

# Chlorophyll enhancement and mixing associated with meanders of the shelf break front in the Mid-Atlantic Bight

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**Abstract.** Meanders of the shelf break front in the Mid-Atlantic Bight (MAB) during April and May of 1997 were associated with chlorophyll enhancement along a hydrographic and a topographic feature. The hydrographic feature was the surface outcrop of the front, which ranged from  $\sim 10$  to  $>100$  km seaward of the shelf break owing to the meanders. The topographic feature was the shelf break (100-m isobath). Chlorophyll enhancement was observed by a satellite instrument, the ocean color and temperature sensor, and by a fluorometer in situ. It developed in near-surface waters typically nutrient depleted during late spring, thus local nutrient enrichment of near-surface waters was probable. Observations of sufficient resolution to define processes were available only for the region of shelf break chlorophyll enhancement. Along two meander troughs (shoreward extremities near the shelf break), we observed shoaling of cold shelf water. Shelf water shoaled  $>20$  m along frontal isopycnals, and phytoplankton absorption maxima coincided directly with the shoaled water. Thus local nutrient enrichment by along-isopycnal upwelling was the supported mechanism of chlorophyll enhancement at the shelf break. The basis for along-isopycnal upwelling was seaward flow of shelf water forced by meander circulation near the shelf break. Strong cross-isobath flow and mixing developed as these meanders propagated along the shelf break front of the MAB at a relatively constant rate of  $\sim 9$  km day<sup>-1</sup>.

## 1. Introduction

The Mid-Atlantic Bight (MAB) extends along the North American east coast from Cape Hatteras to Georges Bank (Figure 1). Shelf waters of the MAB are among the most productive in the world ocean, with seasonality characteristic of the temperate zone [O'Reilly and Bush, 1984; O'Reilly et al., 1987]. During winter, when the water column is well mixed and solar insolation is low, phytoplankton growth is light limited. Light limitation is overcome during the spring bloom as stratification reduces mixing depth [Malone et

al., 1983; O'Reilly and Zetlin, 1998]. Increasing stratification during spring suppresses the vertical mixing that can replenish nutrients. This leads to nutrient depletion in the upper 20–30 m by approximately May [Ketchum et al., 1958; Walsh et al., 1978, 1987] and hence nutrient limitation of phytoplankton growth above the thermocline. A pool of cold shelf water, rich in nutrients recycled from the spring bloom, persists through summer below the thermocline. Nutrients within this cold pool support much of the primary production following the spring bloom, including that within the subsurface chlorophyll maximum of the thermocline [Malone et al., 1983; Houghton and Marra, 1983; Marra et al., 1990; Flagg et al., 1994; O'Reilly and Zetlin, 1998].

The front between shelf and slope waters in the MAB is dynamically and biologically important. The front persists year-round, and its structure varies strongly through the year [Wright, 1976; Mooers et al., 1978; Lyne and Csanady, 1984]. From its bottom intersection

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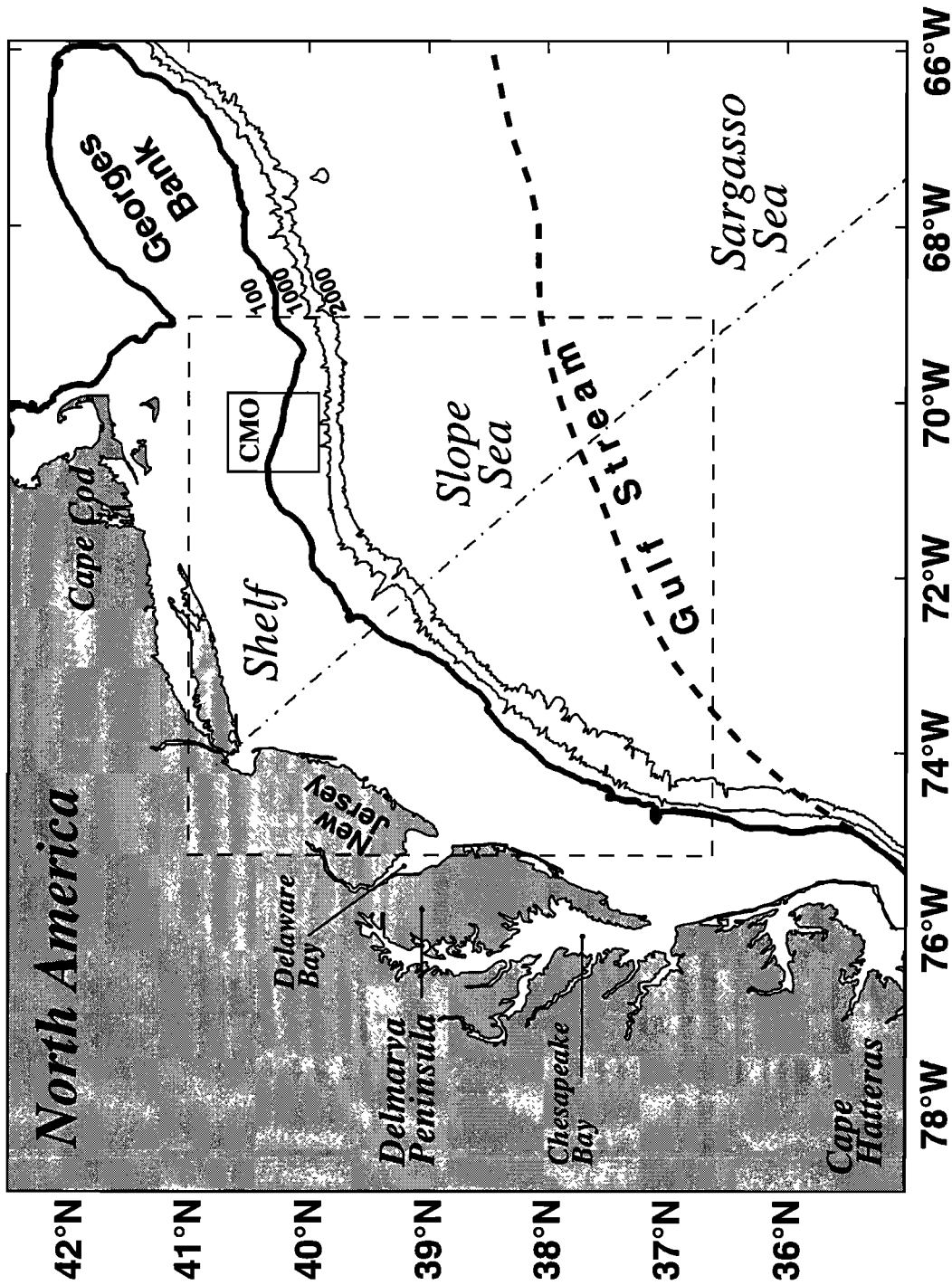


Figure 1. Map of the study region. The Mid-Atlantic Bight extends from Cape Hatteras to Georges Bank. Reference points used in the text are labeled. The mean position of the Gulf Stream north wall, determined from 12 years of satellite sea surface temperature imagery [Gilman, 1988], is shown as the thick dashed line. The 100-m isobath defines the approximate location of the shelf break and the outline of Georges Bank. The transect line (dash-dotted line) shows the path of the M/V *Oleander*. The large (dashed) box shows the domain of the ocean color and temperature sensor (OCTS) images presented in Plate 1. The box south of Cape Cod, labeled CMO, shows the domain of sampling during the Coastal Mixing and Optics program.

near the shelf break (100-m isobath), the front ascends offshore with an average slope of  $\sim 2 \times 10^{-3}$  [Beardsley and Flagg, 1976]. During winter, the shelf break front extends from bottom to surface and impedes exchange between shelf and slope waters. Phytoplankton bloom relatively early during winter-spring where shoaling of the mixed layer by the front locally increases light exposure [Marra *et al.*, 1982; Malone *et al.*, 1983]. During summer, the thermocline caps the front below the surface and shelf waters exchange along isopycnal surfaces above the thermocline [Houghton *et al.*, 1988]. Upwelling of  $\sim 9$  m  $\text{day}^{-1}$  in the front during summer can develop in association with convergence in the bottom boundary layer at the shelf break [Barth *et al.*, 1998]. Phytoplankton production at the shelf break is enhanced during summer where nutrients from the cold pool shoal along frontal isopycnals in response to perturbation of the front [Malone *et al.*, 1983; Marra *et al.*, 1990]. However, under the strongly stratified conditions of summer, enhanced phytoplankton biomass at the shelf break occurs below the depth to which satellite remote sensing can detect.

