Recent Advances and Future Visions: Temporal Variability of Optical and Bio-optical Properties of the Ocean

Tommy D. Dickey and Grace C. Chang
University of California Santa Barbara, Ocean Physics Laboratory • Santa Barbara, California USA

Introduction

Ocean optics concerns studies of light and its propagation through the ocean, and bio-optics connotes biological effects on optical properties and vice versa. These two terms are so intertwined that they are often used interchangeably. Knowledge of the variability of optical and bio-optical properties of the ocean is important for many scientific and practical problems (e.g., Dickey and Falkowski, 2001). A few examples follow. Light and its utilization is key to life in the ocean beginning with phytoplankton and primary productivity, the ecology of the upper ocean, and biogeochemical cycling. The thermal structure and heat budget of the upper ocean are driven by the penetration of solar radiation as modulated by the absorption and scattering of light by water and its particulate and dissolved constituents. Both of the aforementioned examples illustrate key factors that affect and are affected by global climate change. Optical properties are also important indicators of the health of the ocean in the form of changing turbidity, diversity and distributions of species (indigenous and non-indigenous), and harmful algal blooms (e.g., red tides) and associated toxins. Underwater visibility, which has industrial and military relevance, also depends on optical properties. Importantly, *in situ* optical sensors and systems allow us to study a host of oceanographic processes, which bear on these and other problems as well as a variety of interests including quantification and interpretation of satellite- and aircraft-based observations of ocean color and studies of sediment resuspension, pollution, and bathymetry. Readers interested in learning more about the subdisciplines of ocean optics and bio-optics are directed to other papers in this volume and books by Kirk (1994), Spinrad et al. (1989), and Mobley (1994). Other papers focus on new technologies applied to ocean optics and bio-optics (e.g. Dickey, 1991, 2001; Dickey et al., 1998a, 2001; Maffione, this issue) and biogeochemistry (e.g. Tokar and Dickey, 2000; Varney, 2000; Dickey et al., 2000, 2001).

Time series observations have proven valuable for many environmental problems. Perhaps the most famous and one of the more important of these is the Mauna Loa, Hawaii time series, which has shown the dramatic increase of the concentration of atmospheric carbon dioxide (CO_2) since the beginning of the Industrial Revolution. There is no direct equivalent for optical properties of the ocean, in part because of the earlier lack of adequate optical instrumentation and the high degree of natural optical variability in the ocean. Nonetheless, there are growing numbers of scientifically important optical time series data sets. For example, a remarkable time series of Secchi disk[1] depth, a rough and somewhat subjective measure of optical clarity or turbidity, has been described for the Black Sea by Mankovsky et al. (1998). This record shows the dramatic decrease in the Secchi disk depth (increase of turbidity) in the Black Sea from about 15-16 m in the mid-1980s to 6-10 m between 1990 and 1993 with some observations as low as 2-4 m in 1992 (Figure 1). There was some horizontal variability in Secchi disk depths (e.g. due to river inflow), however, the basin-scale variations have been extraordinary. One of the explanations for these changes is that coccolithophores, phytoplankton with highly reflective disks or coccoliths that can cause the sea to appear whitish, increased by up to two orders in magnitude. Some of the variability also may have been caused by increasing colored dissolved organic matter (CDOM). The Black Sea optical time series likely reflects a major change in the community structure and ecology of the Black Sea. Several other examples of optical and bio-optical time series are described below.

The availability of instrumentation and appropriate platforms to measure optical properties has

[1]A Secchi disk is a circular white disk 30 cm in diameter. It is lowered over the side of a ship and the depth at which it is no longer visible is the Secchi depth. This depth is a rough measure of optical clarity or turbidity (e.g. Kirk, 1994). Unfortunately, this measure depends on the eyesight of the observer; thus, individual observers tend to record different values.

advanced at a remarkably rapid rate over the past two decades (e.g. see reviews by Dickey, 2001). The venerable Secchi disk was the primary optical tool for several decades and indeed provided valuable data. For example, Secchi disk measurements were made from ocean weather stations (OWSs) in the North Atlantic and North Pacific Oceans for several decades. (Note: only OWS "M" off the coast of Norway remains active today; this station likely provides the longest ongoing ocean time series record). More sophisticated optical instrumentation was an absolute requirement for further advances in optical oceanography (e.g. Maffione, this issue). In the 1970s and 1980s, *in situ* sensors and systems became available to measure scalar irradiance (photosynthetically available radiation (PAR), 350 or 400 nm to 700 nm), beam attenuation coefficient (660 nm), and natural (upwelled radiance at 683 nm) and stimulated chlorophyll fluorescence. In addition, new devices for spectral measurements of irradiance and radiance were developed. The selected wavelengths were typically those used for the Coastal Zone Color Scanner radiometer (7 wavelengths in the visible). More recently (1990s), *in situ* instruments have been designed to measure spectral absorption and attenuation (inherent optical properties or IOPs, defined as those optical properties that depend only upon the medium [Mobley, 1994]) for 9 to 100 individual wavelengths and spectral radiance and irradiance (apparent optical properties or AOPs, defined as those optical properties that depend on both the medium and the directional structure of the ambient light field [Mobley, 1994]). Also, new instruments are now capable of measuring backscatter and volume scattering function spectrally. These various optical sensors were typically designed for and deployed from ships, usually integrated into standard hydrographic systems profiling temperature along with conductivity and pressure. However, some investigators have modified these for measurements from moorings (with fixed depth or profiled instruments), bottom tripods, drifters, profiling floats, offshore platforms, and autonomous underwater vehicles (AUVs). The utilization of these platforms for time series observations has enabled sampling of optical and bio-optical processes at unprecedented time scales ranging from minutes (seconds in some special cases) to years (e.g. Dickey, 1991, 2001a) as illustrated in Figure 2. Remote sensing of ocean color via satellites and aircraft has provided extraordinary new and insightful views of the spatial features of the near surface ocean). In situ and remote sensing observations of ocean color have been highly complementary and powerful means for studying the optical properties of the ocean. In particular, the near surface spatial domain covered by the satellite-based ocean color sea-viewing wide-field-of-view-sensor, SeaWiFS, which was launched by NASA in 1997 is roughly a few kilometers to global while mooring measurements can span temporal domains of minutes to decades. Importantly, theoretical studies and models based on radiative transfer theory have emerged and provided support for and extended the utility of these collective measurement capabilities (e.g. Mobley, 1994).

The venerable Secchi disk was the primary optical tool for several decades and indeed provided valuable data.

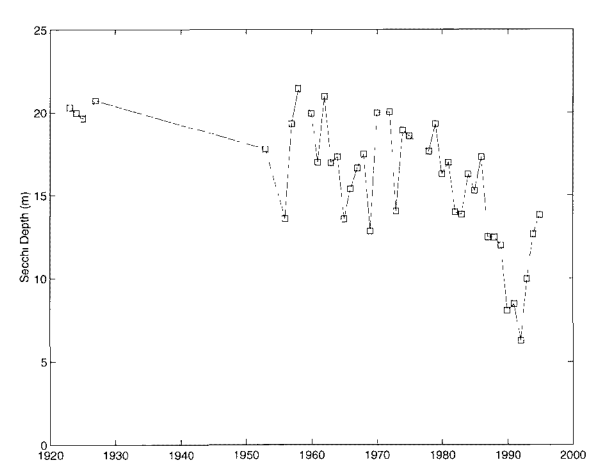


Figure 1. Time series of Secchi disk depths in the Black Sea (after Mankovsky et al., 1998).

Physical, optical, and bio-optical time series enable the identification of some of the major forcing factors for the ocean. Some of these are periodic. Well known periodic forcing processes include the seasonal and daily (diel) cycles of solar insolation and the tides. Biological and bio-optical time series often display enhanced variability at periods (frequencies) associated with these periodic forcings. These are evident in spectral analyses, which are now applied to optical and bio-optical data sets. Many oceanographers have attempted to understand the ocean's physics and ecosystems by utilizing data sets collected over several days for development and modeling of diurnal cycling and over multiple years for seasonal cycles. Periodic or quasi-periodic processes are clearly important, however, there is considerable optical variability that occurs in the continuum time range between seconds and decades (Figure 2). Some of the processes contributing to this variability include: wind events (including hurricanes and typhoons) that cause inertial current and thermocline/pycnocline oscillations as well as mixed layer deepening and entrainment of nutrients and particles, dust events which can stimulate phytoplankton blooms via iron enrichment, surface waves, internal gravity waves, internal solitary waves, fronts, jets, sub-

