OPTICAL VARIABILITY IN COASTAL WATERS OF THE NORTHWEST ATLANTIC

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ABSTRACT

Measurements of spatial and temporal variability in optical properties of northwest Atlantic coastal waters were made in 1996 and 1997. As part of the Coastal Mixing and Optics Experiment, two three-week periods were intensively sampled: during late summer 1996 highly stratified conditions were disrupted by the passage of Hurricane Edouard, and in spring 1997 increasing stratification and a modest phytoplankton bloom occurred. Vertical and temporal patterns in water column optical properties were very different between the two periods, with both inherent and apparent optical properties exhibiting subsurface peaks in late summer and near surface peaks during spring. Most variability was associated with particle distributions and optically important particles were primarily phytoplankton, which were numerically dominated by cyanobacteria in late summer and by larger eukaryotic cells in the spring. We also describe here a new observational program in Gulf of Maine and Georges Bank waters. Spatial and temporal mapping of inherent and apparent optical properties is currently being implemented using a towed vehicle and a profiling mooring. Using these platforms, distributions of optical properties are being assessed contemporaneously with multi-frequency acoustic backscattering and video imaging surveys for assessing plankton distributions.

INTRODUCTION

A complex and varying set of factors regulate optical variability in the coastal ocean and a range of sampling strategies and observational tools are required to study this regulation. Observational modes ranging from satellite- and aircraft-based remote sensing to instrumentation of oceanographic moorings and ship-based surveying address different spatial and temporal scales, each of which can be important for understanding optical variability. Newly available instrumentation allows in situ sampling of optical properties on space and time scales that previously were accessible only for physical properties such as temperature; a number of new research initiatives, including those presented here, are taking advantage of this new capability. At the same time important insights continue to come from detailed characterization of optically important water constituents since matter-specific optical properties vary in ways difficult to assess in situ. A combination of approaches both provides new insights and raises new questions.

THE COASTAL MIXING AND OPTICS EXPERIMENT

The Coastal Mixing and Optics Experiment is a multidisciplinary initiative aimed at quantifying and understanding the role of vertical mixing processes in determining the mid-shelf vertical structure of hydrographic and optical properties and particulate matter. The main experiment was carried out on the continental shelf south of Cape Cod, Massachusetts between mid-summer 1996 and late spring 1997. The observational program included physical and optical sampling from a variety of platforms including moorings, towed vehicles and ship-based vertical profiling systems. Here we report results from intensive ship-based sampling near the central experiment site (40.5° N, 70.5° W) during three week periods in late summer 1996 (R/V Seward Johnson cruise 9610, August 17 - September 7) and in spring 1997 (R/V Knorr cruise 150, April 24 – May 13).

Methods

During each of the cruises, in situ measurements of apparent and inherent spectral optical properties were carried out, along with discrete water sampling for detailed analysis of water constituents. Measurements were typically made three times each day during daylight hours. A tethered free-fall profiling radiometer (SPMR, Satlantic, Inc.) was used to acquire vertical profiles of downwelling irradiance and upwelling radiance in 7 spectral bands (412, 443, 490, 510, 555, 665 and 683 nm; spectral bandwidth, ~10 nm); simultaneous measurements of subsurface (30 cm) reference spectral irradiance were also acquired. Spectral measurements of absorption and scattering coefficients were measured on multiple sampling platforms using in situ dual path absorption and attenuation meters (ac-9, WetLabs, Inc.). Results presented here were acquired by the Oregon State University Optical Oceanography Group, with sensors mounted on their "Slowdrop" profiling system. Two separate ac-9's with matched spectral channels (412, 440, 488, 510, 532, 555, 650, 676 and 715 nm) were used, one measuring whole seawater and the other fitted with an 0.2 μm particle filter on the sample inlet (operational "dissolved" fraction).

Discrete water samples were collected from six depths throughout the water column using a CTD/rosette system equipped with Niskin bottles. Water samples were analyzed for chlorophyll concentration using 90% acetone extraction and standard fluorometric techniques. Individual particle optical properties were assessed on discrete water samples using shipboard flow cytometry. The basic instrument configuration and sample protocols have been reported elsewhere (Olson et al. 1993). Briefly, red and orange fluorescence, forward angle (3-19°) light scattering and side angle (73-107°) light scattering were measured with an EPICS V flow cytometer (Coulter Electronics Corp.), with a Cicero acquisition interface (Cytomation, Inc.). The flow cytometer was modified to simultaneously measure each optical signal at two different gains to increase the dynamic range, allowing particles from 0.6 to 30 μm to be measured in a single 5-ml sample. Using a combination of fluorescence and light scattering signals, we separately quantified the abundance and optical properties of three major classes of particles found to occur in the water samples: phytoplankton of the genus *Synechococcus* (~1 μm prokaryotes), eukaryotic phytoplankton ranging from ~ 1-30 μm, and other particles in the same size range (presumably a mixture of small heterotrophic organisms, organic detritus and mineral particles).

RESULTS AND DISCUSSION

As expected for late summer conditions, the water column was well stratified during the first two weeks of sampling in August 1996 (Fig. 1). During this period, chlorophyll a concentrations were relatively low in surface waters, with a pronounced subsurface maximum between 20 and 30 m (Fig. 1). Mid-depth maxima in diffuse attenuation coefficients for downwelling irradiance (K_d) and in both absorption and scattering coefficients for particulate material (a_p and b_p, respectively) and were also observed (Figs. 1 and 2). These conditions were dramatically disrupted by the passage of Hurricane Edouard. The hurricane traveled northward in the western North Atlantic during late August, with the center of the storm passing within ~100 km of the study site on September 2 when wind speeds were ~75 mph (Thompson and Porter 1997). Stratification was severely disrupted by storm action during the period when sampling was curtailed (September 1-3, Fig. 1). When sampling resumed, the subsurface chlorophyll a peak had disappeared and maxima in a_p, b_p and K_d were found near the bottom, with effects of resuspension evident as shallow as 15 m. Absorption by dissolved material (a_s) was systematically higher below the mixed layer, but relative to signals associated with particulates, a_s was less variable with depth and time (Fig. 2).