Between the spring bloom and the strongly stratified conditions of summer, enhancement of chlorophyll, visible to satellite remote sensing, develops annually along the shelf break of the MAB. Using the coastal zone color scanner (CZCS) archive (1979-1986) with satellite sea surface temperature (SST) and in situ observations, Ryan *et al.* [1999] define fundamental attributes of this annual biological structure and its association with the shelf break front. During late spring 1997, shelf break chlorophyll enhancement developed in association with propagating meanders of the shelf break front. The primary motivations for this work are to describe the frontal meanders and their influence on biological and physical distributions and to define the apparent mechanism of nutrient enrichment of near-surface waters at the shelf break. Using satellite-derived chlorophyll from the ocean color and temperature sensor (OCTS), satellite-derived SST and winds, and in situ observations, we examine structure and processes of this localized biological enhancement.

## 2. Methods

### 2.1. Satellite-Derived Observations

OCTS imagery and ancillary data required for its processing were acquired from NASA Goddard Space Flight Center. Ancillary data were daily ozone maps from the total ozone mapping spectrometer and meteorological variables from the National Centers for Environmental Prediction [McClain *et al.*, 1994]. A single-scattering algorithm was used for atmospheric correction [Gordon *et al.*, 1983], and a three-band chlorophyll algorithm [Saitoh *et al.*, 1997] was used for calculating chlorophyll *a* (hereafter OCTS-Chl). Sea surface tem-

perature (SST) imagery from advanced very high resolution radiometer (AVHRR) satellite instruments was acquired from the Graduate School of Oceanography, University of Rhode Island. OCTS and AVHRR imagery were mapped to the same projection.

NASA scatterometer (NSCAT) wind data were acquired from the Physical Oceanography Distributed Active Archive Center at NASA Jet Propulsion Laboratory (25-km resolution level-two swath data) using the Distributed Oceanographic Data System (Graduate School of Oceanography, University of Rhode Island, 1999, available on-line at <http://www.unidata.ucar.edu/packages/dods/>). From NSCAT winds we calculated Ekman pumping, i.e., upwelling and downwelling from wind-driven divergence and convergence of the Ekman layer. These calculations followed the methodology of McClain *et al.* [1990].

### 2.2. In Situ Observations

We used two sources of in situ observations. The first was the *Oleander*, a merchant vessel serving in the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) volunteer observation program. This vessel crosses shelf and slope waters on its weekly round trip between New Jersey and Bermuda. We used the *Oleander* platform to monitor physical and biological conditions along a fixed transect across the shelf break (Figure 1) via continuous underway sampling.

The *Oleander* is equipped with a 150-kHz narrow-band acoustic Doppler current profiler (ADCP) that can yield velocity measurements within the upper  $\sim 300$  m [Rossby and Gottlieb, 1998]. The coordinate system was rotated  $47^\circ$  clockwise to align with local shelf break isobaths (Figure 1; *u* is positive offshore, along track).

Operated by NMFS on the *Oleander* is an expendable bathythermograph (XBT) system for monthly sampling of vertical thermal structure and a continuous flow system for sampling temperature and salinity by thermosalinograph [Benway *et al.*, 1993a, b]. The intake for the continuous flow system is  $\sim 6$  m below surface when the ship is fully loaded for its outbound (eastbound) crossings. For the 1997 spring transition we added to the continuous flow system a Turner Designs model 10 fluorometer to measure chlorophyll fluorescence. The fluorometer was cleaned prior to each outbound trip. This instrument was not calibrated with in situ samples, so the results are presented as normalized readout. For the *Oleander* observations, we present only data from outbound crossings because (1) data quality for all instruments is much poorer on inbound trips when the ship returns with empty containers, (2) the inbound trip crosses the shelf break  $\sim 10$  km north of the outbound trip, and (3) the fluorometer was consistently cleaned only for the outbound trips.

The second source of in situ observations was the spring 1997 Coastal Mixing and Optics (CMO) pro-

gram south of Cape Cod (Figure 1). The water column across the shelf break was sampled with the towed, undulating vehicle SeaSoar equipped with a conductivity-temperature-depth (CTD) instrument and a nine-wavelength light absorption and attenuation instrument (WETLabs ac-9). The ac-9 optical data were aligned with the CTD data, and light absorption was corrected for temperature dependence [Barth and Bogucki, 1999]. Horizontal separation of the surface and bottom (usually within 5-10 m of the bottom) of the sawtooth-shaped SeaSoar trace was 800 (300) m at the offshore (onshore) end of a cross-shelf section. Vertical profiles of horizontal velocity were obtained with a 300-kHz shipboard ADCP. CTD and ADCP data were processed using techniques described by Barth *et al.* [1999]. ADCP velocities were detided by removing depth-averaged tidal currents estimated from harmonic analysis [Pierce *et al.*, 1998].

### 3. Results

In section 3.1, we illustrate the chlorophyll enhancement as observed by satellite and in situ and define its association with the meanders that propagated through the region during April and May. In section 3.2, processes are examined from a satellite perspective. In section 3.3, we examine processes from an in situ perspective and define the basis of chlorophyll enhancement at the shelf break.

#### 3.1. Structure: Localized Chlorophyll Enhancement

During early May 1997, enhanced chlorophyll was observed by the OCTS along a hydrographic and a topographic feature of the MAB (Plate 1). The hydrographic feature was the shelf break front. Enhanced OCTS-Chl extended along most of the meandering surface outcrop of the front. The meanders are evident in the 9° and 11°C isotherms in Plate 1. Four cyclonic meanders (numbered in Plate 1) were present on May 2 between Delmarva and Georges Bank (defini-

tion of curvature in these shoreward meanders is based on the geostrophic frontal jet that flows W-SW along the front). Meander numbers are geographically fixed to reference meander locations on the 2 days and illustrate their W-SW propagation. The high OCTS-Chl along 38.8°N between ~70.5° and 69.7°W on May 2 (Plate 1a) coincided directly with a sharp secondary SST front (12° to 14°C isotherms, not shown). The primary shelf break front was at that location 2 days earlier.

