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Chloropigment distribution and transport on the inner shelf off Duck, North Carolina

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Abstract. The distribution and movement of chloropigments (chlorophylls and associated degradation products) in the bottom boundary layer near Duck, North Carolina, were examined during July and August 1994. Time series of chloropigment fluorescence, current velocity, and surface wave properties were acquired from instruments mounted on a bottom tripod set at 20 m depth. These data were combined with moored current meter measurements, meteorological data, and shipboard surveys in a comparative assessment of physical processes and chloropigment distribution over a wide range of temporal and spatial scales. Two dominant scales of chloropigment variation were observed. On numerous occasions, small-scale (order m) structure in the near-bottom fluorescence field was observed, even in the absence of identifiable structure in the temperature and salinity fields. Over larger time-scales and space scales, variations in fluorescence were related to changes in water mass properties that could be attributed to alternating events of upwelling and downwelling. This view was reinforced by shipboard measurements that revealed correlations between fluorescence and hydrographic fields, both of which were modified by wind-forced upwelling and downwelling and by the advection of low-salinity water from Chesapeake Bay. Local resuspension of sediments did not contribute appreciably to the near-bottom pigment load seen at the tripod, because of low bottom stress. Estimates of chloropigment flux indicated a net shoreward transport of chloropigments in the lower boundary layer. However, the rapid fluctuations of currents and pigment concentrations gave rise to large and frequent variations in chloropigment fluxes, generating uncertainty in extrapolations of this finding to longer timescales.

1. Introduction

Coastal ecosystems are areas high in biological productivity [*Knauer*, 1993; *Sathyendranath et al.*, 1995; *Verity et al.*, 1996] that serve as critical habitat in the life cycles of a variety of marine organisms including many commercially important fisheries species [*Day et al.*, 1989]. As the interface between land and sea, coastal environments are especially subject to forces of change, both natural and anthropogenic.

An understanding of interactions between physical and biological processes in coastal waters is clearly essential in the assessment and prediction of changes in coastal ecosystems. The range of physical processes that can influence biological populations in shallow coastal environments is broad. It includes wind- and tide-driven circulation and mixing, buoyant freshwater inputs, and frontal motions [*Paffenhoffer et al.*,

1994; *Cloern*, 1996; *Mann and Lazier*, 1996]. Within near-bottom coastal waters, for example, mixing due to waves and currents influences benthic-pelagic interactions (such as grazing by benthic fauna), sediment-water exchanges of nutrients, and resuspension of sediments [*Graf*, 1992; *Cloern*, 1996].

Despite numerous studies in coastal and inland waters the relationship of biological distributions with physical processes and water mass properties remains poorly understood, particularly in exposed inner shelf waters. Studies within the Mid-Atlantic Bight [*Malone et al.*, 1983; *Falkowski et al.*, 1988; *Verity et al.*, 1996], and South Atlantic Bight [*Paffenhoffer et al.*, 1994], have demonstrated that inner shelf waters often contain relatively high, and variable, chlorophyll concentrations. However, the sampling resolution of these studies was not adequate to characterize relationships between phytoplankton biomass distributions and physical variables on critical length scales and timescales. There is a growing body of work indicating the importance of fine-scale structure in phytoplankton distributions resulting from bio-physical interactions in stratified water columns or near fronts [*Seliger et al.*, 1981; *Franks*, 1992, 1995, 1997; *Cowles and Desiderio*, 1993; *Abraham*, 1998; *Cowles et al.*, 1998; *Hanson and Donaghay*, 1998]. Yet the conditions for the existence of such features in exposed inner shelf waters have not been documented.

Here we present the results of a study that combined shipboard observations with moored time series measurements of fluorescence, currents and water properties within inner shelf

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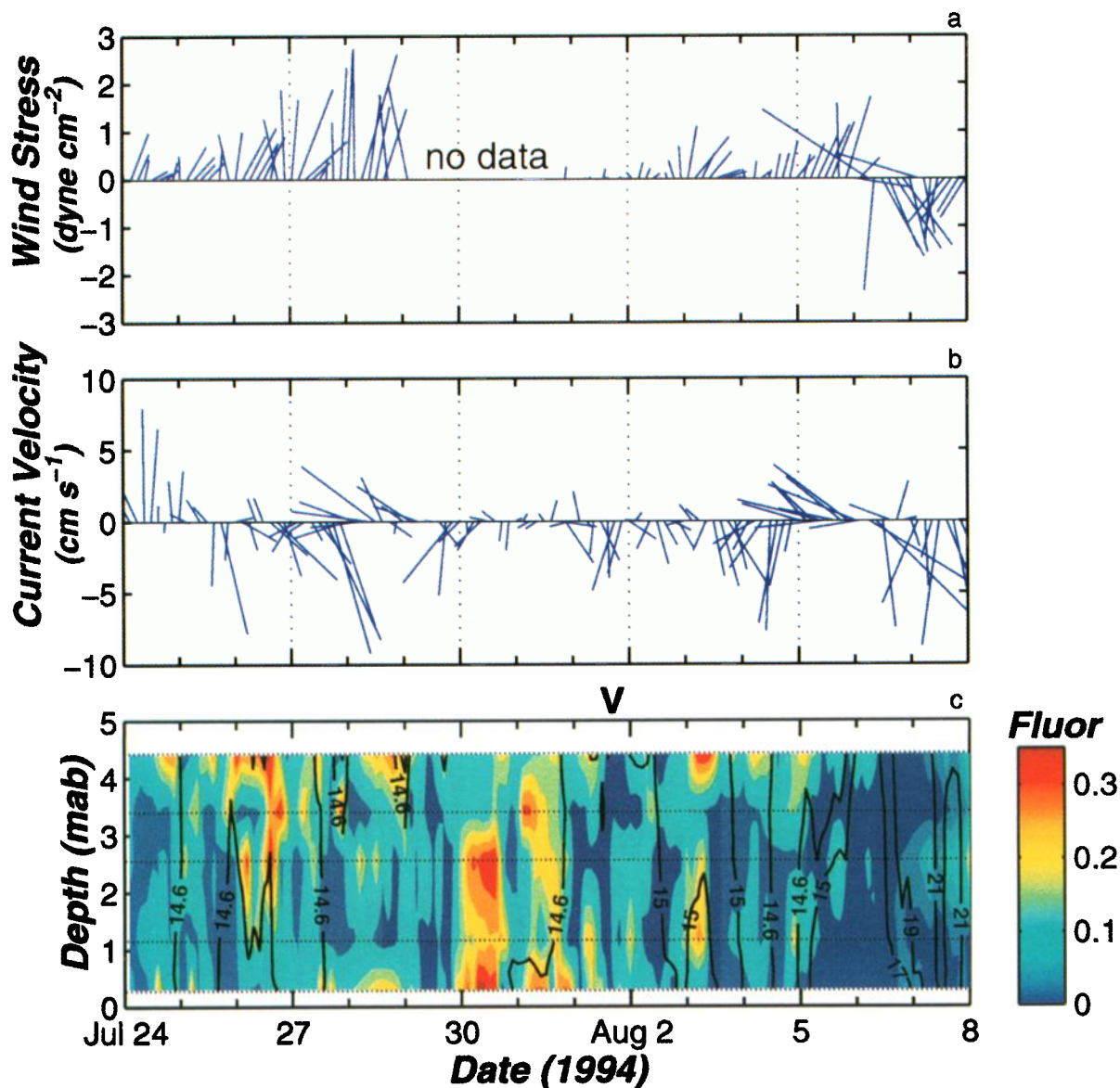
Plate 1. Time series of winds, near-bottom current velocity, and fluorescence and temperature variations in the benthic boundary layer for July 24 to August 8, 1994. (a) The 3 hour low-pass-filtered wind stress vectors from NDBC buoy 44014. The vector coordinates were rotated 10° counterclockwise to provide an alongshore orientation with positive values of stresses to the NNW. (b) The 3 h low-pass-filtered current vectors for the 0.25 mab BASS sensor, expressed using the same coordinates as for winds. (c) Contours of fluorescence (arbitrary units equivalent to those of a calibrated Turner fluorometer as described in methods) overlaid with contours of temperature for data acquired from sensors at 0.27 mab on the BASS tripod. The caret mark indicates the time of the August 1 CTD survey shown in Figure 6a.
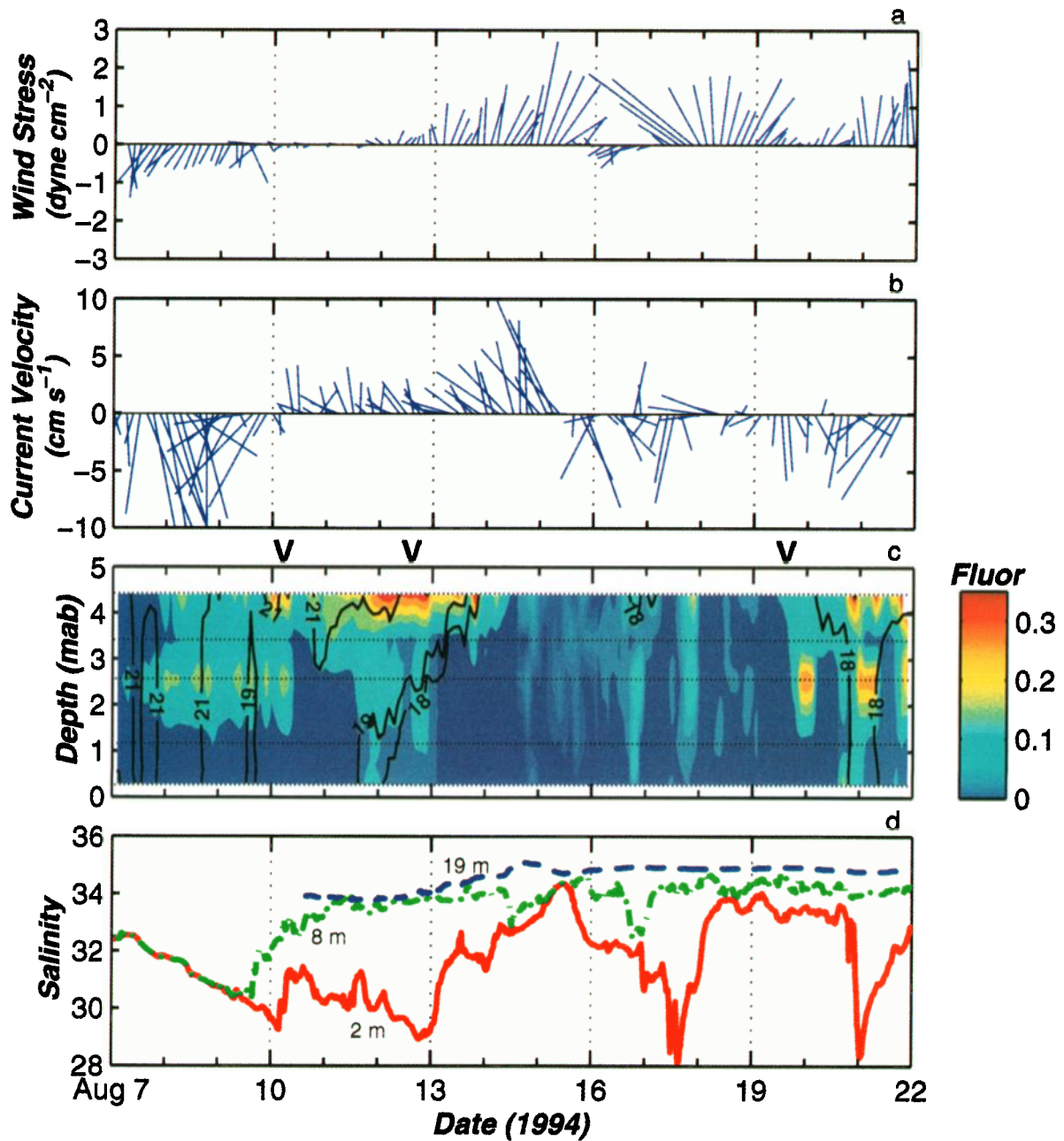
Plate 2. As for Plate 1, but for August 7 to August 21, 1994. Caret marks indicate the times of the August 10, 12, and 19 CTD surveys shown in Figures 6b, 6c and 6d, respectively. Also, Plate 2d shows salinities for three depths recorded at the CoOP mooring site. Note that the series in Plates 1 and 2 overlap by one day (Aug 7) to provide continuity.