Vertical stratification was much weaker during late April than in August, but a steady trend toward increasing stratification due to spring surface warming was evident (Fig. 3). Early in the sampling period, high values of pigment concentration, K_d, a_p, and b_p occurred intermittently in the upper water column (Figs. 3 and 4). The periodic decreases in chlorophyll during this period were associated with several spring storms that passed through the area and resulted in elevated vertical mixing. As stratification increased in early May, we observed the onset of a phytoplankton bloom (after day 125), accompanied by elevated chlorophyll, a_p and b_p in the upper 25 m. Compared to the summer, a_s was even less variable.

Temporal differences in the vertical distributions of phytoplankton cells and other particles were evident both within and between the two cruises. In late summer before the hurricane, *Synechococcus* abundances were very high with a strong subsurface maximum present (> 10^5 cells ml^{-1}), while in spring these cells were 10-fold less abundant. Eukaryotic phytoplankton did not differ in abundance between the two seasons, until the bloom at the end of the spring sampling period when concentrations increased 3-4 fold (Fig. 5 and 6). While significant temporal changes in abundance of these cells were found, they tended to be relatively uniformly distributed in the upper water column at any given time.

While particle abundances were clearly correlated with water column optical variability, particle types were found to have substantial differences in their particle specific optical properties that affected the overall contribution to bulk water column optical properties. In summer, both *Synechococcus* and the eukaryotic phytoplankton had much higher average chlorophyll fluorescence cross-sections below 20 m (see Fig. 5 for eukaryotes), indicative of higher intracellular pigment levels (most likely resulting from photoacclimation to reduced light). This change in cell properties is the source of the mid-water column peaks in bulk chlorophyll concentration and a_p. Important changes in phytoplankton optical properties also occurred in the spring (Fig. 6). Diel variations in average cell light scattering, associated with cell growth and division patterns (Vaulot et al. 1995, DuRand and Olson 1996), were present early in the sampling period; these diel patterns were not, however, clearly seen in total cell (or total particle) scattering due to uncorrelated changes in cell abundance, probably associated with other processes such as advection and loss due to grazing. Large changes in fluorescence and scattering cross-section did occur during the bloom, however, and these changes had substantial affects on the bulk properties. While phytoplankton cell abundance was highest near the end of sampling (after day 127), chlorophyll concentration, a_p and b_p were all less variable and peaked early in the bloom (~ day 126). This was a result of large decreases in cell specific absorption and scattering which occurred in the eukaryotic phytoplankton as the bloom advanced (Fig. 6). This may have occurred because of physiological acclimation or shifting species composition.

While concentrations of non-phytoplankton particulates always exceeded those of phytoplankton, they were not always dominate contributors to total light scattering and exhibited less systematic spatial and temporal variability. During spring, for example, concentrations of eukaryotic phytoplankton were comparable to the other particles only near the surface at the end of the sampling period; in contrast, phytoplankton consistently made the largest contribution to total light scattering in surface waters, with a dramatic decrease with depth (Fig. 7). This is due to elevated scattering cross-sections for near surface phytoplankton and relative uniformity in properties of the other particles.

SUMMARY

A variety of processes contributed to temporal and vertical variability in optical properties in these continental shelf waters. Significant changes were associated with particulates, with phytoplankton usually playing a major role. Direct effects of physical processes on the distribution of optical properties and particulate matter were found primarily associated with storm events: the hurricane in late summer and periodic small storms in late April. Other significant changes in optical properties were associated with indirect interactions between particle abundance, particle specific properties and physical processes. These interactions include net increases in phytoplankton standing stocks due to growth under stratified physical conditions, photoacclimation responses of phytoplankton under persistent stratified conditions, and advection of water masses containing optically significant material previously exposed to different physical and ecological forces. The significance of these interactions can be explored in greater detail in the context of the complete Coastal Mixing and Optics Program data set and will be the focus of future efforts.