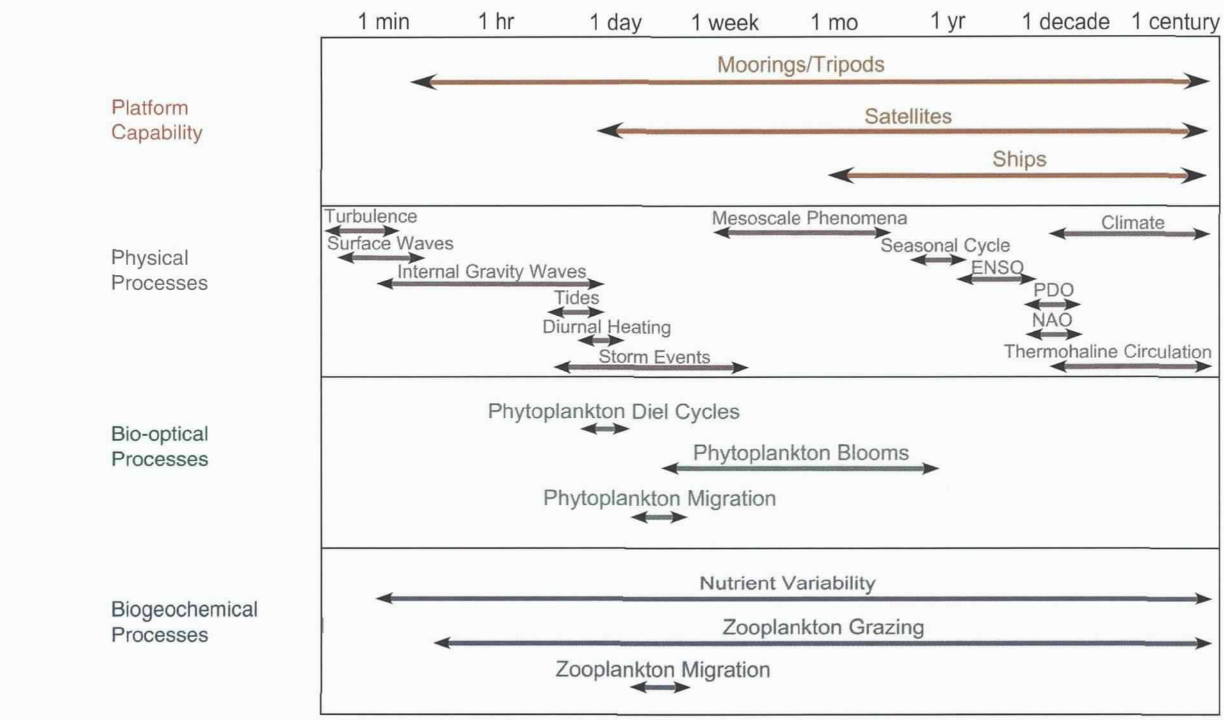


Figure 2. *Rough time scales of physical, bio-optical, and biogeochemical processes along with time scales that are accessible with different sampling platforms. Figure is a schematic and is not to scale. Note: The mooring designation refers to both fixed location and AUVs and gliders used as virtual moorings (Griffiths et al., 1999b).*

mesoscale and mesoscale features including eddies, phytoplankton blooms and cessations, phytoplankton migrations and successions, and phytoplankton/zooplankton (predator/prey) interactions (e.g. grazing), and longer term physical forcing associated with equatorial processes (e.g. El Niño-Southern Oscillation) and other decadal-scale processes around the earth (e.g. North Atlantic Oscillation, Pacific Decadal Oscillation, and others). The ocean system is highly complex with terms such as chaotic, turbulent, nonlinear, non-steady-state, and non-equilibrium all being highly appropriate descriptors. There are cascades of energy (variability) to both smaller and larger time and space scales with couplings of physical, biological, and optical processes. As complex and confusing as this situation appears, time series observations and relatively well developed analytic methods enable us to analyze and often make well-founded interpretations of interdisciplinary data sets.

These tenets of time series theory thus force those interested in processes ranging from internal waves to decadal and even climatic change to sample every few minutes for many decades or over ten orders of magnitude in time.

One of the important points of this review concerns sampling. First, we need to sample rapidly enough for sufficiently long durations to observe the pertinent phenomenology of the ocean. For example, sampling theory (e.g. see Emery and Thompson, 1997) shows that variability occurring at periods less than four months cannot be resolved by monthly observations. Thus, monthly sampling misses many of the important processes (e.g. internal gravity waves, tides, diel cycles, storm events, mesoscale eddies, etc.). Also, observations must be done for several decades to sample several repeated cycles if decadal variability is of interest. These tenets of time series theory thus force those interested in processes ranging from internal waves to decadal and even climatic change to sample every few minutes for many decades or over ten orders of magnitude in time.

The focus of this review is on temporal variability of optical and bio-optical properties. Most of our presentation is restricted to optical and bio-optical time series with temporal resolution on the scale of an hour or less and with durations of months to a year or more. We present several examples of time series data that have allowed us to learn about processes that affect or are affected by optical variability. This review cannot possibly include all relevant optical time series studies and unfortunately the number of references must be limited. However, several bio-optical data sets related to the Joint Global Ocean Flux Study (JGOFS) program have been presented by Dickey (2001a) and Dickey and Falkowski (2001); these will not be discussed in detail here. Our first set of examples focuses on the open ocean, and the second set is devoted to the coastal ocean. Finally, we present a vision of future studies of temporal variability of optical, bio-optical, and related properties.

Examples of Open Ocean Optical Time Series

Optical Dynamics Experiment (ODEX)

Time series measurements of meteorological and physical variables have been done for about five decades in the open ocean using moorings as platforms. One of the first programs to obtain relatively high resolution time series of optical and bio-optical properties was the Optical Dynamics Experiment (ODEX) conducted in the central North Pacific Ocean (e.g. see Dickey, 1991). During ODEX, R/P FLIP, a stable research platform (roughly 100 m in length with approximately 30 m extending above the waterline, 3-4 m in diameter) was located at about 32°N, 142°W and collected data for about 21 days in the fall of 1982. Long booms extended off of R/P FLIP (to avoid platform effects) for the deployment of profiling instruments including a CTD with a rosette for collecting bottle samples for analyses of pigments, nutrients, oxygen, etc., an autonomous profiler (cyclesonde) for measuring temperature and horizontal currents, and an optical package including a beam transmissometer (beam c, or beam attenuation at 660 nm) and spectral downwelling irradiance sensors (7 wavelengths). The profiles extended down to approximately 250 m with sampling intervals of either 15 minutes or 4 hours. Several interesting results were obtained from these unique measurements. For example, the profiles of spectral irradiance showed decaying amplitudes of fluctuations with depth, suggesting the importance of focusing of light rays upon the subsurface light field. This effect is especially deleterious for use of profile data sets for estimating water-leaving radiance and thus groundtruthing ocean color satellite data. Also, thermohaline intrusive features observed in the range of 165-190 m were characterized by optical signatures, particularly higher beam attenuation coefficients (beam c at 660 nm) and chlorophyll fluorescence.

It was also suggested that relatively warm saline water mass intrusions contained higher phytoplankton concentrations. Using data collected during the rapid profiling periods (15 minute intervals), it was evident that low frequency internal gravity waves and internal tides caused these layers (and optical properties of the layers) to heave up and down. It was possible to clearly resolve the diurnal/diel cycle in the optical properties, particularly beam c and chlorophyll fluorescence. Phase relationships between PAR, beam c, and chlorophyll fluorescence were carefully analyzed and raised several fascinating questions, many of which remain unanswered. Using the R/P FLIP optical time series and relationships between particulate organic carbon (POC) and beam c, estimates of water column particulate (i.e. phytoplankton) production were made. This particular use of optical data has received considerable attention and factors other than growth and grazing likely complicate the interpretation (see Ackleson et al., 1993). Nonetheless, the relationship between POC and beam c appears to be quite robust and useful for biogeochemical studies. The ODEX R/P FLIP experiment expanded our knowledge of optical variability into the time domain of low frequency internal gravity waves, internal tides, and diel cycling while providing some new tools for biological studies using optics and for quantifying upper ocean heating rates as modulated by bio-optical variability

Biowatt

The Biowatt program was devoted to studies of bio-optical and bioluminescence variability in the North Atlantic Ocean in the vicinity of 34°N, 70°W (see Dickey, 1991 for review). The first field program (Biowatt I) in the spring of 1985 focused primarily on ship-based observations. However, time series observations were also made from an autonomous multi-variable profiler (MVP) that was tethered to a surface buoy. The MVP profiled through the upper 200 m at hourly intervals to obtain current, temperature, salinity, and chlorophyll fluorescence data. During one four-day period, a wind event deepened the mixed layer, causing entrainment of nutrients into the euphotic layer and thus stimulating a transient phytoplankton bloom event marked by a 3-fold increase in chlorophyll.

While the MVP proved useful, longer-term observations were beyond its design capacity. Therefore, a new interdisciplinary moored system, the multi-variable moored system (MVMS) was developed for Biowatt II. The MVMS utilized a sensor suite including a vector measuring current meter and temperature, conductivity, and dissolved oxygen sensors, a beam transmissometer, and a fluorometer. Another moored bio-optical system (BOMS) was utilized to collect spectral downwelling irradiance and upwelled radiance at 5 wavelengths. A moored bioluminescence system was also deployed for the experiment. The MVMS and BOMS systems were deployed in the upper 160 m and collected data at intervals of about 4 to 30 minutes. Biowatt II spanned a 9-month period beginning in April 1987.

The rapid sampling by the MVMS enabled observations of several episodic phytoplankton bloom-cessation sequences as well as a clear depiction of the spring bloom. Again, the diurnal cycle was evident in beam c and chlorophyll time series. Using the highest frequency datasets (6 samples per second) and spectral analyses, short-term variations in PAR (with maxima at periods of 40 to 100 minutes) were evident with relatively high coherence among beam c, chlorophyll fluorescence, and dissolved oxygen. It is possible that this variability was caused by rapid (scales of minutes) photoadaptive responses in the phytoplankton. These responses could be caused by changes in fluorescence yield, photosynthesis rates, cellular absorption, cell size, or refractive index (e.g. Ackleson et al., 1993). The Biowatt II data set was also valuable because of its relatively long duration. For example, it was sufficient to do spectral and coherence analyses with statistical robustness as the time series spanned four orders of magnitude in frequency space. In particular, some of these analyses were able to characterize relationships including: 1) bio-optical properties as related to mesoscale features; 2) phytoplankton patchiness as related to the spring bloom; and 3) high frequency bio-optical variability due to interaction of the deep chlorophyll maximum with internal gravity waves. In addition, analyses showed relationships between downward propagation of near-inertial energy near a frontal feature and the enhancement of primary production and biomass, likely caused by nutrient fluxes into the euphotic layer. Also, the data set was used to test several different optical models for estimating biomass (including some designed for remote sensing algorithms) and coupled physical-biological models of seasonal transitions. Finally, the Biowatt II data, along with other open ocean data described below, were used to quantify the effects of undersampling and aliasing (Wiggert et al., 1994).

