” formulation [Tennekes and Lumley, 1972]:

\[ u_c = (u_{-c} / \kappa) \ln (z / z_0) \]  

(2.2)

where \( \kappa \) is von Karman’s constant, \( u_{-c} \) is current friction velocity, \( z \) is the vertical distance above the bottom, and \( z_0 \) is a roughness parameter. East and north components of velocity were resolved into a scalar representation of velocity using:

\[ u_c = \sqrt{u_{ex}^2 + u_{ey}^2} \]  

(2.3)

for velocities at all depths \( z \). Plots of \( u_c \) versus \( \ln z \) (natural logarithm of \( z \)) were then constructed at the seven BASS depths for the entire time series. These plots should appear linear within the log-layer, and parabolic outside the log-layer if the law of the wall holds. These criteria were used to determine that the log-layer was between 1.1 and 2.2 mab. Current friction velocity and
the roughness parameter within the log-layer were determined using equation (2.2). Subtidal plus tidal current bottom shear stress was then calculated with the following equation:

\[ \tau_c = \rho u_c^2. \]  \hspace{1cm} (2.4) 

where \( \rho \) is the density of water. Turbulence dissipation rate due to currents was computed using [Tennekes and Lumley, 1972]:

\[ \varepsilon_c = u_c^3 / (\kappa z), \]  \hspace{1cm} (2.5) 

assuming a logarithmic velocity profile.

Wave- orbital velocity was estimated by taking the square root of the integral of energy under the wave peak in velocity spectra between wave periods of 8 and 25 sec. Bottom shear stress from combined current and wave motion at 0.38 mab was computed using the iterative model presented in Christoffersen and Jonsson [1985]. This model employs the governing equations of fluid motion (momentum equations, dissipation equation) in order to describe the velocity field and associated shear stress in a combined current-wave motion. The momentum equations are simplified assuming a steady, large-scale current (small Froude numbers and slowly varying in space), a locally horizontal bed, and time-independent eddy viscosity, and by neglecting lateral shear stresses in vertical sections, the Coriolis force, and tidal forces. These assumptions result in linearized governing equations, which are then solved inside and outside the wave boundary layer for the wave motion and the current motion. This gives formulae for the velocities, shear stresses, friction factors (introduced in order to split the shear stress into a steady current part and an oscillating wave part), and roughness factors.
The necessary equations for calculation of the bottom shear stress from combined current and wave motion are presented below [Christoffersen and Jonsson, 1985].

\[ \tau_{c-w} = 0.5 f_w \rho u_a^2 n. \]  \hspace{1cm} (2.6)

where \( \tau_{c-w} \) is bottom shear stress from combined current and waves, \( f_w \) is a wave friction factor, defined as for a pure wave motion (no current), and \( n \) describes the relationship between the current and the wave:

\[ n = \left[ 1 + \sigma^2 + 2\sigma \cos(\delta - \alpha) \right]^{1/2}. \]  \hspace{1cm} (2.7a)

where \( \delta - \alpha \) is the angle between the current and the wave, and \( \sigma \) is the ratio of the magnitude of current-induced shear stress at the bed to the amplitude of wave-induced shear stress at the bed and is represented by:

\[ \sigma = \left( \frac{f_c}{f_w} \right) \left( \frac{u_c}{u_a} \right)^2. \]  \hspace{1cm} (2.7b)

where \( f_c \) is the current friction factor (defined as for a pure current motion). A pure current was assumed for the first iteration, and the current friction factor was calculated using the expression:

\[ \left( \frac{2}{f_c} \right)^{1/2} = \left( 1 / \kappa \right) \ln \left[ \left( \frac{30 \, h}{(c \, k_n)} \right) - \left( 1 / \kappa \right) \ln \left( k_a / k_n \right) \right]. \]  \hspace{1cm} (2.8)

where \( h \) is the water depth (70 m), \( k_n \) is the Nikuradse roughness and \( k_a \) is the apparent roughness. A pure wave was then assumed \( (n = 1) \), and the wave friction factor was computed:

\[ f_w = \left[ \frac{4 \beta (2 \pi)^{1/2} k_n \pi}{(u_a T)} \right]^{2/3}. \]  \hspace{1cm} (2.9)

where \( \beta \) is an empirical turbulence constant. Measured subtidal plus tidal current and estimated wave orbital velocity, and computed wave and current friction factors were iterated using equations (2.7a, b) and (2.9) to obtain values for \( n \) and \( f_w \), respectively. Then, \( k_a \) was estimated using the relation:

\[ (k_a / k_n) = 30 \left( \delta_a / k_n \right) \exp \left[ - \left( 1 / \beta \right) \left( \delta_a / k_n \right) \left( \sigma / n \right)^{1/2} \right]. \]  \hspace{1cm} (2.10a)

with

\[ \delta_a / k_n = 0.45 \left( \pi / \sqrt{2} \right) (\beta J)^{1/2}, \]  \hspace{1cm} (2.10b)

\[ J = \left[ ((1/2) (n f_w))^{1/2} [u_a / (k_n \omega_b)] \right]. \]  \hspace{1cm} (2.10c)
\[ \omega_n = 2\pi / T. \]  \hspace{1cm} (2.10d)

where \( \delta_w \) is the wave boundary layer thickness, and \( \omega_n \) is the angular wave frequency. A new value of \( f_c \) was computed using equation (2.8), and the procedure was repeated until the value for \( f_c \) converged. Lastly, \( \tau_{c-w} \) was calculated using equation (2.6). Current-wave dissipation rate was estimated using the following relationship [Gross et al., 1994]:

\[ \varepsilon_{c-w} = u_{c-w}^3 / (\kappa z). \]  \hspace{1cm} (2.11)

The Christoffersen and Jonsson [1985] model was chosen for the sediment resuspension study because it utilizes an iterative approach for computing friction factors. It is otherwise similar to the commonly used Grant and Madsen [1979] model. Three main differences between the two models are that the Grant and Madsen [1979] model 1) presents a definition of a friction factor that makes it necessary to introduce a fictitious reference velocity at unknown level, which is different in different current-wave solutions; 2) their estimation of the thickness of the wave boundary layer is rather arbitrary; and 3) their wave friction factor is given by a seemingly complicated equation [Christoffersen and Jonsson, 1985]. Many other bottom boundary layer models have been developed to include sediment and bed responses, and/or stratified flows [Grant and Madsen, 1982; Trowbridge and Madsen, 1984; Glenn and Grant, 1987]. These advanced versions were not used in the present study because no sediment condition data were obtained during the study, and the bottom boundary layer was well mixed during observed times of intense sediment resuspension. A comparison of several wave-current bottom boundary layer models is presented in Soulsby et al. [1993].
Hourly meteorological and oceanic condition data were obtained from NDBC buoys 44008 (40.3°N, 69.25°W) and 44028 (41.4°N, 71.08°W), approximately 90 and 150 km east-southeast and northwest of the CMO site, respectively (Figure 1.1). Details concerning buoy instruments, data processing, and accuracy estimates are provided by National Climatic Data Center (NCDC) [1990]. Wind direction and speed, atmospheric pressure, significant wave height and period, and wave energy spectra data were utilized in this study. Anemometers were at heights of 5 and 13.8 m above sea level for buoys 44008 and 44028, respectively. Winds presented here were adjusted to a height of 10 m above sea level, assuming a logarithmic wind profile above the sea surface. Meteorological data, including shortwave radiation, were also obtained by Steve Lentz (WHOI) on a surface buoy 400 m east of the CMO mooring. However, wave data at the WHOI buoy were not collected over the period of September through October 1996 due to instrument failure. Therefore, we utilized wind and wave data obtained by NDBC buoys. The group velocity of waves was calculated according to linear wave theory [Dean and Dalrymple, 1992]:

\[ C_g = C / 2 \times [1 + (2kh / \sinh 2kh)] \]  

(2.12)

where \( C_g \) is the group velocity in m s\(^{-1}\) and \( k \) is the wave number related to wavelength, \( L \) (expressed in m), by:

\[ k = 2 \pi / L. \]  

(2.13a)

Wavelength was calculated using:

\[ L = (g \cdot T^2 / 2 \pi) \times \tanh (2\pi h / L). \]  

(2.13b)

where \( g \) is the acceleration of gravity in m s\(^{-2}\), and \( T \) is the significant wave period (s). Wave propagation speed, \( C \) (m s\(^{-1}\)), was computed by the following equation:
\[ C = \left( \frac{g T}{2 \pi} \right) \ast \tanh \left( \frac{2 \pi h}{L} \right). \]  

(2.14)

and travel time was determined by:

\[ t = \frac{d}{C_g} \]  

(2.15)

where \( t \) is the travel time in sec. and \( d \) is the distance traveled in meters, estimated using National Hurricane Center (NHC) “best track” data (defined as a subjectively smoothed path used to represent tropical cyclone movement, based on an assessment of all available data).

**Satellite Data**

Advanced Very High Resolution Radiometer (AVHRR) and Synthetic Aperture Radar (SAR) images were contributed by David Porter and Donald Thompson (both from The Johns Hopkins University Applied Physics Laboratory (JHU/APL)). These images were interpreted for sea surface temperature (SST) and wave characteristics [Thompson and Porter, 1997].

**Shipboard Measurements**

*In vivo* total (without water), phytoplankton, detrital, and gelbstoff absorption data derived from discrete bottle samples were provided by Heidi Sosik (WHOI) and Collin Roesler (University of Connecticut (UConn)). These discrete bottle samples were obtained approximately daily by Collin Roesler (UConn) during the fall CMO cruise over the period 17 August – 7 September 1996. Depths of bottle samples varied from just below the water’s surface (≈1 m) to 60 m. Only data sampled within 3 m of the mooring depths were used in this study. Data from 21 and 31 August 1996 at a depth of 37 m and 21 and 25 August 1996 at a depth of 52 m are presented for this study. For the soluble absorption (gelbstoff), a water sample was filtered through pre-rinsed 0.2-μm
polycarbonate filters and the filtrate was stored at 4°C. Gelbstoff absorption spectra were then measured in 10 cm quartz cuvettes with Milli-Q water in the reference beam. Particles were collected on GF/F glass-fiber filters and analyzed in accordance with the guidelines specified by Mitchell [1990]. Particulate absorption spectra were measured with a Perkin Elmer Lambda 18 dual beam UV/visible spectrophotometer, with a 60 μm integrating sphere. Following pigment extraction in hot methanol [Kishino et al., 1985], pad absorption was re-measured, yielding values of detrital absorption. Absorption by phytoplankton pigments was estimated as the difference between total particulate and detrital absorption values. The Mitchell [1990] beta algorithm was used to estimate absolute absorption coefficients from raw optical density. For each spectrum, average values for wavelengths of 780 - 800 nm for particulate samples and of 660 - 670 nm for soluble samples were subtracted from the entire spectrum to correct for residual light scattering. This zero correction for scattering is an approximation, and the choice of wavelength range is somewhat subjective (H. Sosik, personal communications, 1997).

Calibration

All UCSB sub-surface mooring physical sensors utilized manufacturer's calibrations. Inter-calibrations were performed by comparing mooring-derived temperature and salinity measurements to temperature and salinity profiles taken by W. Scott Pegau (OSU) and Wilf Gardner (Texas A&M) between 17 August and 7 September 1996, and between 23 April and 13 May 1997. Temperature and salinity time series were also compared to hydrographic properties measured by Steve Lentz (WHOI) on a nearby mooring.
Several instruments on the BIOPS also utilized manufacturer factory calibrations. The Biospherical Instruments, Inc. PAR scalar irradiance sensor and upwelling radiance sensor (683 nm) were factory calibrated using a National Institute of Standards and Technology (NIST) traceable 1000 watt type FEL Standard of Spectral Irradiance [QSP-200, 1995: MRP, 1995]. Calibrations for the SBE-3 temperature sensor were performed by the Northwest Regional Calibration Center (NRCC), operating under contract to NOAA. The NRCC uses an equation derived from Bennett's formula [SBE-3, 1995].

Combination factory and user calibrations were used for the transmissometer, ac-9, and WETStar fluorometer. Air calibration values for the transmissometers were obtained from the manufacturer, as well as a zero offset value. Because air calibration may change with time due to a decrease in LED light output, a measurement of current air calibration values was necessary to account for the change. The highest voltage recorded in the data file after cleaning of the optical windows with ethyl alcohol and prior to the deployment of the transmissometers was used for the present air calibration. Air calibrations were measured before and after every deployment. The maximum difference between pre- and post-deployment values was ~10.0%, and the majority of calibration changes were within 6.0%.

The ac-9 obtains concurrent measurements of the absorption and attenuation characteristics of a water sample. The ac-9 wavelengths are λ=412, 440, 488, 510, 532, 555, 650, 676, and 715 nm. The output of the ac-9 before corrections is the absorption (a'_{t-w}(\lambda), expressed in m^{-1}) and attenuation (c'_{t-w}(\lambda), expressed in m^{-1}) coefficients with pure water values subtracted from the total. In addition to pure-water factory calibrations, corrections for internal
temperature, scattering for the absorption coefficient, and external temperature and salinity associated with the 715 nm wavelength for the absorption coefficient were applied according to ac-9 protocols [Moore and Bruce, 1996]. First, the algorithm to convert signal and reference values into terms of uncorrected inverse meters was used:

$$a'_{t-w}(\lambda) = a''_{t-w}(\lambda) + (T_{insitu} - T0) Kt.$$  \hspace{1cm} (2.16a)

$$c_{t-w}(\lambda) = c'_{t-w}(\lambda) + (T_{insitu} - T0) Kt.$$  \hspace{1cm} (2.16b)

where $a'_{t-w}(\lambda)$ and $c_{t-w}(\lambda)$ are the internal temperature-corrected absorption and attenuation coefficients. $T_{insitu}$ is the in situ temperature, T0 is the temperature offset, and Kt is the temperature calibration coefficient. T0 and Kt are provided by the manufacturer. Changes in temperature and salinity can lead to variability associated with the 715 nm wavelength for the absorption coefficient. It was reported that a change of \(\sim 0.25 \text{ m}^{-1}\) occurred for a 25°C temperature shift within the range of 0-30°C, the range of oceanographic interest [Pegau and Zaneveld, 1993; Moore and Bruce, 1996; Pegau et al. 1997]. This variability can be accounted for by:

$$a(715)_h = a(715) - [aT (T_{insitu} - T_{cal})]$$ and  \hspace{1cm} (2.17a)

$$a(715)_s = a(715) - (-0.00018 S).$$  \hspace{1cm} (2.17b)

where $a(715)_h$ and $a(715)_s$ are absorption at 715 nm corrected for temperature and salinity, respectively. $aT$ is a temperature constant (0.0029). Tcal is standard temperature (23.7), and S is the in situ salinity. The correction for scattering was applied to the absorption data following:

$$a_{t-w}(\lambda) = a'_{t-w}(\lambda) - \varepsilon b(\lambda).$$  \hspace{1cm} (2.18)

where $a_{t-w}(\lambda)$ is the corrected absorption coefficient, $\varepsilon$ is a scattering constant ($0.14$), and $b(\lambda)$ is the scattering coefficient:

$$b(\lambda) = c(\lambda) - a(\lambda).$$  \hspace{1cm} (2.19)

This method assumes that the scattering correction is a fixed proportion of the scattering coefficient.
Absorption coefficients measured by the ac-9 were also compared with absorption spectra measured from discrete water samples taken by Heidi Sosik (WHOI) near the mooring between 17 August and 7 September 1996. Attenuation coefficients (660 nm) were vicariously calibrated against beam attenuation results from the BIOPS transmissometers (650 nm). The ac-9 data were also inter-calibrated with profile ac-9 values measured by W. Scott Pegau (OSU) near the CMO site. Values obtained from absorption and attenuation measurements were then adjusted according to results from the inter-comparisons. Results from the absorption and attenuation data inter-calibrations are presented in chapter 3. The total (without water) spectral absorption data were then separated into absorption by phytoplankton, and detritus plus gelbstoff according to Chang and Dickey [1999b] to quantitatively partition particles by type.

Chlorophyll-α concentrations (Chl-α) were estimated by directly measuring the amount of fluorescence emission from a given sample of water using the WETStar fluorometer. Initial calibrations were performed using factory calibrations [WETStar, 1995]. Chlorophyll-α concentrations derived from stimulated fluorescence were then adjusted to conform to Chl-α measured simultaneously from discrete water samples taken near the mooring site by Heidi Sosik (WHOI), and to ac-9 absorption-derived Chl-α (following Shifrin [1988]; described below).