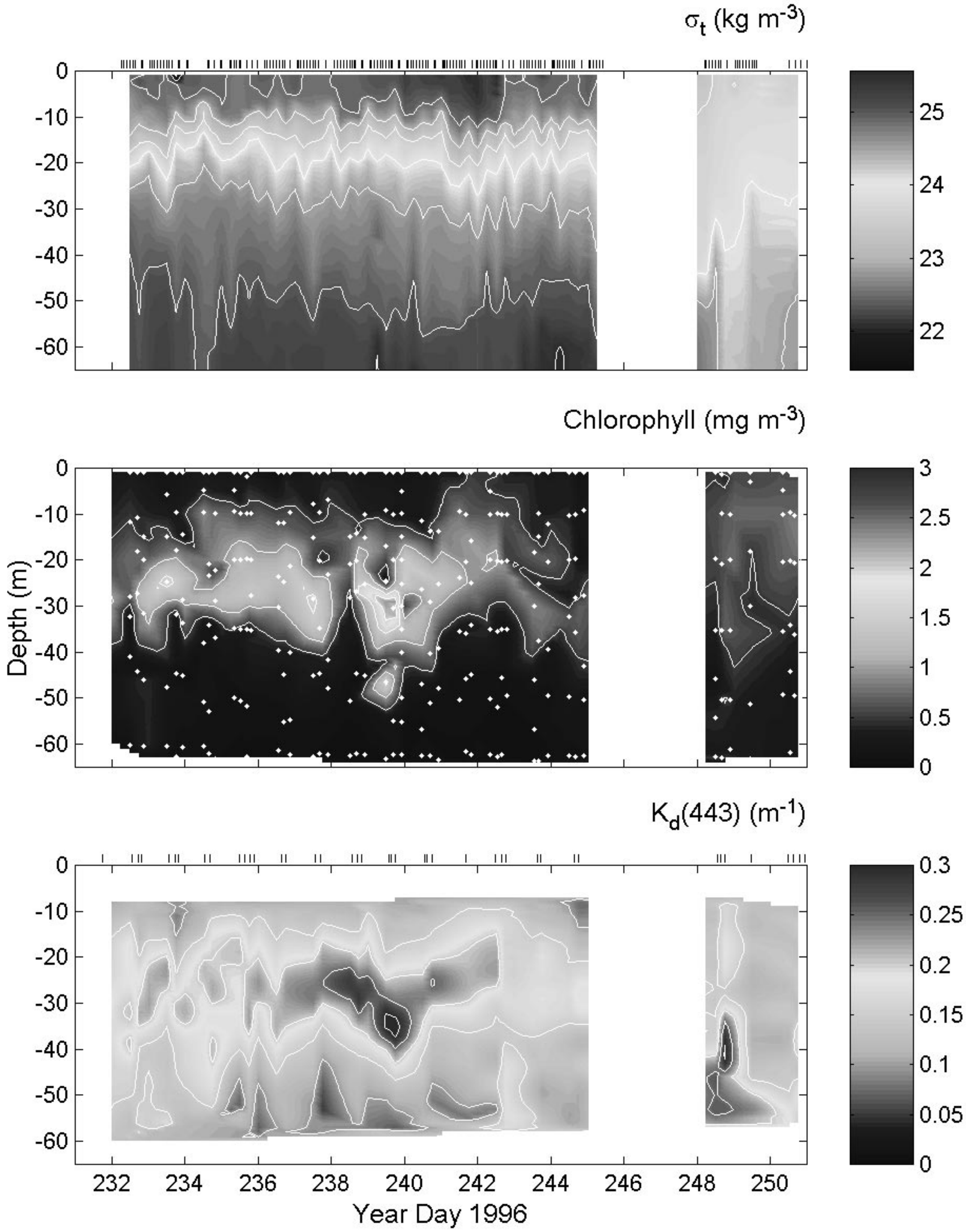

***Figure 1.** Late summer 1996 time series of density (σ_t), chlorophyll concentration and diffuse attenuation for downwelling irradiance (K_d) at 443 nm. Where appropriate, discrete sample positions are indicated on the panels and times of continuous profiles are marked above the panels. Sampling was disrupted on days 245-247 due to Hurricane Edouard.*