Marine Light in the Mixed Layer (MLML)

The Marine Light in the Mixed Layer (see Dickey, 2001a; Dickey et al., 1994) experiment was designed to study upper ocean bio-optical variability and bioluminescence as affected by physical forcing at a high latitude site (mooring location was south of Iceland at 59°N, 21°W, near Ocean Weather Station "I"). MLML was not explicitly part of JGOFS, however, several objectives were similar to those of the 1989 JGOFS North Atlantic Bloom Experiment. A focus of the MLML study was high resolution (sampling intervals at scales of minutes) time series observations of optical and bioluminescence variability. To this end, several optical systems were deployed during the periods of April-June 1989 and May-September 1991. MLML utilized the MVMS, BOMS, and other moored bioluminescence systems. The frequent sampling enabled examination of a variety of processes. For example, transient phytoplankton blooms were observed with even modest stratification events prior to the major springtime shoaling of the mixed layer (from approximately 550 m to approximately 50 m within five days!). It was demonstrated that these blooms contributed to the stratification by trapping heat near the surface. Variability of optical properties associated with diel cycles was also examined. The amplitudes (and statistical significance) of the daily cycles of beam c, chlorophyll fluorescence, and dissolved oxygen varied with the seasonal progression, being more pronounced during the spring. The fluorescence signals were clearly affected by the ambient light field.

JGOFS Regional Studies

A central objective of JGOFS has been to characterize, quantify, and improve understanding of ocean processes causing temporal and spatial variability in carbon inventories and carbon fluxes (see review articles in this issue and several *Deep-Sea Research II* volumes from 1993-present). Studies such as JGOFS rely heavily on interdisciplinary data sets because of the inter-relationships of physical, chemical, and biological processes (e.g. Dickey, 1991; Dickey and Falkowski, 2001). A major challenge to JGOFS (and future biogeochemical studies) has been to increase the variety and quantity of biogeochemical data. Further, these data need to be collected simultaneously (concept of synopticity) and span broad time (and space) scales to observe the relevant processes (Figure 2). JGOFS conducted a series of regional studies from 1989 to 2000, and time series programs near Bermuda (Bermuda Atlantic Time Series, [BATS]) and Hawaii (Hawaii Ocean Time-series, [HOT]) are still ongoing. Each of the following regional studies included a component devoted to time series observations. Several of the highlights relevant to biogeochemical cycling have been presented (Dickey, 2001a; Dickey and Falkowski, 2001), so the following summaries are brief.

The JGOFS equatorial Pacific process study took place in 1992-1993. The physical dynamics of the equatorial Pacific are quite well documented as meteorological and physical measurements have been made over the past two decades from the Tropical Atmosphere Ocean (TAO) mooring array (e.g., McPhaden, 1995). However, little was known of the region's optical or bio-optical variability prior to the JGOFS campaign. During JGOFS, the optics and biogeochemistry of the central equatorial pacific were studied using MVMSs (sampling intervals of a few minutes) that were deployed from a TAO physical mooring at 0°, 140°W for an eighteen-month period in 1992 and 1993 (see Foley et al., 1998; Dickey, 2001a). It was fortunate that the observations spanned both El Niño and "normal" phases. During the El Niño phase, the mixed layer, the thermocline, and a very weak equatorial undercurrent were deep and Kelvin waves (approximately 60 day period) propagated eastward past the site (see Figure 6 of Dickey, 2001a). Light levels were high, however, relatively high concentrations of nutrients including iron were deep. As a result, measured concentrations chlorophyll in the upper layer were low (less than 0.2 mg m^{-3}). However, as "normal conditions" returned, Kelvin waves ceased and the thermocline and the strong undercurrent shoaled allowing for the vertical transport of nutrients into the euphotic layer. Importantly, westward propagating tropical instability waves (TIWs with periods of approximately 20 days) also contributed to large vertical upwelling cycles. TIWs were easily seen in the meridional current records and appear to be manifest in the chlorophyll *a* time series with values doubling and at times tripling those observed during the El Niño period. Importantly, strong, though highly complex, coupling was evident between the physical processes (El Niño, Kelvin waves, and TIWs) and the optical properties and phytoplankton of the equatorial Pacific. Time series studies of bio-optical and biogeochemical variability in the equatorial Pacific are being continued (e.g. Strutton et al., 2001).

JGOFS process studies were conducted in the Arabian Sea in 1994 and 1995. Five moorings with meteorological and physical instruments covered a roughly 7 km x 7 km square (e.g. see Dickey, 2001a; Dickey et al., 1998b). The location was selected to be near the axis of the atmospheric Findlater Jet when fully developed. A mooring placed at the center of the square (15° 30'N, 61° 30'E) was the most heavily instrumented and included MVMSs with sampling at intervals of a few minutes in the upper 80 m from October 15, 1994 to October 20, 1995. The time series featured two mixed layer deepening and shoaling cycles as well as spring and fall blooms, both being associated with the northeast and southwest monsoons (see Figure 4 in Dickey, 2001a). The depth-integrated chlorophyll a generally tracked the 1% light level. Mesoscale eddies played important roles in the evolution of chlorophyll *a* as well as export of carbon to the deep sea. Interestingly, the penetrative component of solar radiation was clearly modulated by phytoplankton blooms. Results of analyses of diel bio-optical variability were generally consistent with those described earlier. In particular, biological responses (amplitudes of optical variables) were greatest during phytoplankton blooms and when mixed layers were shallow. Calculations of net production rates were made using diel changes in beam c (660 nm) as scaled with POC as described earlier. More studies of diel cycles are needed to better understand a host of optical, biological, and physical processes.

The Southern Ocean was selected for study by the JGOFS program because it is likely an ocean of globally significant carbon fluxes, yet it remains a region about which the factors regulating carbon fluxes remain relatively unknown (Dickey, 2001). The JGOFS Southern Ocean experiment marked the first time that SeaWiFS ocean color data were available for a JGOFS study. Migrating frontal features and mesoscale variability are important features of the Southern Ocean. Thus, Abbott et al. (2001) deployed an array of 12 moorings (spacings of about 30 km) equipped with physical and bio-optical sensors in the Antarctic Polar Front Zone from November 1997 through March 1998. The mooring array captured a strong spring phytoplankton bloom beginning in December 1997. Interestingly, the spring bloom lasted only a few weeks, which again supports the need for the fast sampling rates possible only with autonomous moored instruments.

Bermuda Testbed Mooring and Hawaii HALE-ALOHA Mooring Programs

The JGOFS Bermuda Atlantic Time-series Study and the Hawaii Ocean Time-series programs were established in 1988 to observe, quantify, and model temporal variability of the biogeochemistry and ecology of the oligotrophic ocean off Bermuda in the North Atlantic and off Hawaii in the North Pacific, respectively. The Bermuda Bio-optics Program (BBOP) also collects bio-optical data primarily for support of SeaWiFS. These programs utilize shipboard sampling (generally at monthly intervals), and enable extensive sampling of biogeochemical variables. However, as discussed earlier, ship-based sampling cannot capture important phenomena with characteristic time scales from minutes to a few months. Thus, high frequency, long-term, autonomous mooring observations were established first using the Bermuda Testbed Mooring (BTM) at the BATS sampling site in 1994 (Dickey et al., 1998a; Dickey, 2001a) and in 1996 using the HALE-ALOHA mooring at the HOT site (Letelier et al., 2000). The BTM and HALE-ALOHA mooring time series have documented observations showing passages of mesoscale features with high nutrient and phytoplankton concentrations. The BTM has also been used to observe the upper ocean physical and optical response to Hurricane Felix, which passed over the BTM in August 1995 (see Figure 9 in Dickey, 2001a) and other subsequent hurricanes.

The BTM data sets have been used to compute decorrelation time scales of several optical, bio-optical, and physical variables and coherence analyses have been used to explore statistical relationships between different optical and physical variables. Decorrelation time scales range from about 5 to 15 days depending on the variable. In addition, the effects of surface waves and cloud variability were examined using full bandwidth optical data (6 samples per second). Fluctuations in optical properties such as downwelling irradiance were especially large due to wave focusing in the blue and green wavelengths under clear sky conditions. Coefficients of variation were wavelength dependent with greater values toward the red portion of the spectrum. When overcast skies prevailed, light fluctuations were well correlated with water pressure and thus surface displacement due to surface waves. At depth, Raman scattering and natural fluorescence (inelastic scattering) are important in the red portion.

The ongoing BTM program (e.g. Dickey et al., 1998a; Dickey, 2001a) was originally created to enable long-term testing of autonomous, interdisciplinary sensors and systems at the BATS site where complementary ship-based sampling was being conducted on a regular basis. Several of the optical systems (e.g. instruments for measuring spectral AOPs and IOPs including backscatter) that have been tested using the BTM have also been used for coastal experiments (e.g. Coastal Mixing and Optics and HyCODE as described below). Spectral water-leaving radiance data collected from the BTM (Figure 3) and the complementary BBOP program have been used for validation and algorithm development for the SeaWiFS ocean color satellite (Dickey, 2001). The BTM optical data have at times been collected almost continuously (and transmitted to shore in near real-time) and provided a very large number of match-up/intercomparison data between the BTM and SeaWiFS. Further, high temporal resolution radiometric data are especially important since satellite-derived ocean color data are limited to the uppermost ocean layer (roughly one optical depth) and the number of viewing days is limited by cloud obscuration. Other new optical systems tested using the BTM have included a spectral volume scattering function instrument and a spectral fluorometer (SAFire: 6 excitation and 16 emission wavelengths). A limitation of moored optical systems has been biofouling. Recently, copper shutter systems and copper tubing for pumped systems have been engineered and tested and deployments of optical systems can now be done for periods of up to about 6 months in oligotrophic waters (e.g. Chavez et al., 2000; Dickey et al., 2000).