waters off Cape Hatteras, North Carolina. The exposed shelf region off Cape Hatteras is an area of confluence of a variety of water masses, including Chesapeake Bay outflow, Mid-Atlantic Bight shelf water, North Atlantic slope water and Gulf Stream water [Churchill and Cornillon, 1991; Pietrafesa et al., 1994; Wood et al., 1996; Churchill and Berger, 1998]. This region is also subject to frequent wind-forced upwelling and downwelling episodes [Pietrafesa et al., 1985; Lentz et al., 1999; Rennie et al., 1999]. Our study examined the manner in which phytoplankton biomass distributions of this area were related to water properties and physical processes such as wind-forced circulation and sediment resuspension. We also sought to quantify the variability and magnitude of the lateral transport of chloropigments (i.e., chlorophylls and associated degradation products).

2. Measurements

2.1. The Coastal Ocean Processes and Ocean Margins Program Field Project

The data employed in our study came from two coordinated field projects carried out over the inner shelf east of Duck, North Carolina during the summer of 1994. The U.S. Department of Energy funded one of the projects as part of the Ocean Margins Program (OMP). A principal goal of the OMP was to assess the role of carbon cycling and transport in the coastal ocean on the global carbon budget. The other project was funded by the National Science Foundation as part of the Coastal Ocean Processes (CoOP) program. This was an interdisciplinary effort aimed at better understanding processes influencing the movement and fate of larvae of selected marine invertebrate species.

The area offshore of Duck was chosen as the site for the CoOP project partly because of its proximity to the U.S. Army Corps of Engineers' Coastal Engineering Center's Field Research Facility (FRF). The bathymetry of the area is rela-

tively smooth in the alongshore direction (Figure 1). A prominent bathymetric feature in the offshore direction is a steeply sloping region, known as the shore face, which connects the surf zone with the more gently sloping continental shelf. The shore face offshore of Duck extends to about 20 m depth and to 5-10 km offshore. A number of different water masses are known to occupy the study region.

The CoOP and OMP projects both contributed to an array of instruments set out along a line extending offshore of the FRF (Figure 1). The CoOP program supplied the majority of instruments to the array. These included current meters affixed to moorings or submarine structures, meteorological buoys, in situ zooplankton collectors, and conductivity-temperature-depth (CTD) sensors (see Lentz et al. [1999] for a more complete description of the CoOP array). Contributions from OMP investigators included a bottom-mounted acoustic Doppler current profiler (ADCP), an instrumented bottom tripod, and pCO_2 and O_2 sensors [DeGrandpre et al., 1997].

As part of the CoOP project, CTD-ADCP surveys were carried out over the inner shelf east of Duck almost continuously throughout August 1994 [Waldorf et al., 1995; Largier and Millikan, 1996]. Survey measurements were acquired along lines extending offshore. Although the location of transects varied from survey to survey, all surveys included measurements along the line of the moored instrument array, hereinafter referred to as the central CoOP transect (Figure 1). The CTD (Seabird 911 plus) was outfitted with a SeaTech transmissometer and a Chelsea fluorometer. On four occasions this package was lowered repeatedly over periods of 1-2 days at a single "anchor" station near the bottom tripod site.

2.2. Fluorescence Measurements

The CoOP-OMP project produced three types of fluorescence measurements. Relatively large-scale distributions of fluorescence were provided by the CTD surveys. Because the
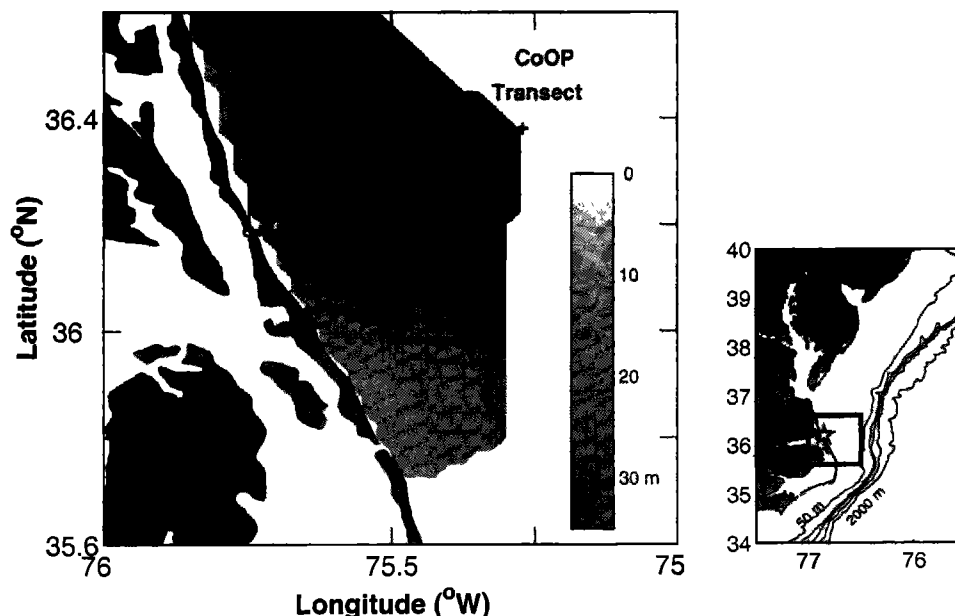
Figure 1. Map of study site showing the location of the Benthic Acoustic Stress Sensor (BASS) tripod (star) and CTD stations (crosses) of a typical survey conducted along the CoOP study's mooring line, hereinafter referred to as the central CoOP transect. Also affixed to the BASS tripod was a string of eight thermistors and a multisensor fiber-optic fluorometer. Depth contours for the large area map include 50, 200, 500, 1000, and 2000 m.

fluorometer attached to the CTD was not calibrated, its measurements are reported here simply in units of output voltage.

A series of vertical fluorescence profiles at a single location were produced by two of the anchor station surveys. Both were on the central CoOP transect. The first was carried out over a 24 hour period on August 22-23 at the 15 m isobath at a location of 36°11.73'N, 75°43.91'W. This effort resulted in 52 vertical fluorescence profiles. The second was conducted over a 48 hour period on August 25-27 at the 20 m isobath at 36°12.50'N, 75°42.00'W, producing 115 profiles.

Time series of fluorescence within the bottom boundary layer were obtained using a multi-sensor in situ fiber-optic fluorometer mounted on a tripod deployed at the 20 m isobath at a location of 36°11.93'N, 75° 42.25' W (Figure 1). This instrument enabled us to acquire fluorescence measurements at a number of levels with minimal flow disturbance [*D'Sa et al.,* 1997]. It was outfitted with eight fiber-optic sensors [*D'Sa and Lohrenz,* 1999], which were mounted along a tripod leg. Usable data were obtained from five sensors (at 0.27, 1.2, 2.6, 3.4 and 4.4 m above bottom (mab)). Sampling was done every 0.67 hours and entailed acquiring 10 fluorescence measurements at ~0.1 s intervals at each sensor. The average of each 10-sample burst was recorded.

Also affixed to the tripod were a Benthic Acoustic Stress Sensor (BASS) array [*Williams et al.,* 1987] and a string of eight thermistors. The BASS array consisted of a pressure sensor (Paroscientific Digiquartz) and four pulsed acoustic travel time current meters (at 0.25, 1.2, 2.6 and 4.4 mab) mounted along the tripod's central axis. Each current meter was composed of four transducer pairs that were used to measure velocities (from acoustic travel differences) within a 12 cm diameter by 12 cm length volume. Acquisition of samples by the BASS sensors occurred at 0.65 s intervals.

Pre-deployment and post-deployment calibrations of the fiber-optic fluorometer sensors were conducted using a Turner Designs Model 10 fluorometer and log phase batch cultures of *Nannochloris atomus* Butcher Strain CCMP509 (Provasoli-Guillard National Center for Culture of Marine Phytoplankton, Bigelow Laboratory for Ocean Sciences). This alga was chosen because it is a coastal isolate, grows relatively rapidly, and is easy to maintain. The cultures were grown in batch conditions at 20°C under an irradiance of ~60 μmol quanta m^{-2} s^{-1} on a 12:12 light:dark cycle. The growth medium was artificial seawater enriched with *f*/2 nutrients [*Guillard,* 1975]. Ammonium chloride was used as the nitrogen source. The cultures were maintained in log phase for the experiments. The calibration procedure entailed immersing each sensor of the fiber-optic fluorometer within a bath in which the phytoplankton concentration was varied sequentially while acquiring fluorescence measurements F_{FO}. Fluorescence was also measured on aliquots of the suspensions using a Turner Designs Model 10 fluorometer (F_T). Because response factors differed among the different fiber-optic sensors, it was desirable to scale the output of each sensor so that results could be expressed in a common set of units. To accomplish this, regression relationships between F_{FO} and F_T for each sensor were determined and subsequently used to convert the outputs of the fiber-optic sensors to the corresponding values of F_T. The r^2 values for these regressions were, in all cases, ≥0.99. The fiber-optic fluorometer time series shown here are expressed as the converted F_T values (arbitrary units). Stability of the Turner fluorometer
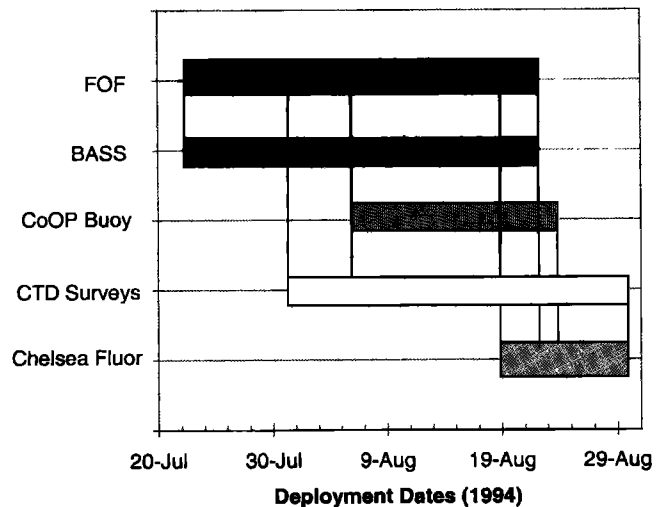

Figure 2. Time line for deployment of various measurement platforms (FOF, fiber-optic fluorometer; BASS, Benthic Acoustic Stress Sensor; and Chelsea Fluor, Chelsea fluorometer on CTD profiling package).

was verified by calibration with pure chlorophyll *a* (Sigma) in 90% acetone [cf. *Walsh et al.,* 1988].