Shifrin [1988] found that the absorption spectra of several different species of phytoplankton are qualitatively similar in shape to each other, and to the absorption spectrum of chlorophyll-α, the main pigment of phytoplankton. The spectra have an absorption peak in the blue waveband (~435 nm), and an
additional peak in the red band (~675 nm). The red peak can be attributed to chlorophyll-α and its derivatives. Using the relationship found in Shifrin [1988]:

$$a_{ph}(\lambda) = C_{ph} a_{ph}^{sp}(\lambda).$$

(2.20)

where $a_{ph}(\lambda) \text{ (m}^{-1})$ is the absorption due to phytoplankton, $C_{ph}$ is the concentration of chlorophyll (µg l$^{-1}$), and $a_{ph}^{sp}(\lambda) \text{ (l µg}^{-1} \text{ m}^{-1})$ is the specific absorption of phytoplankton, the concentration of chlorophyll-α was determined by assuming that $a_{ph}(676)$ is equal to the absorption due to chlorophyll-α at 676 nm ($a_{ch}(676)$). $a_{ch}(676)$ was determined with the assumption that chlorophyll-α is the only absorbing material at 676 nm and was calculated using the following equation [WETView. 1993] and absorption data measured by the ac-9 during the CMO experiment:

$$a_{ch}(676) = a_{ch}(676) - \frac{1}{2} [a_{ch}(650) + a_{ch}(715)].$$

(2.21)

It has been recognized that $a_{ph}^{sp}(\lambda)$ as a function of Chl-α is highly variable depending on water type, the level of pigment packaging, and the contribution of accessory pigments to absorption [Bricaud et al., 1995]. However, because this analysis was performed for rough data inter-calibration purposes, an experimental value of $2.46 \times 10^{-2}$ l µg$^{-1}$ m$^{-1}$ for $a_{ph}^{sp}(676)$ is given in Shifrin [1988] and was applied to the equations above to determine Chl-α from ac-9 data.
CHAPTER 3
Partitioning In situ Total Spectral Absorption

Introduction

The total absorption coefficient, $a_a(\lambda)$ (expressed in m$^{-1}$), is the fraction of the incident light flux that is absorbed per unit thickness of a sample volume [Kirk, 1994]. Whole water absorption is important in determining the magnitude and the spectral shape of the light field in an aquatic medium [Pegau et al., 1995]. In addition, it is a required parameter for solution of the radiative transfer equation (to determine apparent optical properties, AOP, from the inherent optical properties, IOP) for the radiance distribution as a function of depth [Mobley, 1994]. It is also important for the interpretation of remote sensing data, e.g., for obtaining remote sensing reflectance from IOP [Zaneveld, 1995].

Furthermore, accurate measurements of phytoplankton absorption are central to bio-optical models of primary productivity [Behrenfeld and Falkowski, 1997], determinations of changing photoecology, and estimations of the role of phytoplankton in heat flux and light attenuation [Schofield et al., 1991]. The presence of detrital and dissolved matter in seawater complicates the direct measurement of phytoplankton absorption. To partition absorption into its four major absorbing components (water, detritus, phytoplankton, and gelbstoff), spectral decomposition models have been developed (see e.g., Roesler et al. [1989] and Bricaud and Stramski [1990]). The development of these models parallels the evolution of optical instruments designed specifically for the measurement of bio-optical parameters (absorption, attenuation, scattering, etc.).
In recent years, spectral absorption and attenuation meters (e.g., ac-3, ac-9 and Hi-Star [Bruce et al., 1996]) have been used in profile mode, providing high vertical resolution absorption and attenuation data during shipboard operations (e.g., Petrenko et al., [1997]). One advantage of this method is that instruments can be calibrated between successive casts, ensuring accurate measurements over the course of the experiments. However, shipboard profile sampling is usually limited to a few weeks' duration with sampling intervals of hours or greater. An additional disadvantage is that measurements are not taken at time scales short enough to resolve many important higher frequency oceanographic processes and events (i.e., diel, wind-mixing, internal waves, and advection). Long-term variability (seasonal) and episodic events are also difficult to resolve because of the need for nearly continuous shipboard sampling, which can be precluded by sea-state condition. Moored instruments, on the other hand, can sample every few minutes for months and longer with redeployments and thus can provide information that is relevant to high-frequency and episodic events and long-term variability [Dickey, 1991; Dickey et al., 1998b]. The primary disadvantage of moored optical instruments is the tendency for optical windows to bio-foul, depending on the length of the deployment and the rate of growth of organisms.

We collected high-temporal-resolution spectral absorption and attenuation data, using moored, bottom-mounted, and profiled filtered ac-9s at discrete depths during the Coastal Mixing and Optics (CMO) experiment (Figure 3.1). The CMO experiment was designed for the study of the effect of mixing on inherent and apparent optical properties in the water column. Long-term objectives for the CMO study included partitioning particles by type and relating physical processes to optical variability. High-temporal resolution spectral absorption measured during the CMO experiment was partitioned into
Figure 3.1: Geographic map indicating the site of the mooring and tripod used for the absorption study. The depths of instruments is indicated. Schematic diagrams of the mooring and tripod are shown. OPL=Ocean Physics Laboratory; BIOPS=bio-optical systems.
its four major absorbing components using the model of Roesler et al. [1989] to examine the vertical and temporal variability of particle types throughout the water column. A diagram of the procedures used for data analysis in this study is shown as Figure 3.2. Here we present the time series data set, the results of spectral modeling of these observations, and a brief description of the vertical and temporal variability of water column optical and particle characteristics.

Methods

The UCSB BIOPS ac-9 and WETStar fluorometers, and discrete bottle sample data (H. Sosik, personal communications, 1997) were used in this study. Absorption at the 715 nm wavelength measured by the ac-9 was subtracted from the entire ac-9 spectrum to correct for residual light scattering. This zero correction was performed to conform to discrete bottle sample methods of obtaining absorption spectra. This correction is an approximation and a possible source of error (see results and discussion section). Further details about methods and instrumentation are described in chapter 2.

Observations

We recovered 80- and 50-day time series data sets from the 52- and 68-m ac-9s, respectively (Figure 3.3b, c). The 37-m ac-9 was biofouled (exponential growth of the absorption and attenuation signals) shortly after the passage of Hurricane Edouard [Dickey et al., 1998a; Chang et al., 1999] on 6 September 1996, providing us with 60 days of data (Figure 3.3a). The 13-m ac-9 data began to show the effects of biofouling approximately 15 days after the
Figure 3.2: Flow chart diagramming the procedures used for spectral absorption partitioning analysis, beginning with the measurement of $a_{t-w}(\lambda)$ using ac-9s. Model inputs and outputs are shown.
Figure 3.3: Time-series (6-h averaged) of total absorption spectra at (a) 37 m, (b) 52 m, and (c) 68 m. SI=observed phytoplankton bloom, E=time of passage of Hurricane Edouard, H=passage of Hurricane Hortense. Dates are presented as decimal year day with the convention that 0 h UTC on 1 January is day 1.0.
instrument was deployed and hence were not used in this study. Comparisons between all non-biofouled data and available shipboard ac-9 profile measurements were conducted to determine possible errors from calibration and long-term instrument drift (W. S. Pegau, personal communications. 1996). Results from the inter-comparisons revealed that instrument drift over time was negligible. Calibration differences between moored and profiled data were within ±15% and thus, moored data were adjusted over the entire time series according to the results from these inter-comparisons. Data from the 37, 52, and 68-m ac-9 time series were used with the Roesler et al. [1989] spectral absorption model.

37-m ac-9 data
A three-dimensional plot of 37-m ac-9 total absorption spectra (aₐ₋ₐ(λ)) over the available time series (8 July - 6 September 1996: YD (year day) 190 - 250, with the convention that 0 h UTC on 1 January is day 1.0), with a 6-hr average (for a clearer depiction of the data) is shown in Figure 3.3a. The 37-m spectra and wavelength ratio (440:676 nm. wavelengths represent detrital plus gelbstoff and chlorophyll-α, respectively: Figures 3.3 and 3.4) show a phytoplankton signature, which can be seen in the chlorophyll-α red absorption peak (676 nm). The spectral shape, however, was not constant throughout the time series. This fact is demonstrated in a time series plot of the ratio aₐ₋ₐ(440):aₐ₋ₐ(676) (6-hr average: Figure 3.4a: chlorophyll-α concentration time series with an arbitrary scale shown below each absorption ratio time series for comparison). This ratio ranged from 3.5 to 6.5 from 8 July through 6 September 1996 (YD 190-250). The relatively low ratio signifies a higher amount of chlorophyll-α at 37 and 52 m than at 68 m. During most of the 60-day time series the ratio was within one standard deviation of the mean (Figure 3.4a). However, several significant changes in the spectral shape occurred on
Figure 3.4: Time-series of the ratio $a_w(440):a_w(676)$ (6-hr averaged) and chlorophyll-a concentrations derived from the WETStar fluorometer plotted with an arbitrary scale (beneath ratio time-series) at (a) 37 m, (b) 52 m, and (c) 68 m. Note change in scales of ordinate axes. The solid horizontal lines indicate the mean, and the dashed horizontal lines indicate one standard deviation from the mean.
18 July (YD 200), 7 August (YD 220), 26 August (YD 239), and 1 September (YD 245) 1996. The ratio $a_{c,u}(440):a_{c,u}(676)$ decreased on 18 July and 26 August 1996, i.e., chlorophyll-$a$ concentration increased relative to those of other constituents (Figure 3.4a). These changes were most likely the result of relatively small-scale and short-lived phytoplankton blooms (W. S. Pegau, personal communications, 1996). Fluorescence profiles obtained by W. Scott Pegau (OSU) on 26 August 1996 show a greater than three-fold increase in chlorophyll-$a$ centered at the 30-m depth, lasting for ~3 days (data not shown: peak S1 in Figure 3.3a). An increase in the ratio $a_{c,u}(440):a_{c,u}(676)$ indicates an increase in detrital and/or gelbstoff material. This occurred on 7 August and 1 September 1996 and was most likely caused by horizontal advection of different water masses past the CMO site or by resuspension of bottom sediments. The high ratio of $a_{c,u}(440):a_{c,u}(676)$ on 4 September 1996 (peak E in Figure 3.3a) was due to the passage of Hurricane Edouard over the CMO site, which forced bottom sediment more than 30 m upward into the water column [Dickey et al., 1998a; Chang et al., 1999].

52-m ac-9 data
The signature of the 52-m ac-9 spectral time series (6-hr average: Figure 3.3b) was significantly different from that of the 37-m data. The spectral shape varied throughout much of the time series (Figure 3.4), with large increases in magnitude during the passages of two hurricanes. Edouard (3 September 1996: year day 247; peak E in Figure 3.3b) and Hortense (15 September 1996: year day 259; peak H in Figure 3.3b). The higher $a_{c,u}(440):a_{c,u}(676)$ ratio indicates lower concentrations of chlorophyll-$a$ at the 52-m than the 37-m depth. This result was expected because of the proximity to the ocean bottom (<20 m) and the decreased light levels at this depth (1% light level was at ~30 m; data not shown). Similarly to that in the 37-m time series, the ratio $a_{c,u}(440):a_{c,u}(676)$
generally remained within one standard deviation of the mean, except during periods of high sediment resuspension (3 and 15 September 1996).

68-m ac-9 data

The 68-m spectral absorption time series (6-hr average; Figure 3.3c) can be described in two parts: before the passages of the two hurricanes (pre-hurricane: 7 - 29 August 1996: year day 220 - 242) and during the passages of the hurricanes (30 August - 26 September 1996: year day 243 - 270). During pre-hurricane conditions, the spectra were similar in shape to the 37-m data, although the large concentration of detritus at the near-bottom depth (68 m) increased the ratio \( a_t(\lambda) : a_{t,u}(\lambda) \) (Figures 3.3c and 3.4c). Chlorophyll-\( a \) absorption peaks are detectable at the red wavelength (676 nm), possibly because of resuspension of relict pigments from the ocean bottom, sinking of phytoplankton, or both. This phenomenon is difficult to see in Figure 3.3c because of the scale of the absorption axis. During the hurricanes, the magnitude of total absorption and the ratio \( a_{t,u}(\lambda) : a_{t,u}(676) \) increased dramatically owing to resuspended bottom sediments. Absorption decreased exponentially with increasing wavelength during this time.

Analyses

Our analysis procedure to partition total absorption measured by the ac-9 (without water) into absorption by phytoplankton, detritus, and gelbstoff is summarized in Figure 3.2. The total spectral absorption, \( a_t(\lambda) \), can be described as the sum of spectral absorption that is due to water, \( a_w(\lambda) \), to phytoplankton, \( a_{ph}(\lambda) \), to detritus, \( a_d(\lambda) \), and to gelbstoff, \( a_g(\lambda) \) such that

\[
a_t(\lambda) = a_w(\lambda) + a_{ph}(\lambda) + a_d(\lambda) + a_g(\lambda).
\]  

(3.1)
The absorption spectrum for water is known [Smith and Baker. 1981; Pope and Fry. 1997]. The shape and magnitude of the detritus and gelbstoff spectra can be modeled with minimal error [Jerlov. 1968; Kirk. 1994]:

\[ a_\lambda(\lambda) = a_\lambda(\lambda_{\text{ref}}) \exp \left[ -C_0 (\lambda - \lambda_{\text{ref}}) \right]. \]  \hspace{1cm} (3.2)

where \( \lambda_{\text{ref}} \) is a reference wavelength and \( C_0 \) is a constant (expressed in \( \text{nm}^{-1} \)). However, phytoplankton spectral absorption varies significantly in response to environmental changes and community composition. Thus, one generally derives phytoplankton absorption signatures from whole water absorption measurements by first subtracting other, less variable, absorption components (water, detritus, gelbstoff).

The model of Roesler et al. [1989] does not distinguish between detrital absorption and gelbstoff absorption spectra. The model was developed for high chlorophyll coastal waters but can also be used for case I waters (for which phytoplankton determine the optical properties in the water column) [Kirk. 1994] with appropriate determination of model parameters:

\[ a_{d-g}(\lambda) = \{ a_{d-g}(\lambda_{\text{ref}}) \exp \left[ C_{2,\lambda} (\lambda - \lambda_{\text{ref}} - 400) \right] \} \]

\[ \exp \left[ -C_{2,\lambda} (\lambda - 400) \right]. \]  \hspace{1cm} (3.3)

where \( C_{2,\lambda} \) (expressed in \( \text{nm}^{-1} \)) is an unknown model parameter that defines the shape of the detritus-plus-gelbstoff spectra and \( a_{d-g}(\lambda_{\text{ref}}) \) is an unknown absorption for the detritus-plus-gelbstoff spectra at a reference wavelength. The value of \( C_{2,\lambda} \) is estimated from measurements at the specific site (average values are 0.011 - 0.016 \( \text{nm}^{-1} \)) and is influenced by the relative contributions of humic or fulvic acid. \( a_{d-g}(\lambda_{\text{ref}}) \) can be determined under the assumption that total absorption at 676 nm is due to absorption of phytoplankton, with no contribution from gelbstoff and/or detritus absorption. Assuming that \( a_{d-g}(676) \) is negligible compared with \( a_{\text{ph}}(676) \). Roesler et al. [1989] obtained the following relationship:
\[ a_{d-e}(440) = a_{t-w}(440) - a_{t-w}(676) \cdot o_{440/676}. \]  

(3.4)

where \( a_{d-e}(440) \) represents \( a_{d-e}(\lambda_{\text{ref}}) \) in equation (3.3) at a reference wavelength of 440 nm. \( a_{t-w}(\lambda) \) is the total absorption minus the contribution of water, and \( o_{440/676} \) is the measured blue to red absorption peak ratio for phytoplankton. \( o_{440/676} \) depends on water type, species type, light history, nutrients, pigment composition, and pigment packaging effects [Roesler et al., 1989]. Absorption that was due to the presence of phytoplankton was determined with the following relationship from total absorption data obtained during the CMO experiment:

\[ a_{ph}(\lambda) = a_{t-w}(\lambda) - a_{d-e}(\lambda). \]  

(3.5)

where \( a_{t-w}(\lambda) \) is measured by the ac-9 and \( a_{d-e}(\lambda) \) is determined from equation (3.3). Detrital absorption was determined by difference when measured gelbstoff absorption data were available:

\[ a_{d}(\lambda) = a_{d-e}(\lambda) - a_{g}(\lambda). \]  

(3.6)

Details of the methods and model development are described by Roesler et al. [1989].