It is important to note that other instruments and systems have been developed to obtain time series of chemical (e.g. carbon dioxide, oxygen, nitrate, trace elements, etc.) and biological (e.g. primary production from ^{14}C measurement systems, acoustic backscatter for zooplankton, genetic probes, etc.) data. These complementary chemical, biological, and physical measurements are critical for understanding optical and bio-optical variability and vice versa. The BTM project has also tested a variety of telemetry systems (Dickey et al., 1998a). The data sets collected by the BTM and ALOHA-HOST moorings have also been used for several modeling studies.

Examples of Coastal Ocean Time-Series

Improved understanding of coastal ocean physical processes and their effects on biology is especially important since the majority of the world's primary production occurs on continental shelves and the coastal ocean is most utilized and impacted by humans. Nearshore research is difficult because physical and biological processes in the coastal ocean are generally

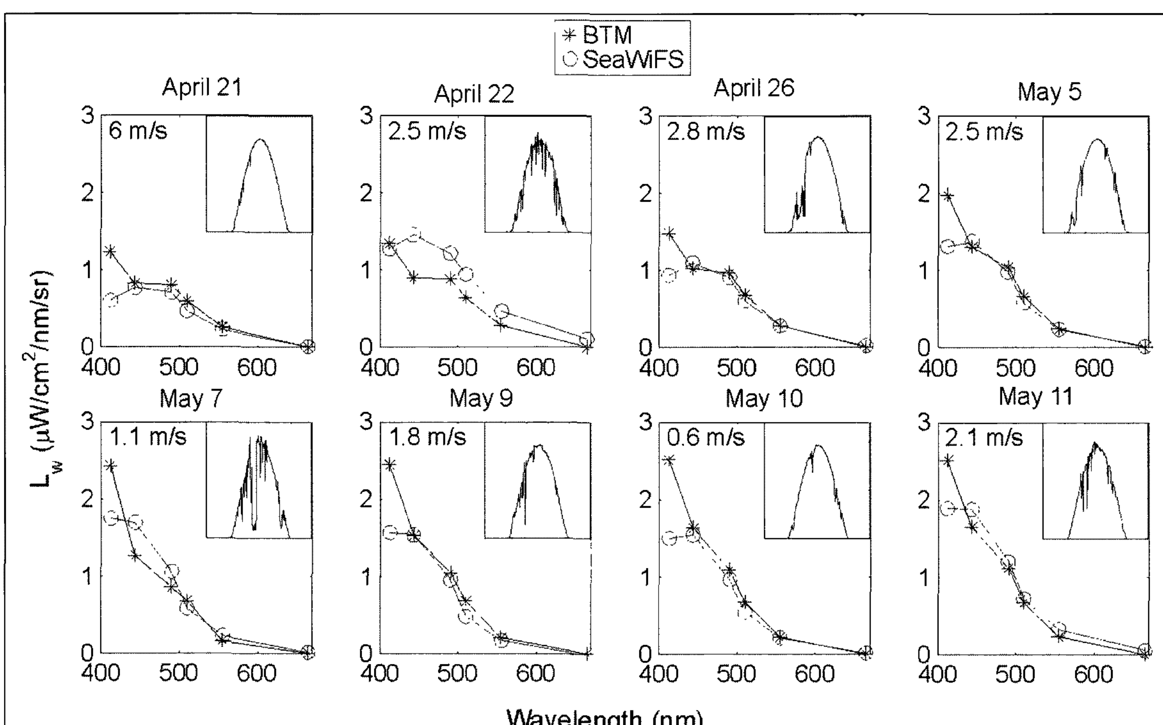


Figure 3. Representative subset of spectral water-leaving radiance, L_W, observations (near noon) that were derived from Bermuda Testbed Mooring radiometers (asterisks) and from SeaWiFS ocean color satellite radiometers (circles) for the period April 21 to May 11, 1999. Wind speed (1-hour average) during noontime observations and daytime time series of incident shortwave radiation for the day of interest are also shown. Cloudy days are evident in jitteriness in the shortwave curves. Agreement is generally quite good except at 412 nm where the SeaWiFS values are typically lower. This is likely due to atmospheric effects that were not completely removed by the SeaWiFS algorithm.

more dynamic and complex than in the open ocean and experimental logistics are often problematic. Time-series measurements of bio-optical properties are necessary for the design of accurate coupled physical-biogeochemical models (e.g. determination of limits on grid spacing and time steps), for long-term monitoring of anthropogenic effects on the biology, chemistry, and geology of the oceans (e.g. sewage outfalls, storm runoff and resuspension of contaminants, river transport of chemicals and tailings, etc.), and for the interpretation of remote sensing data in the nearshore coastal ocean in order to quantify the global carbon budget, visibility, and bathymetry.

Shelf Edge Exchange Processes (SEEP)

The Shelf Edge Exchange Processes (SEEP-I and -II) experiments in 1983-1984 and 1988-1989 were amongst the first multidisciplinary programs to utilize moored bio-optical instrumentation in a coastal environment (Biscaye et al., 1988, 1994). Fluorometers and beam transmissometers, in addition to physical instruments and sediment traps, were deployed on moorings on the continental shelf (to the shelfbreak) of the Middle Atlantic Bight (MAB), south of Cape Cod, Massachusetts to investigate the fate of continental shelf particulate matter, in particular, organic carbon. The major result from the SEEP studies was that there is not an export of a large proportion of particulate matter from the shelf to the adjacent slope and open ocean. Rather, most of the biogenic particulate matter is recycled by consumption and oxidation on the shelf (Biscaye et al., 1994).

The Shelf Edge Exchange Processes (SEEP-I and -II) experiments in 1983-1984 and 1988-1989 were amongst the first multidisciplinary programs to utilize moored bio-optical instrumentation in a coastal environment.

Sediment TRansport Events on Shelves and Slopes (STRESS)

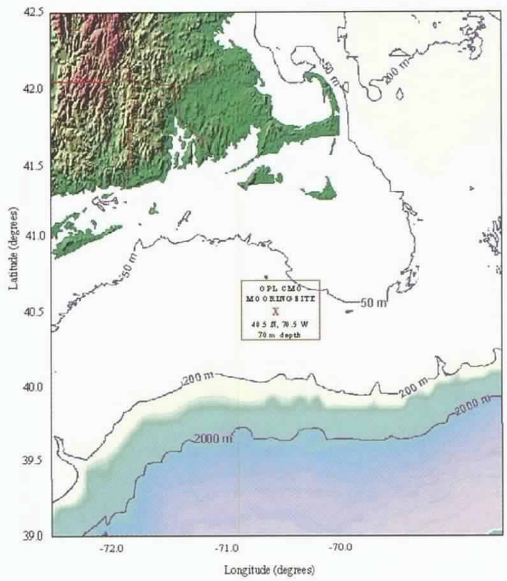
The Sediment TRansport Events on Shelves and Slopes (STRESS) program was designed to investigate the processes controlling sediment transport and to develop models to predict these processes on a continental shelf (see *Continental Shelf Research*, Vol. 14, 1994). The site of the STRESS experiment was on the Russian River shelf off the coast of northern California. Measurements in the field were obtained in fall and winter 1988-1989 and 1990-1991 and focused on storm-generated sediment resuspension. Optical time series were obtained with bottom-mounted optical instrumentation: optical backscatterance sensors (OBSs), beam transmissometers, an optical settling box, a stereocamera for photographs of bed conditions, and Laser *In Situ* Settling Tubes (LISSTs; see *Continental Shelf Research*, Vol. 14, 1994). The time-series of interdisciplinary parameters collected during the STRESS program successfully resolved small-scale topography and estimated particle concentration, size, and settling velocity by use of optics. Supporting physical measurements determined the vertical distribution of velocity, temperature, and salinity throughout the continental shelf bottom boundary layer.

Coastal Mixing and Optics (CMO)

The Coastal Mixing and Optics (CMO) program was conducted in the "Mud Patch" of the MAB continental shelf off the southern coast of Massachusetts (Figure 4a; see Journal of Geophysical Research, Vol. 106, pp. 9425-9638, 2001; introduction/overview by Dickey and Williams, 2001). CMO was an interdisciplinary program focused on the mixing of ocean water on a continental shelf and the effects of mixing and other physical processes on water column and ocean bottom optical properties. Several particularly interesting oceanographic conditions and processes occur at the CMO study site, e.g. seasonal cycle in hydrography and biology, internal solitary waves, shelf-slope dynamics (frontal intrusions, jets, meanders, filaments, eddies, etc.), and intense storms ("nor'easters") and hurricanes.