It is important to note that the measurement windows of the various types of observations did not coincide (Figure 2). The fiber-optic fluorometer and BASS array acquired data from July 24 through August 22. Acquisition of temperature and salinity time series from the CoOP mooring adjacent to the BASS tripod did not commence until August 7. Hydrographic surveying of the study region began on August 1 and continued through August 30. The final 12 days of surveying included fluorescence data collected with the Chelsea fluorometer on the ship's CTD, thereby extending the period over which fluorescence data were collected.

2.3. Water and Sediment Sampling

During deployment and retrieval of the BASS tripod (on July 23 and August 31 respectively), water samples were acquired at the tripod site in 10 L Niskin bottles attached to a General Oceanics, Inc., rosette. The samples were analyzed for concentrations of chlorophyll *a*, phaeopigments, and total particulate carbon (PC). Determination of the chlorophyll and phaeopigment content of the water samples began with filtration on GF/F filters followed by extraction in a 1:1 mixture of dimethylsulfoxide and 90% acetone in darkness at –20°C for a minimum of 2 hours. The extracts were centrifuged (5 min at 1000 rpm), and concentrations of chlorophyll and phaeopigments were determined by fluorescence [*Holm-Hansen et al.,* 1965] using a Turner Designs Model 10 fluorometer. PC was determined by filtration on 0.4 μm silver filters (Poretics) followed by drying and analysis using a Carlo-Erba NA1500 carbon/nitrogen analyzer with sulfanilamide as a primary standard.

Surficial sediment samples near the tripod were collected by divers and were analyzed for chloropigments, dry weight and particulate carbon (PC). The chloropigment analysis was carried out by combining a 3 cm^3 aliquot of sediment with 10 mL of a 1:1 mixture of dimethylsulfoxide and 90% acetone. Extracts of the mixture were analyzed for chloropigment con-

centration as described previously. For dry weight determination a 3 cm^3 aliquot of sediment was transferred onto a tared 47 mm 0.45 μm polycarbonate filter (Poretics) and rinsed three times with 5 mL of a 1 M ammonium formate solution. The rinsed sediment was transferred to a tared petri dish and dried at 60°C until weight was constant.

2.4. Conversion of fluorescence to chloropigment concentrations

For pigment flux calculations, fluorescence units were converted to pigment concentrations on the basis of relationships determined for laboratory phytoplankton cultures. Log phase batch cultures of *N. atomus*, as well as *Amphidinium* sp. and *Thalassiosira* sp. (Carolina Biological Supply's D8-15-3240 and D8-15-3110, respectively) were used. Growth conditions were as described for *N. atomus*. For *Thalassiosira* sp. the growth medium was supplemented with 250 μM sodium silicate. For *Amphidinium* sp. the medium was supplemented with 10 mL L^{-1} soil water extract (Carolina Biological Supply). Fluorescence of algal cultures was determined using the Turner fluorometer (F_T) and was related to pigment concentrations determined as described for water samples in section 2.3. Fitting a power function to the data yielded the relationship pigment (mg m^{-3}) = $820(F_T)^{1.01}$ (r^2 = 0.970, N = 177, and p < 0.001). Fluorescence values determined with the fiber optic fluorometer (F_{FO}) were converted into the equivalent Turner fluorescence units F_T, and pigment concentrations were subsequently estimated using the power function. We recognize that conversion of fluorescence to pigment concentrations in natural waters provides only an approximation because of the variable nature of chloropigment fluorescence [*e.g.*, *D'Sa and Lohrenz*, 1999]. However, because the natural variations in fluorescence (and presumably pigment concentrations) were quite large, such errors in conversion are unlikely to alter substantially our conclusions about relative magnitudes of chloropigment fluxes.

2.5. Wind Data

Meteorological data from National Oceanic and Atmospheric Administration buoy 44014 were obtained from the Data Buoy Center archive. The buoy was moored in 58 m of water at 36°34.59'N, 74°50.01'W, roughly 60 km east of our study region. Its measurements of wind speed and direction were converted to wind stress as described by *Pietrafesa et al.* [1994].

3. Large-Scale Pigment Distribution

Views of pigment distribution across the inner shelf of the study region were provided by data from the seven CTD surveys carried out over August 19-30 (when the CTD carried an operational fluorometer). To characterize the fluorescence measurements of these surveys, we computed a mean distribution of fluorometer voltage measured over the CTD transect spanning the instrument array. This was accomplished by averaging the vertical profiles of fluorometer voltage measured at each of the repeated stations. These temporal means of fluorometer voltage identified a stable trend in the pigment field as each exceeded the standard deviation about the mean by a factor of 4-7. The field of mean fluorometer voltage (Figure 3) shows that pigment concentrations tended
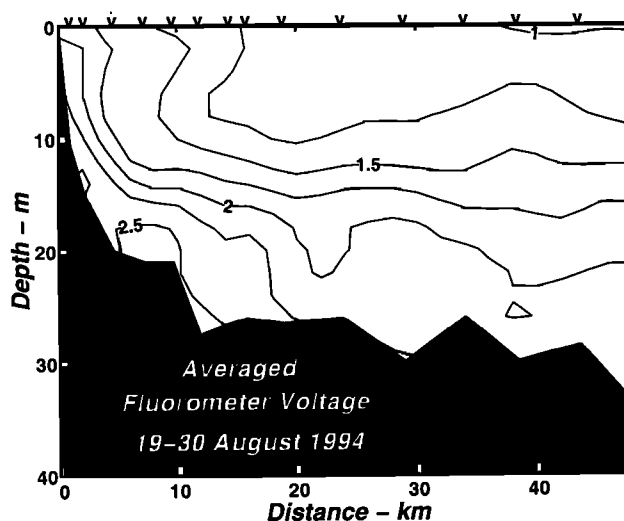

Figure 3. Mean distribution of fluorometer voltage measured across the central CoOP transect (Figure 1) during August 19-30, 1994. The field was computed from the data of seven CTD transects extending across the line. The stations at which fluorometer voltage profiles were acquired are indicated by the caret marks along the upper axis. The field was created using the average profile at each station.

to increase with depth. This field also showed a dramatic onshore increase in pigment concentration over the shore face. Near-surface waters seaward of the shore face had relatively low pigment concentrations as evidenced by uniformly low averaged fluorometer voltages of <1.25.

Details of the near-shore pigment distribution appeared to change because of upwelling and downwelling. Fluorometer measurements acquired during times of an upwelled thermocline showed the highest pigment concentrations over the shore face, with pigment-enriched water extending to the surface in the very near-shore zone (Figure 4a). By contrast, pigment concentrations observed during times of a downwelled thermocline were highest in the near-bottom waters just seaward of the shoreface (Figure 4b).

A feature often seen in the presence of a downwelled thermocline was a band of relatively fresh near-surface water adjacent to the coast (Figure 4b). This was presumably an extension of the low-salinity plume emanating from the Chesapeake Bay mouth (hereinafter referred to as Chesapeake plume water) driven into the study region by southward (downwelling favorable) winds. Fluorometer measurements indicated that this water often, but not always, carried relatively high pigment concentrations.

The issue of whether high pigment concentrations tended to reside in particular water masses was explored by examining the temperature-salinity (T-S) properties and associated fluorometer voltages of water measured along the moored array line during August 19-30, (Figure 5). The T-S properties revealed that the mooring line was occupied by a number of dissimilar water masses. The range of T-S properties was particularly great at more than 10 km from shore (Figure 5b). Contributing to this broad T-S distribution were a near-surface intrusion of Gulf Stream water (with T > 20°C and S > 35), a near-bottom intrusion of relatively cold and high-salinity water (T < 18°C and S > 35), and a warm and low-salinity water mass of presumably Chesapeake plume water (T > 22°C

(a)
29 August 1994

Temperature

Salinity

Fluorometer Voltage

(b)
25 August 1994

Temperature

Salinity

Fluorometer Voltage
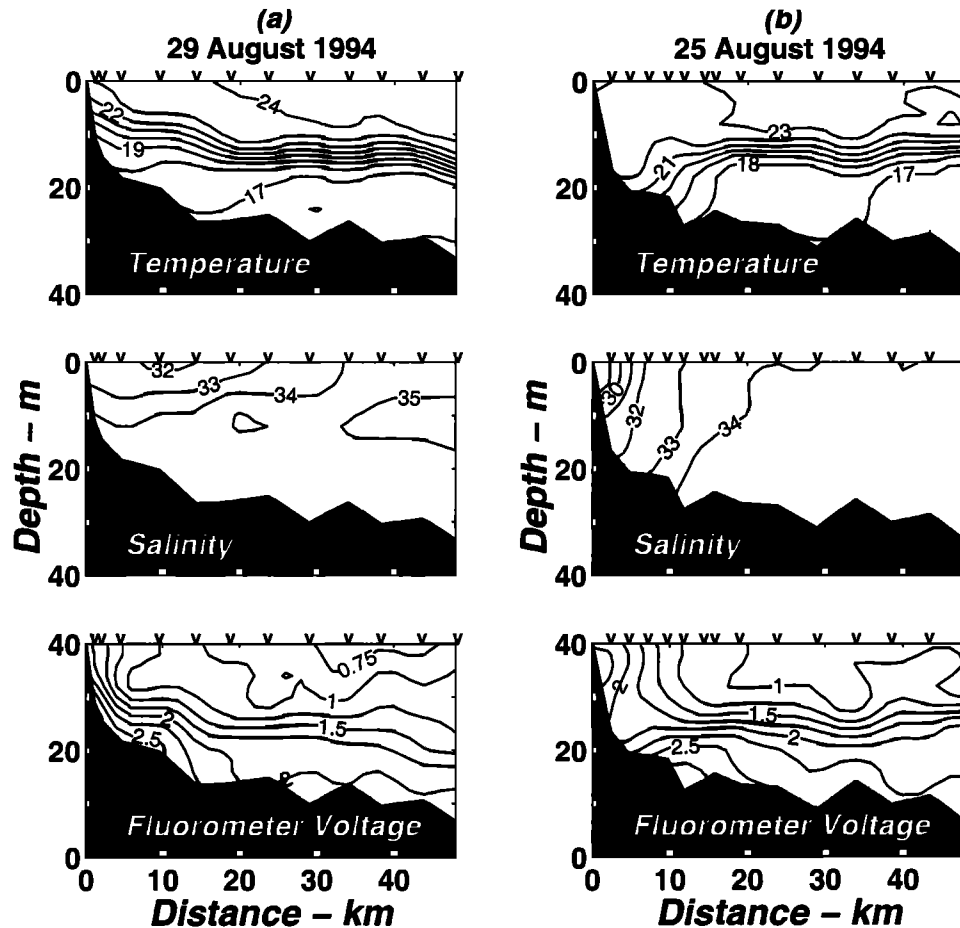
Depth – m

Distance – km

Figure 4. Cross-shelf distributions of temperature, salinity, and fluorometer voltage determined from CTD profiles along the central CoOP transect line (Figure 1) during conditions of (a) upwelling and (b) downwelling.