The partitioning of total absorption spectra into absorption by phytoplankton, detritus, and gelbstoff was performed for days when validation in vivo absorption data and measured gelbstoff data were available at depths within 3 m of the ac-9 mooring measurements. The Roesler et al. [1989] model was applied to the total absorption spectra at 37-m for 21 and 31 August 1996 and at 52 m for 21 and 25 August 1996 at exact times of discrete bottle sample collection and gelbstoff absorption measurements to partition \( a_{t-w}(\lambda) \) into \( a_{ph}(\lambda), a_{d}(\lambda), \) and \( a_{g}(\lambda) \). Gelbstoff absorption spectra were measured by W. Scott Pegau (OSU) ~3 times daily during the period 17 August – 7 September 1996 using shipboard profiling methods with a 0.2-\( \mu \)m filter on the intake of an ac-9 absorption tube. Therefore gelbstoff absorption is defined for the
purpose of this study as any particle that passes through a 0.2-μm filter. Total and partitioned absorption spectra measured by the ac-9 and determined from the model were then compared with total, phytoplankton, detritus, and gelbstoff absorption spectra measured with the in vivo absorption data. Figures 3.5 and 3.6 show modeled and measured absorption spectra at 37- and 52-m depths, respectively (phytoplankton absorption spectra shown have been normalized to the 676-nm wavelength). Parameters used for the model of Roesler et al. [1989] are found in Table 3.1. Modeled spectra were optimized by varying the model parameter $C_{2\text{d-f}}$ from 0.011 to 0.016 nm$^{-1}$ in steps of 0.001 nm$^{-1}$ and by varying $\sigma_{\text{d-f,676}}$ from 1.0 to 2.0 in steps of 0.1 to yield the best correlations. After the optimizations were performed, average values for the constants $C_{2\text{d-f}}$ and $\sigma_{\text{d-f,676}}$ were computed and applied to the entire 37- and 52-m ac-9 time series data (8 July - 6 September 1996 and 8 July - 26 September 1996, respectively) for estimates of $a_{\text{ph}}(\lambda)$ and $a_{\text{d-f}}(\lambda)$. The results are shown in Figures 3.7 and 3.8. Model constants for 68-m absorption data were estimated by varying $C_{2\text{d-f}}$ and $\sigma_{\text{d-f,676}}$ until the shapes of $a_{\text{ph}}(\lambda)$ and $a_{\text{d-f}}(\lambda)$ simultaneously appeared to be consistent with published partitioned absorption spectra at all time periods [Roesler et al., 1989; Bricaud and Stramski, 1990; Cleveland, 1995]. These model constants were then applied to the entire 68-m total absorption time series data (50 days: Figure 3.9).

Results and Discussion

Regression analysis was performed between partitioned in situ ac-9 data (modeled) and in vivo validation absorption spectra (measured) for the 37-m depth on 21 and 31 August 1996 and for the 52-m depth on 21 and 25 August 1996 (Table 3.1) for all ac-9 wavelengths with the exception of 715 nm. The
Figure 3.5: In vivo bottle sample—measured (solid) and ac-9—derived (dashed) (a) total absorption spectra without water, (b) phytoplankton absorption normalized to 676 nm, (c) detrital absorption, (d) gelbstoff absorption for 21 August 1996 (year day 234), (e) total absorption minus water, (f) phytoplankton absorption normalized to 676 nm, (g) detrial absorption, and (h) gelbstoff absorption for 31 August 1996 (year day 244) partitioned using the model of Roesler et al. [1989] at 37 m
Figure 3.6: In vivo bottle sample—measured (solid) and ac−9−derived (dashed) 
(a) total absorption spectra without water, (b) phytoplankton absorption 
normalized to 676 nm, (c) detrital absorption, (d) gelbstoff absorption for 21 
August 1996 (year day 234), (e) total absorption minus water, (f) phytoplankton 
absorption normalized to 676 nm, (g) detrital absorption, and (h) gelbstoff 
absorption for 25 August 1996 (year day 238) partitioned using the model of 
Roesler et al. [1989] at 52 m
<table>
<thead>
<tr>
<th>Day</th>
<th>Depth(^a) (m)</th>
<th>(C_{2-d} \text{ (nm}^{-1}))</th>
<th>(\phi_{440.676})</th>
<th>(r^2) (ph)(^b)</th>
<th>(r^2) (d)(^b)</th>
<th>(r^2) (g)(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>38</td>
<td>0.015</td>
<td>1.60</td>
<td>0.979</td>
<td>0.988</td>
<td>0.998</td>
</tr>
<tr>
<td></td>
<td>53</td>
<td>0.015</td>
<td>1.50</td>
<td>0.881</td>
<td>0.997</td>
<td>0.996</td>
</tr>
<tr>
<td>25</td>
<td>55</td>
<td>0.015</td>
<td>1.90</td>
<td>0.873</td>
<td>0.997</td>
<td>0.996</td>
</tr>
<tr>
<td>31</td>
<td>36</td>
<td>0.016</td>
<td>1.75</td>
<td>0.942</td>
<td>0.932</td>
<td>0.972</td>
</tr>
</tbody>
</table>

Regression analysis was performed between partitioned *in situ* ac-9 and *in vivo* validation absorption spectra for the 37-m depth on 21 and 31 August 1996 and for the 52-m depth on 21 and 25 August 1996 for all ac-9 wavelengths with the exception of 715 nm. Regression analysis for gelbstoff absorption was performed between bottle sample-derived and ac-9-measured spectra.

\(^a\)Depths of discrete bottle samples, chosen within 3 m of the mooring depths (37- and 52-m).

\(^b\)ph = phytoplankton, d = detrital, g = gelbstoff.
Figure 3.7: Time-series (6-hr averaged) of 37 m (a) total absorption spectra (without water) measured by the ac-9, (b) phytoplankton absorption spectra, and (c) detrital plus gelbstoff absorption estimated using the model by Roesler et al. [1989]. SI=observed phytoplankton bloom, E=Hurricane Edouard.
Figure 3.8. Time-series (6-hr averaged) of 52 m (a) total absorption spectra (without water) measured by the ac-9, (b) phytoplankton absorption spectra, and (c) detrital plus gelbstoff absorption estimated using the model by Roesler et al. [1989]. SI=observed phytoplankton bloom, E=Hurricane Edouard, H=Hurricane Hortense.
Figure 3.9: Time-series (6-hr averaged) of 68 m (a) total absorption spectra (without water) measured by the ac-9, (b) phytoplankton absorption spectra, and (c) detrital plus gelbstoff absorption estimated using the model by Roesler et al. [1989]. SI=observed phytoplankton bloom, E=Hurricane Edouard, H=Hurricane Hortense.
715-nm wavelength was excluded because of its variability associated with changes in temperature and salinity [Moore and Bruce, 1996; Pegau and Zaneveld, 1993; Pegau et al., 1997]. Gelbstoff absorption comparisons were made between bottle sample-derived and ac-9-measured spectra. High correlation was found between modeled and measured phytoplankton, detritus, and gelbstoff spectral shapes at 37- and 52-m depths (Table 3.1). The phytoplankton spectra consistently yielded the lowest correlation (0.873 - 0.979), and the gelbstoff spectra yielded the highest (0.972 - 0.998). Detritus spectra correlation ranged from 0.932 - 0.997. These rates of correlation were to be expected because gelbstoff spectra were measured, and detritus spectra are relatively well known and easily modeled, whereas phytoplankton spectra vary according to phytoplankton concentration, community structure, and physiology as well as changes in pigment composition and packaging [Roesler et al., 1989; Bidigare et al., 1990].

It should be noted that magnitude differences between in situ and in vivo $a_v(\lambda)$ exist (Figures 3.5 and 3.6). In situ $a_v(\lambda)$ measured by the ac-9 was consistently greater than in vivo $a_v(\lambda)$, most likely because of the arbitrary wavelength selection for the zero correction for scattering. Bottle sample-derived total absorption data drop below zero at ~680 nm, which is near the peak in chlorophyll $a$ absorption (Figure 3.5), providing evidence that the in vivo total absorption is too low. An additional reason for these differences may be dissimilar sampling schemes. The sample volumes measured by the moored instruments and the bottle samples were not obtained from the same water mass and there is clearly considerable spatial variability (horizontal and vertical) in the region [Barth et al., 1998]. Evidence for this difference can be found in ac-9 profile data taken by W. Scott Pegau (OSU; data not shown). Great variations can be found in profile absorption data over several casts at
one location. These variations may have been due to internal waves, advection, and measurement errors. Slight variations in sampling depth (e.g., 35 versus 37 m or 50 versus 52 m) may have also contributed to the differences in magnitude.

The differences in magnitude of separated absorption spectra (bias) are quantified in Table 3.2 as average percent differences between modeled and measured phytoplankton and detrital absorption, and between bottle sample and ac-9 measured gelbstoff absorption for all wavelengths except 715 nm. These magnitude differences can be attributed to bottle sample analyses (as mentioned above), ac-9 measurements, model assumptions, and determination of model parameters. The high percent differences in the blue and red wavelengths (412, 440, 650, and 676 nm) of the phytoplankton and detrital absorption are possibly due to residual pigments that were not removed from detrital spectra during determination of the in vivo spectra. Evidence for this can be seen in the slight peaks at 440 and 676 nm of the in vivo detrital curves (Figures 3.5 and 3.6). Calibration errors of the ac-9s may have also affected the total absorption spectral shape used as inputs into the model. The model parameters C2_d-3 and o_{d-3} greatly affected the model results. Varying C2_d-3 and o_{d-3} for the model of Roesler et al. [1989] resulted in a change in the correlation from 0.197 to 0.979 for 21 August 1996 (data not shown). Therefore, although it cannot be quantified, the extrapolation of optimized model parameters to the entire time series can lead to substantial errors in modeled absorption spectra.

The use of the spectral model presented by Roesler et al. [1989] to partition total absorption for the entire time series at 37-, 52-, and 68-m depths at the CMO site allowed us to determine particle types and the relative concentration
Table 3.2: Average percent difference between measured and modeled absorption for the Roesler et al. [1989] spectral model throughout all depths and time periods$^a$.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>$a_{ph}(\lambda)^b$ (%)</th>
<th>$a_d(\lambda)^b$ (%)</th>
<th>$a_g(\lambda)^{ab}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>412</td>
<td>+43.6</td>
<td>+20.3</td>
<td>-5.0</td>
</tr>
<tr>
<td>440</td>
<td>+48.2</td>
<td>+10.7</td>
<td>-8.6</td>
</tr>
<tr>
<td>488</td>
<td>+7.4</td>
<td>+9.2</td>
<td>+0.6</td>
</tr>
<tr>
<td>510</td>
<td>-11.1</td>
<td>+3.1</td>
<td>+11.9</td>
</tr>
<tr>
<td>532</td>
<td>-21.0</td>
<td>-3.4</td>
<td>+12.5</td>
</tr>
<tr>
<td>555</td>
<td>-37.3</td>
<td>-10.0</td>
<td>-0.4</td>
</tr>
<tr>
<td>650</td>
<td>-78.3</td>
<td>-51.4</td>
<td>-213.7</td>
</tr>
<tr>
<td>676</td>
<td>-24.7</td>
<td>-56.6</td>
<td>-125.5</td>
</tr>
</tbody>
</table>

$^a$ $a_g(\lambda)$ average percent differences were computed for 37 m depth on 21 and 31 August 1996, and for 52 m depth on 21 and 25 August 1996.

$^b$ $ph$ = phytoplankton. $d$ = detrital. $g$ = gelbstoff.
of each type, given total absorption in the water column (Figures 3.7-3.9; 6-hr averages shown). Average total and partitioned absorption, and percent contribution of partitioned to total absorption at the 412 nm wavelength are listed in Table 3.3. Before the use of the spectral partitioning model, analysis of absorption data revealed only that higher absorbing materials were present at the bottom (68-m) than the top (37-m) and the middle (52-m) of the water column.

The results from this model reveal the vertical structure of absorption by phytoplankton and detritus plus gelbstoff. The contribution of phytoplankton to total absorption was highest at 37-m, which was near the depth of the chlorophyll maximum (25 – 35 m), determined from profiles of chlorophyll fluorescence (OSU data; not shown). Relative phytoplankton absorption decreased with increasing depth, to a minimum of 15.0% of total absorption at 68-m, which was well below the euphotic depth (1% light level; ~35 m). The contribution of detrital plus gelbstoff matter to total absorption was greatest at the deepest depth (68-m), decreasing toward the top of the water column. This result was not unexpected because of the influence of high concentrations of sediment resuspended from the ocean bottom through tides, currents, and waves.

37-m Partitioned absorption time series

The phytoplankton absorption spectral shape at 37-m was variable with time before 2 September 1996 when Hurricane Edouard passed over the mooring (Figure 3.7). The phytoplankton absorption spectra exhibited a shape similar to that of the specific absorption coefficient of chlorophyll a, with peaks in absorption at the blue and red (440 and 676 nm) wavelengths (Figure 3.7) [Cleveland, 1995]. The time series of the phytoplankton absorption
Table 3.3: Average total and partitioned absorption and percent contribution to total absorption at the 412 nm wavelength at 37-, 52-, and 68-m derived using the Roesler et al. [1989] spectral model averaged over the available time series at each depth.

<table>
<thead>
<tr>
<th>Absorption (m$^{-1}$)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>37 m</td>
</tr>
<tr>
<td>$a_{t-\omega}(412)^a$</td>
<td>0.2013 (100%)</td>
</tr>
<tr>
<td>$a_{ph}(412)^a$</td>
<td>0.0456 (22.7%)</td>
</tr>
<tr>
<td>$a_{d-g}(412)^a$</td>
<td>0.1557 (77.3%)</td>
</tr>
</tbody>
</table>

$^a$t-w = total without water, ph = phytoplankton, d+g = detrital plus gelbstoff.
wavelength ratios (all divided by the 676 nm wavelength; Figure 3.10) were different at all wavelengths, representing fluctuations in the spectral shape of phytoplankton absorption over time. Frequency autospectra were constructed for ac-9 time series data at all wavelengths (except 715 nm) over the period 8 July - 6 September 1996 by use of 512-point fast Fourier transforms (FFTs), Hanning windows, and zero overlap to determine the dominant periods in the time series records. Small peaks in the frequency autospectra were observed at the semi-diurnal tidal (0.52 day) and the diel period (1 day) at 440, 488, 510, 532, and 676 nm (line labeled “SD” in Figure 3.11). These are the wavelengths typically associated with chlorophyll-a (∼440 and 676 nm), carotenoids (<500 nm), and fucoxanthin (∼475-550 nm) photosynthetic pigments [Prezlin, 1981]. This implies photoadaptation (changes in pigments per cell, pigment ratios, or pigment packaging) of photosynthetic organisms due to tidal and diel oscillations, which changed the light levels and/or temperature sensed by the organisms [Prezlin et al., 1991; Kirk 1994]. It was expected that a peak in frequency autospectra would be found at ∼3-5 days, which is approximately the period of community (large-scale) phytoplankton physiological adaptation (B. B. Prezlin, personal communications, 1998) induced by mixing and advection events. However, no such peak was found, most likely due to high horizontal and vertical variability (patchiness and advection). Detrital and gelbstoff spectra remained relatively constant with time throughout the entire time series (Figure 3.7).

During a phytoplankton bloom on 26 August 1996 (year day 239; peak SI in Figure 3.7), lasting approximately 3 days (W. S. Pegau, personal communications, 1996), total absorption increased by ∼0.2 m⁻¹. Phytoplankton absorption at 488, 510, 532, and 676 nm wavelengths increased relative to that of all other wavelengths during this time. The phytoplankton absorption
Figure 3.10: Time-series of 6-hr averaged (a) $a_{1}(412)$:$a_{2}(676)$, (b) $a_{1}(440)$:$a_{2}(676)$, (c) $a_{1}(488)$:$a_{2}(676)$, (d) $a_{1}(510)$:$a_{2}(676)$, (e) $a_{1}(532)$:$a_{2}(676)$, and (f) $a_{1}(555)$:$a_{2}(676)$ at 37 m estimated using the model by Roesler et al. [1989]. Solid horizontal line=mean, dashed horizontal line=one standard deviation from mean. SI=Observed phytoplankton bloom. E=Hurricane Edouard.
Figure 3.11: Frequency autospectra for 1-hr averaged (a) $a_{ph}(412)$, (b) $a_{ph}(440)$, (c) $a_{ph}(488)$, (d) $a_{ph}(510)$, (e) $a_{ph}(532)$, (f) $a_{ph}(555)$, (g) $a_{ph}(650)$, and (h) $a_{ph}(676)$ at 37 m estimated using the model by Roesler et al. [1989]. SD = semi-diurnal tidal period (0.52 day), D = diel period (1 day). Light blue lines indicate 95% confidence intervals.
spectra during the bloom are similar in shape to diatom absorption spectra (Figure 3.12 and Kirk [1994]). Previous studies showed that the diatom species *Rhizosolenia alata* dominates the MAB continental shelf and slope waters during the late summer months [Cura, 1987].

*52- and 68-m Partitioned absorption time series*

Phytoplankton absorption spectra at 52- and 68-m exhibited shapes similar to those of the spectra of the specific absorption coefficient of chlorophyll-*a* throughout the period before the passage of Hurricanes Edouard and Hortense (1 and 14 September 1996: Figures 3.8, 3.9, and 3.13), although the relative contribution of phytoplankton to total absorption was lower at these depths. Frequency autospectra of wavelength ratios were similar to those at the 37-m depth (data not shown). The phytoplankton bloom on 26 August 1996 at 37-m did not affect absorption values at 52- or 68-m. All components of absorption (total, phytoplankton, and detrital plus gelbstoff) increased dramatically during the hurricanes at 52- and 68-m, with a greater increase seen in the blue wavelengths of detritus-plus-gelbstoff absorption (Figures 3.4, 3.8, 3.9, and 3.13). Resuspension of detrital pigments and downward mixing of phytoplankton most likely caused the increase of phytoplankton absorption during the hurricanes (Figure 3.13) [Dickey et al., 1998a; Chang et al., 1999].