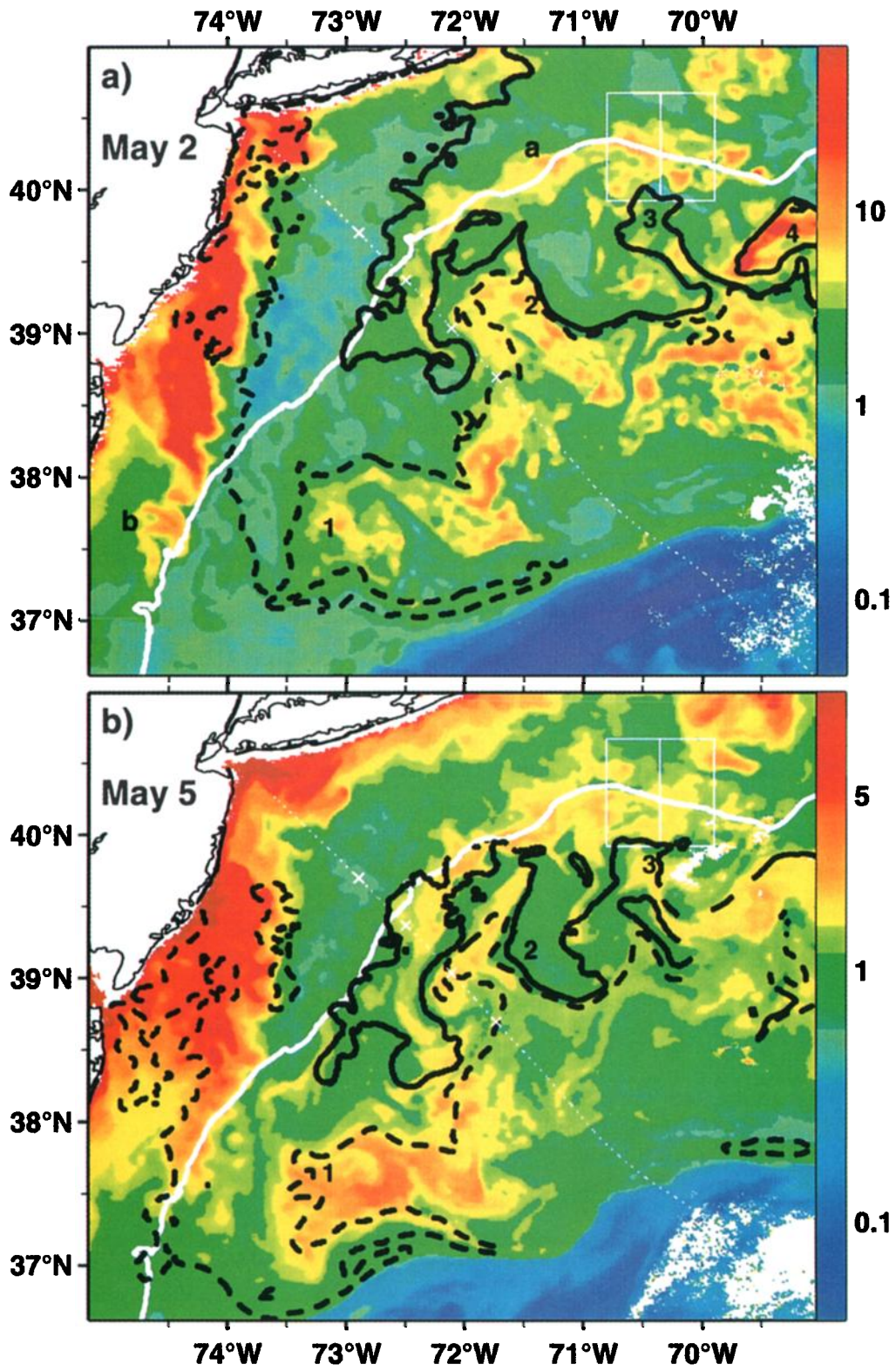
The topographic feature along which enhanced chlorophyll developed was the continental shelf break. There were two separate regions of this structure. The first extended >250 km along the shelf break between ~69.5° and 72.5°W (labeled a inshore of the 100-m isobath in Plate 1a). Here the enhanced chlorophyll was between the shoreward extremities (troughs) of meanders 2-4 (meanders referenced hereafter as M1-M4). The second extended ~70 km along the shelf break between ~37.3° and 38.1°N (labeled b inshore of the 100-m isobath in Plate 1a). Here the enhanced chlorophyll was centered ~15 km inshore of the 100-m isobath and was directly west of M1; the N-S dimension of the enhancement matched that of the trough of M1. This region of enhanced shelf break chlorophyll was contiguous with high chlorophyll concentrations in shelf waters farther north, between Chesapeake and Delaware Bays.

To illustrate the shelf break and frontal chlorophyll enhancement as sampled in situ along the *Oleander* transect, we show a time-space plot of chlorophyll fluorescence during April and May (Plate 2). Contours show temperature from thermosalinograph; we use the 10°C isotherm to indicate the approximate center of the front [Moore *et al.*, 1978]. During April and May, there was a seasonal trend of increasing temperature and decreasing fluorescence, more pronounced over the shelf. This is consistent with the seasonal development of thermal stratification and associated decrease in mixed layer phytoplankton biomass. The location of the shelf break (100-m isobath) along the transect is shown by the dashed white line at 188 km. Relatively high fluores-

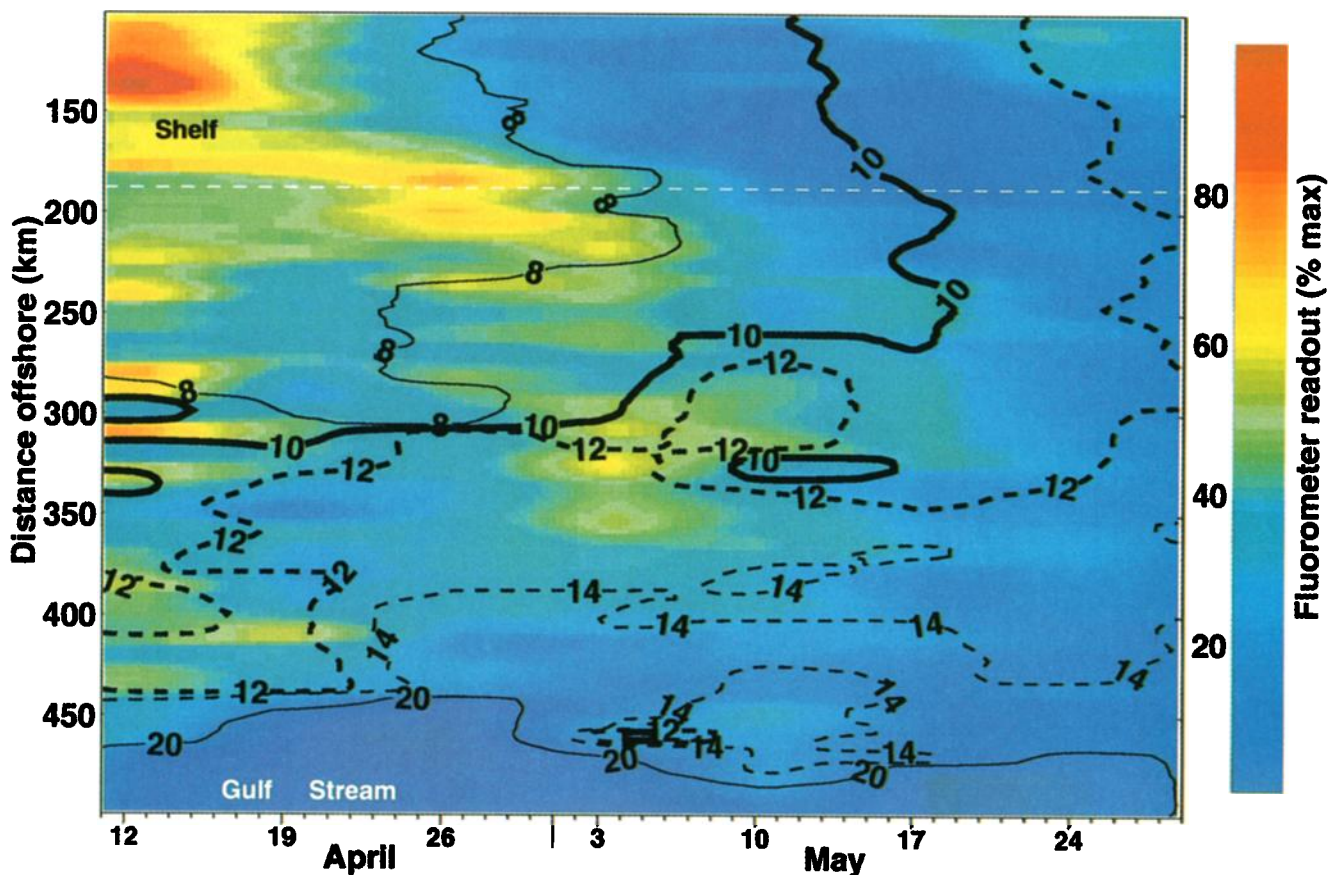
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**Plate 1.** Ocean color and temperature sensor (OCTS) chlorophyll images of the Mid-Atlantic Bight (MAB) for May (a) 2 and (b) 5, 1997, showing the shelf break and frontal chlorophyll enhancement. Use Figure 1 for geographic reference points. Labels a and b inshore of the 100-m isobath on the May 2 image indicate adjacent shelf break enhancement. Black contour lines are sea surface temperature (SST) from advanced very high resolution radiometer (AVHRR) images closest in time to the OCTS images. OCTS-AVHRR time differences for the 2 days were -2 and +4 hours, respectively. Although both SST images were daytime, the May 5 image was from early morning and would thus be more influenced by nighttime cooling. Shown are the 9°C (solid line) and 11°C (dashed line) SST isotherms. Absence of isotherms north of 40° on May 5 is due to cloud cover. Meanders of the shelf break front, outlined by the isotherms, are labeled 1-4; the numbers are geographically fixed to serve as reference points. White pluses are distance markers for the *Oleander* transect: 150, 200, 250, and 300 km from shore (for reference to Plate 2 and Figure 4). The white box shows the domain of sampling for the Coastal Mixing and Optics (CMO) program (see Plate 3), and the N-S line through the box shows the central CMO transect (see Plate 4).