and $S < 32$). Also observed farther than 10 km from shore, by a small number of measurements, was cold water ($T < 16°C$) of intermediate salinity (~34.2). Its T-S properties were typical of subthermocline Mid-Atlantic Bight shelf water seen farther to the north, often referred to as cold-pool water [*Houghton et al.*, 1982; *Churchill et al.*, 1993; *Wood et al.*, 1996]. T-S properties of water observed <10 km from shore were not as widely scattered (Figure 5a). They revealed the presence of Chesapeake plume water and warm and saline water, presumably containing a portion of the surface Gulf Stream water intrusion. However, most of the water observed <10 km from shore had T-S properties that were tightly distributed about a line extending from roughly $T = 17°C$, $S = 35$ to $T = 22.5°C$, $S = 32.3$. This was water residing within and below the thermocline-halocline, which intercepted the bottom in the near-shore zone (Figure 4). It included the near-bottom intrusion of cold high-salinity water, presumably of slope water or Gulf Stream origin.

High pigment concentrations, indicated by fluorometer voltage in excess of 2.5, were observed only in the thermocline and subthermocline water described above (Figure 5c). Intermediate pigment concentrations, marked by fluorometer voltages of 2-2.5, spanned a wider range of T-S properties that included Chesapeake plume water (Figure 5d). However, low-pigment concentrations, evidenced by fluorometer voltages

<1.5, were also observed in Chesapeake plume water (Figure 5e). Of particular note was the low fluorescence in the near-surface intrusion from the Gulf Stream, indicative of the low pigment concentrations characteristic of this oligotrophic water mass.

4. Temporal Variations

Measurements from the BASS tripod provided time series of current and vertical structure of temperature and pigment concentration in the bottom boundary layer near the base of the shore face (Plates 1 and 2). With the aid of CTD data acquired along the central CoOP transect line (Figure 6) and the buoy 44014 wind measurements (Plates 1 and 2) we have traced the passages of water masses over the BASS tripod and related these to wind-forced circulation. Throughout the first 12 days of the BASS deployment (July 24 to August 4), winds over the study region were directed northward, or upwelling favorable, and near-bottom currents were weak and variable (Plate 1a and 1b). During this time the BASS tripod was occupied by subthermocline water (Figure 6a) with salinity of roughly 34.1 and vertically uniform temperatures in the range of $14.5°-15°C$. Strong southward (downwelling favorable) winds persisted over the next 4 days (August 6-9; Plates 1a and 2a). These were accompanied by a southeastward (along-
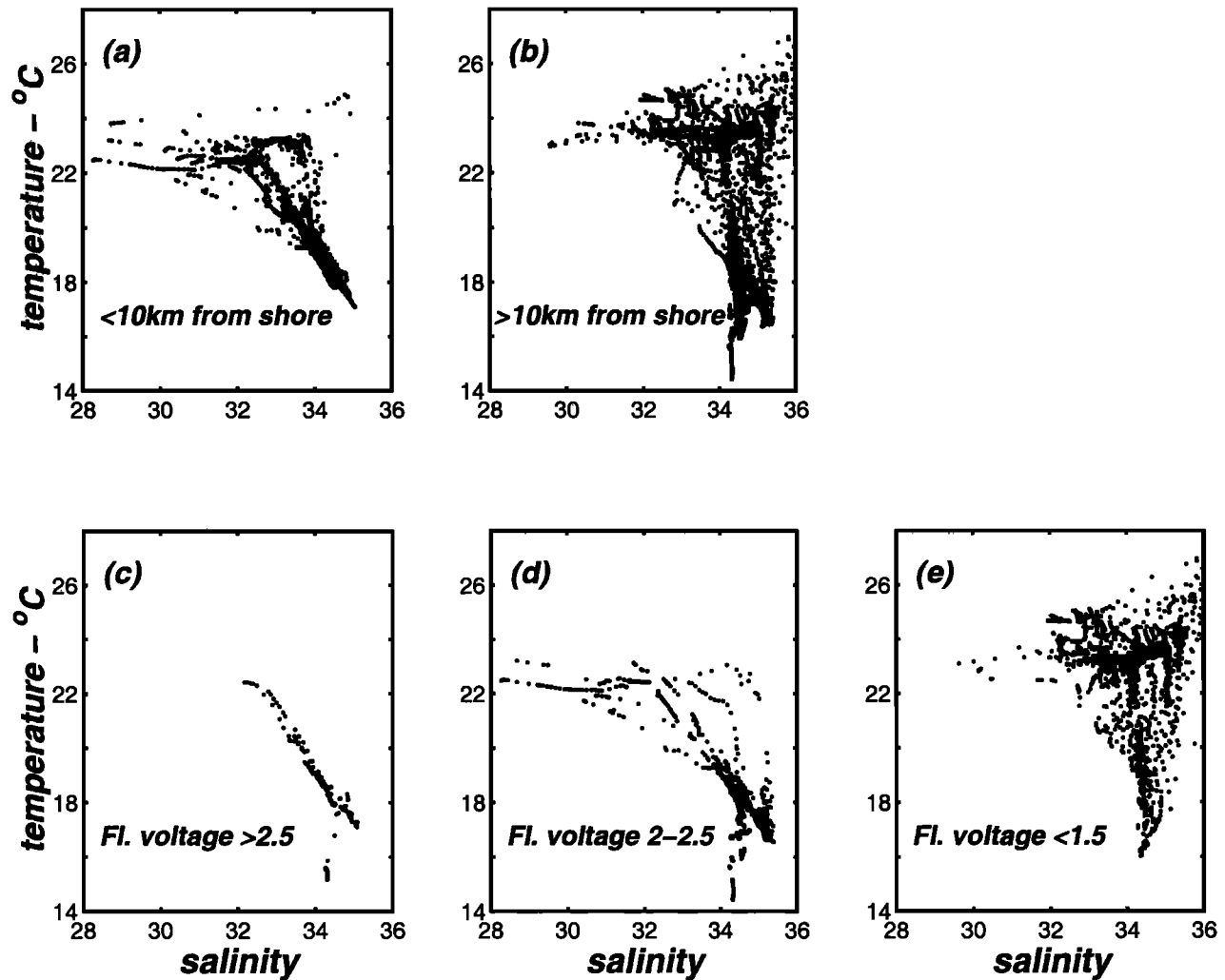
Figure 5. *T-S* properties determined from CTD profiles along the central CoOP transect during August 19-30, 1994. (a) and (b) *T-S* properties measured over the indicated distances from shore, and (c)-(e) *T-S* properties corresponding to the indicated ranges of fluorometer voltage.

shore) flow in the near-bottom water (Plates 1b and 2b) and a depression of the nearshore thermocline (Figure 6b). Movement of the retreating thermocline past the tripod was evidenced by a rapid increase in temperature, from 15° to 21°C (Plates 1c and 2c). Near-bottom currents shifted to the northwest, and the thermocline migrated shoreward during the ensuing period of weak winds (Plate 2 and Figure 6c). Its movement past the tripod was marked by vertical stratification of the tripod's temperature measurements (Plate 2c). Salinity stratification was evident in the CoOP buoy data (Plate 2d). Strong winds out of the south were predominant over the last 9 days of the BASS measurement period (Plate 2a). This pattern was interspersed with brief periods of light winds during August 16 and 19-20. Throughout this 9 day period, near-bottom currents were again generally weak and variable and the tripod occupied a near-bottom intrusion of warm (*T* ~ 17°-18°C) and highly saline (*S* ~ 35) water (Plate 2 and Figure 6d).

The BASS fluorometer measurements revealed a complex and rapidly changing vertical structure of near-bottom pigment concentration (Plates 1 and 2). Of particular note is that most features with relatively high pigment concentration were