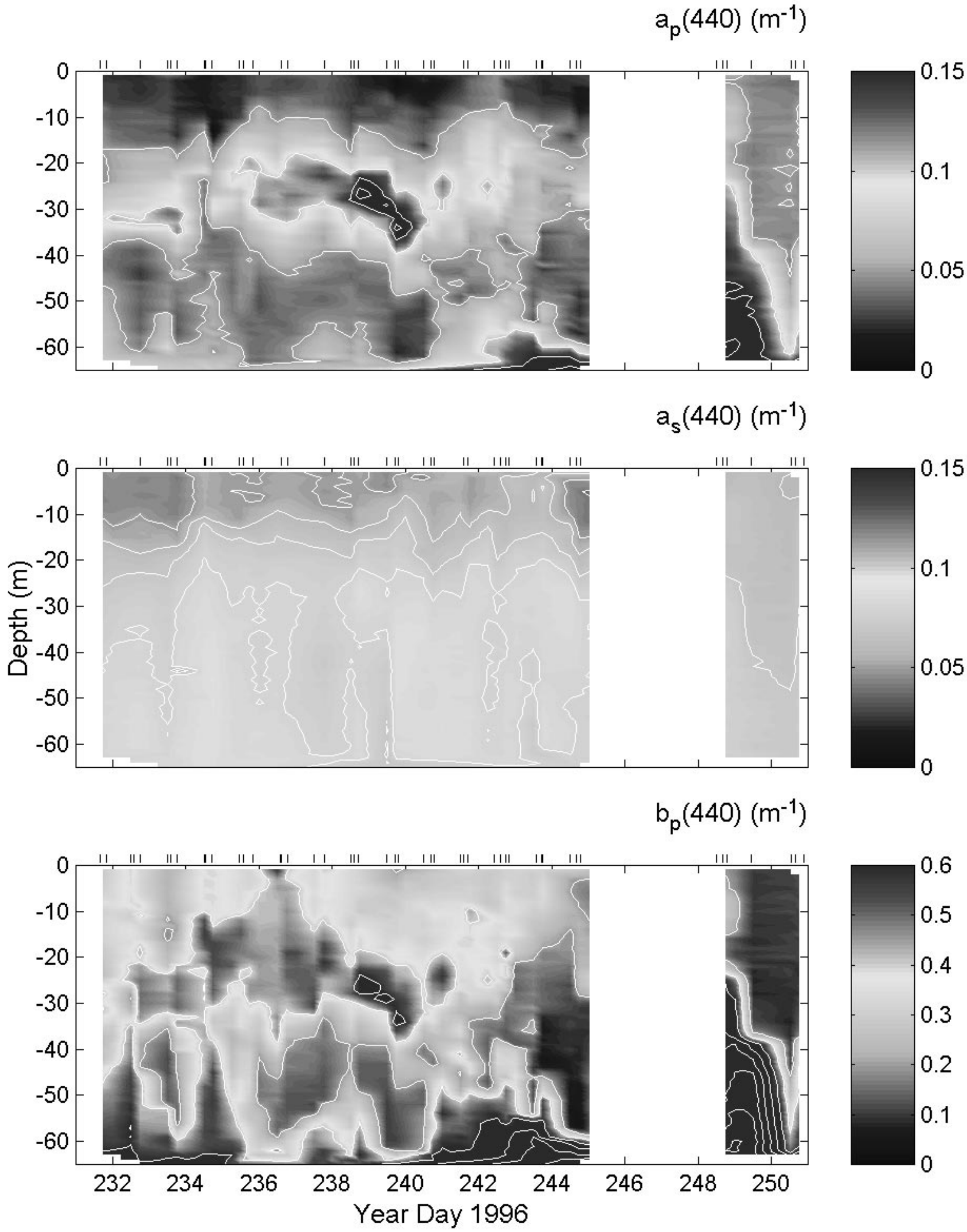

Figure 2. Time series for the same period as in Fig. 1, but for absorption coefficients for particulate (ap) and soluble (as) material and scattering coefficients for particulates (bp), all at 440 nm.

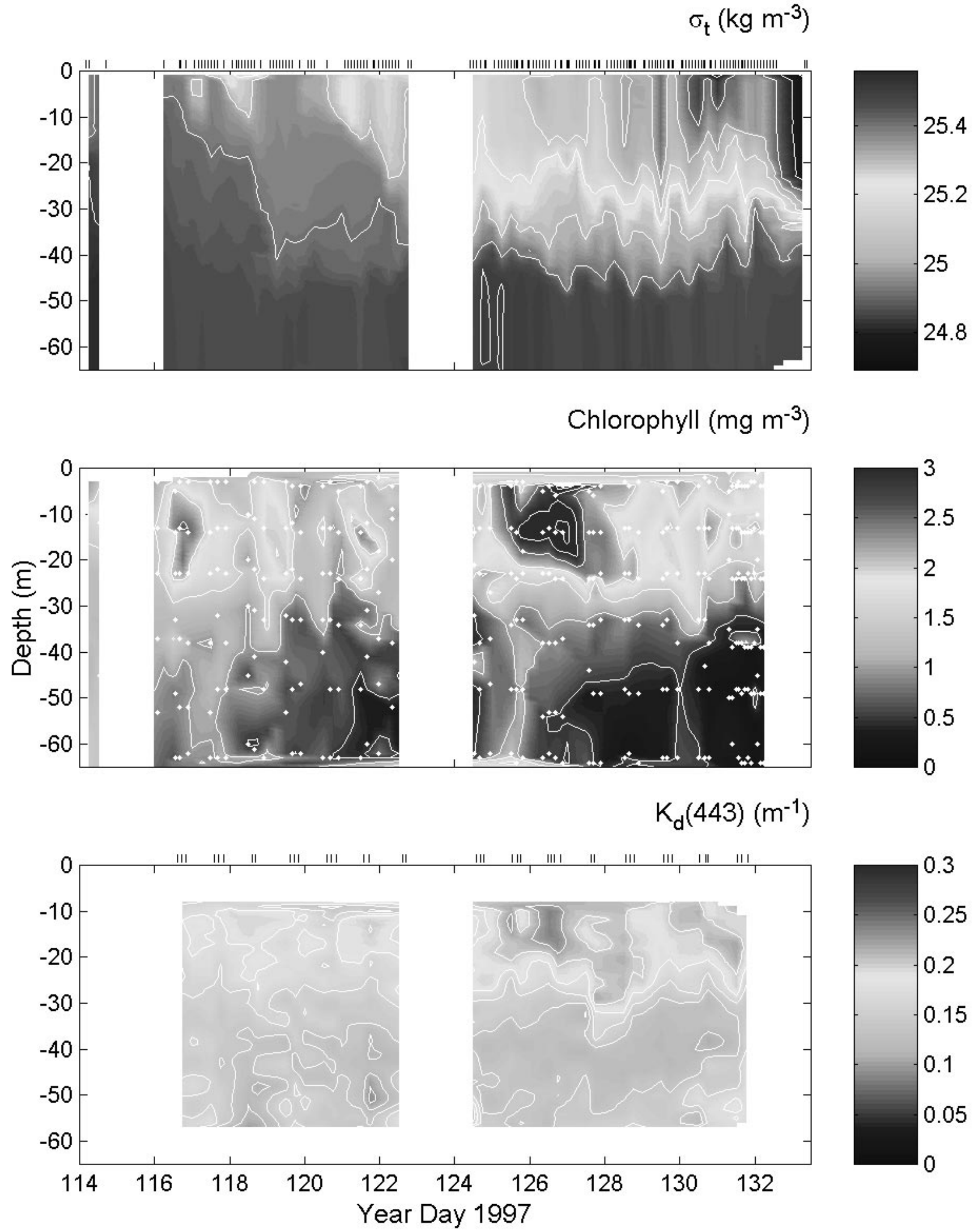

Figure 3. Spring 1997 time series of density (σ_t), chlorophyll concentration and diffuse attenuation for downwelling irradiance (K_d) at 443 nm. Note difference in density color scale compared to Fig. 1.