A number of sampling platforms were utilized during CMO: moorings, tripods (Figure 4b), towed profilers (SeaSoar), shipboard profiles, satellites, and acoustical arrays (part of the Primer study, see Dickey and Williams, 2001). Time-series of bio-optical properties at several depths were collected by use of moored and bottom-mounted 9-wavelength absorption-attenuation meters (ac-9s), beam transmissometers, fluorometers, scalar irradiance sensors (for PAR), and upwelling radiance sensors (683 nm). Total minus water spectral absorption data collected by the ac-9s were partitioned into phytoplankton absorption and detritus components plus gelbstoff absorption following the methods in Chang and Dickey (1999) to investigate particle types. Time series of sediment characteristics were also obtained from a bottom-mounted floc camera and LISST-100 instruments. A meteorological buoy, temperature and conductivity sensors and an uplooking acoustic Doppler current were also deployed for supporting physical measurements. Instruments sampled several times per hour between July 1996 and June 1997. This allowed the study of temporal variability of bio-optical properties as related to physical processes on time scales of minutes to seasons, covering the range of scales associated with internal gravity and solitary waves, phytoplankton light and nutrient adaptations, phytoplankton community-scale blooms and successions, tides, upwelling, storms and hurricanes, shelf/slope frontal activity and other

(a)



(b)

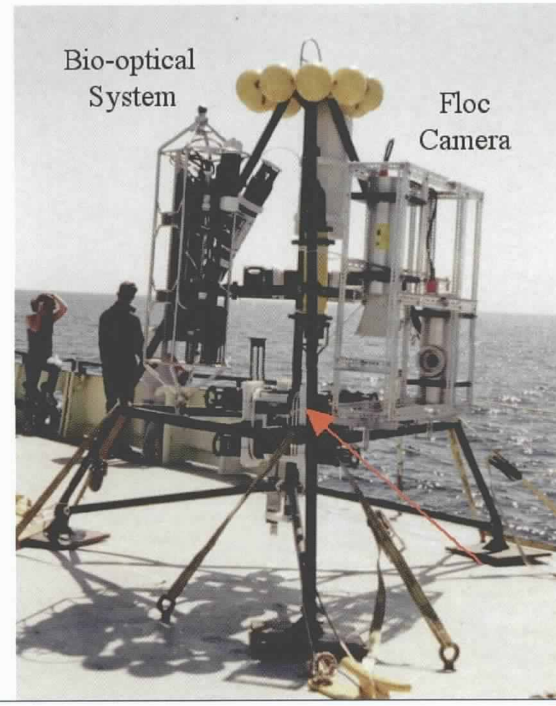
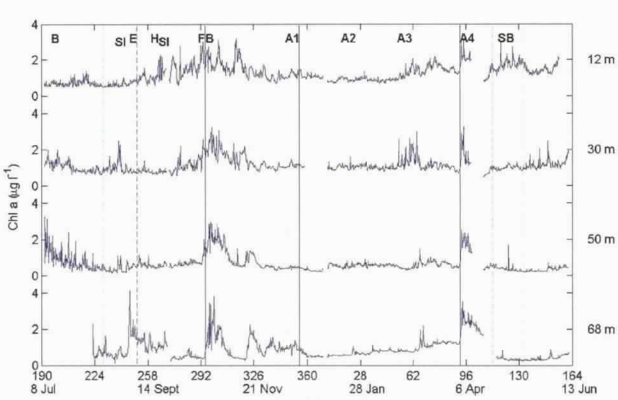


__Figure 4. (a)__ Coastal Mixing & Optics (CMO) site map showing the location of the mooring and optical tripod; __(b)__ photograph of the optical tripod; and __(c)__ time series of 6-hour averaged chlorophyll a concentration (Chl a) at 12, 30, 50, and 68 m during CMO. Dates are also presented as decimal year day, with the convention that 0 h UTC January 1 is day 1.0. Episodic events are labeled: "B, E, and H" = Hurricanes Bertha, Edouard, and Hortense, respectively; "SI" = high salinity water mass intrusions; "FB and SB" = fall and spring bloom, respectively; "A1, A2, and A3" = slope-water advection events; and "SR" = spring runoff. Hydrographic seasons are separated by blue vertical lines. The green vertical dashed lines indicate the time periods when complementary shipboard profile data were obtained.

(c)



mesoscale events, and the seasonal cycle in hydrography, optics, and biology (Figure 2).

The most prominent physical and bio-optical signals were associated with the seasonal cycle. However, several episodic events (e.g. hurricanes, storms, and water mass intrusions) interrupted the seasonal cycle (Figure 4c). These episodic events had a great impact on biogenic and non-biogenic matter (inferred from bio-optical properties). Sediment resuspension during the passages of two hurricanes, Edouard and Hortense, within a two-week period in late-summer 1996 resulted in beam c (676 nm) at 68 m increasing from mean values of about 1 m^{-1} to greater than 30 m^{-1} and 20 m^{-1}, respectively (Figure 5). Analyses of bio-optical properties indicate that resuspended materials consisted of detrital material and relict pigments. Results from the floc camera and the LISST-100 data during the hurricanes show that floc size in the bottom boundary layer was controlled by disaggregation in the strongly sheared near-bed region. Several water mass intrusions influenced hydrographic conditions and thus affected particle concentrations and distributions on time scales of days to several weeks. An intrusion of high-salinity water from a meander in the shelf/slope front was observed at the CMO mooring site in late-summer 1996. This intrusion resulted in a build-up of phytoplankton at 30 m depth. Chlorophyll *a* values tripled and total and partitioned spectral absorption increased during the intrusion (Figure 5). Partitioned phytoplankton absorption at 440 and 676 nm (associated with chlorophyll *a*) and 488, 510, and 532 nm (associated with fucoxanthin pigment) increased relative to the 412 nm wavelength during the period when maximum

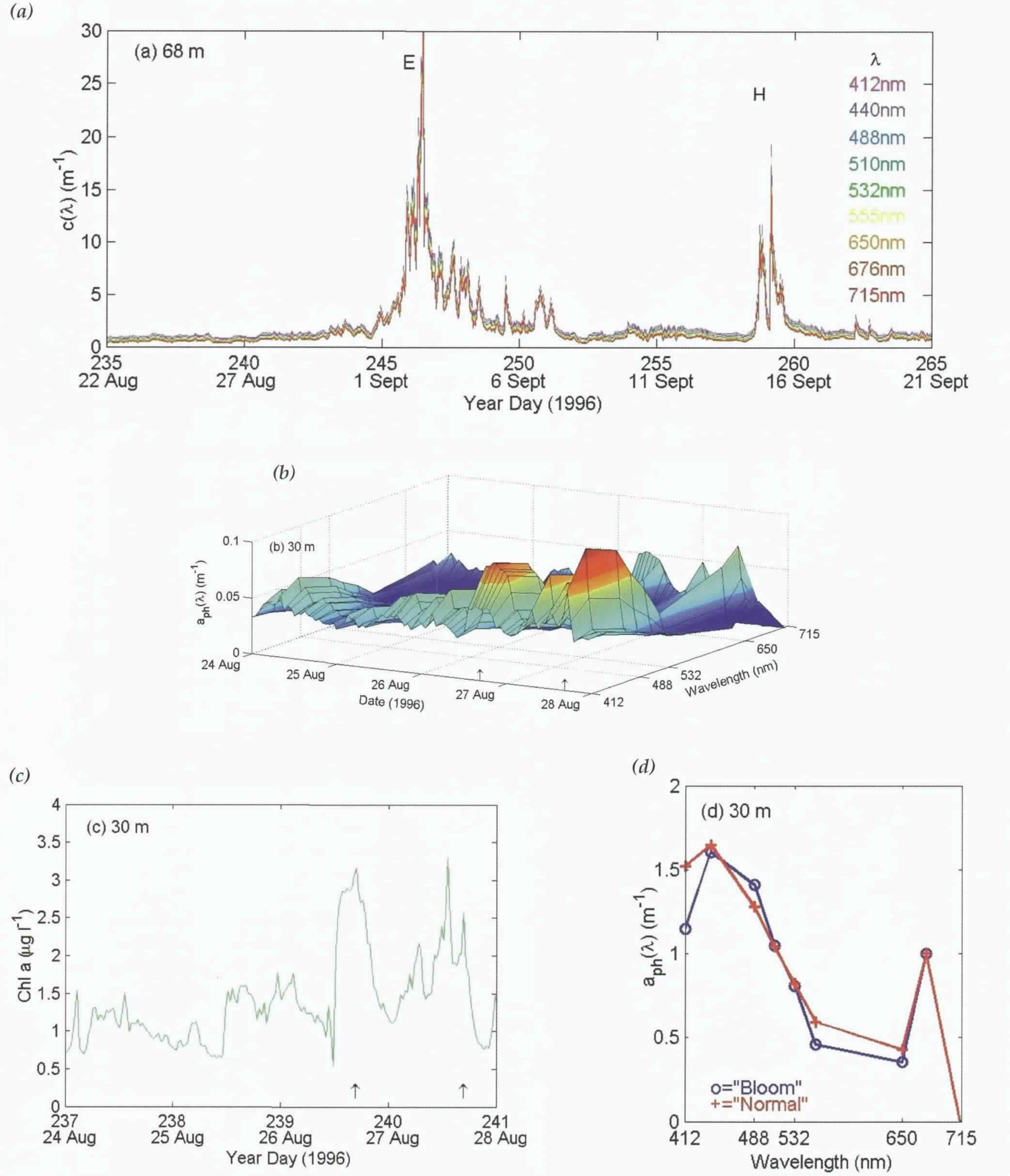


*Figure 5. Coastal Mixing & Optics **(a)** hourly averaged time series of beam attenuation coefficient at nine wavelengths as recorded by the bottom-mounted (68 m) ac-9 ("E" and "H" represent the times when Hurricanes Edouard and Hortense were closest to the CMO site); **(b)** time series of 30 m partitioned phytoplankton spectral absorption; **(c)** chlorophyll a concentration derived from the fluorometer (arrows indicate the phytoplankton bloom associated with the salinity intrusion); and **(d)** normalized (to 676 nm) partitioned 30 m phytoplankton absorption spectra on 26 August 1996 during a phytoplankton bloom and on 22 July 1996 during non-bloom conditions. See Figure 4 caption for year day convention.*

chlorophyll *a* values were observed, resulting in phytoplankton absorption spectra that were similar in shape to diatom absorption spectra (Figure 5). When the meander/salinity intrusion departed the CMO site, subsurface chlorophyll *a* concentrations and absorption values rapidly decreased as the bloom was advected with the front.