localized to vertical bands of 0.5-2 m thickness. These features tended to be transient, most lasting for less than a day. In spite of this, pigment concentrations observed by the BASS fluorometer measurements changed in a recognizable pattern with time and with water mass. The subthermocline water observed at the tripod during the first 12 days of the deployment contained numerous patches of relatively pigment-rich water (Plate 1c). These appeared both near the bottom and at the upper range of the fluorometer string. Fluorescence levels were generally lower in the warm water that appeared at the tripod during the downwelling episode of August 6-10 (Plates 1c and 2c). Pigment-rich water returned to the site during the time when the thermocline migrated shoreward past the tripod during August 10-14 (Plate 2c). Highest levels were largely confined to the 20°-21°C water at the top of the thermocline. High pigment concentrations persisted in this water over the entire 4 days of the thermocline's passage. Moderate pigment concentrations were seen extending to the bottom in the colder (18°-19°C) thermocline water. Pigment concentrations in the warm high-salinity subthermocline water that appeared at the tripod during the last 9 days of the deployment were initially low (Plate 2c). Episodes of slightly
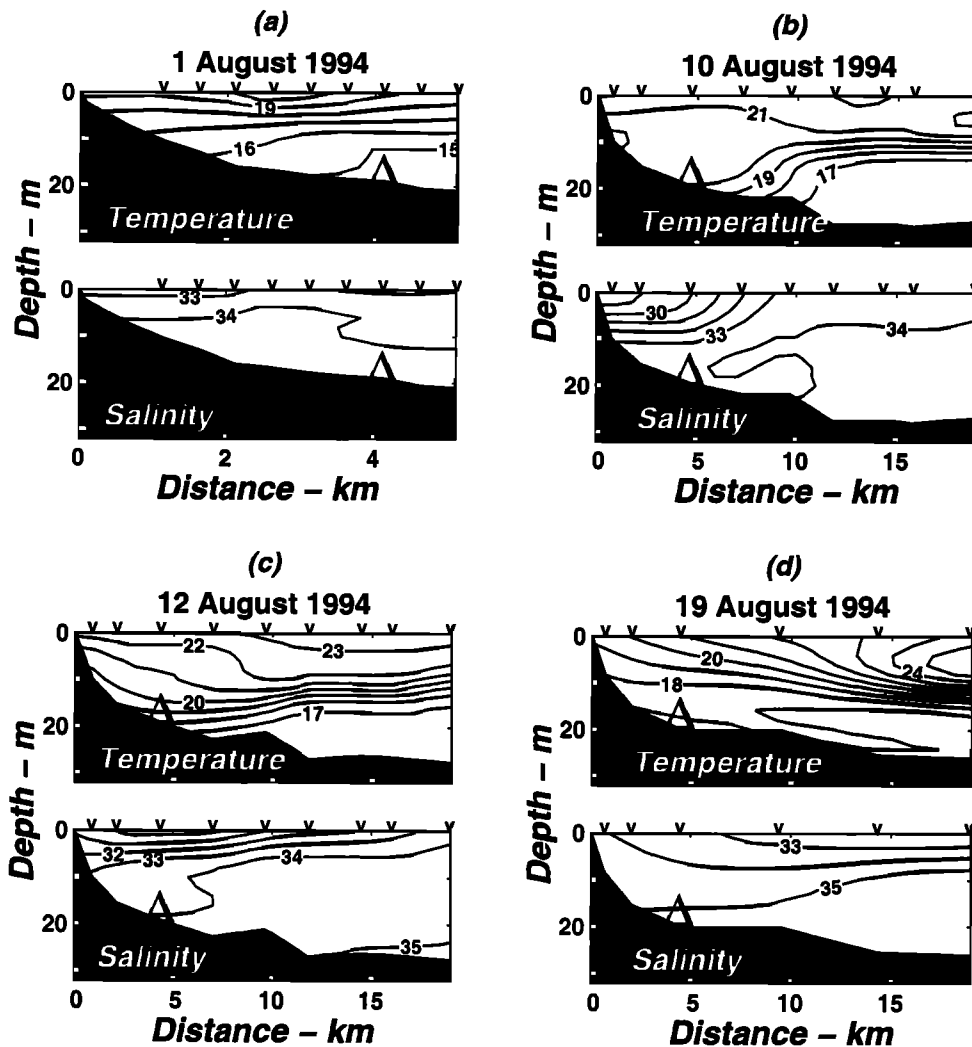
Figure 6. Cross-shelf distributions of T and S determined from CTD measurements along the central CoOP transect (Figure 1) during the indicated dates. The location of the BASS tripod is marked by a triangle.

increased fluorescence were seen during August 16 and 17 that coincided with decreased surface salinities. During the final 2-3 days of the time series, fluorescence exhibited large temporal and vertical variations. The patches of pigment-enriched water seen during this latter period were similar in magnitude to those observed in the early stages of the deployment. They were confined to 1-2 m vertical layers and persisted over short periods (typically <1 day). Decreased surface salinities were also evident during the final day of the time series.

The anchor station survey of August 25-27 gave an additional view of the pigment and water property structure at the tripod site. The survey occurred after a downwelling episode. CTD measurements from the central CoOP transect (Figure 4) indicated that the thermocline was seaward of the survey site on August 25 and migrated past the site during the course of the survey. This scenario was consistent with the anchor station temperature measurements (Plate 3) which showed vertically mixed warm water at the outset of the survey that was gradually displaced by stratified water as the survey continued. Significant variations in pigment concentration were seen in the waters above and shoreward of the thermo-

cline. Fluorometer voltages measured in these waters were mostly low but also revealed midlevel patches of relatively high pigment concentration. These extended over vertical distances of 2-8 m and persisted at the site for of the order of 6 hours. The highest fluorometer voltages were recorded in near-bottom water beneath the thermocline. The fluorescence monotonically increased toward the bottom, raising the possibility that it may have been due to pigments in resuspended material that was confined beneath the thermocline.

5. Temporal and Spatial Correlation Scales

As noted above, the tripod measurements showed a patchy near-bottom pigment field at the study site, varying over much shorter temporal and vertical scales than the near-bottom temperature field seen at the tripod (Plates 1c and 2c). A systematic comparison of the scales of property variation in the bottom boundary layer was performed using correlation analysis.

To quantify temporal scales of variation, we computed autocorrelation functions of temperature, fluorescence, and velocity components measured at the tripod (Figure 7). The
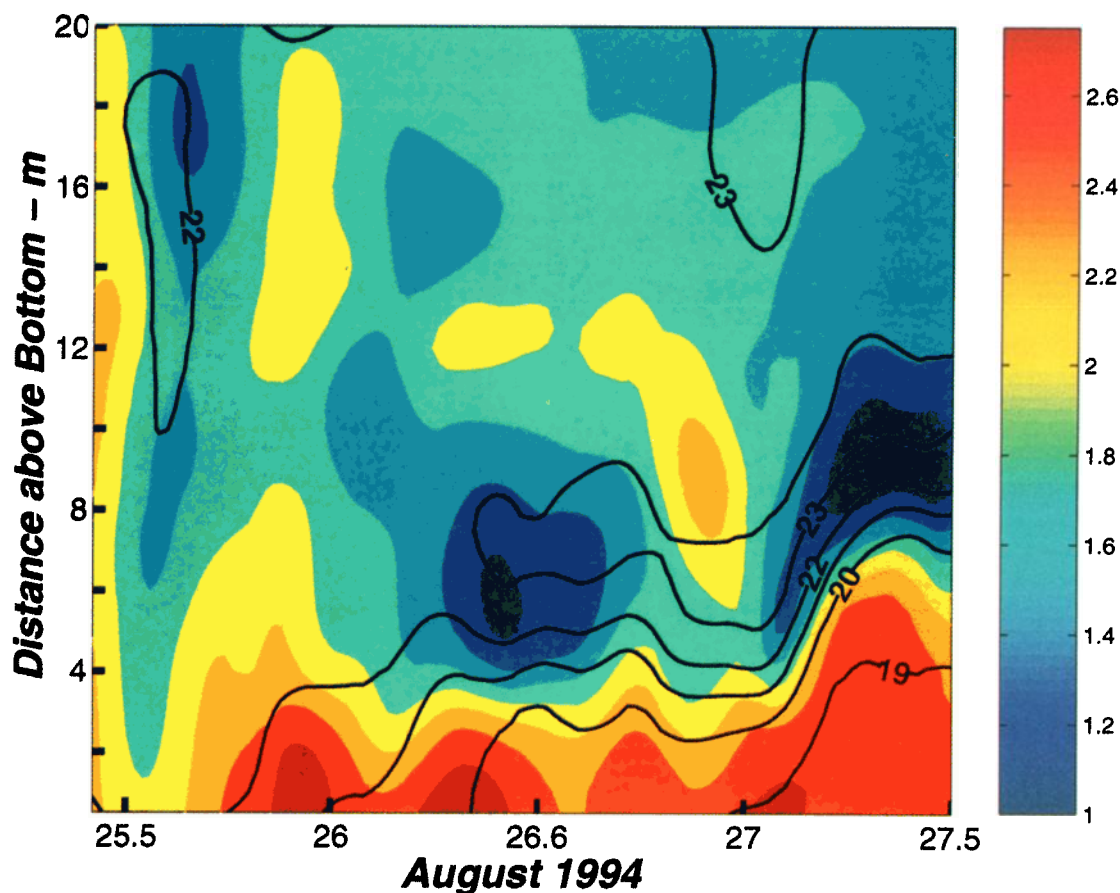
Plate 3. Contoured time series of fluorometer voltage (colors) and temperature (solid lines) measured by repeated CTD profiling from a vessel anchored at the BASS tripod site (Figure 1).

autocorrelation estimates were computed at time lags set equal to the time intervals between measurements (0.33 hours for currents and temperature and 0.67 hours for fluorescence). All autocorrelation estimates at the initial time lag were relatively high (exceeding 0.95 for currents, 0.99 for temperature, and 0.85 for fluorescence), indicating that the measurement intervals were adequate to resolve major temporal variations of the measured properties. The subsequent decay of the functions with increasing time lag revealed significant differences between the temporal variations of temperature with those of currents and fluorescence. At all measurement levels the autocorrelation function of temperature decayed far more gradually than the autocorrelation functions of velocity and fluorescence. The autocorrelation function of the cross-shelf current component exhibited the most rapid decay with increasing lag time.

The correlation timescales (Table 1), defined here as the time lag at which the autocorrelation function decayed to 0.1, demonstrated the uniqueness of fluorescence variations as compared with the fluctuations of other properties. The correlation timescales of temperature and current components exhibited small differences (<40%) between measurement levels. Apparently, each of these properties varied with a nearly uniform temporal scale throughout the bottom boundary layer. By contrast, fluctuations of fluorescence changed significantly going upward through the bottom boundary layer. Correlation timescales of fluorescence dif-

fered by a factor of 3, averaging about 4.5 days at the 2.6 and 4.4 mab sensors and 1.5 days at the 0.27 and 1.2 mab sensors.

Differences in fluorescence fluctuations going upward through the bottom boundary layer were also indicated by the zero time lag cross-correlation matrix of the fluorescence measurements (Table 2). Correlations of the fluorescence series decayed rapidly with vertical separation, reflecting the heterogeneous vertical structure of near-bottom fluorescence. By contrast, variations of currents and temperature were strongly coupled throughout the bottom 4.4 m. All correlations were highly significant ($p < 0.001$).