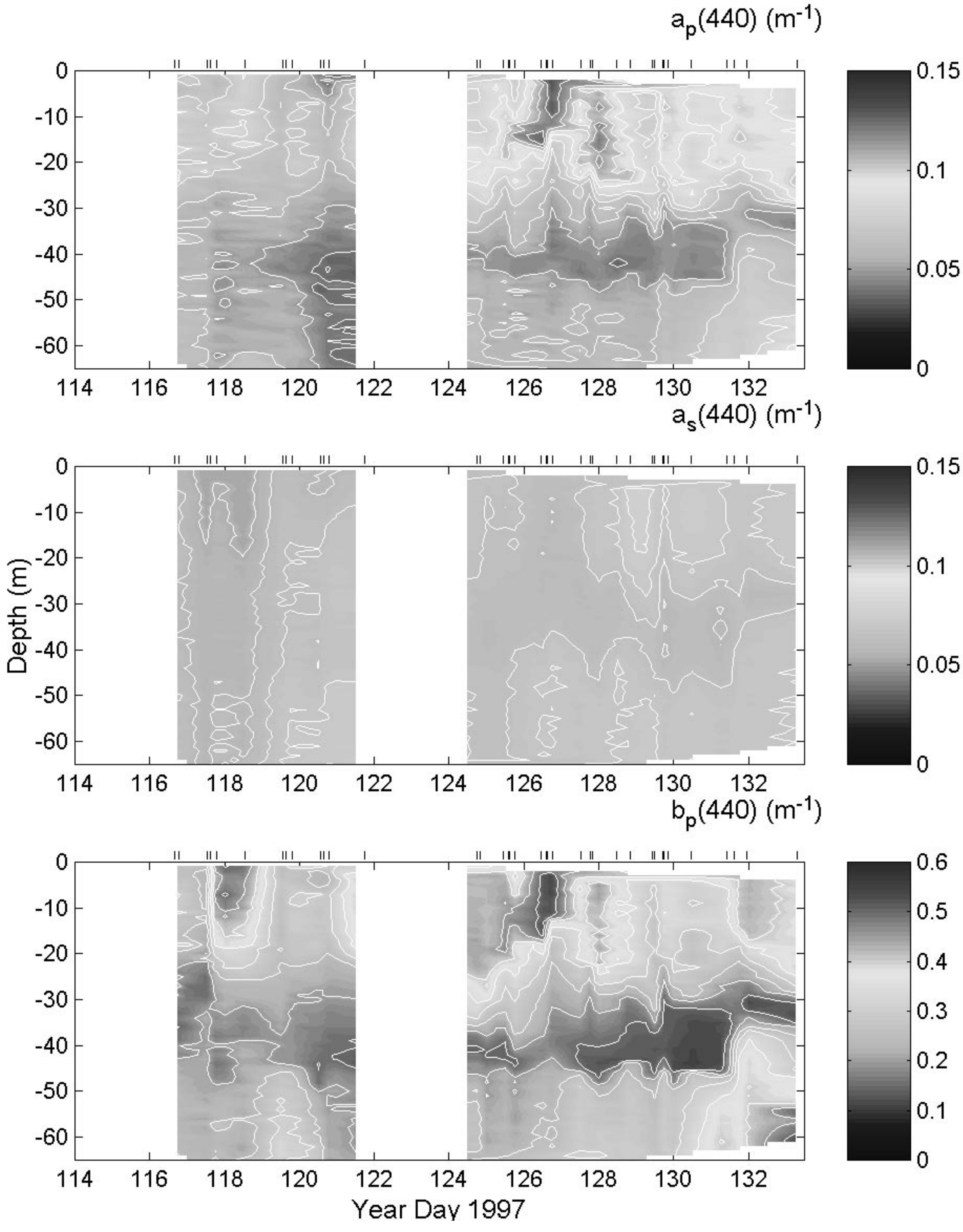

Figure 4. Time series for same period as in Fig. 3, but for absorption coefficients for particulate (ap) and soluble (as) material and scattering coefficients for particulates (bp), all at 440 nm.