**Summary**

The success of the application of a spectral absorption model demonstrates an important advantage of taking *in situ* high frequency, long time series measurements. Ship-based methods for determining absorption by major components require filtering and pigment extraction of discrete bottle samples. These samples are taken at one discrete time and therefore are not capable of
Figure 3.12: Phytoplankton absorption spectra partitioned from total absorption at 37 m using the model of Roesler et al. [1989] on 26 August 1996 (year day 239) during a phytoplankton bloom (—o—), and on 22 July 1996 (year day 204) during non-bloom conditions (—x—).
Figure 3.13: Time-series $a_{ph}(440)$:$a_{ph}(676)$ estimated using the model by Roesler et al. [1989] at (a) 37 m, (b) 52 m, and (c) 68 m. Note the change in scales of ordinate axes. Solid horizontal line=mean, dashed horizontal lines=one standard deviation from the mean. SI=Observed phytoplankton bloom. E=Hurricane Edouard, H=Hurricane Hortense.
resolving processes on high frequency time scales, e.g., internal waves, tides, wind mixing and advection events, and eddies, or for extended periods. The application of newly developed instrumentation (e.g., WET Labs, Inc. ac-9 and Hi-Star meters) with the spectral model described above along with complementary shipboard data (profiles and bottle samples) can now be used to measure spectral absorption and to partition total absorption into absorption that is due to water, phytoplankton, detritus, and gelbstoff and to resolve processes on a broad range of spatial and temporal scales.

High-temporal-resolution spectral absorption data measured with moored and bottom-mounted spectral absorption and attenuation meters (ac-9s) during the fall deployment of the Coastal Mixing and Optics experiment were used with a spectral absorption model to separate total absorption (without water) into absorption by phytoplankton, detritus, and gelbstoff. Comparison of model results with in vivo absorption data during 2 days at 37- and 52-m reveal that the model successfully determined the spectral shape of each component, with correlations that varied from 0.873 to 0.998. The greatest correlation was found in gelbstoff spectra, and the lowest in phytoplankton spectra. However, there was considerable bias between modeled and measured results. This variability in the magnitudes of absorption is due primarily to differences in wavelength selection for the zero scattering correction technique and to spatial variability caused by differences in sampling techniques. Additional errors associated with the results are attributed to differences in instruments and measurement techniques as well as in model assumptions and model parameter determination.

The separated absorption spectra determined for the entire time series at 37-, 52-, and 68-m depths allowed us to examine vertical and temporal variability
of particle types and of relative concentrations of each particle type. It was found that the contribution of phytoplankton to total absorption was highest at 37 m and decreased with increasing depth. The contribution of detrital plus gelbstoff matter to total absorption was greatest at the deepest depth and decreased with decreasing depth. Frequency autospectra of partitioned phytoplankton absorption revealed that tidal and diel oscillations were likely caused by changes in phototaxis (photoadaptations, pigment packaging, etc.). It is hypothesized that lower frequency oscillations were due to changes in phytoplankton concentrations, species composition, or both: induced by changing light or nutrient conditions or by advection of new populations past the CMO site. It was found that a change in spectral shape of phytoplankton absorption occurred during a phytoplankton bloom. It is hypothesized that this spectral change was the result of a short-lived shift in phytoplankton community composition. The partitioned phytoplankton absorption permits us to investigate particular episodic events (e.g., phytoplankton blooms, hurricanes, and storms; see chapter 5) and physical-biological coupling as well as to estimate primary productivity in future studies.
CHAPTER 4
Physical and bio-optical time series

Introduction

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, several water mass intrusions, and the evolution of the seasonal cycle in hydrography and phytoplankton biomass as inferred from chlorophyll-a concentration. Our 11-month time series measurements of physical and bio-optical parameters also enable other CMO investigators to utilize high temporal resolution physical and bio-optical data relevant to their research, as most other studies focus on the details of specific events or disciplinary processes (see Dickey and Williams [1999]). In addition, 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 and as inputs into data assimilation models to predict bio-optical responses to physical forcing.

The present chapter 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. The experimental methods are presented in chapter 2.0. A description of the time series is provided in the observations section. The discussion section summarizes physical and bio-optical relationships by statistical analyses. A
comparison of our findings with those of analogous open ocean results is also presented in the discussion section.

**Observations**

For interpretation purposes, physical and bio-optical data were divided into four oceanographic seasons (summer/fall, winter mixing, winter stratification, and spring) by distinguishing water column hydrographic characteristics based on our eleven-month time series data (Figure 4.1). The lengths of these periods were not equal. The summer/fall period was from 8 July through 21 October 1996 (year day 190-295). The two winter periods extended from 22 October to 20 December 1996 (winter mixing: year day 296-355), and 21 December 1996 to 2 April 1997 (winter stratification: year day 356-92). The spring period (year day 93-162) ended on 11 June 1997. Below, is a description of the winds, currents, hydrography, and bio-optics, which is followed by detailed analyses of episodic events and dominant processes during each of our specified periods.

**Time series Overview**

**Winds and Currents**

The wind direction was predominately from the southwest (≈210°) during the entire 11-month time series record (Figure 4.2a: note wind rose convention: “from”). Southwesterly winds are locally upwelling favorable, which likely results in increased nutrient availability to the CMO site. The primary variability of the wind direction and speed was at time scales of ≈6-7 days.
Figure 4.1: Time series stackplots of 36-hr averaged (top) temperature, (middle) salinity, and (bottom) $\sigma_t$ between 8 July 1996 and 11 June 1997. The depths of the sensors are given in Tables 2.1, 2.2, and 2.3. Dates are also presented as decimal year day, with the convention that 0 hr UTC on 1 January is day 1.0. Events are labeled: "B, E, H" = Tropical Storm Bertha, Hurricanes Edouard and Hortense, respectively; "S1" = salinity intrusions; "FB, SB" = fall and spring bloom, respectively; "A1, A2, A3" = slope water advection events; and "SR" = spring runoff. Seasons are separated by black lines and labeled. The green vertical dashed lines indicate the time periods when complementary profile data were obtained.
Figure 4.2: Time series of 1-hr averaged (top) wind direction with a wind rose diagram (far right; convention: direction from) and (bottom) wind speed (converted to a height of 10 m above sea level assuming a logarithmic wind profile above the sea surface) with a rose diagram of vector winds (far right; radius of circle represents 14 m s⁻¹, arrows point in the direction the wind is blowing towards) measured by National Data Buoy Center buoys 44008 (1996) and 44028 (1997). See Figure 4.1 for year day convention and event abbreviations.
(data not shown). NDBC wind data from May until June 1997 are not available. The means, minima, maxima, and standard deviation of wind speed at 10 m above the sea surface and current speed at 10 and 58 m are given in Table 4.1.

Subtidal currents were computed by averaging ADCP-measured currents over 36 hr (Figure 4.3). The current transport direction was generally to the west-northwest, roughly parallel to bathymetry during most of the 11-month time series record (Figure 4.3). Our results indicate that tidal currents were approximately the same magnitude as subtidal currents (Figures 4.4 and 4.5a). Barotropic tidal modes (currents flowing in the same direction at all depths) and first baroclinic tidal modes (currents flowing in opposite directions at two equal-depth layers) were observed throughout the 11-month experimental period (Figure 4.5a). Supra-tidal velocity variability is typically associated with processes such as surface and internal waves, mainly caused by local and remote winds over the MAB (Figure 4.4). Northeasterly storms and hurricanes are relatively common in the area, and can lead to extreme wave conditions. Internal solitary waves (ISWs) were observed to pass through the mooring site (Figures 4.5b-e). Sub-tidal velocity variability was observed during the CMO experiment (described below).

Hydrography

Temperature versus salinity, hereafter referred to as T-S, was plotted using 36-hr filtered temperature and salinity mooring data at all depths available and throughout the 11-month observational period and compared with past studies (e.g., Flagg 1987) to identify water masses. Water masses at the CMO site were primarily a mixture of Georges Bank Water (GBW) and Maine Surface
Table 4.1: Mean, minimum, maximum, and standard deviation of temperature, salinity, current speed, and wind speed during the four seasons of the 11-month time series.

<table>
<thead>
<tr>
<th></th>
<th>Temperature (°C)</th>
<th>Salinity (psu)</th>
<th>Current Speed (cm s⁻¹)</th>
<th>Wind Speed (m s⁻¹) (10 m above)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Surf./Bot.)ᵇ</td>
<td>(Surf./Bot.)ᵇ</td>
<td>(Surf./Bot.)ᵇ</td>
<td></td>
</tr>
<tr>
<td><strong>Summer/Fall (8 July – 21 October 1996)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>15.02 / 9.16</td>
<td>31.90 / 32.34</td>
<td>15.47 / 8.94</td>
<td>4.90</td>
</tr>
<tr>
<td>Minimum</td>
<td>10.13 / 7.15</td>
<td>29.08 / 31.33</td>
<td>1.93 / 0.94</td>
<td>1.39</td>
</tr>
<tr>
<td>Maximum</td>
<td>20.85 / 12.66</td>
<td>35.05 / 34.15</td>
<td>44.87 / 30.16</td>
<td>14.55</td>
</tr>
<tr>
<td>Stdᶜ</td>
<td>1.61 / 1.41</td>
<td>0.26 / 0.21</td>
<td>9.89 / 6.89</td>
<td>2.22</td>
</tr>
<tr>
<td><strong>Winter Mixing (22 October – 20 December 1996)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>10.83 / 9.93</td>
<td>31.94 / 32.33</td>
<td>17.15 / 11.16</td>
<td>7.54</td>
</tr>
<tr>
<td>Minimum</td>
<td>7.41 / 8.20</td>
<td>29.51 / 31.62</td>
<td>2.68 / 1.45</td>
<td>3.51</td>
</tr>
<tr>
<td>Maximum</td>
<td>15.49 / 12.97</td>
<td>32.89 / 34.42</td>
<td>51.83 / 35.84</td>
<td>12.47</td>
</tr>
<tr>
<td>Stdᶜ</td>
<td>2.04 / 0.90</td>
<td>0.19 / 0.32</td>
<td>11.53 / 8.89</td>
<td>2.02</td>
</tr>
<tr>
<td><strong>Winter Stratification (21 December 1996 – 2 April 1997)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>5.45 / 7.19</td>
<td>31.95 / 32.63</td>
<td>13.43 / 8.37</td>
<td>8.02</td>
</tr>
<tr>
<td>Minimum</td>
<td>3.82 / 4.71</td>
<td>31.40 / 30.73</td>
<td>2.47 / 0.50</td>
<td>4.13</td>
</tr>
<tr>
<td>Maximum</td>
<td>7.26 / 10.77</td>
<td>32.71 / 35.08</td>
<td>34.79 / 23.42</td>
<td>14.25</td>
</tr>
<tr>
<td>Stdᶜ</td>
<td>0.76 / 1.74</td>
<td>0.28 / 0.39</td>
<td>6.45 / 5.32</td>
<td>2.15</td>
</tr>
<tr>
<td><strong>Spring (3 April – 11 June 1997)ᵈ</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>8.58 / 6.15</td>
<td>32.00 / 32.43</td>
<td>12.45 / 9.15</td>
<td>6.98</td>
</tr>
<tr>
<td>Minimum</td>
<td>2.85 / 5.29</td>
<td>30.65 / 32.33</td>
<td>1.38 / 1.30</td>
<td>4.33</td>
</tr>
<tr>
<td>Maximum</td>
<td>12.21 / 7.00</td>
<td>32.62 / 32.71</td>
<td>39.61 / 34.39</td>
<td>12.94</td>
</tr>
<tr>
<td>Stdᶜ</td>
<td>1.63 / 0.30</td>
<td>0.38 / 0.06</td>
<td>9.40 / 7.55</td>
<td>1.64</td>
</tr>
</tbody>
</table>

ᵃMean-current speed calculated by averaging ADCP-measured currents over 36 hr.

ᵇDesignations for Surf./Bot. represent approximate depths of 11 m/68 m, 15 m/60 m, and 10 m/58 m for temperature, salinity, and mean-currents speed, respectively.

ᶜStd = standard deviation.

ᵈSpring wind data dates were 3 – 21 April 1997.
Figure 4.3: Time series of mean current speed (36-hr averaged) stickplots during the (top-left) summer/fall, (top-right) winter mixing, (bottom-left) winter stratification, and (bottom-right) spring period at 10, 22, 34, 46, and 58 m depths. Average values of east and north component mean currents (u and v, respectively) are shown to the right of each time series. Legends are shown at the top left of the panels. See Figure 4.1 for year day convention and event abbreviations.
Figure 4.4: Time series of 6-hr averaged 10 m east (u) and north (v) component current velocity during the (a) summer/fall, (b) winter mixing, (c) winter stratification, and (d) spring period. See Figure 4.1 for year day convention and event abbreviations.
Figure 4.5: Time series of (a) 12-hr averaged north-component current velocity contoured with depth illustrating barotropic and baroclinic tidal modes; and north-component current velocity at 31 m and chlorophyll-a concentration derived from the WETStar fluorometer at 30 m between decimal year day (b) 224.75–225.25, (c) 231.5–232.0, (d) 235.5–236.0, and (e) 242.0–243.0. Arrows indicate when internal solitary waters and responses in [Chl–a] were observed. Data are plotted in arbitrary units. See Figure 4.1 for year day convention.
Water (MSW) (Figure 4.6). Descriptions of GBW and MSW are found in chapter 1. In addition to the presence of GBW and MSW water masses, a persistent, yet spatially varying shelf-slope front is a commonly observed feature (water mass) at the CMO site [Pickart et al., 1999]. The shelf-slope front separates the shelf water described above from slightly stratified, warmer, more saline, and relatively nutrient-rich water from the upper continental slope of the North American East Coast (e.g., Flagg [1987]; Barth et al. [1998]). Seasonal regimes of water mass anomalies can be recognized in the T-S diagrams (Figure 4.6).

Bio-optics

Time series of bio-optical properties are shown in Figures 4.7 and 4.8 (note differences in scales of ordinate axes). Missing and/or anomalously low values of data during the winter periods were due to bio-fouling of the PAR and ac-9 sensors. Chlorophyll-\(a\) concentrations (derived from fluorometers; see chapter 2, calibration section) were highly variable in depth and time throughout the 11-month time series (Figure 4.7b). The reason for the peaks in Chl-\(a\) found at 50 m between 8 July and 11 August 1996 is unknown (Figure 4.7b). It is not likely attributable to instrument error, as the Sea Tech. Inc. and the WETStar fluorometers, and Chl-\(a\) derived from the ac-9 (after Shifrin [1988]) exhibited similar signals. The high Chl-\(a\) signal could have been due to advection of high biomass waters past the CMO site at ~50 m. However, horizontal advection, which is important to our site, cannot be quantified from our data because no other bio-optical data (e.g., absorption, attenuation, chlorophyll fluorescence) were collected from other nearby CMO moorings. The peaks in Chl-\(a\) at the 68 m depth throughout the time series were most likely due to relict pigment resuspension and downward mixing of phytoplankton during the
Figure 4.6a: Temperature versus salinity scatter plots (26-hr filtered data) during (top-left) summer/fall, (top-right) winter mixing, (bottom-left) winter stratification, and (bottom-right) spring. Density lines were calculated according to UNESCO [1981] algorithms and are labeled. "SR" = spring runoff, and "SW" indicates the presence of slope-water at the experimental site.
Figure 4.6b: Temperature versus salinity scatter plot (36-hr filtered data) at (top-left) 15 m, (top-right) 35 m, and (bottom) 60 m. Density lines were calculated according to UNESCO [1981] algorithms and are labeled. "SR" = spring runoff. "SW" indicates the presence of slope-water at the experimental site.
Figure 4.7: Time series of 6-hr averaged (top) photosynthetically available radiation (PAR) at 12, 30, and 50 m; and (bottom) chlorophyll-a concentration at 12, 30, 50, and 68 m. Note the differences in scales of ordinate axes. Missing or anomalously low data were due to bio-fouling of instruments (e.g., 30 m PAR between 26 September to 4 January). See Figure 4.1 for year day convention and event abbreviations.
Figure 4.8: Time series of 8-hr averaged (top) absorption coefficient and (bottom) beam attenuation coefficient at 676 nm at 12, 30, 50, and 68 m. Note differences in scales of ordinate axes. Missing data were due to bio-fouling of ac-9s. See Figure 4.1 for year day convention and event abbreviations.
hurricanes and storms (YDs 245-260, 294-310, and 92-99). The highest values of absorption and attenuation coefficients at 676 nm ($a_{\text{c\-a}}(676)$ and $c_{\text{c\-a}}(676)$) were found at the 68 m depth, and were likely caused by resuspension of bottom particles. Temporal and vertical variability in $a_{\text{c\-a}}(676)$ and $c_{\text{c\-a}}(676)$ were similar to each other and to the Chl-a signals. The temporal variability in absorption and attenuation signals at the other eight wavelengths was consistent with the signals seen in $a_{\text{c\-a}}(676)$ and $c_{\text{c\-a}}(676)$, but different in magnitude (not shown).