High frequency internal solitary waves (ISWs) were observed in band-passed filtered north-component (cross-shelf) current, temperature, chlorophyll *a*, and beam c (660 nm) data at the CMO site. The highest amplitude ISWs were observed at 20 and 50 m, which were the depths of strongest stratification. Oscillations in chlorophyll *a* at 30 m were at times correlated with ISWs seen in 31 m current data (Figure 6a and b). It appears that ISWs may have temporarily displaced higher concentrations of phytoplankton from the bottom of the pycnocline higher into the water column. ISWs were also observed to resuspend sediment from the nepheloid layer; high frequency bursts in beam c (660 nm) data were at times correlated with velocity data at 52 m (Figure 6c and d). Sediment resuspension by ISWs was also observed earlier during the Pacific Outfall experiment on the southern California shelf off of the Palos Verdes peninsula (Bogucki et al., 1997). There, bottom-mounted transmissometers recorded increased concentrations of particulates in the water column that accompanied the passage of ISWs along a strongly stratified bottom layer in spring 1992.

Decorrelation timescales for bio-optical data at CMO were generally longer than those for physical and hydrographic data in the upper water column (12 and 30 m depths). Chlorophyll *a* and beam attenuation decorrelation time-scales were 20-30 days during stratified conditions and 5-10 days during periods when the water column was well-mixed, whereas decorrelation scales for temperature and currents were 10-20 and approximately 5 days, respectively. At 50 and 68 m, bio-optical decorrelation scales were similar to hydrographic scales, but longer than physical scales (about 20 days for bio-optics and hydrography and about 5 days for currents). Many of the key results from the CMO experiment would not have been obtained if not for the use of moorings and tripods, as 1) ships were unable to sample during the extreme meteorological conditions during the hurricanes and storms; 2) ISWs cannot be systematically observed using traditional shipboard measurements (periods of less than 20 minutes); and 3) shipboard operations were restricted to twice per year because of costly ship-time, hence the seasonal cycle, several episodic events, and decorrelation time scales would not have been resolved. Nonetheless, complementary ship-based profile and tow-yo data sets collected near the CMO mooring and tripod site were valuable for intercalibrations and interpretation.

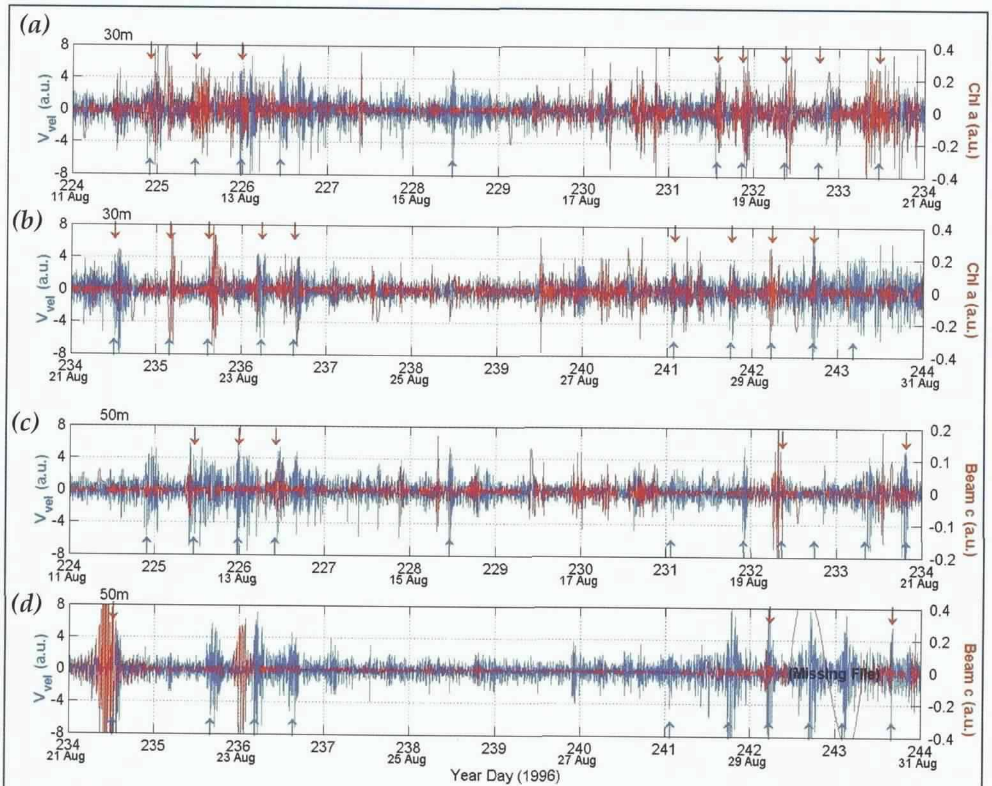
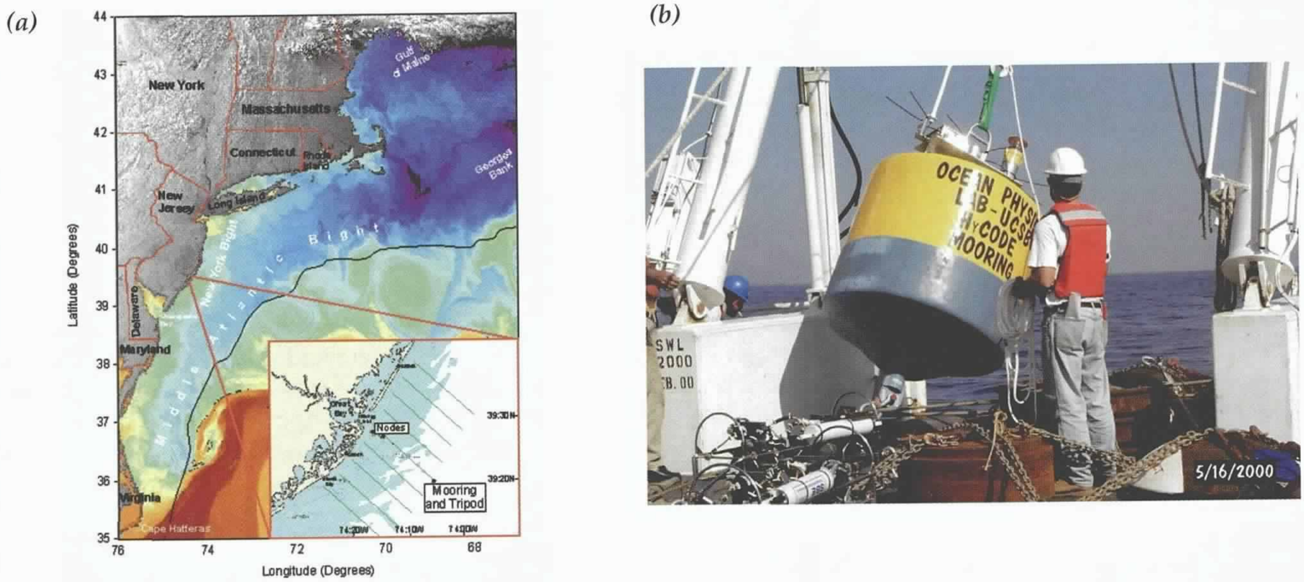


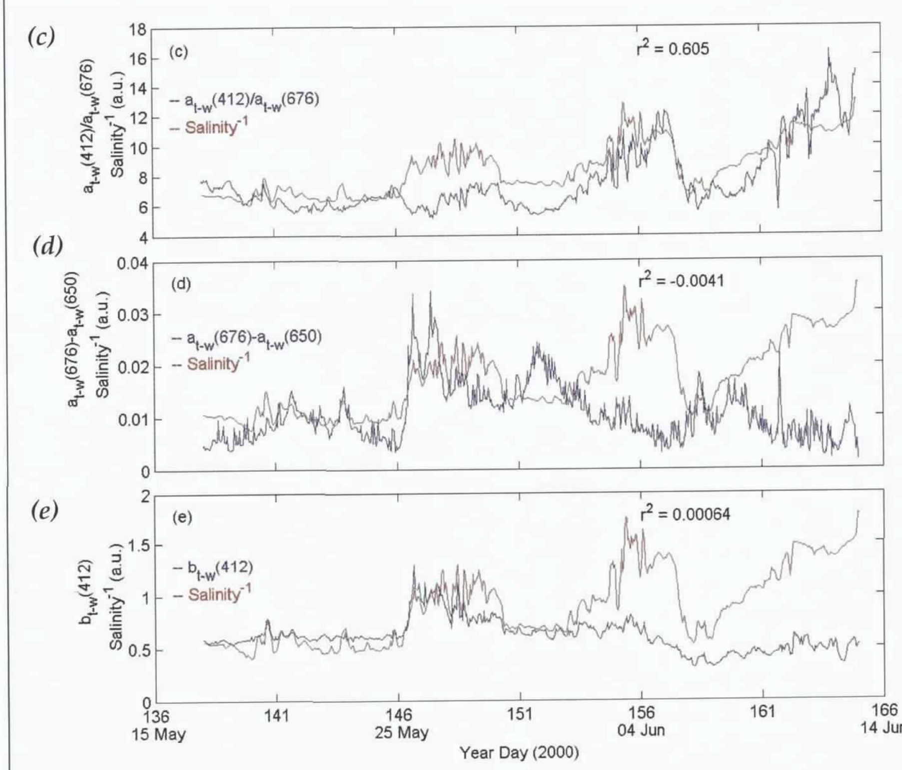
*Figure 6. Time series of band-passed filtered north-component velocity (blue) measured at **(a)** and **(b)** 31 m and chlorophyll* a *concentration (red) measured at 30 m; and **(c)** and **(d)** 51 m and beam attenuation (beam c, 660 nm; red) measured at 50 m during the Coastal Mixing & Optics experiment. The arrows represent times when internal solitary waves were observed.*