6. Contribution of Locally Resuspended Sediment

An objective of our study was to assess the contribution of locally resuspended sediments to the chloropigment load of the study area. Analysis of sediment and water column samples taken during tripod deployment and recovery cruises (Table 3) revealed a large reservoir of PC in bottom sediment at the tripod. The PC loads in the upper 3 cm of this sediment exceeded the PC loads measured in the overlying water column by more than a factor of 5. However, materials to which our fluorometers responded, chloropigments, were not as abundant in the bottom sediments. Chloropigment loads of the water column and upper 3 cm of sediment were comparable.
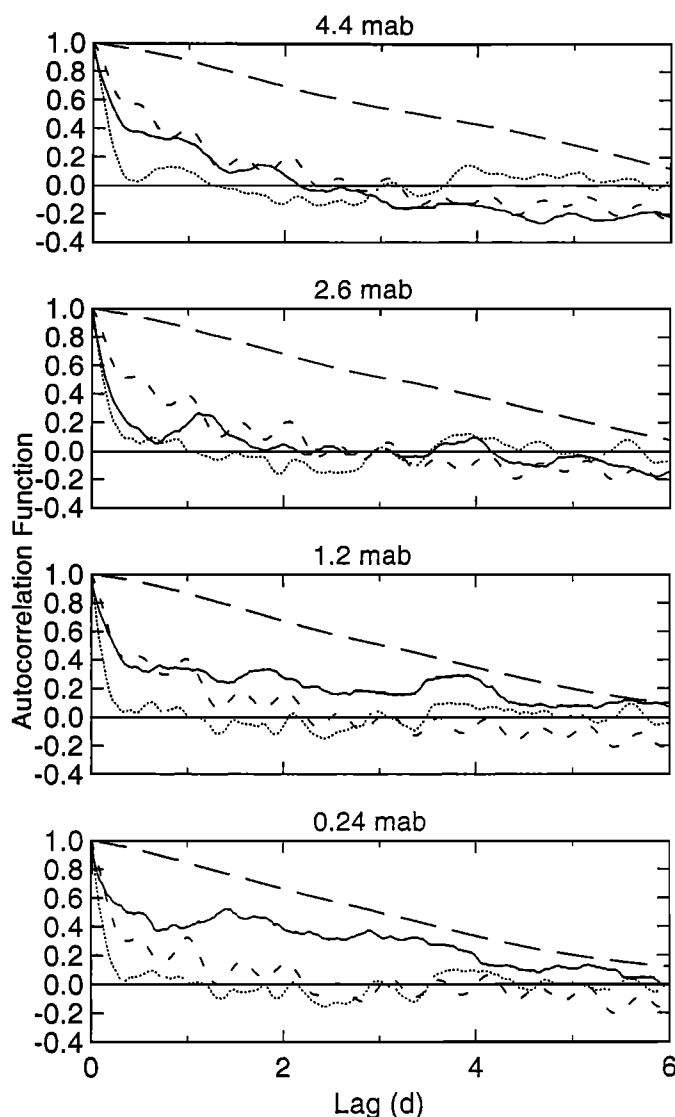
4.4 mab

2.6 mab

1.2 mab

0.24 mab

Autocorrelation Function

Lag (d)

Figure 7. Autocorrelation functions of alongshore (dashed line) and cross-shore (dotted line) components of currents, temperature (long-dashed line), and fluorescence (solid line) measured at the BASS tripod.

To assess the contribution of resuspended sediments to the chloropigment loads seen at the tripod, we used the tripod's velocity and pressure measurements to estimate the stress acting on the bottom sediment. The computations were done according to the method outlined by *Grant and Madsen* [1979]. In following their scheme, bottom stress was determined using the nonlinear product of orbital velocities due to surface waves and more slowly varying "steady" flow. Flow parameters required to implement the scheme included the steady flow at a specified distance above the bottom and a characteristic amplitude and period of the near-bottom orbital wave velocities. These were specified over 20 min intervals. The steady flow over an interval was taken as the mean of the velocity at the lowest BASS current meter (at 0.25 mab). The required wave properties of each interval were determined by first converting BASS pressure measurements to a spectrum of orbital wave velocities using linear wave theory. The characteristic orbital velocity amplitude U_o was then computed from

$$U_o = 2\sqrt{\int S(f)df} \ ,$$

where $S(f)$ is the orbital wave velocity spectral estimate at frequency f. According to *Longuet-Higgins* [1952] this is roughly equal to the mean of the strongest third of the orbital wave velocities represented in the spectrum. The characteristic orbital velocity frequency f_o was computed as a weighted average over the spectra, i.e.,

$$f_o = \int f S(f)df \Big/ \int S(f)df$$

In computing the stresses the wave-induced and steady currents were assumed to be colinear.

The results (Figure 8) showed that flows and stresses acting on bottom sediments at the tripod site were relatively weak throughout most of the study period. Except for the period of the middeployment storm (August 6-7), the 20 min current averages and near-bottom orbital velocity amplitudes never exceeded 15 cm s^{-1}, and bottom stress estimates never exceeded 1.2 dyn cm^{-2}.

Lacking was evidence of significant chloropigment resuspension at the tripod. At no time were corresponding rises of fluorescence and estimated bottom stress observed (Figure 8). Most notably, the large stresses of the August 6-7 storm were not matched by rises in chloropigment concentration. In addition, near-bottom fluorescence was highest during the prestorm period when the estimated stresses were consistently low. We conclude that the majority of chloropigments seen at the tripod were not made up of locally resuspended material.

7. Lateral Transport of Chloropigments in the Bottom Boundary Layer

Measurements from the tripod's sensors allowed for the calculation of lateral chloropigment flux in the bottom boundary layer. To do this, chloropigment concentrations were estimated from fluorescence measurements as described in section 2.4. The scalar product of velocity x pigment

Table 1. Correlation Timescales for Time Series Measured at the BASS Tripod

Depth, mab	Variable	τ, days
4.4	alongshelf current	1.8
4.4	cross-shelf current	0.30
4.4	temperature	6.1
4.4	fluorescence	1.4
2.6	alongshelf current	1.3
2.6	cross-shelf current	0.33
2.6	temperature	5.8
2.6	fluorescence	1.5
1.2	alongshelf current	1.2
1.2	cross-shelf current	0.25
1.2	temperature	5.9
1.2	fluorescence	4.4
0.25	alongshelf current	1.2
0.25	cross-shelf current	0.25
0.27	temperature	6.3
0.27	fluorescence	4.4

Table 2. Cross-Correlation Matrices (Zero Time Lag) of Measurements Acquired at Different Depths Within the Benthic Boundary Layer

Variable	Depth, mab	Cross Correlation			
		4.4	2.6	1.2	0.25[a]
alongshore	4.4	1.0	0.962	0.893	0.802
current	2.6		1.0	0.952	0.861
	1.2			1.0	0.950
	0.25				1.0
cross-shelf	4.4	1.0	0.862	0.723	0.709
current	2.6		1.0	0.895	0.860
	1.2			1.0	0.955
	0.25				1.0
temperature	4.4	1.0	0.979	0.955	0.936
	2.6		1.0	0.986	0.967
	1.2			1.0	0.988
	0.27				1.0
fluorescence	4.4	1.0	0.328	0.292	0.164
	2.6		1.0	0.355	0.396
	1.2			1.0	0.475
	0.27				1.0

[a]Fluorescence and temperature sensors were set at 0.27 mab.

concentration, chloropigment flux, was determined at each of the BASS sensor depths (0.25, 1.2, 2.6, and 4.4 mab). The fluxes were specified in a local coordinate system in which the along-isobath direction was set at 10° counterclockwise of north. Also computed was the mean flux of each time series together with its 90% confidence limits (Table 4). In determining the confidence limits, the number of degrees of freedom was taken as the ratio of the time series length (29 days) to the correlation timescale of each flux series (specified as described in section 5).

All chloropigment flux time series exhibited a high degree of variability marked by frequent reversal in flux direction (Figure 9). The fluctuations occurred over timescales ranging from a few hours to a number of days. Owing to these large variations, means of the fluxes were not well determined. Most means were smaller than, or comparable to, their 90% confidence intervals. Mean fluxes that could be judged to be statistically significant showed a net shoreward transport of chloropigments in the lower boundary layer. However, because of the short duration and spatially localized nature of the flux series, it would be inappropriate to extrapolate such findings over longer timescales.

8. Summary and Discussion

An unanticipated finding of our study was the high degree of small-scale structure seen in the near-bottom fluorescence distribution. Most remarkable was the small (0.5-2 m) vertical extent of chloropigment patches seen at the tripod, many of which did not extend to the bottom. These enriched chloropigment patches were not, as a rule, associated with strong discontinuities of water properties. Rather, most were embedded in much larger scale water masses. Previous investigators [e.g., *Derenbach et al.*, 1979; *Cowles and Desiderio*, 1993; *Palowitch and Jaffe*, 1995; *Jaffe and Franks*, 1997] have also observed small-scale structure in fluorescence distributions. *Mitchell and Fuhrman* [1989], using high-precision vertical sampling, observed centimeter-scale variations in chlorophyll *a* concentrations and bacterial abundance in the pycnocline of Chesapeake Bay waters. More recent studies have provided evidence for the existence of thin layers of biological, optical, and chemical properties that persist over ecologically relevant timescales of hours [e.g., *Cowles et al.*, 1998; *Hanson and Donaghay*, 1998]. The presence of such features reflects the interplay of biological and physical processes. Physical mechanisms that have been invoked to explain the presence of small-scale features in phytoplankton distributions include accumulation at density interfaces or fronts, horizontal intrusion of adjacent water masses, localized shear or turbulence, chaotic mixing, and internal waves [e.g., *Franks*, 1992, 1995, 1997; *Cowles et al.*, 1998; *Osborn*, 1998]. *Franks* [1992, 1995, 1997] produced a series of models to simulate many of these phenomena including accumulation at density interfaces or fronts, near-inertial wave shear, chaotic mixing in nonturbulent flows, and internal wave banding. *Osborn* [1998] noted that because of different initial distributions of particles relative to physical properties and different motion of particles relative to water, there is no a priori reason why the fine structure of biological layers should align with that of temperature/salinity/density fields. Motion of particles relative to water can be due to factors such as buoyancy differences or swimming behavior. In addition to physical mechanisms, changes in abundance of particles may result from in situ biological processes such as growth and grazing. However, the relatively short timescales of duration of pigment features in our data led us to conclude that advection of features past the tripod was primarily responsible for the short-term variability, as opposed to in situ production or removal of pigments by biological activity. *Whitledge and Wirick* [1986] also cited advection of pigment patches as an explanation for the variability they observed in time series of fluorescence in the Mid-Atlantic Bight.