Observations of Physical-Bio-optical Coupling

Important physical processes and their possible relationships with bio-optical properties during each of the four oceanographic seasons are discussed below. Statistical analyses of variability (frequency autospectra, Figures 4.9-4.11; autocovariances, Figures 4.12-4.13; and cross coherence, Figures 4.14A-D) on time scales from minutes to the seasonal cycle are utilized (see Appendix B). The autospectra for current speeds at all depths (14, 34, and 58 m shown) and all time periods reveal that most of the current energy was found at the M2 semi-diurnal tidal frequency (12.42 hr; labeled "M2" in Figure 4.9). The inertial period (~18.5 hr; "I" in Figure 4.9) was likely not as important at the CMO site, except perhaps following the hurricanes ("B", "E", and "H" in Figure 4.4). Current speed autospectra were similar in shape at all depths, but decreased in magnitude below 34 m (Figure 4.9). Autospectra for temperature and salinity were similar in shape to each other. Autospectra of temperature and salinity increased at longer temporal periods, i.e., red spectra (Figure 4.10). Similar to temperature and salinity autospectra, Chl-a and beam c autospectra increased at lower frequencies (Figure 4.11).
Figure 4.9: Autospectra of current speed (cycles per day) during summer/fall at (a) 14 m, (b) 34 m, and (c) 58 m; during winter mixing at (d) 14 m, (e) 34 m, and (f) 58 m; during winter stratification at (g) 14 m, (h) 34 m, and (i) 58 m; and during spring at (j) 14 m, (k) 34 m, and (l) 58 m. Light lines = 95% confidence interval, “M2” = semi-diurnal (12.42 hr), “O1” = diurnal (25.82 hr), and “I” = inertial (∼18.5 hr).
Figure 4.10: Autospectra of temperature and salinity in cycles per day during (a, c) summer/fall; (b, d) winter mixing; (e, g) winter stratification; and (f, h) spring at 15 m (blue), 35 m (green), and 60 m (red). “M2” = semidiurnal (12.42 hr), “O1” = diurnal (25.82 hr), and “I” = inertial (18.5 hr).
Figure 4.11: Autocorrelates of chlorophyll-a concentration and beam attenuation coefficient at 660 nm in cycles per day during (a, c) summer/fall; (b, f) winter mixing; (e, g) winter stratification; and (d, h) spring at 12 m (blue), 30 m (green), and 50 m (red). "M2" = semi-diurnal (12.42 hr), "O1" = diurnal (25.82 hr), and "I" = inertial (~18.5 hr).
Figure 4.12: Autocovariance of chlorophyll-a concentration (- - -), beam attenuation coefficient at 660 nm (- - -), temperature (- - -), and current speed (- - -) plotted versus period in days during (a, c) summer/fall; (b, f) winter mixing; (c, g) winter stratification; and (d, h) spring at 12 m and 60 m.
Figure 4.13: Autocovariance of chlorophyll-a concentration (---), beam attenuation coefficient at 660 nm (---), temperature (---), and current speed (---) plotted versus period in days during (a, c) summer/fall; (b, f) winter mixing; (e, g) winter stratification; and (d, h) spring at 50 m and 68 m.
Figure 4.14A: Coherence between PAR and Chl-α and phase angle at 12 m (x-), 30 m (o-), and 50 m (-) during (a, b) summer/fall; (c, d) winter mixing; (e, f) winter stratification; and (f, h) spring. The dark horizontal lines on coherence plots indicate the statistical significance levels, calculated according to Thompson [1979]. The legend is found in the upper right corner of (a).
Figure 4.14B: Coherence between temperature and Chl-a and phase angle at 12 m (-x-), 30 m (-o-), 50 m (-), and 68 m (+-+) during (a, b) summer/fall; (c, d) winter mixing; (e, f) winter stratification; and (f, h) spring. The dark horizontal lines on coherence plots indicate the statistical significance levels, calculated according to Thompson [1979]. The legend is found in the upper right corner of (a).
Figure 4.14C: Coherence between current speed and beam c and phase angle at 12 m (-x-), 30 m (-o-), 50 m (-.), and 68 m (-.-) during (a, b) summer/fall; (c, d) winter mixing; (e, f) winter stratification; and (f, h) spring. The dark horizontal lines on coherence plots indicate the statistical significance levels, calculated according to Thompson [1979]. The legend is found in the upper right corner of panel (a). Figure 4.14A.
Figure 4.14D: Coherence between beam c and Chl-a and phase angle at 12 m (-x-), 30 m (-o-), 50 m (- - ), and 68 m (---) during (a, b) summer/fall; (c, d) winter mixing; (e, f) winter stratification; and (f, h) spring. The dark horizontal lines on coherence plots indicate the statistical significance levels, calculated according to Thompson [1979]. The legend is found in the upper right corner of panel (a). Figure 4.14B.
Chlorophyll-α concentrations were plotted versus beam attenuation coefficient (beam c; derived from the transmissometer: 660 nm) for 12, 30, 50, and 68 m depths during the four oceanographic seasons to qualitatively differentiate between biogenic and detrital constituents in the water column [Wu et al., 1994] (Figure 4.15). High Chl-α values with relatively low beam c values are indicative of biogenic matter, while high values of beam attenuation with relatively low Chl-α values imply detrital matter. Detrital matter is defined as all non-pigmented matter such as sediment, dead organic, and dissolved matter. At 12 m, high biogenic matter and low detritus existed throughout the year (Figure 4.15a). The pattern was similar at the 30 m depth (Figure 4.15b). The high concentrations of biogenic matter at the 50 and 68 m depths during the summer/fall, winter mixing, and spring periods were most likely caused by sinking or vertical mixing of pigments from the upper water column and by relict pigment resuspension. Sosik et al. [1999] found significant contributions of degraded forms of chlorophyll from dead cells and/or fecal material in near-bottom waters. The 68 m depth was dominated by detrital matter during most of the experiment, with beam c values more than 10 times those of the near-surface (Figure 4.15d).

**Summer/Fall Period: 8 July – 21 October 1996 (Year Day 190-295)**

The summer/fall season is characterized as a stratified period (Figure 4.1), with frequent episodic events such as hurricanes [Dickey et al., 1998a; Chang et al., 1999], high salinity water mass intrusions [Pegau et al., 1999], and internal solitary waves [Colosi et al., 1999] (Figure 4.5). Wind speeds were relatively low (~5 m s⁻¹) and from the south, except during the passages of the hurricanes (Figure 4.2). Subtidal currents were primarily toward the northwest (Figure 4.3a); average subtidal current speeds were 30 cm s⁻¹ at the sub-surface
Figure 4.15: Chlorophyll-a concentration plotted versus beam c at a) 12 m, b) 30 m, c) 50 m, and d) 68 m by season, where x – summer/fall, o – winter mixing, * – winter stratification, and + – spring. 6-hr averaged data used. Light signals indicative of biogenic and detrital matter are indicated. Note differences in abscissa axes.
A strong M2 semi-diurnal tidal signal was observed in the temperature data at 15 m (Figure 4.10), most likely because of tidal oscillation of the thermocline (at ~15 m). Chlorophyll-a concentrations were moderate despite the stratified conditions, which limited nutrients to the euphotic layer (Figure 4.7b: see results by O'Reilly et al. [1987]). High concentrations of particles in the water column from hurricane resuspension resulted in relatively high values of absorption and attenuation coefficients (Figures 4.8a, b).

The eyes of Tropical Storm (TS: former hurricane) Bertha, and Hurricanes Edouard and Hortense passed within approximately 150, 110, and 350 km of our mooring site on 12 July, 31 August, and 13 September 1996, respectively ("B", "E", and "H" in Figure 4.1) [Chang et al., 1999]. During the high wind speed conditions of the storms and hurricanes, wind directions were highly variable because of the passages of low atmospheric pressure systems (vector wind rose diagram in Figure 4.2b, where the radius of the circle represents 14 m s⁻¹ and arrows point in the direction the wind is blowing towards). The high wind speed conditions of Hurricane Edouard resulted in mixing of the water column ("E" in Figure 4.2). Inertial oscillations in currents were observed in the upper water column following the passage of TS Bertha ("B" in Figure 4.4). The greatest effects of the hurricanes on the bio-optics were in resuspension of bottom sediments and relict pigments, and downward mixing of phytoplankton [Dickey et al., 1998a; Chang et al., 1999] (Chl-a, aₐₐₐ(676), and cₐₐₐ(676) time series: Figures 4.7b and 4.8). This is further illustrated in qualitative and quantitative assessments of particles in the water column (Chl-a versus beam c scatter plots, partitioning of total spectral absorption [Chang and Dickey, 1999b], and coherence between Chl-a and beam c: Figures 4.14Da, b and 4.15). Chl-a versus beam c scatter plots reveal high detrital components.
relative to biogenic material during the summer/fall at 30, 50, and 68 m (Figure 4.15). The relatively high biogenic as compared to detrital matter at 50 and 68 m (Figures 4.15c, d) was likely the result of resuspension of relict pigments from the seafloor, or downward mixing of phytoplankton. This is further evidenced in the significant coherence between Chl-α and beam c with about ±10° phase lag between the two signals (Figure 4.14Da, b).

Water mass intrusions on 25 August and 18 September 1996 were caused by a rapidly moving meander in the shelf-slope front, resulting in increased subtidal current speeds during the summer/fall period (see Pegau et al. [1999]; difficult to distinguish in Figure 4.3a due to averaging). These intrusions were most easily identified in time series of hydrographic data (“SI” in Figure 4.1) as short-lived (3-5 days) increases of temperature and salinity at the near-bottom depths (~50-68 m) and in the upper layer (~5-15 m). In addition to changes in temperature and salinity, we suggest that higher concentrations of nutrients or Chl-α were advected past the CMO site (see above for shelf-slope frontal water characteristics), resulting in increases in phytoplankton (“blooms”), implied by increases in Chl-α and changes in the spectral absorption of phytoplankton (Figures 4.7b; Figure 8 in Pegau et al. [1999]: Chang and Dickey. [1999b]).

Internal solitary waves are commonly observed in the coastal ocean with instruments that sample rapidly (e.g., Sandstrom et al. [1989]). ISWs can be generated under a variety of conditions, e.g., internal hydraulic flows, collapsing mixed layers, internal tides, and shear flow instabilities [Farmer and Armi. 1999; Colossi et al. 1999; Wang et al. 1999]. ISWs have the potential to lead to mixing of the water column via breaking waves leading to small-scale turbulence. Biological processes can be influenced by ISWs through pumping of nutrients and phytoplankton to higher or lower light levels.
[Sandstrom and Elliott, 1984], or pumping of particles or nutrients from the ocean bottom [Bogucki et al., 1997]. The highly stratified conditions at the CMO site during summer/fall enabled the generation of packets of high frequency ISWs from the propagation of internal tides onto the continental shelf. Colossi et al. [1999] report that energetic internal tides rapidly evolved into an internal tidal bore, forming soliton-like internal waves offshore from the mooring location (Figure 4.5b-e). Packets of these ISWs contained between 2 and 12 waves (with periods of ~20 min or less). It appears that the ISWs propagating past the CMO site may not have been as important to the bio-optics as expected. The measured turbulent kinetic energy associated with ISWs were not great enough to mix or pump nutrients, phytoplankton, or cause sediment resuspension (J. MacKinnon, personal communications, 1999).

Vertical displacement of phytoplankton past our bio-optical sensors on the mooring is the most likely explanation of the correlation of oscillations in Chl-a at 30 m with ISWs (Figures 4.5b-e). It should be noted that ISWs may have been more important at depths and locations other than those of our bio-optical instruments.


The water column during the winter mixing period was the least stratified of all the seasons (Figure 4.1). Wind speed increased during this time, with an average wind speed of ~8 m s\(^{-1}\) (Table 4.1; Figure 4.2). Subtidal current speed, however, changed little from the summer/fall period (Figure 4.3a). Episodic events during the winter mixing period included several northeasterly storms and a high temperature event lasting one-day (15 December 1996: “A1” in Figure 4.1). Temperature and salinity autospectra exhibited almost the same shape due to the nearly homogeneous hydrographic conditions during this time.
(Figure 4.10). Despite seasonally low light levels, Chl-a throughout the water column was at its highest level of the 11-month time series (explained below: Figure 4.7).

A northeasterly storm that was about as intense as Hurricane Edouard accelerated the mixing of the water column at the beginning of the winter mixing period on 20 October 1996. The storm and the subsequent mixing of the water column likely entrained and/or advected nutrients into the euphotic layer from near the ocean bottom or remote sources or both, resulting in a near-surface fall bloom ("FB" in Figure 4.7b). Chlorophyll-a concentrations increased almost 3-fold, with the highest biogenic matter found at 30 m (Figures 4.7b and 4.15b). It is interesting to note that the light signals indicative of particles at 50 and 68 m during this time were likely the result of both the sinking of phytoplankton from the bloom and the northeasterly storm-induced sediment resuspension. The sediment resuspension is evidenced by high values of beam attenuation coefficient seen first at 68 m beginning on 20 October (YD 294), then seen at 50 m shortly thereafter ("*"s in Figure 4.8b). The sinking of phytoplankton is represented by an increase in Chl-a occurring first at 12 m, then several days later at 30 m, and finally, a few weeks later at 50 and 68 m ("*"s in Figure 4.7b). Current shear throughout the upper water column was relatively low at this time (not shown), promoting settling and resuspension of particles with little horizontal advection. Likely as a result of frequent storm-induced mixing and resuspension of pigmented materials, shorter decorrelation time scales of Chl-a were observed at 68 m (Figure 4.13f). Significant coherence between beam c and Chl-a was found at the near-bottom depths (50 and 68 m) with ~0° phase lag at periods greater than one day during the winter mixing period, likely due to sinking of
phytoplankton and storm-induced vertical mixing and resuspension of pigmented materials (Figures 4.14Dc. d and 4.15).

High temperature, high salinity water was observed on 15 December 1996 between ~35 and 68 m depths, with the greatest influence near the ocean bottom ("A1" in Figure 4.1). This water mass feature persisted for only 1 day, and was apparently advected northeastward (a direction of ~310°) during a period of high speed subtidal currents (~60 cm s⁻¹; Figure 4.3b). Chlorophyll-α concentrations and total absorption coefficient decreased at 50 and 68 m during the water mass intrusion (not seen in the 36-hr averaged data presented here). The origin of this low-biomass water and the mechanism of transport are unknown.


The water column was thermally inverted, but stably stratified because of the stabilizing vertical salinity structure during the winter stratification period (Figure 4.1). Considerable variability in stratification was observed, with the full water column being virtually homogenous (~3 February 1997; Figure 4.1). Wind conditions were similar to those during the winter mixing period (Figure 4.2). Oceanic circulation patterns, however, were more variable (Figure 4.3c). Sporadic periods of high subsurface PAR values were observed during the middle and near the end of the winter stratification period (Figure 4.7a). Chlorophyll-α concentrations, aₐ₋ₐ(676), and cₑ₋ₑ(676) were at their lowest values at all depths until an apparent phytoplankton bloom occurred on about 19 February 1997 (described below; "A3" in Figure 4.7b).
Slope-water from the shelf-slope front was twice observed at the CMO site during the winter stratification period (starting 25 December 1996 and 19 February 1997, lasting about 35 and 20 days, respectively). This was evidenced by the T-S characteristics at 60 m (relatively high temperature and salinity; “SW” in Figures 4.6a and b), stratification of the water column (“A2” and “A3” in Figure 4.1), and the relatively strong mean currents during these time periods (“A2” and “A3” in Figure 4.3). Advection of the shelf-slope front toward the north via a jet, meander, or filament off of the front, or the detachment of an eddy from the front are possible explanations for slope-water at the CMO site (features similar to those reported earlier by Pickart et al. [1999]). Although the T-S properties were similar, the vertical structure in hydrographic properties was significantly different between the two events (Figure 4.1). In addition, the mean current directions were more variable during the first advection event (“A2” in Figure 4.3). It is hypothesized that the detachment of a shelf break eddy caused the second advection event, and pushed slope-water onto the shelf. An Advanced Very High Resolution Radiometer (AVHRR) image of sea surface temperature (SST) at the CMO site shows a clockwise rotating eddy protruding from the shelf-slope front toward the coast of Cape Cod on 26 February 1997 (Figure 4.16). AVHRR SST images for days prior to and following 26 February 1997 are not useful for our analysis because of extensive cloud cover. It is also hypothesized that the increase in Chl-a starting on about 19 February 1997 was caused by either increased light levels (Figure 4.6a), or shelf-slope front-induced advection of high nutrient slope-water or of phytoplankton, or a combination of the two processes (“A3” in Figures 4.1 and 4.6). Chlorophyll-a concentration, beam c, and temperature were observed to have similar time scales of decorrelation at 68 m (~35-40 days: Figure 4.12g), possibly due to the advection of several distinctive water masses past the CMO site near the bottom during winter.
Figure 4.16: Advanced Very High Resolution Radiometer (AVHRR) SST images of the Mud Patch region showing a shelf-break eddy and subsequent slope-water intrusions onto the continental shelf on (a) 18 February at 1742 GMT, (b) 20 February at 0734 GMT, (c) 24 February at 0650 GMT, and (d) 26 February at 1754 GMT. The site of the CMO experiment is labeled with a white "X". Images courtesy of Johns Hopkins University Applied Physics Laboratory.
stratification. Interestingly, however, the 50 m autocovariances of these different parameters were quite different from each other and from the 68 m data (Figure 4.12c).