OCTS Chlorophyll *a* ( $\text{mg m}^{-3}$ )







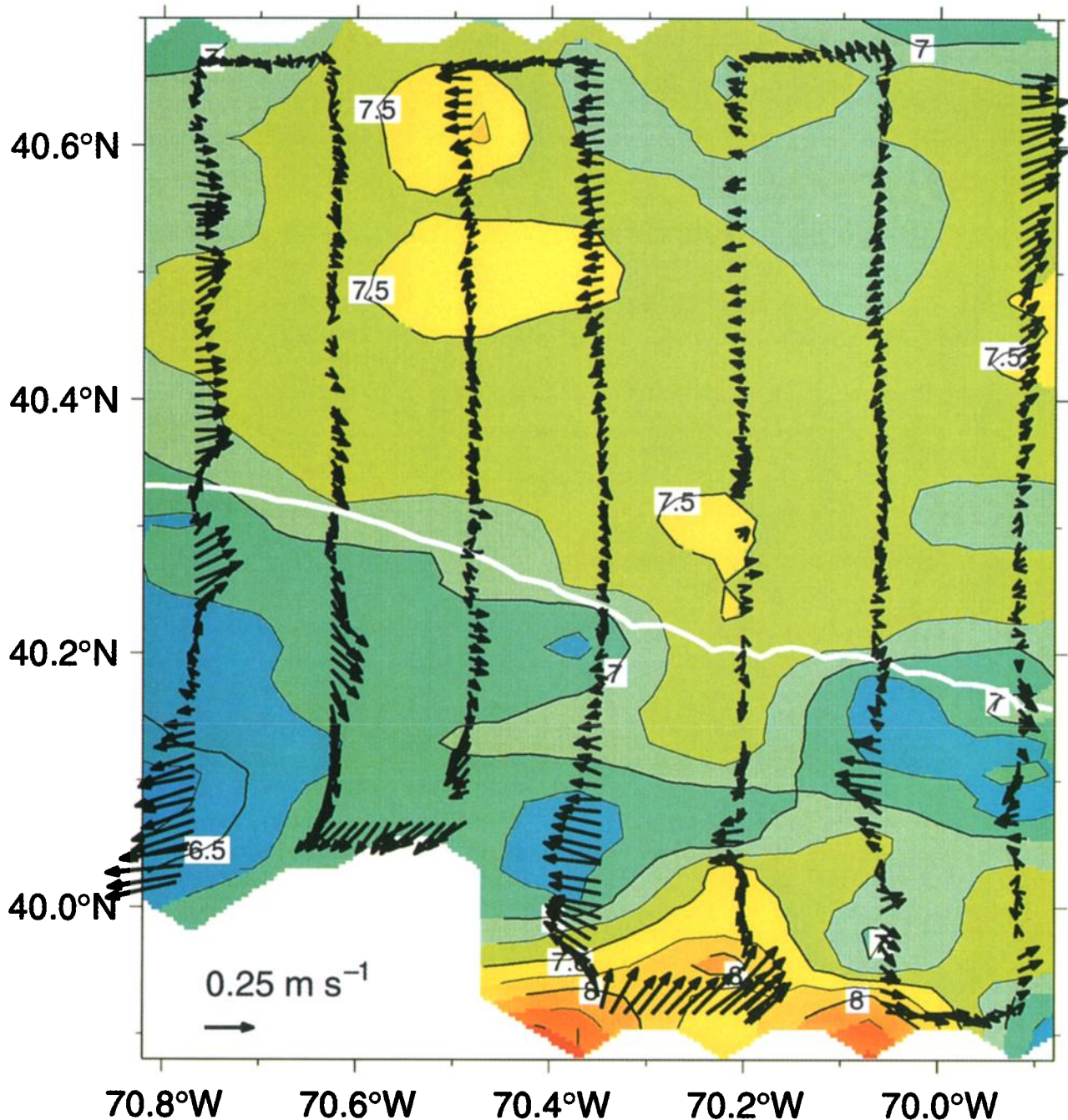
**Plate 2.** Time-space plot of normalized, interpolated fluorometer readout and temperature ( $^{\circ}\text{C}$ ) at 6 m depth along the *Oleander* transect during April and May 1997. Weekly sampling dates are numbered. Fluorescence is normalized to the maximum observed within the domain (color scale). Temperature (contoured) is shown as a water mass indicator because salinity cannot be compared between cruises (the salinometer is calibrated only once each month). Distances are from the New Jersey coast. The dashed white line at 188 km shows the location of the 100-m isobath (shelf break) along the transect.

cence was present near the shelf break from mid-April through early May. Near the front ( $10^{\circ}\text{C}$  isotherm), the highest fluorescence developed during two periods: (1) between April 12 and 19 and (2) between May 3 and May 10. As we illustrate below, both periods coincided with the passage of a frontal meander across the transect.

Meander locations and circulation along the transect during this period are illustrated in Figure 2. The dashed  $11^{\circ}\text{C}$  SST isotherm approximates meander boundaries, vectors represent velocity along the transect, and the solid contour is the 100-m isobath. On April 12, the highest fluorescence was in midshelf waters and high fluorescence extended to the shelf break (Plate 2). There were also three bands of relatively high fluorescence in the frontal region in relatively cold/fresh water (centered near 280, 310, and 335 km), interleaved with bands of low fluorescence in relatively warm/saline water (salinity not shown). The  $11^{\circ}\text{C}$  SST isotherm from 1 day earlier (Figure 2a) shows that the leading flank of M1 was encountered along the ship transect and

that the frontal boundary along this leading flank was convoluted with interleaving of shelf and frontal water. The patch of high fluorescence between  $\sim 225$  and 250 km was within a local salinity maximum. This could indicate upwelling (salinity increases with depth) or horizontal mixing (salinity within the patch was equal to that at the shoreward base of the front). High fluorescence was again observed at the shelf break on April 19, and banded structure near the front was weakly evident (Plate 2). The April 26 transect crossed the front between M1 and M2 (Figure 2b), where frontal gradients of  $\sim 5^{\circ}\text{C}$  and 2.4 practical salinity units (psu) in 3 km were associated with a strong geostrophic jet ( $>60\text{ cm s}^{-1}$ ) convergent toward the jet core. Fluorescence was highest at the shelf break (Plate 2), where the flow was primarily cross shelf and convergent (Figure 2b).

The May 3 transect crossed the shelf break enhancement toward its southern extreme, where enhanced chlorophyll extended seaward along the SW flank of M2 (Plate 1a and Figure 2c). Fluorescence was highest near the shelf break, seaward of where the maximum



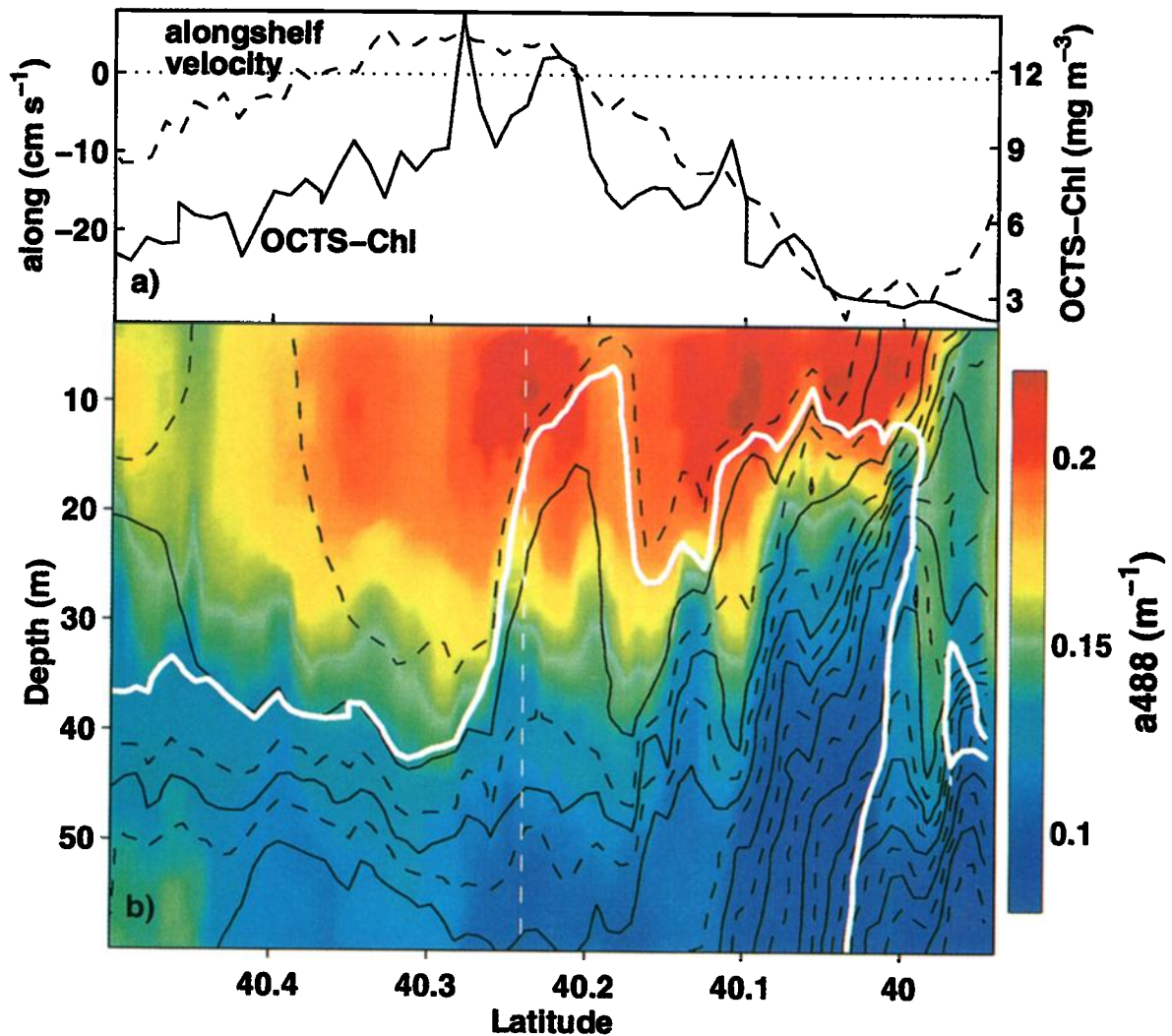
**Plate 3.** Temperature at 15 m and subtidal acoustic Doppler profiler (ADCP) velocity at 18 m from May 4–6 sampling within the CMO domain (shown in Figure 1 and Plate 1). The white contour is the 100-m isobath.