Table 3. Water Column and Sediment Inventories of Chloropigments and PC

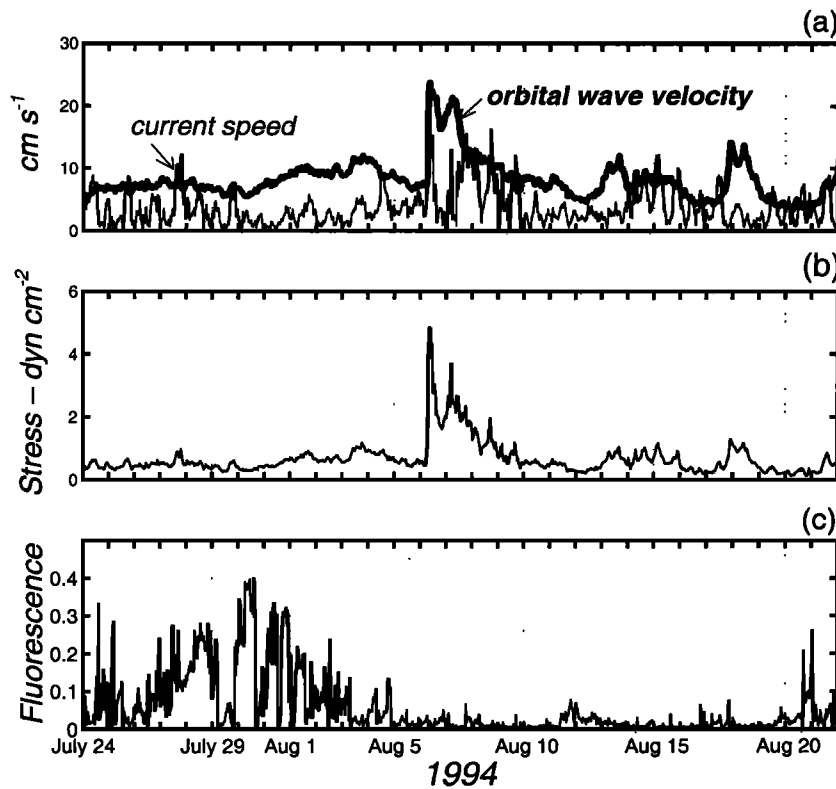| Date	Water Column			Sediments (upper 3 cm)		
	Pigments, mg m^{-2}	PC, mg m^{-2}	PC/Pigment	Pigments, mg m^{-2}	PC, mg m^{-2}	PC/Pigment
July 23, 1994	121	9000	74.4	210	53400	254
Sept. 1, 1994	86.1	5840	67.8	54.5	31200	572
Sept. 1, 1994	268	13600	51	.	.	.

Figure 8. (a) Current speed (thin line) and characteristic orbital wave velocity (bold line) at 0.25 mab at the BASS tripod, both at 20 min intervals. Also shown are estimates of (b) bottom stress and (c) fluorometer signal at 0.27 mab.

The existence of small-scale structure in phytoplankton distributions may have profound implications for biological interactions. Cowles et al. [1998] noted that grazing and growth rates of herbivorous microzooplankton might change dramatically depending on whether an organism resides within or outside a thin layer of enhanced phytoplankton abundance. Indeed, fine-scale sampling has shown that microzooplankton distributions can be aggregated within 20-50 cm intervals [Bjornsen and Nielsen, 1991]. The possibility of active or passive aggregation of zooplankton in relation to spatially heterogeneous food concentration could significantly alter our perceptions of trophic interactions from those based on conventional sampling methodology. Zooplankton grazing may also contribute to pigment structure through differential grazing pressure [Therriault and Platt, 1978, Roman et al., 1986].

In addition to the small-scale features, our fluorescence measurements showed fairly well defined larger-scale patterns of the chloropigment distribution. Seaward of the shore face,

Table 4. Estimates of Mean Chloropigment Flux at the BASS Current Meter Depths[a]

Depth, mab	Alongshelf Flux	Offshelf Flux
4.4	1.9±4.1 x10⁻⁶	0.9±1.2 x10⁻⁶
2.6	-1.3±2.4 x10⁻⁶	-0.4±0.8 x10⁻⁶
1.2	0.2±0.6 x10⁻⁶	-0.6±0.3 x10⁻⁶
0.25	-0.5±0.5 x10⁻⁶	-0.1±0.3 x10⁻⁶

[a]Flux is in kg m⁻² s⁻¹. The errors are the 90% confidence intervals. The alongshore axis is positive to the NNE.

high chloropigment concentrations were confined principally to thermocline and subthermocline waters. This water often contained patches of chloropigment-enriched water. Within the shore face region, high chloropigment concentrations were observed over the entire water column. The source of near-surface chloropigments seen over the shore face appeared to vary with wind forcing. During times of southward (down-welling favorable) winds, Chesapeake plume water was seen over the shore face. During times of northward winds the Chesapeake plume water was replaced by pigment-enriched thermocline and subthermocline water apparently carried shoreward by upwelling circulation. Previous studies in this region have observed a similar pattern of high chlorophyll in thermocline and subthermocline waters during May [Verity et al., 1996] and July [Wood et al., 1996] of 1993. This pattern is also consistent with observations in the New York Bight [Malone et al., 1983; Falkowski et al., 1988]. In addition, Verity et al. [1996] reported high chlorophyll concentrations in low-salinity surface waters over the middle shelf south of the mouth of Chesapeake Bay, again consistent with our findings.

Our analysis clearly showed that locally resuspended sediments did not appreciably contribute to the chloropigment load observed at the tripod. However, this does not preclude the possibility that some fraction of the chloropigments sensed at the tripod may have been contained in recently resuspended sediment advected to the study site. For example, recently resuspended chloropigments may have been carried to the tripod from shallower water, where bottom stresses were likely greater, or from deeper water, where the supply of more easily resuspended sediment with chloropigments may
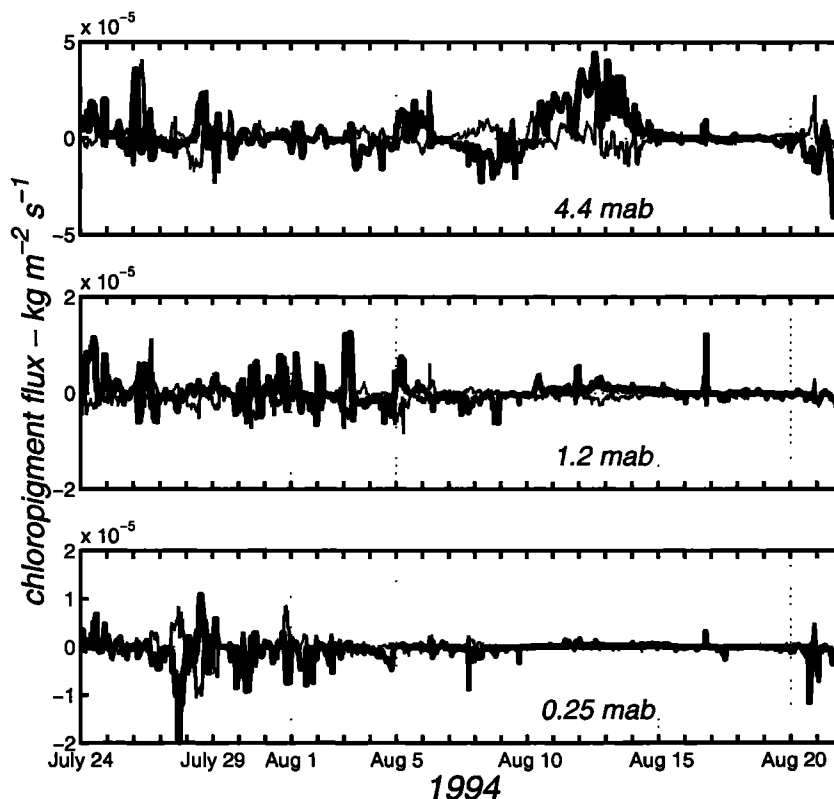
Figure 9. Chloropigment fluxes in the offshelf (thin lines) and alongshelf (bold line) directions at the indicated levels (from BASS tripod measurements). The alongshelf axis is $10°$ counterclockwise of north and is positive to the NNW.

have been greater. The anchor station measurements, discussed in section 4, gave some support to the second possibility. These showed pigment-enriched bottom water carried shoreward with the advance of the thermocline following the succession of upwelling favorable winds. However, analyses of pigment concentrations of samples from near-bottom waters during deployment and retrieval of the BASS tripod did not provide evidence of substantially higher concentrations of phaeopigments (data not shown), which would have been the case if resuspension accounted for a major fraction of the fluorescent material.

Sources of high concentrations of near-bottom pigments other than resuspension include sinking of phytoplankton from surface waters or growth stimulated by nutrient inputs from regeneration in bottom waters or deep water sources. Evidence for the importance of such mechanisms has been provided by studies in the New York Bight [*Malone et al.*, 1983; *Falkowski et al.*, 1988]. Sinking of phytoplankton from surface waters may have represented an important source. During the latter part of the time series it was evident that higher fluorescence in bottom waters generally coincided with reduced surface salinities (Plate 2c and 2d). This may reflect inputs of phytoplankton from the Chesapeake Bay outflow plume, which has been shown to extend south as far as our study region [*Rennie et al.*, 1999]. Furthermore, Lagrangian time series of biological processes within the plume revealed a decline in phytoplankton biomass over time largely attributable to the loss of larger phytoplankton [*Boicourt et al.*, 1987; *Malone and Ducklow*, 1990] possibly through sinking.

Another potential source of elevated phytoplankton biomass in near-bottom waters could be in situ production given

sufficient light penetration. During the July 1994 deployment cruise, diffuse attenuation of irradiance (K_{PAR}) of 0.25 m^{-1} was measured at the tripod site with a Li-Cor LI-192SA underwater quantum sensor and LI-190SA surface reference. On the basis of this value, light availability at 20 m was ~0.7% of surface irradiance, a level likely sufficient to support some level of phytoplankton growth. The potential for in situ growth to be a source of high chlorophyll in near-bottom waters was consistent with conclusions of *Wood et al.* [1996]. They observed relatively high chlorophyll concentrations in near-bottom shelf waters off Cape Hatteras that exhibited temperature and salinity properties characteristic of Mid-Atlantic Bight cold pool water. Their findings of relatively low ratios of phaeopigments to chlorophyll, microscopic observations of phytoplankton cells with intact chloroplasts, and estimates of available irradiance from Secchi Disk data led them to conclude that in situ production could have been responsible for the high chlorophyll.

The presence of elevated levels of phytoplankton biomass in near-bottom waters highlights the possibility that near-bottom transport of material may represent an important term in coastal carbon budgets. We were unable to resolve the net transport of chloropigments through the region with our relatively short time series. The rapid fluctuations of currents and pigment concentrations combined to produce large variations in horizontal chloropigment flux (Figure 9), with the result that 90% confidence intervals were comparable to or larger than the mean fluxes (Table 4). The situation was further complicated by vertical fluxes into and out of the bottom boundary layer that were unconstrained by our measurements. Our results are useful, however, in illustrating

the high degree of structure and variability in chloropigment distributions, even in the apparent absence of analogous structure in physical properties. Properly resolving near-bottom chloropigment transport at this site, and in similar areas, is a challenge that will require long-term (i.e., months) current and fluorescence measurements with a high degree of spatial and temporal resolution.

References

Abraham, E. R., The generation of plankton patchiness by turbulent stirring, *Nature, 391*, 577-580, 1998.

Bjornsen, P. K., and T. G. Nielsen, Decimeter scale heterogenity in the plankton during a pycnocline bloom of *Gyrodinium aureolum*, *Mar. Ecol. Prog. Ser., 73*, 263-267, 1991.

Boicourt, W. C., S. Y. Chao, H. W. Ducklow, P. M. Glibert, T. C. Malone, M. R. Roman, L. P. Sanford, J. A. Fuhrman, C. Garside, and R. W. Garvine, Physics and microbial ecology of a buoyant estuarine plume on the continental shelf. *Eos, Trans., AGU, 68*, 666-668, 1987.