Spring Period: 3 April – 11 June 1997 (Year Day 93-162)

The water column was more mixed due to strong wind forcing (northeasterly storms) and intense subtidal currents at the end of the winter stratification/beginning of the spring period ("A4" in Figures 4.1, 4.2, and 4.3). This breakdown of stratification of the water column, likely resulting in nutrient replenishment to the euphotic layer, was followed by restratification in the spring. This is the classical sequence that leads to the spring bloom. The increase of Chl-a during this time ("SB" in Figure 4.7b) was likely caused by upwelling of high nutrient water near the shelfbreak and can be identified by satellite ocean color imagery as a band of high chlorophyll water [Sosik et al., 1999]. Our statistical analyses support this interpretation (Figure 4.14).

Following the spring bloom, subtidal current speeds decreased to their lowest levels of the 11-month time series record (Table 4.1: Figure 4.3). Peaks at the semi-diurnal tidal period were observed in temperature data at the 35 m depth, most likely due to tidal oscillation of the thermocline (Figure 4.10d). Low salinities observed in the upper layer thick starting 15 May 1997 ("SR" in Figures 4.1 and 4.6) were due in part to springtime warming and subsequent runoff. This low salinity band has been observed by Flagg [1987] to flow south and west along the coast of Cape Cod in a layer typically <20 m.
Discussion

Statistical analyses were used to establish the relationships between physical and bio-optical processes at several time scales. Frequency autospectra analyses identified that the most dominant signal of the time series was the seasonal evolution, including stratification, mixing, and re-stratification of hydrographic properties, and associated blooms and death of phytoplankton. The semi-diurnal tidal period was prominent in current speed data, sometimes resulting in the generation of ISWs, which have the potential to mix nutrients and phytoplankton. However, phytoplankton were apparently only temporarily vertically displaced past our instruments on the CMO mooring during the passage of ISWs in summer/fall. The relatively short time scales of variability (~5 days) associated with wind and current speeds at all depths and time periods was expected in autocovariance analyses (Figures 4.12-4.13). 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 decorrelation time scales as well (<10 days) at 12, 30, and 68 m depths (Figures 4.12-4.13). High variability existed in beam c (660 nm) due to fluctuations in all relevant components of attenuation (phytoplankton and detritus). Relatively low concentrations of phytoplankton at 50 m likely resulted in longer decorrelation time scales or less variability in beam c seen at this depth (Figure 4.13). Autocovariance spectra for temperature were generally similar at each depth: the temporal decorrelation scale was relatively long (>20 days; Figures 4.12-4.13). Temperature decorrelation time scales were dependent on mixing, advection, and water mass movements through mesoscale activity.
Chlorophyll-α concentration autocovariance, a result of biological processes, was highly variable with depth and season.

Specific processes of physical-bio-optical coupling were investigated using coherence and associated phase lags between various parameters. Phytoplankton growth with respect to light levels was examined with coherence between PAR and Chl-α (Figures 4.14A). PAR and Chl-α were correlated with ~180° phase at the 12 m depth at periods of >4 days, and the 12 m Chl-α data exhibited longer time scales of decorrelation as compared to the other parameters during the summer/fall period (Figures 4.12Aa, b). This suggests that high phytoplankton biomass results in greater vertical attenuation through the water column and thus, decreased light levels measured by the PAR sensor. An additional possibility, although not as likely, is that a >4 day time lag between phytoplankton growth and light levels exists at relatively shallow depths. At greater depths (30, 50 and 68 m), the growth of phytoplankton was less significantly affected by PAR levels; coherence between PAR and Chl-α was low (Figure 4.14Aa). This was to be expected at the near-bottom depths (below the depth of the 1% light level: ~50-55 m; J. Blakey, personal communications, 1998), but higher coherence was anticipated at the depth of the chlorophyll maximum (~30 m). Phytoplankton growth was apparently nutrient-limited at 30 m during the stratified conditions of summer/fall, although high PAR values caused higher than expected Chl-α values at shallower depths (also previously observed by O’Reilly et al. [1987]; Figures 4.7b and 4.14Aa). We expected phytoplankton growth to be limited by the low light conditions found in winter (previously observed by O’Reilly et al. [1987]). However, coherence between PAR and Chl-α in the upper layer (12 and 30 m) at periods of 1-2 days was significant (>0.5) during the winter mixing period with phases of approximately -135° at 12 m and -45° at 30 m
(Figures 4.14Ac, d). Again, this is likely because of greater vertical attenuation resulting from high phytoplankton biomass and decreased light levels measured by the PAR sensor. PAR and Chl-α coherence was insignificant during the winter stratification and spring periods (Figures 4.14e, g). In addition, Chl-α decorrelation time scales were generally relatively short during these periods (~5 days, except 12 m during winter stratification: Figures 4.12d, g, h). This suggests that phytoplankton growth was highly variable and likely more dependent on nutrient conditions during winter stratification and spring.

Phytoplankton growth as influenced by nutrient conditions through upwelling was investigated with coherence between temperature (Figure 4.14B) and wind direction (data not shown) with Chl-α. Little or no coherence was found between wind direction and Chl-α at all time scales, likely because of the high spatial (vertical and horizontal) and directional variability of the winds (winds were measured ~90 km east of the CMO site). The only significant coherence between temperature and Chl-α was found at the 68 m depth at periods of ~2.5 and 5 days during summer/fall and at periods of 1-2 days during winter mixing (Figures 4.14Ba, c). The phase lags associated with the significant coherence were between 0-45° during both seasons (Figures 4.14Bb, d). The high coherence between temperature and Chl-α at the near bottom was likely due to advection of different water masses (salinity intrusions during summer/fall and high temperature event during winter mixing: see Observations of Physical-Bio-optical Coupling section).

The relationship between current speed and beam c was examined in an effort to identify sediment resuspension events (Figure 4.14C). In addition, water column particle types were distinguished using coherence and phase plots of
beam c and Chl-a (Figure 4.14D). No significant coherence was found between current speed and beam c at all depths and time periods available. It is hypothesized that significant coherence would be found during stormy seasons (summer/fall, winter mixing, and spring) if bottom (68 m) current speed data were available. High coherence existed between beam c and Chl-a with a phase of $\sim 0^\circ$ at the 68 m depth at periods of $\sim 1$-2 days during all seasons except winter stratification (Figure 4.14D). This further demonstrates the resuspension of bottom sediments and relict pigments during storms and hurricanes. High coherence between beam c and Chl-a was expected in the upper layer (12 and 30 m) during spring, related to the spring bloom. High coherence was found between beam c and Chl-a, but with a phase of $\sim 180^\circ$ at a period of $\sim 1.5$ days at the 30 m depth (Figures 4.7b and 4.14Dg). This implies high beam c and low Chl-a and/or vice versa during periods of 1-2 days, possibly due to advection of water masses carrying high detrital loads and little phytoplankton (note the relatively high beam attenuation signals seen during spring at 30 m: Figure 4.8). Little or no coherence was found between beam c and Chl-a at the 12 m depth, likely because of biofouled and limited beam c data at this depth during spring.

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. However, time scales of variability of bio-optical properties on a continental shelf have not been resolved in the past. Our results allow us to compare important mixing processes relevant to bio-optical variability on a continental shelf versus those of the open ocean. Analogous measurements of physical and bio-optical variability in the open ocean (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. Important differences between the two regions arise because of coastal bottom boundary layer effects and large-scale water mass intrusions and the relatively greater role of tides on the shelf. 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). The inertial period is less important at the CMO site than reported by open ocean studies, except perhaps following major storms or hurricanes. Mixing processes important to bio-optics in the open ocean include inertial oscillations, eddies, storms and hurricanes, and shear instabilities. Water mass variability (except eddies), advection, frontal gradients, and internal solitary waves are less relevant processes in the open than the coastal ocean. The bottom boundary layer and associated processes (resuspension of sediments and nutrients) are not important for upper ocean processes in the open ocean. Sosik et al. [1999] report that more diverse assemblages of optically important material are present on and near continental shelves, as compared to the open ocean. Our measurements identify key mixing processes on continental shelves and establish statistical relationships between related physical and bio-optical parameters. This study is necessary for compiling data assimilation models used to produce three-dimensional maps of the important physical and bio-optical variables for the estimation and prediction of primary productivity and an accurate assessment of the carbon budget.

Summary

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 newly developed 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 events interrupted the seasonal cycle. 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 southern New England continental shelf. Episodic events appear to have had a great impact on biogenic and non-biogenic matter. For example, hurricanes and storms often passed over or near the CMO site, resulting in intense mixing within surface and bottom boundary layers, reduced stratification of the water column, particle redistribution, nutrient replenishment, and sediment resuspension. Thus, 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 likely primary productivity in the upper water column. Changing hydrographic and nutrient conditions that resulted from the influence of several water mass intrusions also affected particle concentration and likely primary productivity on time scales of days to several weeks. 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.

Coherence was calculated between physical and bio-optical parameters in an attempt to quantify various processes of physical-bio-optical coupling. Significant coherence was found between PAR and Chl-α at low frequencies
with a 180° phase lag at upper water column depths during summer/fall and winter mixing, likely because of increased vertical attenuation and decreased light levels as a result of high phytoplankton biomass. Little or no coherence was found between wind direction and temperature with Chl-a in the upper water column; we were unable to quantify the coupling between upwelling processes and phytoplankton growth. Beam attenuation and Chl-a were oftentimes coherent with −0° phase at the near-bottom depths at periods of 1-2 days, most likely because of sediment and relict pigment resuspension during storms and hurricanes.

This experiment also sets the context for comparing our unique coastal ocean results with previous open ocean findings. Important differences arise because of coastal bottom boundary layer effects and large-scale water mass intrusions 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; e.g., Souza et al. [1999]) to establish and possibly predict relationships between physical, optical, and biological processes in a coastal environment.
CHAPTER 5

Sediment Resuspension during Hurricanes Edouard and Hortense

Introduction

Knowledge of the processes that control sediment resuspension and transport in the coastal ocean can be used to help predict and possibly control the fate of sediments, as well as of pollutants that are introduced onto the shelf at the coastline, offshore, or at the sea surface [Biscaye et al., 1988]. Currents and the intensity, frequency, and duration of sediment mixing in the water column and along the seafloor determine the movement of chemical, biological, and particulate wastes in the coastal ocean. Sediment and pollutant motion can influence organic matter and primary production, and thus the base of the food web. The fate of organic matter on continental shelves is of great interest, especially with regard to the impact on the global carbon budget (e.g., Bacon et al. [1994]). Comprehensive reviews concerning sediment resuspension and cross-shelf transport are given by Cacchione and Drake [1990] and Nittouer and Wright [1994].

The Coastal Mixing and Optics (CMO) experiment was designed to study the mixing of ocean water on the continental shelf, and the effect of mixing on water column optical properties. Several high-intensity mixing events occurred during the fall 1996 deployment of the CMO mooring and tripod arrays. Wave motion, current and hydrographic variability, shear, and turbulence (dissipation rates) in the bottom boundary layer were some of the physical aspects relevant to these mixing events. The relationships among these physical processes and particle responses (e.g., particle type, size
distribution, and relative concentrations) were examined to understand particle effects of vertical and horizontal mixing in the coastal ocean.

For the present study, we investigated physical and particle relationships via optical properties. We acquired a unique and extensive set of physical and optical data during the passage of two hurricanes using a suite of technologically advanced instruments. The overall objective of our research was to determine how particles and optical properties respond to physical forcing under various oceanic conditions on a broad continental shelf. Specifically, our goal was to relate physical processes (tides, currents, surface waves, internal waves, etc.) to optical variability, and associated optical and particle variability near the ocean bottom to physical processes affecting sediment resuspension. This thesis reports on physical processes and optical effects observed during the period 22 August to 21 September 1996, with emphasis on the passages of two hurricanes, Edouard and Hortense [Dickey et al., 1998a]. Methods and instrumentation are presented in chapter 2.

Observations

Weather conditions

Meteorological data for Hurricane Edouard and Hurricane Hortense were reported by the National Hurricane Center (NHC; Figures 5.1 and 5.2). Hurricane Edouard reached its maximum intensity, category 4 status on the Saffir-Simpson Hurricane Scale (132-155 mph winds), on 29 August 1996. Edouard’s winds reached a maximum of 140 mph (~225 km hr⁻¹), atmospheric pressure dropped to about 930 mb, and translational speed peaked at 1000 km
Figure 5.1: National Hurricane Center "best track" of (a) wind speed, (b) atmospheric pressure, and (c) translational speed data for Hurricane Edouard (eye) from 13.0°N, 29.5°W to 42.8°N, 65.9°W. The arrows represent the point when Edouard passed closest to the CMO site. (d) The track of the eye of Hurricane Edouard. Colored circles represent changing wind speeds of the eye of Edouard and are labeled.
Figure 5.2: National Hurricane Center "best track" of (a) wind speed, (b) atmospheric pressure, and (c) translational speed data for Hurricane Hortense (eye) from 14.9°N, 47.4°W to 46.5°N, 57.8°W. The arrows represent the point where Hortense passed closest to the CMO site. (d) Track of the eye of Hurricane Hortense. Colored circles represent changing wind speeds and are labeled.
day\(^{-1}\) (~10 m s\(^{-1}\)) approximately 700 km south of the mooring. Hurricane Edouard maintained category 4 status for approximately seven days, then decreased in intensity to category 3 (112-131 mph winds) when the eye of Edouard passed within about 110 km of the CMO mooring on 2 September 1996 (Figure 5.1). On 13 September 1996, Hurricane Hortense reached category 4 status, roughly 800 km south of the mooring site, but decreased in intensity to category 3 after just 6 hr. Its winds reached a maximum of 120 mph (~190 km hr\(^{-1}\)), atmospheric pressure dropped by approximately 80 mb, and translational speed reached 1500 km day\(^{-1}\) (~15 m s\(^{-1}\)). The eye of Hurricane Hortense passed within 350 km of the mooring on 14 September 1996 (Figure 5.2) with a wind speed of approximately 90 mph (~145 km hr\(^{-1}\)).

Optical effects

Sediment resuspension was dramatic and is easily seen in the optical data, in particular, the spectral beam attenuation coefficient, \(c_{s-a}(\lambda)\). The time series of \(c_{s-a}(\lambda)\) at nine wavelengths (collected with the ac-9) at 37, 52, and 68 m depths is shown in Figures 5.3a, b, and c, respectively. Due to biofouling, the 13 m beam attenuation data are not useful for analysis during the period of the hurricanes. Beam attenuation coefficient values at 676 nm (beam c) ranged from nearly 1 m\(^{-1}\) to greater than 30 m\(^{-1}\) at 68 m, from 0.2 m\(^{-1}\) to greater than 5 m\(^{-1}\) at the 52 m depth, and from 0.2 m\(^{-1}\) to greater than 2 m\(^{-1}\) at 37 m during the passage of Hurricane Edouard. Sediment was resuspended more than 30 m up into the water column. The increase in beam c is seen first at 68 m, then a half-day later at 52 m, and an additional half-day later at 37 m (Figure 5.3). The large oscillations in beam c at 37 m and 52 m during and following the passage of Edouard are likely the result of large amplitude internal waves, which can be seen in the temperature data as well. The relaxation of sediment
Figure 5.3: Time series of beam attenuation coefficient at nine wavelengths (1-hr avg) as recorded by the (a) 37 m, (b) 52 m, and (c) 68 m ac—9. Dates are also presented as decimal year day, with the convention that 0 h UTC 1 January is day 1.0. "E" and "H"=Time of passage of Hurricanes Edouard and Hortense, respectively.
concentration (as indicated by reduced beam c) to pre-Edouard conditions occurred at about the same time (8 September 1996: ~6 days since Edouard’s eye was closest to the CMO site) at all depths (Figure 5.3). This observation suggests that the resuspended sediment was advected following the passage of the storm. Current meter data show high westward currents (Figure 5.4) and shear throughout the water column at this time. Tidal currents are also evident in these time series. Stickplots of 36-hr averaged currents (Figure 5.5) show a net movement of water toward the northwest. This implies transport toward the U.S. East Coast of high volumes of sediment and possibly high concentrations of contaminants that were previously deposited in the Mud Patch.

Volume distribution data (data not shown; [Dickey et al., 1998a: Agrawal and Traykovski, 1999: Hill et al., 1999]) indicate the presence, disappearance, and reestablishment of large particles in the water column as the intensity of the hurricane-induced bottom currents and oscillations increased to their maximum and then weakened as the hurricane moved away from the bottom tripod. These data support the photographic results (data not shown) that reveal high levels of localized shear and turbulence (e.g., turbulence dissipation rate) in the water column due to currents and waves, broke up flocculates. These flocs then rapidly reappeared as the intensity of turbulence weakened.