had been the previous week, and at the front (Plate 2). On May 10, the *Oleander* crossed the trailing flank of M2 (Figure 2d), when the meander was highly convoluted and interleaved with shelf water along its leading and trailing flanks. Fluorescence was highest along the boundary of M2 (Plate 2 and Figure 2d). The May 17 transect passed between M2 and M3 (Figure 2e). M3 reached the transect by May 24 (Figure 2f), but no local chlorophyll enhancement was observed (Plate 2).

### 3.2. Processes: Satellite Perspective

The meanders of the shelf break front propagated W–SW along a trajectory approximately parallel to local slope isobaths. A time series of SST along this trajectory illustrates the relatively constant rate of meander propagation, despite intermittence in the strength of their expression in SST (Figure 3). The inset of Figure 3 shows the 11°C isotherm on May 2, with cyclonic meanders labeled (M1–3), the 100-m isobath (thick solid





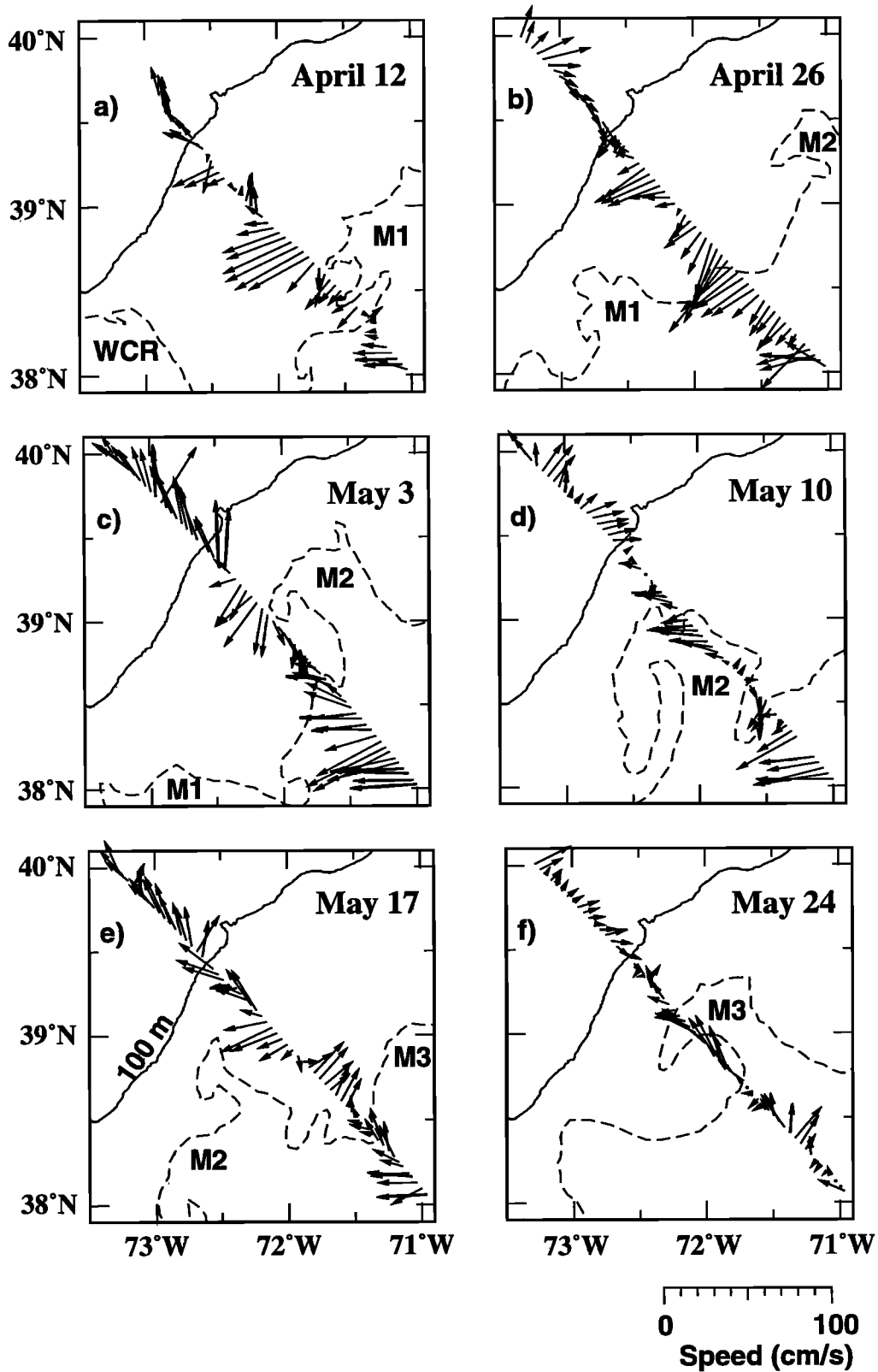
**Plate 4.** Observations along the central N-S transect within the CMO sampling domain (see Plates 1 and 3 for location). (a) Along-shelf velocity at 18 m and OCTS-Chl averaged from May 2 and 5 images and (b) absorption by phytoplankton at 488 nm. Overlaid are the 7°C isotherm (white contour) and density (black contours are  $\sigma_{\theta}$  in 0.05 increments; the shallowest contour is 25.25). The vertical dashed white line shows the location of the shelf break.

line), and the approximate meander trajectory (dashed line). At a fixed point in time, the meanders are identifiable along this trajectory as relatively warm water (SST  $>10^{\circ}\text{C}$  is shaded in Figure 3 to emphasize the meanders). Their propagation NE to SW along the trajectory is manifested by the orientation of the warm (shaded) bands; that is, the relatively warm water of each meander moved from NE to SW with time. Our description of their propagation is based on Figure 3 and an animation of regional SST during this period (on-line, <http://brando.gso.uri.edu/SST>). As suggested by the  $11^{\circ}\text{C}$  isotherm on May 2 (Figure 3 inset), M1 and 2 were more strongly pronounced than M3. M1 was evident from early April (near 75 km) through mid-May (470 km). Its relatively slow propagation and discontinuity in early to mid-April developed as frontal water detrained from M1 and mixed with cold shelf water. M2 was evident from late April (150 km) through late May

(400 km). M3 was evident intermittently in late April (40 km) and early to mid-May (100–150 km). From Figure 3 we estimate the translation speed of the meanders at  $\sim 9 \text{ km day}^{-1}$ . During this period of meander propagation past the *Oleander* transect, mean along-shelf velocity measured by ADCP in the zone of meander propagation was also  $\sim 9 \text{ km day}^{-1}$ . Thus simple advection with the mean flow may explain their propagation.