Churchill, J. H., and T. J. Berger, Transport of Middle Atlantic Bight shelf water to the Gulf Stream near Cape Hatteras, *J. Geophys. Res., 103*, 30,605-30,621, 1998.

Churchill, J. H., and P. C. Cornillon, Gulf Stream water on the shelf and upper slope north of Cape Hatteras, *Cont. Shelf Res., 11*, 409-431, 1991.

Churchill, J. H., E. R. Levine, D. N. Connors, and P. C. Cornillon, Mixing of shelf, slope and Gulf Stream water over the continental slope of the Middle Atlantic bight, *Deep Sea Res., Part I, 40*, 1063-1085, 1993.

Cloern, J. E., Phytoplankton bloom dynamics in coastal ecosystems: A review with some general lessons from sustained investigation of San Francisco Bay, California, *Rev. Geophys., 34*, 127-168, 1996.

Cowles, T. J., and R. A. Desiderio, Resolution of biological microstructure through in situ fluorescence emission spectra, *Oceanography, 6*, 105-111, 1993.

Cowles, T. J., R. A. Desiderio, and M.-E. Carr, Small-scale planktonic structure: Persistence and trophic consequences, *Oceanography, 11*, 4-9, 1998.

Day, J. W., Jr., C. A. S. Hall, W. M. Kemp, and A. Yáñez-Arancibia (Eds.), *Estuarine Ecology*, John Wiley, New York, 1989.

DeGrandpre, M. D., T. R. Hammar, D. W. R. Wallace, and C. D. Wirick, Simultaneous mooring-based measurements of seawater CO_2 and O_2 off Cape Hatteras, North Carolina, *Limnol. Oceanogr., 42*, 21-28, 1997.

Derenbach, J. B., H. Astheimer, H. P. Hansen, and H. Leach, Vertical microscale distribution of phytoplankton in relation to the thermocline, *Mar. Ecol. Prog. Ser., 1*, 187-193, 1979.

D'Sa, E. J., and S. E. Lohrenz, Theoretical treatment of fluorescence detection by a dual-fiber-optic sensor with consideration of sampling variability and package effects associated with particles, *Appl. Opt., 38*, 2524-2535, 1999.

D'Sa, E. J., S. E. Lohrenz, V. L. Asper, and R. A. Walters, Time-series measurements of chlorophyll fluorescence in the oceanic bottom boundary layer with a multi-sensor fiber-optic fluorometer, *J. Atmos. Oceanic Technol., 14*, 889-896, 1997.

Falkowski, P. G., C. N. Flagg, G. T. Rowe, S. L. Smith, T. E. Whitledge, and C. D. Wirick, The fate of a spring phytoplankton bloom: Export or oxidation?, *Cont. Shelf Res., 8*, 457-484, 1988.

Franks, P. J. S., Sink or swim: Accumulation of biomass at fronts, *Mar. Ecol. Prog. Ser., 82*, 1-12, 1992.

Franks, P. J. S., Thin layers of phytoplankton: A model of formation by near-inertial wave shear, *Deep Sea Res., Part I, 42*, 75-91, 1995.

Franks, P. J. S., Spatial patterns in dense algal blooms, *Limnol. Oceanogr., 42*, 1297-1305, 1997.

Graf, G., Benthic-pelagic coupling: A benthic view, *Oceanogr. Mar. Biol. Annu. Rev., 30*, 149-190, 1992.

Grant, W. D., and O. S. Madsen, Combined wave and current interaction with a rough bottom, *J. Geophys. Res., 84*, 1797-1808, 1979.

Guillard, R. R. L., Culture of phytoplankton for feeding marine invertebrates, in *Culture of Marine Invertebrate Animals*, edited by W. L. Smith and M. H. Chanley, pp. 29-60, Plenum, New York, 1975.

Hanson, A. K., Jr., and P. L. Donaghay, Micro- to fine-scale chemical gradients and layers, *Oceanography, 11*, 10-17, 1998.

Holm-Hansen, O., C. J. Lorenzen, R. W. Holmes, and J. D. H. Strickland, Fluorometric determination of chlorophyll. *J. Cons. Int. Explor. Mer., 30*, 3-15, 1965.

Houghton, R. W., R. Schultz, R. Schlitz, R. C. Beardsley, B. Butman, and J. L. Chamberlain, The Middle Atlantic Bight cold pool: Evolution of the temperature structure during summer, *J. Phys. Oceanogr., 12*, 1019-1029, 1982.

Jaffe, J. S., and P. J. S. Franks, Small scale optical structure measured via images of fluorescence emission, *Proc. SPIE Int. Soc. Opt. Eng. 2963*, 278-283, 1997.

Knauer, G. A., Productivity and new production of the oceanic system, in *Interactions of C, N, P and S Biogeochemical Cycles and Global Change*, edited by R. Wollast, F. T. Mackenzie, and L. Chou, pp. 211-231, Springer-Verlag, New York, 1993.

Largier, J. L., and K. S. Millikan, Coastal Ocean Processes (CoOP) pilot project data report: August-October 1994 R/V *Moby Duck* CTD and underway data, *SIO Ref. Ser. 96-29*, Cent. for Coastal Stud., Scripps Inst. of Oceanogr., Univ. of Calif., San Diego, La Jolla, 1996.

Lentz, S. J., R. T. Guza, S. Elgar, F. Feddersen, and T. H. C. Herbers, Momentum balances on the North Carolina inner shelf, *J. Geophys. Res., 104*, 18,205-18,226, 1999.

Longuet-Higgins, M. S., On the statistical distribution of the heights of sea waves, *J. Mar. Res., 11*, 245-266, 1952.

Malone, T. C., and H. W. Ducklow, Microbial biomass in the coastal plume of Chesapeake Bay: Phytoplankton-bacterioplankton relationships, *Limnol. Oceanogr., 35*, 296-312, 1990.

Malone, T. C., T. S. Hopkins, P. G. Falkowski, and T. E. Whitledge, Production and transport of phytoplankton biomass over the continental shelf of the New York Bight, *Cont. Shelf Res., 1*, 305-337, 1983.

Mann, K. H., and J. R. N. Lazier, *Dynamics of Marine Ecosystems. Biological-Physical Interactions in the Oceans*, 2nd ed., Blackwell Sci., Malden, Mass., 1996.

Mitchell, J. G., and J. A. Fuhrman, Centimeter scale vertical heterogeneity in bacteria and chlorophyll *a*, *Mar. Ecol. Prog. Ser., 54*, 141-148, 1989.

Osborn, T., Finestructure, microstructure, and thin layers, *Oceanography, 11*, 36-43, 1998.

Paffenhofer, G. A., L. P. Atkinson, T. N. Lee, J. O. Blanton, B. K. Sherman, and T. B. Stewart, Variability of particulate matter and abundant zooplankton off the southeastern United States during spring of 1984 and 1985, *Cont. Shelf Res., 14*, 629-654, 1994.

Palowitch, A. W., and J. S. Jaffe, Optical serial sectioned chlorophyll *a* microstructure, *J. Geophys. Res., 100*, 13,267-13,278, 1995.

Pietrafesa, L. J., G. S. Janowitz, and P. A. Wittman, Physical oceanographic processes in the Carolina Capes, in *Oceanography of the Southeastern U.S. Continental Shelf, Coastal Estuarine Sci.* vol. 2, edited by L. P. Atkinson, D. W. Menzel, and K. A. Bush, pp. 23-32, AGU, Washington, D.C., 1985.

Pietrafesa, L. J., J. M. Morrison, M. P. McCann, J. Churchill, E. Böhm, and R. W. Houghton, Water mass linkages between the Middle and South Atlantic Bights, *Deep Sea Res., Part II, 41*, 365-389, 1994.

Rennie, S. E., J. L. Largier, and S. J. Lentz, Observations of a pulsed buoyancy current downstream of Chesapeake Bay, *J. Geophys. Res., 104*, 18,227-18,240, 1999.

Roman, M. R., C. S. Yentsch, A. L. Gauzens, and D. A. Phinney, Grazer control of the fine-scale distribution of phytoplankton in warm-core Gulf Stream rings, *J. Mar. Res., 44*, 795-813, 1986.

Sathyendranath, S., A. Longhurst, C. M. Caverhill, and T. Platt, Regionally and seasonally differentiated primary production in the North Atlantic, *Deep Sea Res., Part I, 42*, 1773-1802, 1995.

Seliger, H. H., K. R. McKinley, W. H. Biggley, R. B. Rivkin, and K.

R. H. Aspden, Phytoplankton patchiness and frontal regions, *Mar. Biol.*, *61*, 119-131, 1981.

Therriault, J.-C., and T. Platt, Spatial heterogeneity of phytoplankton biomass and related factors in the near-surface waters of an exposed coastal embayment, *Limnol. Oceanogr.*, *23*, 888-899, 1978.

Verity, P. G., G.-A. Paffenhöfer, D. Wallace, E. Sherr, and B. Sherr, Composition and biomass of plankton in spring on the Cape Hatteras shelf, with implications for carbon flux, *Cont. Shelf Res.*, *16*, 1087-1116, 1996.

Waldorf, B. W., J. L. Largier, S. Rennie, J. Austin, and C. Greengrove, Coastal Ocean Processes (CoOP) pilot project data report: R/V Cape Hatteras shipboard measurments; underway, CTD, and ADCP data, August, 1994, *SIO Ref.* Ser. *95-29*, Cent. for Coastal Stud., Scripps Inst. of Oceanogr., Univ. of Calif., San Diego, La Jolla, 1995.

Walsh, J. J., C. D. Wirick, L. J. Pietrafesa, T. E. Whitledge, F. E. Hoge, and R. N. Swift, High-frequency sampling of the 1984 spring bloom within the Mid-Atlantic Bight: Synoptic shipboard, aircraft, and in situ perspectives of the SEEP-I experiment, *Cont. Shelf Res.*, *8*, 529-563, 1988.

Whitledge, T. E., and C. D. Wirick, Development of a moored in situ fluorometer for phytoplankton studies, in *Lecture Notes on Coastal and Estuarine Studies*, vol. 17, *Tidal Mixing and Plankton Dynamics*, edited by J. Bowman, M. Yentsch, and W. T. Peterson, pp. 449-462, Springer-Verlag, New York, 1986.

Williams, A. J., J. S. Tochko, R. L. Koehler, W. D. Grant, T. F. Gross, and C. V. R. Dunn, Measurement of turbulence in the oceanic bottom boundary layer with an acoustic current meter array, *J. Atmos. Oceanic Technol.*, *4*, 312-327, 1987.

Wood, A. M., N. D. Sherry, and A. Huyer, Mixing of chlorophyll from the Middle Atlantic Bight cold pool into the Gulf Stream at Cape Hatteras in July 1993, *J. Geophys. Res.*, *101*, 20,579-20,593, 1996.

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