Scatter plots of chlorophyll a (Chl-a. values were derived from the fluorometer using factory calibrations and comparison with chlorophyll-a data derived from in vivo bottle samples) versus beam c (here, beam attenuation coefficient at 660 nm measured with the transmissometer) at 37, 52, and 58 m (Figure 5.6) were used to qualitatively differentiate the phytoplankton from non-phytoplankton components that were in the water column [Wu et al., 1994].
Figure 5.4: Time series of east and north component velocity recorded by the moored ADCP at (a) 35 m, (b) 39 m, (c) 51 m, and (d) 55 m. See Figure 5.3 for year day convention and event abbreviations.
Figure 5.5: Stickplots of currents at (a) 23 m, (b) 39 m, and (c) 51 m depths. Current speeds are represented by the length of the lines scaled to 25 cm s\(^{-1}\) (legend at top left corner). See Figure 5.3 for year day convention and event abbreviations.
Figure 5.6: Chlorophyll-a concentration derived from WETStar fluorescence plotted versus beam c (660 nm: derived from transmissometer) at 37 m (---), 52 m (--*--), and 68 m (--o--) depths over the period of (a) 26–28 August 1996, (b) 2–4 September 1996, and (c) 8–10 September 1996. Note differences in scales of abscissa and ordinate axes.
High Chl-α values with relatively low beam c values are indicative of biogenic matter, while high beam c values with relatively low Chl-α values imply detrital matter (defined as all non-living matter such as sediment, dead organic matter, etc.). Data were sorted by time periods: 26-28 August, 2-4 September, and 8-10 September 1996 for pre-Edouard, during Edouard, and post-Edouard conditions, respectively (Figure 5.6; note differences in scales of abscissa and ordinate axes). Prior to the passage of Hurricane Edouard, material at the 37 m depth was mostly biogenic, as evidenced by the high values of Chl-α and relatively low beam c values (Figure 5.6a). This is supported by vertical profiles of chlorophyll a fluorescence measured by W. Scott Pegau (OSU), which show that the depth of the chlorophyll maximum varied between 25 and 35 m (data not shown). At 52 m before Edouard, approximately half of the material was biogenic, and half was detrital matter (Figure 5.6a). Optical signals at 68 m at all times are primarily attributed to detrital matter as indicated by the high values of beam c and relatively low Chl-α signals. During Edouard, Chl-α signals decreased at 37 m, and increased at 52 m. Chlorophyll a values increased by about a factor of two at 68 m. This increase is hypothesized to be due to downward mixing of phytoplankton from mid-water depths (the chlorophyll maximum) and from resuspension of relict pigments from the ocean bottom. Beam c values increased dramatically as compared to Chl-α values at 68 m during Edouard (Figure 5.6b). This implies massive bottom resuspension of previously deposited detrital matter. About one week following the passage of Hurricane Edouard, Chl-α and beam c values at all depths nearly returned to those of pre-Edouard conditions. This analysis was not performed for Hurricane Hortense due to biofouling of the transmissometers and ac-9s at 37 m.
Analysis of absorption data shows the change in percent contribution of each of the important components of seawater (Table 5.1) at 68 m with the passage of Hurricanes Edouard and Hortense. Total absorption data (without water) measured by the ac-9 ($a_{oc} (\lambda)$, expressed in m$^{-1}$) were partitioned into absorption due to phytoplankton, $a_{ph} (\lambda)$, and detritus plus gelbstoff, $a_{d-g} (\lambda)$, using methods described in chapter 3 [Chang and Dickey, 1999b]. The percent contribution (at 440 nm wavelength) of phytoplankton to total absorption increased from 12.3 to 34.6% at 68 m. This is again from mixing of phytoplankton throughout the water column and resuspended relict pigments and sediment (Table 5.1). Similar analysis was performed for partitioned absorption during the passage of Hurricane Hortense (Table 5.1). The percent contribution of phytoplankton at 68 m increased slightly during the passage of Hortense, and then returned to pre-hurricane values about five days later (data not shown).

Two peaks in the 68 m beam attenuation time series records are noticeable during Hurricane Hortense sediment resuspension. (14 September 1996: arrows in Figure 5.3c). Advection of resuspended sediments past the mooring is one possible explanation for this event. However, if this were the case, the increase in beam attenuation would be seen at all depths at the same time. The increase in beam attenuation occurs first near the bottom, then three-quarters of a day later at 52 m, and another three-quarters of a day later at 37 m (Figures 5.3a, b, and c). In addition, shear values calculated for the 37 and 52 m depths were not significantly different from those during non-hurricane conditions. Beam attenuation values decreased between each depth from greater than 20 m$^{-1}$ (mean values of ~0.9 m$^{-1}$) at 68 m to ~4 m$^{-1}$ (mean of 0.7 m$^{-1}$) at 52 m, and to less than 1.5 m$^{-1}$ (mean of 0.4 m$^{-1}$) at 37 m. We hypothesize that two distinct trains of wind-generated surface waves associated with Hortense
Table 5.1: Percent contribution of phytoplankton and detrital plus gelbstoff absorption to total absorption at the 440 nm wavelength at 68 m depth for Hurricane Edouard, Hurricane Hortense, and non-hurricane conditions.

<table>
<thead>
<tr>
<th></th>
<th>68 m</th>
<th>$a_{ph}(440)^a$</th>
<th>$a_{d+g}(440)^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-hurricane</td>
<td>12.3%</td>
<td>87.7%</td>
<td></td>
</tr>
<tr>
<td>Edouard</td>
<td>34.6%</td>
<td>65.4%</td>
<td></td>
</tr>
<tr>
<td>Hortense</td>
<td>29.5%</td>
<td>70.5%</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ph = phytoplankton, d = detrital, g = gelbstoff.
caused the successive rise, dip, and rise sequence in beam attenuation. The results from the combined current-wave shear stress analysis (to be discussed later), the presence of large amplitude, high frequency temperature oscillations in the 68 m record (data not shown) just prior to the rapid increase in beam attenuation, and SAR images (not shown; [Thompson and Porter, 1997]) provide supporting evidence for this hypothesis. The relaxation of sediments to pre-Hortense conditions occurred first at 37 m on 17 September 1996, then about a half-day later at 52 m, and then an additional day later at 68 m. The increase in sediment settling time with increasing depth in addition to the comparatively low values of currents and shear (Figures 5.4 and 5.5) indicates settling of sediment from the upper part of the water column down to the ocean bottom with little horizontal advection.

Oceanic conditions

The temperature time series (Figure 5.7a) show a highly stratified water column before the passage of Hurricane Edouard, which is common in the MAB during the late summer/early fall months. With the passage of Hurricane Edouard, the mixed layer depth (MLD) deepened rapidly with temperature differences from the top (13 m) to the bottom (68 m) of the water column decreasing from 12°C to about 4°C (Figure 5.7a). The MLD was calculated (using a 1°C temperature difference criterion) to be ~11 m prior to Edouard, deepening to ~70 m during the passage of the storm. The large oscillations in temperature at 37 m after the onset of the hurricane are attributed to large amplitude internal waves, which can be seen in the optical data as well (Figure 5.3a). The water column began to re-stratify roughly six to seven days following the passage of Edouard. Hurricane Hortense, which passed 12 days following Edouard, resulted in the re-mixing of the water column with
Figure 5.7: (a) Temperature time series at 14, 37, 52, and 68 m measured by BFOPS. NDBC buoy 44008 (3-hr avg) of (b) wind speed (5 m above sea surface), (c) significant wave height, (d) dominant wave period, and (e) wave energy density spectra for calm conditions (o-o), the period when sediment resuspension began at mooring (---), and when Hurricane Edouard was closest to mooring site (-*--). See Figure 3.3 for event abbreviations.
with temperature differences from the top (13 m) to the bottom (68 m) of the water column changing from about 6°C to 3°C. The MLD deepened from ~18 m to ~50 m.

The sediment resuspension (as seen in the optical data: Figure 5.3) caused by Hurricane Edouard was first observed when the storm was greater than 900 km south of the CMO site on 31 August 1996. NDBC buoy 44008 recorded decreased wind speeds (0.4 m s⁻¹ down from 3.2 m s⁻¹ the hour prior), a significant wave period of 12.5 s, and a significant wave height of 1.74 m at this time (Figures 5.7b-d). The wavelength for waves associated with Edouard was computed using linear wave theory (see chapter 2) and estimated using SAR satellite wave data to be approximately 230 m. Group velocity was calculated to be ~11 m s⁻¹, and wave propagation speed was ~19 m s⁻¹. The travel time of the wave group was estimated to be 2.8 hr. The most dramatic increases in the optical data occurred 3 hr after the eye of Edouard passed nearest to the mooring (within 110 km: 2 September 1996), which is approximately equal to the travel time of the waves. The major increase in beam attenuation was caused by sediment resuspension, primarily through local wind, current, and wave forcing of Edouard. The NDBC buoy data show that winds peaked at near 25 m s⁻¹, significant wave height exceeded 9 m, and significant wave period was 12.5 s at the time of closest passage (Figures 5.7b-d).

The peak in wave energy density measured by NDBC buoy 44008 increased in magnitude from about 1.5 m² Hz⁻¹ at 0.18 Hz in "calm conditions", to 4 m² Hz⁻¹ at 0.08 Hz at the onset of resuspension at the CMO site, to near 70 m² Hz⁻¹ at 0.08 and 0.12 Hz when Hurricane Edouard was nearest to the mooring (Figure 5.7c). These data and SAR satellite images [Thompson and Porter, 1997]
show that long, low frequency, high-amplitude waves originated from Hurricane Edouard and traveled to the CMO site. NDBC wave energy density spectra during the passage of Hurricane Hortense (13-14 September 1996) are unavailable.

The onset of Hurricane Hortense did not coincide with the local wind forcing or highest sediment resuspension. At the time of Hortense's closest passage, winds were variable, peaking at \( \sim 11 \text{ m s}^{-1} \), and significant wave height was 4 m (Figures 5.7b and c). Given a significant period of 20.0 s recorded by NDBC buoy 44008, wavelength was computed to be 460 m. Wave propagation speed was \( \sim 23 \text{ m s}^{-1} \), and group velocity was \( \sim 18 \text{ m s}^{-1} \) with a wave group travel time of 5.31 hr. In contrast to Hurricane Edouard, the wave group travel time for Hortense did not equal the time between closest passage of the storm and the highest resuspension event. The sediment response to Hurricane Hortense was likely primarily caused by surface waves generated at a great distance away.

**Currents**

Current velocities in the upper water column (35 m) increased from mean values of \( \sim 20 \text{ cm s}^{-1} \) to values greater than 65 cm s\(^{-1}\) during the passages of Hurricanes Edouard and Hortense (Figure 5.4a). Increased velocities continued for nearly six days during Edouard, and for less than one day with Hurricane Hortense. Shear at 37 and 52 m peaked at \( \sim 4.5 \text{ s}^{-1} \) (from average values of \( \sim 0.8 \text{ s}^{-1} \)) during the passage of Hurricane Edouard. Interestingly, did not increase significantly from mean values during Hurricane Hortense (data not shown). Subtidal current (36-hr averaged) stickplots show unidirectional flow of water toward the northwest at greater than 25 cm s\(^{-1}\)
throughout the water column during Edouard (Figure 5.5). Subtidal current speeds were weaker with Hortense and the direction of flow was more variable.

At 0.38 meters above the bottom (mab), currents increased from average values of 5-10 cm s\(^{-1}\) to approximately 30 cm s\(^{-1}\) and remained at this level for four days with the passage of Hurricane Edouard. Hurricane Hortense forced peak currents of 25 cm s\(^{-1}\) lasting for about one day at 0.38 mab (Figure 5.8a). Bottom shear increased by greater than a factor of two with the passage of Hurricane Edouard, and by approximately a factor of 1.5 with the passage of Hurricane Hortense between 0.0 and 0.38 mab (Figure 5.8b). Hurricane Edouard resulted in values of subtidal current dissipation rates (see chapter 2) increasing from 0.02 to about 0.4 cm\(^2\) s\(^{-3}\). During and following the passage of Hurricane Hortense, \(\varepsilon_c\) did not change significantly from calm condition values (Figure 5.8c). Subtidal current bottom shear stress (without tides) increased with the passage of Edouard from \(<0.05\) to \(-3\) dynes cm\(^{-2}\), but did not increase substantially with the passage of Hortense (Figure 5.8d). Beam attenuation at 676 nm is presented in Figures 5.8e and 5.9d as an indicator of periods of sediment resuspension.

Wave-orbital velocity (estimated by taking the square root of the integral of energy under the wave peak in the velocity spectra; see chapter 2) increased from about 2 cm s\(^{-1}\) to greater than 20 cm s\(^{-1}\) during the passage of Hurricane Edouard. Hortense resulted in \(u_w\) values increasing from 2 cm s\(^{-1}\) to approximately 15 cm s\(^{-1}\) (Figure 5.9a). Peaks in wave-orbital velocity coincided with the highest sediment resuspension seen in the beam attenuation record for both Edouard and Hortense (Figure 5.9). Current-wave dissipation rates increased from near zero to greater than 0.4 cm\(^2\) s\(^{-3}\) during the passage of
Figure 5.8: Time series of half-hour burst-averaged (a) east and north current velocity at 0.38 mab. (b) mean-current bottom shear between 0.38 and 0.0 mab. (c) mean-current dissipation rate, 0.38 mab. (d) mean-current bottom shear stress at 0.38 mab. and (e) beam c (676 nm) measured by 68 m ac-9 (1-hr avg). See Figure 5.3 for year day convention and event abbreviations.
Figure 5.9: Time series half-hour burst-averaged (a) wave orbital velocity, 0.58 m/s, (b) combined current–wave dissipation rate, (c) combined current–wave bottom shear stress (critical shear stress labeled), and (d) beam c (676 nm) measured by 68 m ac–9 (1-hr avg). See Figure 5.3 for year day convention and event abbreviations.
Hurricane Edouard, and increased again from near zero to about 0.2 cm$^2$ s$^{-3}$ during Hortense (Figure 5.9b).

Hurricane Edouard resulted in $\tau_c$ and $\tau_{c-w}$ increasing from approximately 0.5 dynes cm$^{-2}$ to greater than 3.5 dynes cm$^{-2}$ (Figures 5.8c and 5.9c). Current and current-wave shear stress remained greater than 1.0 dynes cm$^{-2}$ for about seven days following Edouard. Values of $\tau_c$ during Hurricane Hortense were relatively low throughout the period of the storm (Figure 5.8d), never exceeding 1.0 dynes cm$^{-2}$. However, $\tau_{c-w}$ during Hurricane Hortense increased from from 0.1 to 2 dynes cm$^{-2}$ and remained relatively high for approximately 2 days (Figure 5.9c).

Regression analyses between $\tau_c$ and beam c. and $\tau_{c-w}$ and beam c (Figure 5.10a) near the bottom reveal correlations of 0.68 and 0.81, respectively, over the period of passage of Hurricane Edouard (22 August to 6 September 1996). These correlations provide strong evidence that the sediment resuspension during Hurricane Edouard was locally forced by high currents and waves at the bottom. However, a correlation of 0.007 was found between $\tau_c$ and beam c during the passage of Hurricane Hortense (6-21 September 1996). A correlation of 0.73 was found between $\tau_{c-w}$ and beam c over the same period (Figure 5.10b). This suggests that sediment resuspension associated with Hurricane Hortense resulted from remotely forced bottom turbulence induced by wave-orbital velocity with little interaction with near-bottom currents.

Grant and Madsen [1979], Glenn and Grant [1987], Lyne et al. [1990], and many others have shown that sediment resuspension by waves without strong subtidal currents is not uncommon. The major physical processes governing the structure of the near-bottom flow on a continental shelf are the interaction
Figure 5.10: Combined current-wave bottom shear stress plotted versus beam c (676 nm) measured by the 68 m ac-9 for the time period of passage of (a) Hurricane Edouard (22 August–6 September 1996): \( r^2 = 0.81 \) and (b) Hurricane Hortense (6–21 September 1996): \( r^2 = 0.73 \). The dark dashed lines indicate the "best fit" lines. The light lines indicate the 95% confidence interval.
of surface waves with relatively low-frequency currents [Glenn and Grant, 1987]. This interaction has been found to be non-linear (e.g., Grant and Madsen [1979]; Christoffersen and Jonsson [1985]). As waves approach shallower water, the values of near-bottom wave-orbital velocities are of the same magnitude as those of strong coastal currents. The boundary shear stress associated with wave motion, however, is oftentimes an order of magnitude larger than the boundary shear stress associated with a mean current of comparable magnitude [Grant and Madsen, 1979]. This phenomenon is largely due to the formation of an oscillatory wave boundary layer within a relatively steady current boundary layer. The result is that waves are capable of resuspending bottom sediment when a current of comparable magnitude may be too weak to initiate sediment motion [Grant and Madsen, 1979]. For example, Wright et al. [1986] reported sediment resuspension during a northeasterly storm in the absence of strong currents. The sediment resuspension coincided with the peak in wave-orbital velocity.