The OCTS and AVHRR imagery shows that these meanders coincided with strong horizontal mixing. This was most pronounced along M2. SW of M2 on May 2 (Plate 1a), shelf water  $<9^{\circ}\text{C}$  extended seaward from the shelf break (from  $\sim 72.5^{\circ}\text{W}$ ,  $39.5^{\circ}\text{N}$  to  $\sim 72^{\circ}\text{W}$ ,  $38.5^{\circ}\text{N}$ ). Within this relatively cold shelf water was a filament of high OCTS-Chl. From the meander trough, a filament of water  $>9^{\circ}\text{C}$  extended to the shelf break and NE along the shelf break (from  $\sim 72.2^{\circ}\text{W}$ ,  $39.25^{\circ}\text{N}$  to  $\sim 71.7^{\circ}\text{W}$ ,  $39.75^{\circ}\text{N}$ ). Between May 2 and 5, M2 experienced three





**Figure 2.** Weekly vector plots of velocity at 24 m along the *Oleander* transect between April 12 and May 24 (excluding April 19, for which ADCP data quality was very poor). The solid line is the 100-m isobath, showing the location of the shelf break. The dashed line is the 11°C isotherm, showing the outline of frontal meanders that propagated past the *Oleander* transect (labeled M1-3), and a Gulf Stream warm-core ring (WCR in Figure 2a). Owing to limits in AVHRR coverage, isotherms in Figures 2a, 2c and 2f are from 1 day preceding ship crossing. Each transect represents ~10 hours of sampling along ~300 km.

major changes (compare isotherms and OCTS-Chl on May 2 and 5 using the ship transect, 100-m isobath, and meander numbers for fixed reference): (1) M2 propagated SW, (2) the 9°C isotherm and chlorophyll enhancement within this isotherm (<9°C) moved seaward SW of M2, and (3) frontal water (>9°C) and enhanced frontal chlorophyll moved shoreward from the trailing (NE) flank of M2. These distributions defined counterflow between meander and shelf break. As M2 propagated SW, the frontal water detrained from the trailing flank, and interleaving of shelf and frontal water developed along the leading and trailing flanks (Figure 2d and on-line SST animation). Similar circulation developed with M1 during mid-April and was responsible for its apparent discontinuity at that time (Figure 3).

Seaward flow of shelf water at M1 was also evident in the satellite imagery. West of M1 on May 2 (Plate 1a), water <11°C extended southward from the shelf break (~73.5°W, 38 to 37°N). South of M1, this water turned east and extended to the Gulf Stream front (~73.5 to 71°W along 37.2°N). Shelf water was sampled in situ along the Gulf Stream front on May 3, as we will show later. Between May 2 and 5, the N-S extent of water <11°C expanded between the Gulf Stream and M1. M1 was laterally compressed as its trailing flank propagated southward, and the Gulf Stream meandered northward; this is evident in both SST and OCTS-Chl. Along with compression developed a wave-like SST pattern along the trough of M1 (Plate 1b; ~73.4°W, 37.1 to 37.8°N). Also between May 2 and 5, the region of enhanced shelf break chlorophyll inshore of M1 shifted seaward. On May 5, OCTS-Chl at M1 exhibited a pattern similar to that at M2 (Plate 1b). Relatively high OCTS-Chl extended from the shelf break toward the leading flank of M1 (seaward extremity near 74°W, 37.25°N), while a filament of relatively high OCTS-Chl extended between the trailing flank of M1 and the shelf break (meandering filament between ~73.5°W, 37.7°N and ~73°W, 38.7°N). These distributions and their changes between May 2 and 5 suggest counterflow between meander and shelf break at M1, as at M2.

Although not evident in the isotherms shown, offshore flow of shelf water at M3 is indicated by enhanced chlorophyll along its leading (SW) flank contiguous with the enhanced shelf break chlorophyll on both May 2 and 5 (Plate 1). Our on-line SST animation shows that M3 exhibited filament formation and exchange with spatial and temporal characteristics similar to those observed for M2 during early May. The counterflow between meander and shelf break defined by SST and OCTS-Chl at M1 and M2 was confirmed at M3 with in situ observations (section 3.3).

M4 did not persist. By May 2, M4 had calved most of its volume, and OCTS-Chl was highest within the calved volume (Plate 1a). Between May 2 and 5, a storm system passed over the region and NSCAT wind stress at M4 increased approximately threefold, after

which M4 was not distinct and OCTS-Chl was more homogeneous (Plate 1b).

In summary of processes evident in the satellite ocean color and temperature: The meanders propagated W-SW along the slope at a relatively constant rate of ~9 km day<sup>-1</sup>. Strong cross-isobath flows were associated with the meanders. Specifically, shelf water flowed offshore along the leading flanks of the meanders, while frontal water flowed toward the shelf break from the meander troughs.

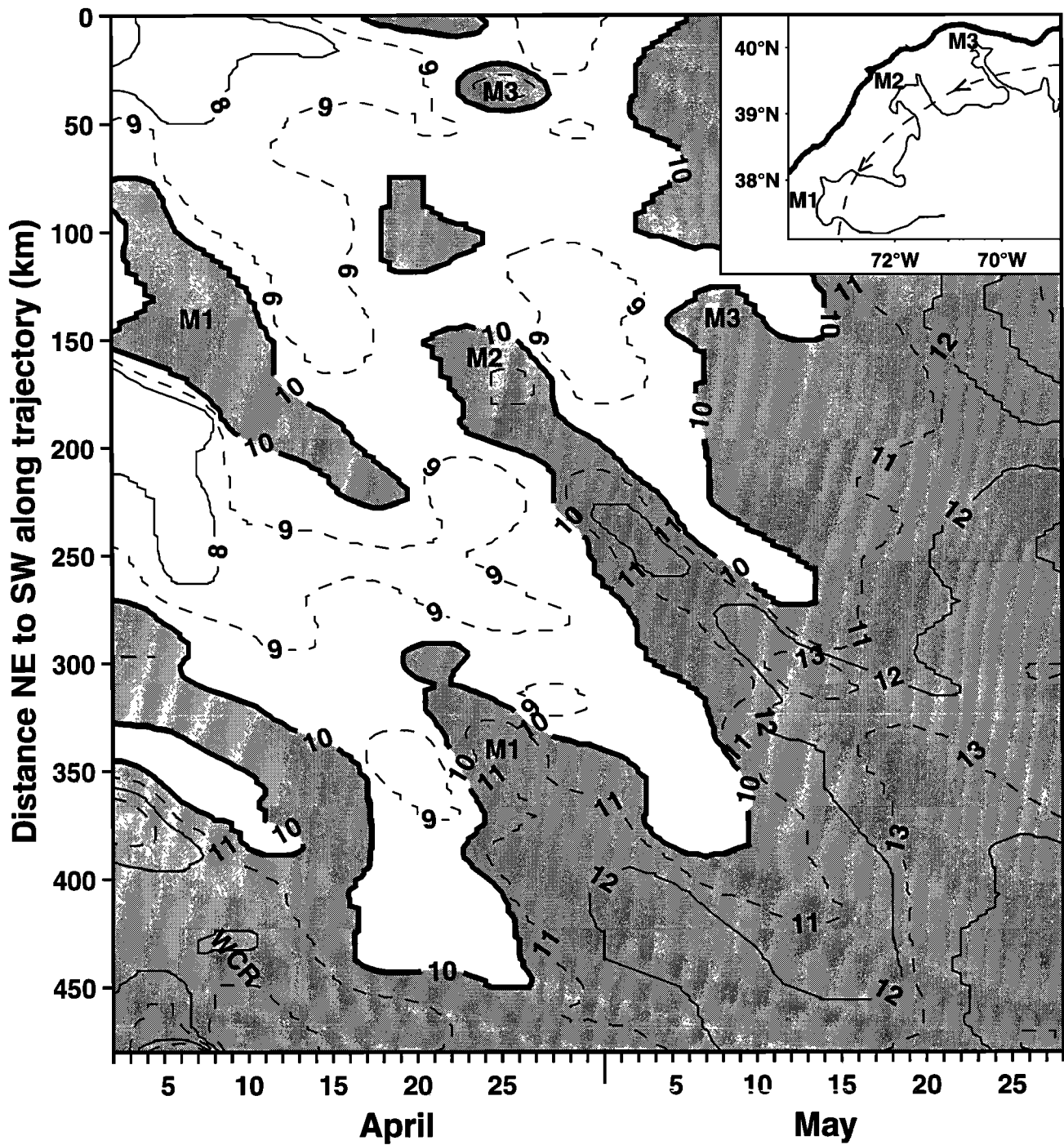
During this period of increasing stratification and nutrient limitation in near-surface waters, vertical flux of nutrients by upwelling or vertical mixing is important to phytoplankton growth. From satellite-derived wind fields, we examined a potential upwelling process: Ekman pumping. During the week preceding the localized chlorophyll enhancement observed by OCTS during early May, mean NSCAT Ekman pumping was negative (downwelling) over most of the region where the enhancement developed. Thus this wind-driven vertical motion was not conducive to nutrient and chlorophyll enrichment in the upper water column, and the role of oceanic forcing by the meanders is emphasized.