Thin Layers

The objective of the Thin Layers program was to resolve small vertical scale patterns (less than 1 m) and processes in the upper ocean including nutrient flux, phytoplankton growth, feeding by zooplankton, reproductive behavior, and predation by animals at higher trophic levels (see references in *Oceanography,* 11[1]). Profiles of chlorophyll *a* fluorescence, spectral absorption and attenuation, and optical images (optical system, or OSST, to measure laser-induced fluorescence)

Figure 7. *(a) Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature map of the Middle Atlantic Bight and the New York Bight on 10 June 2000. The black line denotes the approximate location of the shelf-slope front. Inset: HyCODE site map illustrating the approximate locations of the nearshore nodes and mid-shelf mooring and tripod (green lines extending offshore indicate ship tracks);* **(b)** *photograph of mid-shelf buoy/mooring recovery (provided by Janet Fredericks, Woods Hole Oceanographic Institution); and time series comparisons between the* **(c)** *ratio of $a_{t-w}(412)$:$a_{t-w}(676)$ and salinity$_{-1}$,* **(d)** *difference of $a_{t-w}(676)$-$a_{t-w}(650)$ (in m_{-1}) and salinity$_{-1}$, and* **(e)** *b(412) (in m_{-1}) and salinity$_{-1}$ showing the influence of low salinity estuarine runoff on bio-optical properties at 5 m depth at the HyCODE/LEO-15 mid-shelf site. Salinity is scaled to match bio-optical signals, thus is reported in arbitrary units (a.u.).*





were made from a moored boat for about a month in East Sound, WA in summer 1996 and again in summer 1998. Results suggest that distinct shifts in spectral optical properties can be found between nearby small-scale features, indicating different phytoplankton community composition or photoadaptive states between thin layers in the upper ocean. Optical image data reveal information about the relationships between phytoplankton and zooplankton; for example, zooplankton were not always found to correlate with the microscale heterogeneity of phytoplankton.

Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE)

Field experiments for the Hyperspectral Coastal Ocean

Dynamics Experiment (HyCODE; see website www.opl.ucsb.edu) program have been conducted in three locations: New Jersey shelf (at the Long-term Ecological Observatory site [LEO-15]), west Florida shelf (as part of Ecology and Oceanography of Harmful Algal Blooms [ECOHAB]), and Lee Stocking Island of the Bahamas (as part of Coastal Benthic Optical Properties [CoBOP]). One of the central goals of the program is to develop ocean color algorithms for remote sensing of the coastal ocean. Some other objectives include understanding of visibility, the relation of IOPs to AOPs, and the relationships between optical properties and physical, biological, geological, and chemical processes. Other goals are to develop radiative transfer models of the subsurface light field and optical measurement techniques for coastal benthic environments. Each of the HyCODE studies is summarized below.

New Jersey Shelf (LEO-15)

Several bio-optical instruments were deployed on a nearshore profiling node (about 5 km offshore; 15 m water depth), an optical tripod near the node, and a mid-shelf mooring and bottom tripod (about 25 km offshore; 24 m water depth) on the New Jersey shelf (LEO-15 site; Figure 7) for time series measurements in summer 2000 and 2001 (May-September). Optical instruments on the profiling node (a moored platform connected to a positively buoyant instrument package by an electro-optic cable) include an ac-9, HydroScat-6 for backscattering at 6 wavelengths and fluorescence at 2 wavelengths, fluorometer, optical backscatterer, LISST-100, and a bioluminescence profiler. Profiles were taken every half-hour, with an ascent/descent rate of about 2.5 m min^{-1}. LISST-100, LISST-ST, MSCAT, and fluorometer instruments were deployed on the optical bottom tripod to investigate sediment characteristics near the ocean bottom. Bio-optical instruments on the mooring included (sampling rates in parentheses): ac-9s (once per hour), beam transmissometers (once per minute), fluorometers (once per minute) and a spectral fluorometer (SAFire; once per hour), PAR sensors (eight times per hour), and a HydroScat-6 (once every 2 hours).

Processes on the New Jersey shelf are similar to those found at the CMO site, however, waters are more turbid and river and estuarine flows and upwelling fronts are more important at the LEO-15 site. Also, decorrelation time scales are shorter in the shallower waters at LEO-15; bio-optical parameters exhibit 1 to 3 day decorrelation scales from nearshore to mid-shelf. Time series measurements of spectral absorption at the mid-shelf mooring show that CDOM, possibly from the Hudson River outflow, dominated optical signals in late-spring 2000 (Figure 7). In summer 2000, a persistent front separated the lower salinity, more turbid waters nearshore from more saline, relatively clearer waters at mid-shelf. Mid-shelf total absorption was dominated by phytoplankton and CDOM, each accounting for roughly 50% of all absorbing materials at 440 nm. On the other hand, nearshore absorption was mainly influenced by particulate material (~70% of absorbing material) as compared to CDOM (~30%). A coastal jet was observed between July 22 and July 25, 2000. This coastal jet originated from an upwelling center north of the LEO-15 site. It was a relatively fast, southward moving, low temperature, high salinity, low particulate/biomass water mass, which extended approximately 5-10 km offshore, and was about 8-15 m deep. The effects of this jet can be seen in both nearshore and mid-shelf optical and biological variability. The coastal jet resulted in shoaling of the chlorophyll *a* maximum from depths of 16 to 10 m at the mid-shelf mooring. Noticeable increases in chlorophyll *a*, absorption, and attenuation at mid-shelf occurred during the time period of the jet due to advection of lower salinity, higher biomass nearshore waters to the mid-shelf region by the coastal jet. More details on HyCODE/LEO-15 results are given by Chang et al. (2001) and on website www.opl.ucsb.edu.

Coastal Benthic Optical Properties (CoBOP) and West Florida Shelf

Portable optical moorings were deployed in the optically shallow waters at the CoBOP Lee Stocking Island site for time series measurements spanning approximately 2-3 weeks (Maffione, personal communication). Instruments were deployed to measure downwelling and upwelling irradiance at the ocean bottom and at the surface to calculate bottom and surface reflectance, respectively. Supporting optical measurements were made with HydroScat-2s (for backscattering and fluorescence at 2 wavelengths), and a-betas and c-betas (for absorption and attenuation, and scattering by difference). Similar moorings were deployed on the west Florida shelf, but for periods of about two months, also as part of HyCODE.

A fast-repetition-rate fluorometer (FRR) was placed on a benthic platform (waters less than 10 m deep) near a coral head of *M. faveolata* by Gorbunov et al. (2001) to investigate the diel variability of chlorophyll fluorescence yields and photosynthetic parameters in corals off Lee Stocking Island during January and May 1999. The results identified, for the first time, several biophysical mechanisms that optimize photosynthesis and provide photoprotection in symbiotic corals. For other results from CoBOP, see Mazel (this issue).

Bio-optical time-series data have also been collected off the coast of San Diego and off the coast of central California near Monterey. D. Lapota (personal communication) collected daily to monthly bioluminescence time-series for 2-3 years off of San Diego to San Clemente Island, southern California, using MOORDEXs, University of California at Santa Barbara (UCSB) designed bioluminescence profilers. Fluorometers and beam transmissometers were also deployed. Also, since 1992, several mooring deployments have been conducted in Monterey Bay, California, as part of Monterey Bay Aquarium Research Institute's (MBARI) Ocean Acquisition System for Interdisciplinary Science (OASIS) to: 1) make long-term continuous observations of physical, chemical, and biological processes in an eastern boundary current, coastal upwelling environment; 2) test real-time data access and two-way telemetry; and 3) test new oceanographic sensors (Chavez et al., 1997). Bio-optical instruments have included: spectroradiometers, irradiance (PAR) sensors, light-scattering sensors, fluorometers, and other optical instruments (HydroRad, HydroScat, a-beta, and c-beta). Results show the evolution of coastal upwelling and its effect on hydrography, physics, chemistry, and bio-optics of the water column (Chavez et al., 1997).

...many envision the use of hyperspectral optical data for identification of phytoplankton species...

A Vision of Future Studies of Temporal Variability of Optical Properties

There has been a phenomenal increase in optical measurement capabilities, especially with the development of high spectral resolution sensors for both *in situ* and remote (satellite and airplane) platforms. Yet, there remains a need for better understanding and interpretation of our present optical measurements and for measuring additional optical parameters *in situ*. Several new systems are being developed for moored optical measurements (see Dickey, 2001a; Maffione, this issue), including: flow cytometers, particle cameras using holographic and other methods, and spectral fluorometers. Optical instrumentation has been shown to be especially effective for biological studies and expansion to others is likely. For example, many envision the use of hyperspectral optical data for identification of phytoplankton species, at least by groups. This would lead to improved understanding of community succession and perhaps allow prediction of harmful algal blooms. It is anticipated that optical measurements may prove valuable for other disciplines as well. Optical measurements have already been demonstrated to be important for upper ocean heating rates and heat budgets. In the future, it may be possible to use optical signatures and measurements for remotely estimating mixed layer depth in some oceanic regions. In addition, increasing numbers of chemical variables will be measured from moorings (e.g. Tokar and Dickey, 2000; Dickey et al., 2000) and will be useful for understanding and modeling biological processes like primary and new production.

The temporal range of *in situ* measurements of several of the fundamental spectral optical variables (irradiance, radiance, absorption, scattering, etc.) can in principal capture most of the processes of interest. Spectral and coherence analyses are certainly powerful analytical methods. However, the processes of interest are often non-stationary, nonlinear, and out of equilibrium and thus not strictly amenable to conventional statistical methods. However, new techniques such as wavelets and fractals may well prove to be valuable analytical tools (e.g. Emery and Thomson, 1997). The development of optical time series programs, akin to the Mauna Loa CO_2 program, in key oceanic regions is feasible because we can now use well-calibrated radiometers deployed from dedicated and moorings-of-opportunity (e.g. shared use of moorings with programs such as CLIVAR, Global Ocean Observation System, etc.). The temporal resolution of both airplane and satellite platforms are still rather coarse and suffer from cloud obscuration. However, there are plans for multiple ocean color satellite missions, which should improve both temporal and spatial coverage (C. Davis, personal communication). In particular, some hyperspectral color satellites with spatial resolutions on order of tens of meters are being planned for coastal observations; some color systems with similar resolutions are already being flown from aircraft. These capabilities will provide improved opportunities for comparing and synthesizing optical time-series obtained from moorings and satellites.