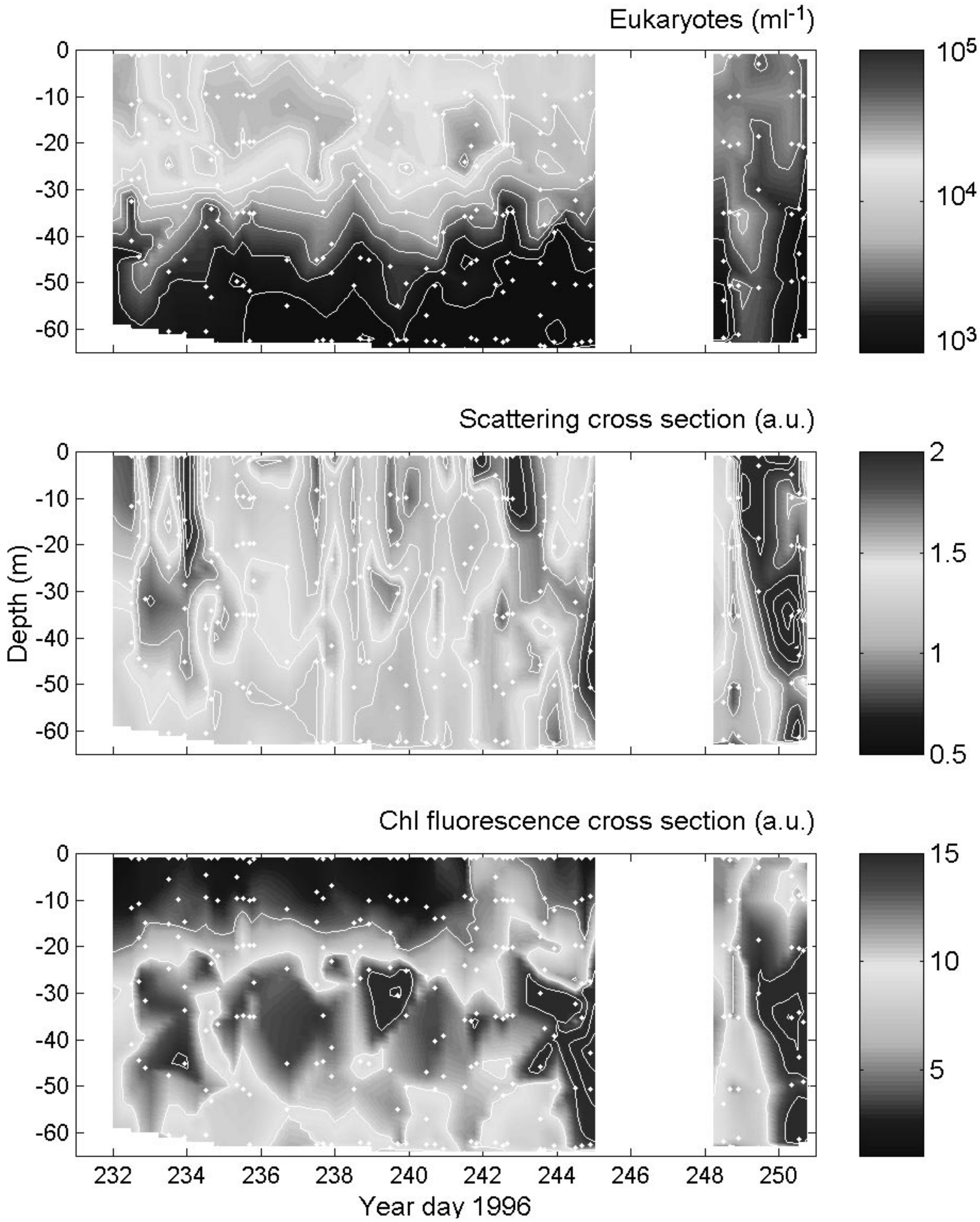

Figure 5. Time series for same period as in Fig. 1, but for eukaryotic phytoplankton properties derived from flow cytometric analysis. Shown are cell abundance and individual cell-based mean cross-sections for forward angle light scattering and chlorophyll fluorescence. Cross-sections are normalized to measured signals from standard polystyrene microspheres.

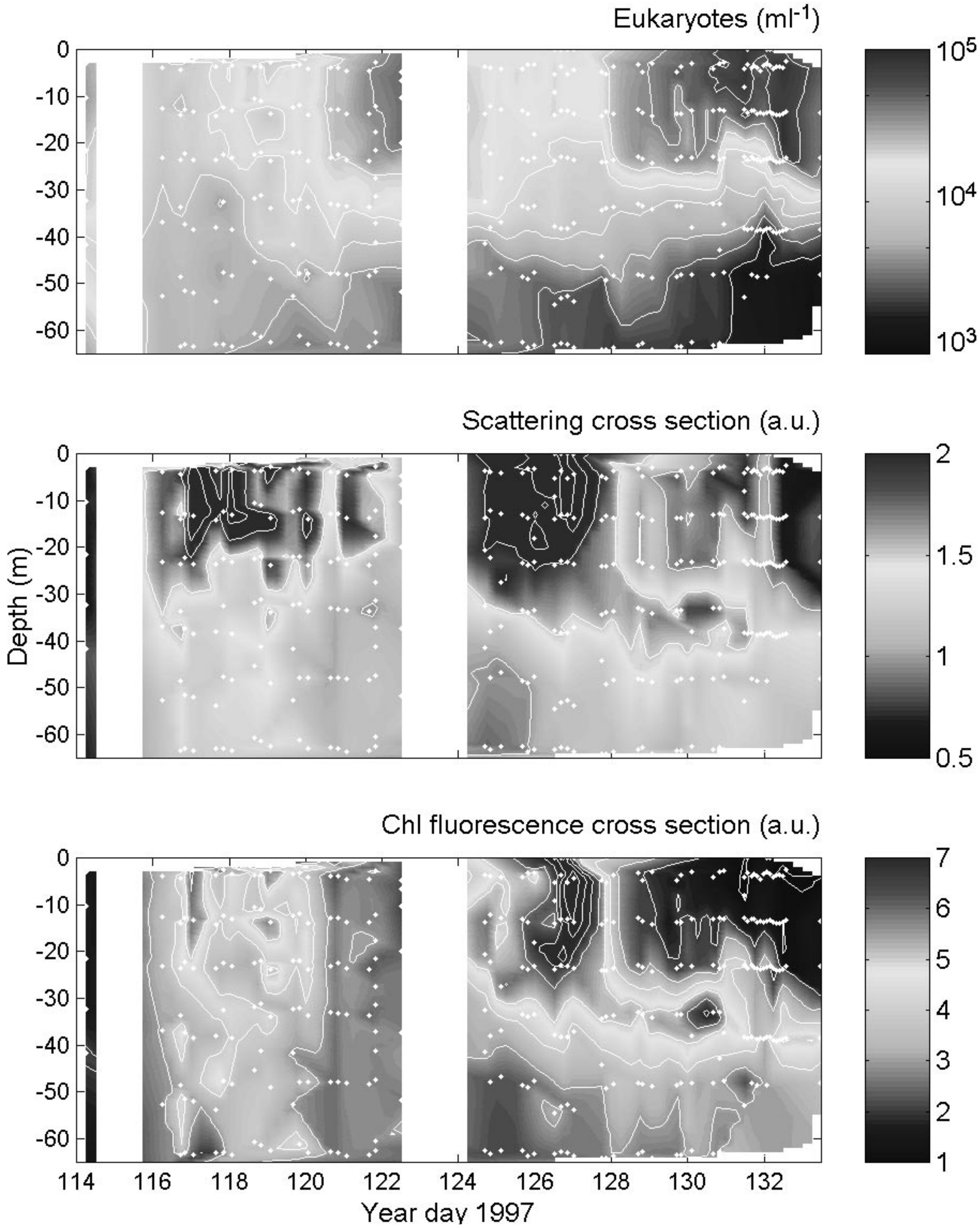

Figure 6. Time series for same period as Fig. 2, but for eukaryotic phytoplankton properties derived from flow cytometric analysis, as described for Fig. 5. Note difference in color scale for fluorescence cross section compared to Fig. 5.