### 3.3. Processes: In Situ Perspective

Because nutrients are generally depleted in near-surface waters of the MAB during late spring, it is probable that local nutrient enrichment occurred where near-surface chlorophyll enhancement developed. The satellite observations illustrate horizontal circulation from near-surface chlorophyll and temperature distributions. The in situ observations allow inference of vertical circulation from the vertical and horizontal distributions of biological and physical properties. In situ observations of sufficient resolution to define processes were gathered only near the shelf break. Thus we attempt to define a mechanism of nutrient enrichment only where enhanced chlorophyll was observed along the shelf break.

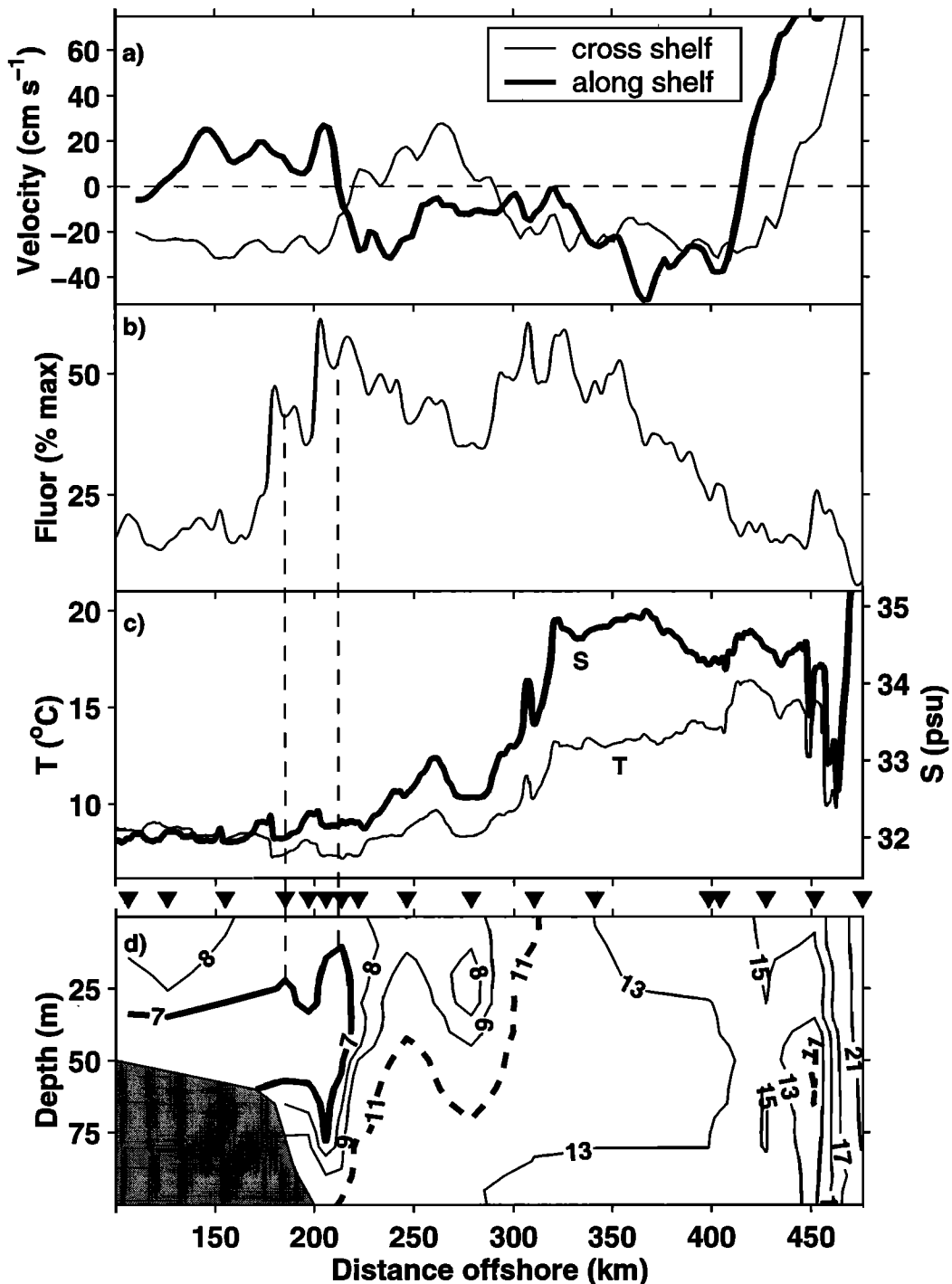
The trough of meander M3 was sampled on May 4-6. Plate 3 shows temperature at 15 m and subtidal velocity at 18 m for the outer shelf region along which M3 was propagating in early May (sampling domain shown in Figure 1 and Plate 1). The trough of M3 is evident as water >7.5°C, south of 40.05°N. Flow was offshore at the western (leading) flank of M3 (70.6°W) and onshore near the center of its trough (southernmost velocity vectors between 70.2° and 70.4°W). The onshore flow brought meander waters nearest the shelf break (Plate 3). This is the exact circulation pattern evident in SST and OCTS-Chl, as described in section 3.2.

Locally cold water extended along the shelf break north of M3 (Plate 3); this suggests local upwelling. Properties along the central CMO transect are shown in Plate 4 (see transect location in Plate 1). At the meander trough, frontal isopycnals within the upper 65 m



**Figure 3.** Inset shows the 100-m isobath (thick contour), the 11°C isotherm (thin contour) from a May 2 AVHRR image, with meanders of the shelf break front labeled M1-3, and the approximate meander trajectory (dashed line). Main figure shows a time-space plot of interpolated AVHRR SST along the meander trajectory, illustrating propagation of the meanders. The 10°C isotherm is used to identify meander boundaries (over the MAB, the meanders were most clearly defined by the 9°-11°C isotherms). Meanders are labeled for reference to inset and Plate 1 and Figure 2. WCR label identifies a Gulf Stream warm-core ring that propagated along the SW end of the trajectory during April (Figure 2a).





**Figure 4.** *Oleander* observations from May 3, 1997, 1 day after the OCTS image of May 2 (Plate 1a). (a) Average ADCP velocity in the layer 16 to 40 m. (b) Fluorescence at 6 m, normalized as in Plate 2. (c) Temperature and salinity at 6 m. Salinity was calibrated with bottle samples. (d) Vertical thermal structure from XBT (locations of XBT drops are shown above Figure 4d).

had a slope of  $\sim 6 \times 10^{-3}$  or  $\sim 3$  times greater than the average frontal slope. Thus offshore flow along isopycnals would have efficiently upwelled water. Cold shelf water shoaled along frontal isopycnals ( $7^{\circ}\text{C}$  isotherm in Plate 4b). Absorption by phytoplankton (a488) ex-

hibited two distinct maxima within the upper  $\sim 20$  m where cold water reached the shallowest depth (Plate 4b). The first was between  $\sim 40^{\circ}$  and  $40.14^{\circ}\text{N}$ . Within this segment, along-shelf flow was westward, i.e., in the direction of the frontal jet (Plate 4a). The second, cen-

tered at the 100-m isobath (40.24°N), coincided with locally shoaled isopycnals and 7°C isotherm at the shelf break (Plate 4b), and it was associated with weak eastward flow (Plate 4a). This eastward flow shoreward of the cyclonic meander crest is likely a secondary instability spinning off anticyclonically and carrying upwelled water NE toward the shelf break, as suggested by temperature at 15 m (Plate 3). The distribution of mean OCTS-Chl along the central CMO transect agrees well with a488 (Plate 4).