Souza et al. [1999] reproduced the main features of the thermal structure of the water column and the suspended particulate matter (SPM) observed during Hurricanes Edouard and Hortense using a one-dimensional turbulence closure model with a simple SPM module. Souza et al. [1999] found good agreement between modeled and observed thermal structure, but with a lack of semi-diurnal tidal variability because the model did not include advective effects. The modeled SPM was in qualitative agreement with the beam c data. However, it did not resolve the time lag between the 68 and 52 m resuspension, likely due to the model's inability to represent the break-up of flocs, which would slow the settling rate and allow a great effect of the vertical diffusion. In addition, the model did not show sediment resuspension at depths less than 40 m when both Edouard and Hortense forced sediment to at least the
37 m depth. This discrepancy is likely a result of the exclusion of primary productivity in the model, which eliminates the source of SPM near the surface. The model results agree with our assessment that the waves generated by Edouard and Hortense are primarily responsible for the observed sediment resuspension [Souza et al., 1999].

Conclusions

It has long been recognized that storms can play an important role in mixing, resuspending, and dispersing shelf sediments and pollutants (e.g., Madsen et al. [1993]; Nittouer and Wright [1994]; and Wright et al. [1994]). However, few direct observations had been made previously. The present comprehensive physical and optical measurements have captured two consecutive hurricane events that passed over the CMO study site within a two-week period in the fall of 1996. Hurricane Edouard led to massive sediment resuspension of bottom sediments more than 30 m above the ocean bottom with beam attenuation values increasing by about a factor of 30. Sediment resuspension was primarily locally driven through near bottom current and wave processes. Optical analyses reveal that resuspended matter consisted mainly of detritus and relict pigments. The resuspended sediments are hypothesized to have been advected toward the northwest following the passage of the storm. This is evidenced by the time of relaxation to pre-Edouard values of beam attenuation throughout the water column and the intense currents and shear associated with the passage of Hurricane Edouard. Unlike Edouard, Hurricane Hortense passed much further from the experimental site. Sediment resuspension was likely caused by remote wave-induced forcing with comparatively little interaction with currents. Hurricane Hortense resulted in resuspension of
bottom sediments about 30 m up into the water column, with a 20-fold increase in beam c values at the bottom. Similar to Edouard, resuspended material was mostly detritus. Relaxation of sediment to pre-Hortense conditions occurred through settling processes, with low shear and apparently little advection. The main features of the thermal structure of the water column and the suspended particulate matter (SPM) observed during Hurricanes Edouard and Hortense were successfully reproduced using a one-dimensional turbulence closure model with a simple SPM module. The model confirmed the hypothesis that the sediment resuspension observed during Hurricanes Edouard and Hortense were caused primarily by wave-induced forcing.
CHAPTER 6
General Conclusions

Recently, many technologically advanced optical instruments have been
developed and used in the open and coastal ocean. The accurate measurement
of optical properties can be used to estimate phytoplankton biomass and
primary productivity rates, and to derive particle characteristics and reflectance
of light from the ocean, which is important for remote sensing of surface ocean
optical characteristics. The study of physical processes coupled with optical
responses is important for establishing an understanding of particulate
(including organisms, sediment, and contaminants) movement and distribution
in the water column and along the ocean bottom. In addition, particulate
motion influences organic matter and primary production, which is important
for quantifying the global carbon budget. The high temporal resolution
physical and bio-optical data collected during the Coastal Mixing and Optics
experiment is currently being used with interdisciplinary models (e.g.,
physical-bio-optical, radiative transfer, and sediment resuspension and
transport) to establish and possibly predict relationships between physical,
optical, and biological processes in a coastal environment.

The CMO experiment was unique in that high-frequency temporal resolution
physical and bio-optical data were collected with newly developed
oceanographic instruments on a mooring and a bottom tripod. The extensive
observations of concurrent physical and bio-optical parameters have never
before been made on a continental shelf. This thesis contributes to fulfillment
of several of the objectives of the CMO experiment. Qualitative and
quantitative distinctions among particle types were determined by use of
partitioned total spectral absorption. The relationships between physical
processes and bio-optical variability on time scales from minutes to the
seasonal cycle were identified and quantified by use of statistical methods. Physical processes affecting sediment resuspension during two hurricanes were modeled and related to optical and particle variability near the ocean bottom.

The application of spectral absorption models with data collected from absorption-attenuation meters and shipboard methods can be used to measure spectral absorption and to partition total absorption into absorption that is due to water, phytoplankton, detritus, and gelbstoff. Differences between model results and coincident in vivo bottle sample measurements are attributed to differences between instruments and measurement techniques as well as in model assumption and model parameter determination. The separated absorption spectra permitted the investigation of relationships between physical processes and bio-optical parameters on a broad range of spatial and temporal scales.

Results from time series analysis showed that the most prominent physical and bio-optical signals observed were associated with the semi-diurnal tidal frequency and the seasonal cycle. However, several important episodic events oftentimes interrupted the seasonal cycle. Storms and hurricanes resulted in mixing of the water column and particle redistribution. Several water mass intrusions affected hydrographic and nutrient conditions, particle concentrations, and likely primary productivity on time scales of days to several weeks. High-frequency packets of internal solitary waves were observed and may be important for redistribution and mixing (horizontal and vertical transport) of sediments, phytoplankton, and nutrients. These results were compared with analogous results from open ocean studies. Important differences between the continental shelf and the open ocean arise because of coastal bottom boundary layer effects and large-scale water mass intrusions.
and the relatively greater role of tides on the shelf. 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). However, the inertial period is less important at the CMO site than reported by open ocean studies. Mixing processes important to bio-optics in the open ocean include inertial oscillations, eddies, storms and hurricanes, and shear instabilities. Water mass variability (except eddies), advection, frontal gradients, and internal solitary waves are less relevant processes in the open than the coastal ocean. It was found that time scales of optical variability are generally shorter for the coastal environment as compared with the open ocean.

Hurricanes Edouard and Hortense passed over the CMO site in fall 1996, resulting in reduced stratification of the water column, thickening of the surface and the bottom boundary layer, particle redistribution, nutrient replenishment, and sediment resuspension. Edouard-induced sediment resuspension was primarily locally driven through near bottom current and wave processes, whereas remote wave-induced forcing with comparatively little interaction with currents likely caused Hortense-induced resuspension. A turbulence closure model [Souza et al., 1999] confirmed that the sediment resuspension during both hurricanes was caused primarily by wave-induced processes. The relaxation of sediments to pre-hurricane conditions was shown to be different between the two hurricanes. High currents and shear following the passage of Edouard likely resulted in advection of resuspended sediments, and low currents and shear suggest relaxation of sediments through settling processes following Hortense. Analyses of optical data revealed that the resuspended matter consisted mainly of detritus and relict pigments.
Acknowledgements

This research was supported by the Office of Naval Research under grants N0014-96-1-0669 and N0014-98-1-0508 (AASERT award). We thank the crews of the research vessels Oceanus and Knorr.
REFERENCES


Blakey, J., Department of Oceanography, Texas A&M University, College Station, TX 77843. personal communications. 1998.


Twichell, D. C., B. Butman, and R. S. Lewis. Shallow structure, surficial geology, and the processes currently shaping the bank. in: *Georges*


## APPENDIX A

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{ch}(\lambda)$</td>
<td>Absorption due to chlorophyll-$a$ (m$^{-1}$)</td>
</tr>
<tr>
<td>$a_d(\lambda)$</td>
<td>Detrital spectral absorption coefficient (m$^{-1}$)</td>
</tr>
<tr>
<td>$a_{d-g}(\lambda)$</td>
<td>Detrital plus gelbstoff spectral absorption coefficient (m$^{-1}$)</td>
</tr>
<tr>
<td>$a_g(\lambda)$</td>
<td>Gelbstoff spectral absorption coefficient (m$^{-1}$)</td>
</tr>
<tr>
<td>$a_{ph}(\lambda)$</td>
<td>Phytoplankton spectral absorption coefficient (m$^{-1}$)</td>
</tr>
<tr>
<td>$a_{ph}^{sp}(\lambda)$</td>
<td>Specific absorption of phytoplankton (l $\mu$g$^{-1}$ m$^{-1}$)</td>
</tr>
<tr>
<td>$a_t(\lambda)$</td>
<td>Total spectral absorption coefficient (m$^{-1}$)</td>
</tr>
<tr>
<td>$a_{t-w}(\lambda)$</td>
<td>Total minus water spectral absorption coefficient (m$^{-1}$)</td>
</tr>
<tr>
<td>$a_T$</td>
<td>Temperature constant for ac-9 calibration (0.0029 °C$^{-1}$)</td>
</tr>
<tr>
<td>$b(\lambda)$</td>
<td>Scattering coefficient (m$^{-1}$)</td>
</tr>
<tr>
<td>$c(\lambda)$</td>
<td>Spectral beam attenuation coefficient (m$^{-1}$)</td>
</tr>
<tr>
<td>$c_{t-w}(\lambda)$</td>
<td>Total minus water spectral attenuation coefficient (m$^{-1}$)</td>
</tr>
<tr>
<td>$C$</td>
<td>Wave propagation speed (m s$^{-1}$)</td>
</tr>
<tr>
<td>$C_g$</td>
<td>Wave group velocity (m s$^{-1}$)</td>
</tr>
<tr>
<td>$C_{ph}$</td>
<td>Concentration of phytoplankton (μg l$^{-1}$)</td>
</tr>
<tr>
<td>$C_{2d-g}$</td>
<td>Roessler et al. [1989] model parameter (nm$^{-1}$)</td>
</tr>
<tr>
<td>$C_r$</td>
<td>Constant to describe gelbstoff absorption spectral shape (nm$^{-1}$)</td>
</tr>
<tr>
<td>$d$</td>
<td>Wave travel distance (m)</td>
</tr>
<tr>
<td>$e$</td>
<td>Natural logarithm base (~2.718)</td>
</tr>
<tr>
<td>$f_c$</td>
<td>Current friction factor (unitless)</td>
</tr>
<tr>
<td>$f_w$</td>
<td>Wave friction factor (unitless)</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration of gravity (m s$^{-2}$)</td>
</tr>
<tr>
<td>$h$</td>
<td>Water depth (m)</td>
</tr>
<tr>
<td>$J$</td>
<td>Christoffersen and Jonsson [1985] model parameter (unitless)</td>
</tr>
</tbody>
</table>
\( k \)  
Wave number (m\(^{-1}\))

\( k_a \)  
Apparent roughness (cm)

\( k_n \)  
Nikuradse roughness (0.4 cm)

\( K_t \)  
Temperature calibration for ac-9 (°C\(^{-1}\))

\( L \)  
Wavelength (m)

\( n \)  
Christoffersen and Jonsson [1985] model parameter (unitless)

\( N \)  
Number of points (unitless)

\( S \)  
\textit{In situ} salinity for ac-9 calibration (psu)

\( t \)  
Wave group travel time (s)

\( T \)  
Significant wave period (s)

\( T_{\text{in situ}} \)  
\textit{In situ} temperature of ac-9 during operation (°C)

\( T_{\text{cal}} \)  
Standard temperature used in ac-9 calibration (23.7 °C)

\( T_0 \)  
Temperature offset for ac-9 calibration (°C)

\( u_c \)  
Scalar representation of low-pass filtered current speed (cm s\(^{-1}\))

\( u_{cx} \)  
East-component of velocity (cm s\(^{-1}\))

\( u_{cz} \)  
North-component of velocity (cm s\(^{-1}\))

\( u_w \)  
Wave-orbital velocity (cm s\(^{-1}\))

\( u_{w^*} \)  
Current friction velocity (cm s\(^{-1}\))

\( u_{w^*-w} \)  
Combined current and wave friction velocity (cm s\(^{-1}\))

\( z \)  
Distance above the ocean bottom (cm)

\( z_i \)  
Roughness parameter (cm)

\( \beta \)  
Empirical turbulence constant (0.0747)

\( (\delta-\alpha) \)  
Angle between current and wave (assumed to be 0°)

\( \delta_w \)  
Wave boundary layer thickness (cm)

\( \varepsilon \)  
Scattering constant for ac-9 calibration (0.14)

\( \varepsilon_c \)  
Mean-current dissipation rate (cm\(^2\) s\(^{-3}\))

\( \varepsilon_{w^*-w} \)  
Combined current and wave dissipation rate (cm\(^2\) s\(^{-3}\))

\( \phi_{140.676} \)  
Roesler et al. [1989] model parameter (unitless)
\[ \lambda \]  Wavelength (nm)

\[ \lambda_{\text{ref}} \]  Reference wavelength (chosen to be 440 nm)

\[ \kappa \]  Von Karman's constant (0.4)

\[ \rho \]  Density of seawater (g cm\(^{-3}\))

\[ \sigma \]  Christoffersen and Jonsson [1985] model parameter (unitless)

\[ s_{h_b} \]  Bottom shear (s\(^{-1}\))

\[ \tau_c \]  Mean-current bottom shear stress (dynes cm\(^{-2}\))

\[ \tau_{c-w} \]  Combined current and wave bottom shear stress (dynes cm\(^{-2}\))

\[ \tau_{\text{crit}} \]  Critical shear stress (dynes cm\(^{-2}\))

\[ \omega \]  Angular wave frequency (s\(^{-1}\))

**Acronyms**

hr  Hour(s)

mab  Meters above the bottom

min  Minute(s)

sec  Second(s)

ADCP  Acoustic doppler current profiler

AVHRR  Advanced very high resolution radiometer

BASS  Benthic acoustic stress sensors

Beam c  Beam attenuation coefficient at 660 or 676 nm

BIOPS  Bio-optical system

Chl-a  Chlorophyll-a concentration

CMO  Coastal Mixing and Optics

GBW  Georges Bank Water

FFT  Fast Fourier transform

ISW  Internal solitary wave

JHU/APL  Johns Hopkins University/Applied Physics Laboratory
MAB  Middle Atlantic Bight
MLD  Mixed layer depth
MSW  Maine Surface Water
NCDC National Climatic Data Center
NDBC National Data Buoy Center
NHC National Hurricane Center
OPL  Ocean Physics Laboratory
OSU  Oregon State University
PAR  Photosynthetically available radiation
PMEL Pacific Marine Environmental Laboratory
SAR  Synthetic Aperature Radar
SEEP Shelf Edge Exchange Processes study
SST  Sea surface temperature
UConn University of Connecticut
UCSB University of California at Santa Barbara
USGS United States Geological Survey
WHOI Woods Hole Oceanographic Institution
YD   Year day
APPENDIX B
Statistical methods

Frequency autospectra were computed in order to quantify the variability of the current speed and bio-optical time-series data described in the observation section of chapter 4. and autospectra of temperature and salinity were computed to investigate water mass variability (e.g., Figures 4.9-4.11). The autospectra were calculated using 1024-point fast Fourier transforms (FFTs) tapered with a Hanning window, zero overlap, and N=15,000 points ( broadband data). The 95% confidence intervals were calculated for the autospectra and are shown for the current speed only. Fluctuations in autospectra at frequencies higher than 10 cycles per day (cpd) seen in Figures 4.9-4.11 were due to noise.

Autocovariances were computed for Chl-\(a\), beam c. temperature, and wind and current speed data at all depths available to determine the time scales of decorrelation of the various physical and bio-optical properties (e.g., Figures 4.12 and 4.13, wind speed data not shown). A 36-hr filter was applied to the data after autocovariances were calculated for plotting purposes only. Data were plotted with depth and time for comparison between time-scales of physical-biological processes. Salinity data were omitted from autocovariance calculations since they were unavailable at the depths of bio-optical data.

Coherence and associated phase functions are used to quantify the relationship between two signals at a range of frequencies for specified phase lags. Coherence and phase estimates were made between PAR and Chl-\(a\) to assess the impact of light levels on primary productivity (Figures 4.14A). Temperature and Chl-\(a\) (Figure 4.14B) and wind direction and Chl-\(a\) (data not
shown) coherence were calculated to investigate the impact of upwelling on phytoplankton growth. Current speed and beam c coherence and phase were calculated to quantify current-induced sediment resuspension processes (Figure 4.14C). Beam c and Chl-a coherence estimates were used to quantitatively assess the relation of biogenic material in the water column with total particle concentration at specific frequencies (Figures 4.14D). Three-hr filters were applied to the time-series prior to computation of coherence functions to remove spikes in the data. Coherence functions and phase were calculated using 4096-point FFTs for periods with N ≥ 15,000 data points (summer/fall and winter stratification), and 2048-point FFTs for periods with N < 15,000 data points (winter mixing and spring) for ~10 degrees of freedom. Time series were tapered with Hanning windows, with 72-point overlaps and removal of means. Frequencies have been converted to periods in days. Statistical significance levels were calculated according to Thompson [1979], and are denoted by black horizontal lines (Figures 4.14A-D).