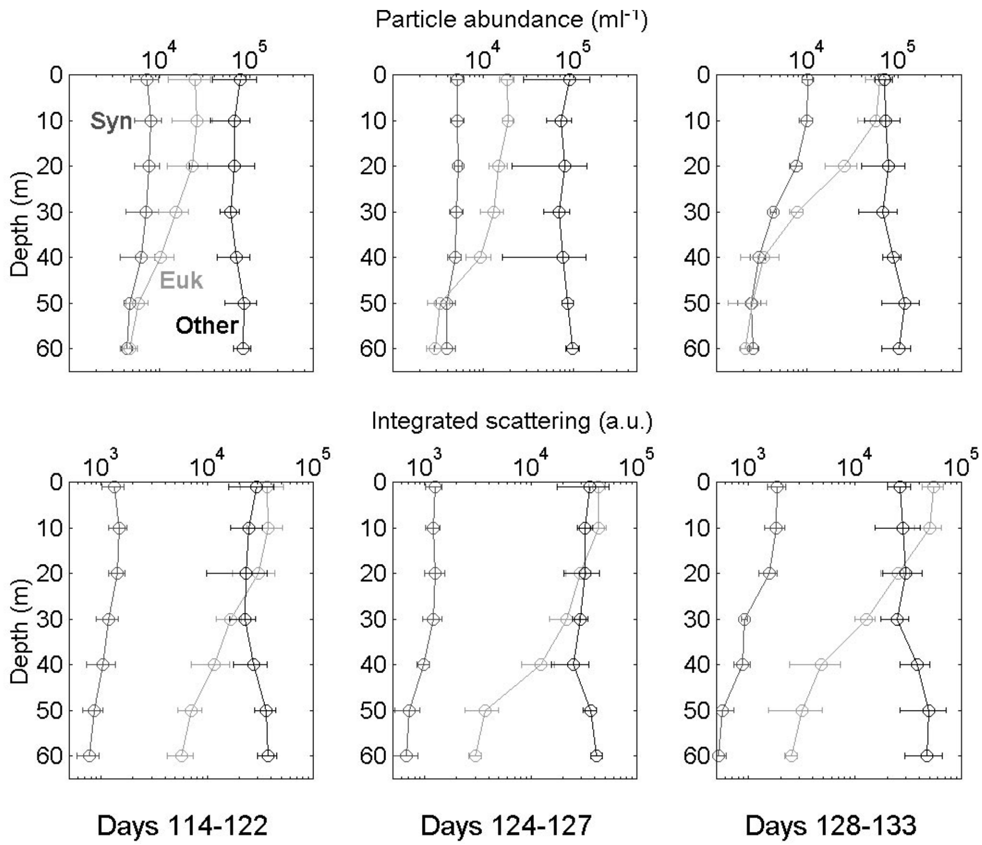

Figure 7. Abundance and integrated forward light scattering for different types of particles sampled by flow cytometry in spring 1997. Mean +/- standard deviation are shown for three time periods and three particle types: **Synechococcus** *(red), eukaryotic phytoplankton (green) and other particles in the same size range (black).*

A NEW OBSERVATIONAL PROGRAM

Sampling aimed at elucidating sources of optical variability in the northwest Atlantic must necessarily resolve a range of space and time scales. To address this issue, we have begun a new observational program in collaboration with investigators participating in the on-going Northwest Atlantic/Georges Bank GLOBEC program (GLOBEC 1992). Observations include both conventional ship-based sampling and satellite-based remote sensing, as well as two new systems for resolving time and space scales missed by these methods. These new approaches are described here.

BIOMAPER II – Towed Vehicle Observations

With the availability of convenient in situ optical instruments, implementation of towed vehicle sampling for spectral inherent and apparent optical properties has become a reality (e.g., Robins et al. 1996, Barth et al. 1998). We have recently implemented this kind of sampling with BIOMAPER II (Bio-Optical Multifrequency Acoustical and Physical Environmental Recorder), a second generation towed vehicle designed and constructed at the Woods Hole Oceanographic Institution (Wiebe et al. 1997).

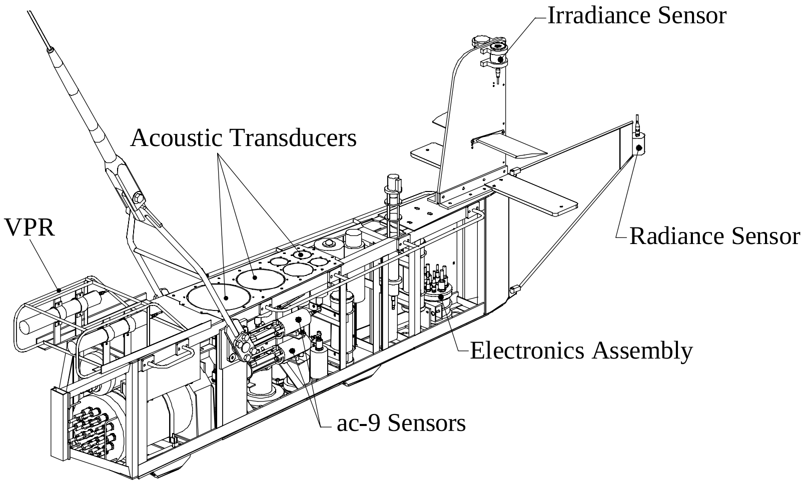

Figure 8. BIOMAPER II vehicle with exterior panels cut away to show the complete interior layout, included optical sensors integrated as part of this project. Two ac-9's, associated pumps and the optical system electronics assembly are mounted in the interior of the vehicle, the irradiance sensor is located on top of the stabilizing tail fin and the radiance sensor is supported by a specially constructed rear-mounted open frame intended to lower vehicle shadow effects.