A new thrust for time series observations will be toward fully three-dimensional observations, which will increase the spatial sampling domain (see Figure 2 in Dickey, 2001a). Moorings with fixed depth and profiling instrumentation will remain important and platforms such as AUVS, gliders, drifters, offshore platforms, and profiling floats will become important components complementing moorings and satellites. Recently, bio-optical measurements have been made from AUVs at the BTM site in both Massachusetts Bay and Monterey Bay (e.g. Griffiths et al., 1999a; Yu et al., 2001). Increasingly, there is interest in utilization of optical data in near real-time and for data assimilation models (Bissett, this issue). Prediction of optical and bio-optical variables has become a realistic goal.

Acknowledgements

The present work has benefited greatly from interactions with numerous international collaborators and colleagues. Support of our research has been provided by the U.S. Office of Naval Research, National Science Foundation, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, Minerals Management Service, and the University of California at Santa Barbara. We would like to thank Temel Oguz for his input and for providing Figure 1.

References

Abbott, M.R., J.G. Richman, R.M. Letelier and J.S. Bartlett, 2001: The spring bloom in the Antarctic Polar Frontal Zone as observed from a mesoscale array of bio-optical sensors. *Deep-Sea Res. II*, 47, 3285–3314.

Ackleson, S.G., J.J. Cullen, J. Brown and M.P. Lesser, 1993: Irradiance-induced variability in light scatter from phytoplankton in culture. *J. Plankton Research*, 15(7), 737–759.

Biscaye, P.E., R.F. Anderson and B.L. Deck, 1988: Fluxes of particles and constituents to the eastern United States continental slope and rise: SEEP-I. *Cont. Shelf Res.*, 8, 855–904.

Biscaye, P.E., C.N. Flagg and P.G. Falkowski, 1994: The Shelf Edge Exchange Processes experiment. SEEP-II: an introduction to hypotheses, results, and conclusions. *Deep-Sea Res. II*, 41, 231–252.

Bissett, P., 2001: Resolving the impacts and feedbacks of optical processes on ocean ecology, *Oceanography*, this volume.

Bogucki, D., T. Dickey and L.G. Redekopp, 1997: Sediment resuspension and mixing by resonantly generated internal solitary waves. *J. Phys. Oceanogr.*, 27, 1181–1196.

Chang, G. C. and T. D. Dickey, 1999: Partitioning *in situ* total spectral absorption by use of moored spectral absorption-attenuation meters. *Appl. Opt.*, 38, 3876–3887.

Chang, G.C., T.D. Dickey, O.M. Schofield, A.D. Weidemann, E. Boss, W.S. Pegau, M.A. Moline and S.M. Glenn, 2001: Nearshore physical forcing of bio-optical properties in the New York Bight. Submitted to *J. Geophys. Res.*

Chavez, F.P., J.T. Pennington, R. Herlien, H. Jannasch, G. Thurmond and G.E. Friederich, 1997: Moorings and drifters for real-time interdisciplinary oceanography. *J. Atmos. Ocean. Tech.*, 14, 1199–1211.

Chavez, F.P., D. Wright, R. Herlien, M. Kelley, F. Shane and P.G. Strutton, 2000: A device for protecting moored spectroradiometers from biofouling. *J. Atmos. Ocean. Tech.*, 17, 215–219.

Dickey, T., 1991: The emergence of concurrent high-resolution physical and bio-optical measurements in the upper ocean. *Rev. of Geophys.*, 29, 383–413.

Dickey, T., 2001: Sensors: inherent and apparent optical properties. *Encyclopedia of Ocean Science*, in press.

Dickey, T., 2001a: New technologies and their roles in advancing recent biogeochemical studies. *Oceanography, in press.*

Dickey, T.D. and P.G. Falkowski, 2001: Solar energy and its biological-physical interactions in the sea. In: *The Sea, Volume 12, Biological-Physical Interactions in the Sea.* A.R. Robinson, J.J. McCarthy and B.J. Rothschild eds., in press.

Dickey, T.D. and A.J. Williams, III, 2001: Interdisciplinary ocean process studies on the New England shelf. *J. Geophys. Res.*, 106, 9427–9434.

Dickey, T., J. Marra, M. Stramska, C. Langdon, T. Granata, R. Weller, A. Plueddemann and J. Yoder, 1994: Bio-optical and physical variability in the sub-arctic North Atlantic Ocean during the spring of 1989. *J. Geophys. Res.*, 99, 22, 541–22,551.

Dickey, T., D. Frye, H. Jannasch, E. Boyle, D. Manov, D. Sigurdson, J. McNeil, M. Stramska, A. Michaels, N. Nelson, D. Siegel, G. Chang, J. Wu and A. Knap, 1998a: Initial results from the Bermuda Testbed Mooring Program. *Deep-Sea Res. I*, 45, 771–794.

Dickey, T., J. Marra, R. Weller, D. Sigurdson, C. Langdon and C. Kinkade, 1998b: Time-series of bio-optical and physical properties in the Arabian Sea: October 1994-October 1995. *Deep-Sea Res. II*, 45, 2001–2025.

Dickey, T., N. Bates, R. Byrne, F. Chavez, R. Feely, C. Moore and R. Wanninkhof, 2000: A Review of the NOPP Ocean-Systems for Chemical, Optical, and Physical Experiments (O-SCOPE) Project. In: *Fifth Symposium on Integrated Observing Systems*, Proc. Amer. Met. Soc.

Dickey, T., S. Zedler, D. Frye, H. Jannasch, D. Manov, D. Sigurdson, J.D. McNeil, L. Dobeck, X. Yu, T. Gilboy, C. Bravo, S.C. Doney, D.A. Siegel and N. Nelson, 2001: Physical and biogeochemical variability from hours to years at the Bermuda Testbed Mooring site: June 1994-March 1998. *Deep-Sea Res. II*, 48, 2105–2131.

Emery, W.J. and R.E. Thomson, 1997: *Data Analysis Methods in Physical Oceanography.* Pergamon, Oxford, 634pp.

Foley, D., T. Dickey, M. McPhaden, R. Bidigare, M. Lewis, R. Barber, C. Garside and D. Manov, 1998: Longwaves and primary productivity variations in the equatorial Pacific at 0°, 140°W. *Deep-Sea Res. II*, 44, 1801–1826.

Gorbunov, M.Y., Z.S. Kolber, M.P. Lesser and P.G. Falkowski, 2001: Photosynthesis and photoprotection in symbiotic corals. *Limnol. Oceanogr.*, 46, 75–85.

Griffiths, G., A. Knap and T. Dickey, 1999a: Autosub experiment near Bermuda. *Sea Technology*, December.

Griffiths, G.R., C. Davis, C. Erikson, D. Frye, P. Marchand and T. Dickey, 1999b: Towards new platform technology for sustained observations. *OCEAN OBS 99*, Intern. Conf. on the Ocean Observation System for Climate, Saint-Raphael, France.

Kirk, J.T.O., 1994: *Light and Photosynthesis in Aquatic Ecosystems.* Cambridge University Press, Cambridge, UK, 1-509pp.

Letelier, R.M., D.M. Karl, M.R. Abbott, P. Flament, M. Freilich, R. Lukas and T. Strub, 2000: Role of late winter mesoscale events in the biogeochemical variability of the upper water column of the North Pacific Subtropical Gyre. *J. Geophys. Res.*, 105, 28,723–28,739.

Maffione, R., 2001: Evolution and revolution in measuring ocean optical properties, this issue.

Mankovsky, V.I., V.L. Vladimirov, M.V. Solov'ev and S.T. Besiktepe, 1998: Optical properties of the Black Sea: results of the ComSBlack and TU-Black Sea programs. In: *Ecosystem Modeling as a Tool for the Black Sea*, Vol. 2., Ivanov, L.I. and T. Oguz eds., Kluwer Academic Publishers, Dordrecht, 145–161.

Mazel, C., 2001: Optics of the sea floor. *Oceanography*, this issue.

Mobley, C.D., 1994: *Light and Water: Radiative Transfer in Natural Waters.* Academic Press, San Diego, 592pp.

McPhaden, M.J., 1995: The Tropical Atmosphere-Ocean Array is completed. *Bull. Amer. Meteorol. Soc.*, 76, 739–741.

Spinrad, R.W., K.L. Carder and M.J. Perry, 1989: *Ocean Optics.* Oxford University Press, New York, 283pp.

Strutton, P.G., J.P. Ryan and F.P. Chavez, 2001: Enhanced chlorophyll associated with tropical instability waves in the equatorial Pacific. *Geophys. Res. Lett.*, 28, 2005–2008.

Tokar, J.M. and T. Dickey, 2000: *Chemical sensor technology: current and future applications, in Chemical Sensors in Oceanography.* M.S. Varney ed., Gordon and Breach Science Publishers, 303–329.

Varney, M.S. (ed.), 2000: *Chemical Sensors in Oceanography.* Gordon and Breach Science Publishers, 333pp.

Wiggert, J.D., T.D. Dickey and T.C. Granata, 1994: The effect of temporal undersampling on primary production estimates. *J. Geophys. Res.*, 99, 3361–3371.

Yu, X., T. Dickey, J. Bellingham, D. Manov and K. Streilein, 2001: The application of autonomous underwater vehicles for interdisciplinary measurements in Massachusetts and Cape Cod Bays. *Cont. Shelf Res.*, in review.