Although conditions were not completely sampled in the southwest corner of the CMO domain (Plate 3), shoaling of cold shelf water along frontal isopycnals was suggested west of the central transect. East of the central transect, the highest absorption by phytoplankton (a488) along all sections coincided directly with cold shelf water shoaled to near surface along frontal isopycnals. In summary, the CMO observations confirmed strong cross-isobath exchange at the trough of M3 and defined upwelling of cold shelf water along frontal isopycnals at the shelf break. Deeper shelf water is rich in recycled nutrients during this time of year (following the spring bloom), and its upwelling defines the probable basis for the shelf break chlorophyll enhancement.

Observations at M2 also support the role of along-isopycnal upwelling in the development of enhanced shelf break chlorophyll. One day after the OCTS image of May 2 (Plate 1a), an XBT section defined shoaling of shelf water <7°C at the shelf break inshore of the trough of M2 (Figure 4d, ~210 km offshore; use distance markers in Plate 1 for reference). This shoaled cold water coincided directly with the locally highest fluorescence (Figure 4b). Similar to the observations at M3 (Plate 4), there was a secondary fluorescence maximum and temperature minimum (at 6 m) and shoaling of the 7°C isotherm at the shelf break inshore of M2 (~185 km in Figures 4b-4d). Although the vertical section at M2 (Figure 4d) was of much coarser resolution than that at M3 (Plate 4b), physical and biological distributions at the shelf break inshore of both meander troughs were remarkably similar.

These observations also illustrate the complex interleaving of shelf and frontal water that developed along the leading flank of M2 (described from fluorometer and thermosalinograph observations in Plate 2 and Figure 2). Along this meander flank, frontal water extended shoreward of the shelf water flowing seaward (Plate 1). The frontal water was centered at ~250 km and is clearly defined in  $T/S$  (Figure 4c) as the locally warm/saline water and in vertical thermal structure (Figure 4d) as the local shoaling of the 9° and 11°C isotherms. The shelf water was centered at ~275 km and is clearly defined in  $T/S$  (Figure 4c) as the locally cold/fresh water and in vertical thermal structure (Figure 4d) as the water <8°C. The velocity observations (Figure 4a) show that as frontal and shelf waters interleaved along the meander's leading flank, they

moved offshore and along shelf in the direction of meander propagation (SW). This interleaving persisted for at least 2 more weeks (Figures 2d and 2e). Also shown in this transect is shelf water that flowed offshore around M1 and along the Gulf Stream front (Plate 1a, 11°C isotherm ~73.5° to 71°W, 37.2°N). It is the relatively cold, fresh, high fluorescence water just seaward of 450 km (Figures 4b-4d; the XBT section did not resolve its core as defined by  $T/S$  at 6 m) within the advective domain of the Gulf Stream (Figure 4a).

#### 4. Discussion

The hydrography and circulation of the frontal meanders were conducive to upwelling of deeper, relatively nutrient rich shelf water near the shelf break. The hydrographic disturbance introduced by the meanders was a relatively steep frontal slope. At a meander trough, observed isopycnal slopes were ~3 times greater than the average slope of the shelf break front. The circulation disturbance introduced by the meanders was seaward flow of shelf water. Both satellite and in situ observations showed that shelf water flowed seaward ahead of the meander troughs. This is consistent with entrainment in the shelf break frontal jet, which flows W-SW. A frontal disturbance that increases frontal slope and induces seaward flow along isopycnals will effectively force upwelling of deeper shelf water. At two meander troughs, we observed shoaling of cold shelf water at the shelf break. The high-resolution SeaSoar observations at one meander trough clearly showed that cold shelf water shoaled >20 m along frontal isopycnals and that absorption by phytoplankton exhibited maxima in direct coincidence with the shoaled water. Thus the supported mechanism of chlorophyll enhancement along the shelf break was upwelling of relatively nutrient rich shelf water along frontal isopycnals inshore of meander troughs. Enhanced OCTS-Chl was evident along the shelf break only where the frontal meander troughs were propagating along the shelf break. Shelf break chlorophyll enhancement was contiguous between three of the meanders that were relatively closely and regularly spaced. The enhanced shelf break chlorophyll reflected not only a history of forcing by the meanders but also all other processes influencing phytoplankton distributions.

The ~70-km segment of shelf break chlorophyll enhancement directly west of M1 matched the along-shelf dimension of the meander. Further, the OCTS-Chl distribution around M1 indicated shelf-break-meander exchange similar to that so clearly defined for M2 and M3, and the enhanced chlorophyll inshore of M1 moved seaward between May 2 and 5. These observations support the role of along-isopycnal upwelling during seaward flow at the shelf break inshore of M1. This region of shelf break chlorophyll enhancement was also contiguous with high chlorophyll concentrations in shelf waters shoreward of the shelf break, implying a possible role

for horizontal advection of chlorophyll. We have no in situ observations near M1 to more clearly define local processes. However, the satellite imagery indicates that the plume of high chlorophyll on the shelf may have been related to offshore transport of shelf water at M1: the chlorophyll plume followed the same isotherm that defined offshore transport at M1.

Seaward flow of shelf water is the fundamental process associated with all shelf break chlorophyll enhancement observed by the CZCS during late spring [Ryan *et al.*, 1999]. Forcing mechanisms include entrainment by Gulf Stream warm-core rings (most frequent), Gulf Stream meanders, and other disturbances of the shelf break front. The frontal meanders that propagated along the MAB shelf break during late spring 1997 forced seaward flow of shelf water. The associated shelf break chlorophyll enhancement observed by the OCTS was thus consistent with all previous observations from the CZCS (late spring to early summer of 1979-1986). The high-resolution SeaSoar observations across the shelf break provided the first clear evidence of a mechanism for the association: upwelling along isopycnals of the shelf break front during seaward flow. This is the very process that enhances phytoplankton biomass and production at the shelf break front during the strongly stratified conditions of summer [Malone *et al.*, 1983; Marra *et al.*, 1990], below the depth to which satellite remote sensing can detect.

Seaward of the shelf break, chlorophyll enhancement observed in situ coincided with the passage of two successive meanders and chlorophyll enhancement observed by satellite followed the physical meander boundaries. These observations support the role of frontal dynamics in the chlorophyll enhancement along the surface outcrop of the front. Our in situ observations were not sufficient to examine processes underlying this biological pattern. However, a process of potential importance is worthy of mention. Associated with the shelf break front is a geostrophic jet, evident in mean and synoptic velocity observations [Aikman *et al.*, 1988; Gawarkiewicz *et al.*, 1996]. Meandering jets force vertical motions. In the Gulf Stream, isopycnal floats upwell along isopycnals between cyclonic meander troughs and anticyclonic meander crests, reaching their shallowest depth near crests [Bower and Rossby, 1989]. Surveys along Gulf Stream meanders showed maximum chlorophyll concentrations on the cyclonic side of the stream near meander crests, where upwelling along isopycnals can introduce nutrients into the euphotic zone [Hitchcock *et al.*, 1993]. Zooplankton distributions have also been correlated with the vertical motions that occur in the meandering Gulf Stream [Ashjian, 1993]. If similar dynamics occur within the shelf break frontal jet, the combination of upwelling and rapid horizontal advection within the jet could enhance chlorophyll along the meandering surface outcrop of the front.

Biological effects of frontal processes, particularly those inferred from satellite remote sensing, require in-

terpretation within the context of seasonal changes in stratification. This late spring chlorophyll enhancement developed within the context of the seasonal progression toward stratification of the upper water column. Passage of the first two meanders strongly influenced phytoplankton fluorescence observed along the fixed transect. However, by the time the third meander passed the ship transect, thermal stratification was more developed, and no chlorophyll enhancement was observed at the shallow depth of sampling.

The Mid-Atlantic Bight is a very complex region, extraordinarily so during spring when physical, chemical, and biological conditions evolve between the extremes of winter and summer. Amidst this complexity, the shelf break front provides physical structure around which circulation and biological processes are organized. Many processes influence phytoplankton and other biological distributions, and it is difficult to isolate critical processes. Through integration of satellite and in situ observation, we have identified processes critical to phytoplankton growth and distribution during the period of increasing nutrient limitation in near-surface waters of the MAB. Satellite observations define synoptic surface distributions, and in situ observations define subsurface structure. Understanding mesoscale phytoplankton distributions requires drawing upon the strengths of each method of observation.

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