BIOMAPER II in its original conception was designed primarily for acoustic monitoring of plankton and includes both up- and down-looking acoustic transducers of different frequencies, as well as a suite of conventional environmental sensors (including conductivity, temperature, pressure, chlorophyll fluorescence and beam transmission). In the upgraded vehicle, we have integrated a pair of dual path absorption and attenuation meters (ac-9, Wet Labs, Inc.), one for whole water and the other for a filtered fraction (0.2 μm), and two spectral radiometers (OCI/OCR-200 series, Satlantic, Inc.) for measuring downwelling irradiance and upwelling radiance (Fig. 8). This integration included construction of a data acquisition assembly that takes advantage of the optical fiber and network communication systems already active on the vehicle and allows real time storage of data on a shipboard computer. The BIOMAPER II is particularly well suited to assessment of apparent optical properties during towed operation because the vehicle is designed to maintain a horizontal attitude regardless of flight pattern.

The new vehicle configuration and optical sensor acquisition system has been successfully tested on a recent cruise in the Gulf of Maine (R/V Endeavor cruise 307, October 8-17, 1997). During this operation, BIOMAPER II was towed behind the ship at speeds as high as 6 knots and controlled to produce "tow-yo" flight patterns for near continuous sampling of optical, acoustic and hydrographic properties over large areas of the Gulf of Maine. Future efforts to survey this region at different times of year will be carried out in conjunction with additional sampling including mooring based operations.

AVPPO – Profiling Mooring Observations

Moored sampling of inherent and apparent optical properties has been implemented in a variety of programs during the last decade (see Dickey and Jones 1997 and references therein), with the advantages of excellent temporal resolution and

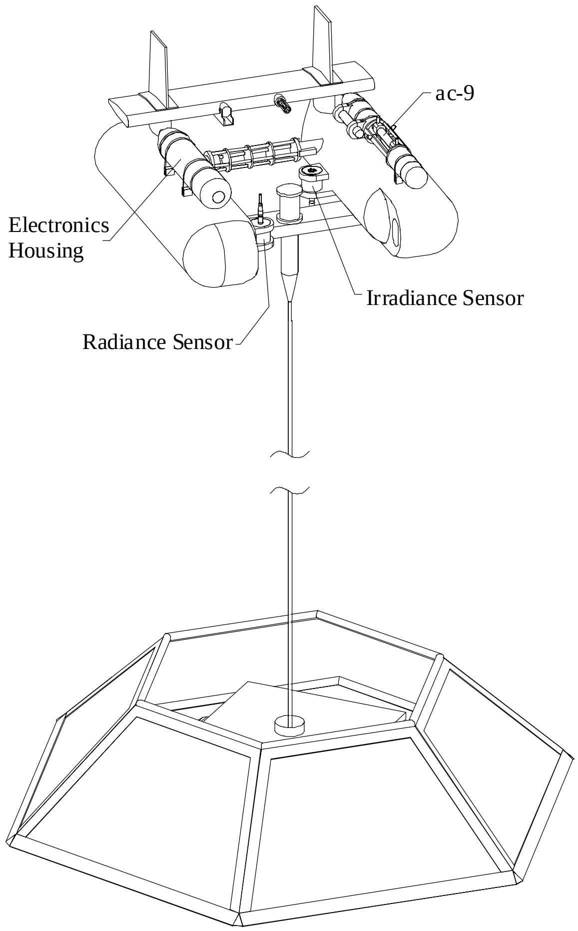

Figure 9. View of the upgraded AVPPO showing the optical sensor system integrated into the profiling vehicle. CTD sensors and a single wavelength transmissometer are also visible on the vehicle; the VPR sensing system is housed in the nose of the vehicle. The winch in the bottom-mounted housing is not visible.

typically moderate vertical resolution. New applications with spectral resolution and continuous vertical sampling are now possible and are being actively explored in this program. The Autonomous Vertically Profiling Plankton Observatory (AVPPO) is a mooring system for operation in coastal environments, designed and constructed at the Woods Hole Oceanographic Institution (Gallager et al. 1998, Thwaites et al. 1998). The AVPPO consists of a combination of a buoyant sampling vehicle and a trawl-resistant bottom-mounted enclosure, which holds a winch, the vehicle (when not sampling) and batteries. The AVPPO is set to sample at preprogrammed times; the vehicle is released and floats to the surface, with power and data connection maintained through the winch cable, and is then returned to the bottom with the winch. High resolution vertical sampling can be conducted on the up and/or downward profiles and on scales of minutes to weeks and months, limited by power and data capacities. The primary sampling system on the original vehicle is a dual camera Video Plankton Recorder (VPR), but it also carries accessory environmental sensors (including conductivity, temperature, pressure, chlorophyll fluorescence and beam transmission). In a recent upgrade, we have integrated the same suite of optical sensors as on BIOMAPER II (except with only one ac-9) into the AVPPO sampling vehicle (Fig. 9). The new optical sensor data acquisition system includes power and network connections to the main vehicle systems and on-board data storage.

The new AVPPO configuration has been tested using both shore link and autonomous modes in waters off Woods Hole, MA. Hydrographic, optical and video data were successfully recorded during hourly profiles over one week. Following further testing, an approximately 2-month deployment on Georges Bank is planned for later this year. This deployment will coincide with collection of SeaWiFS ocean color imagery and will encompass a planned BIOMAPER II survey cruise. We anticipate that this complementary spatial and temporal information will contribute to better understanding of the sources and mechanisms leading to optical variability in this region.

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