

## Mixing of chlorophyll from the Middle Atlantic Bight cold pool into the Gulf Stream at Cape Hatteras in July 1993

A. Michelle Wood and Nelson D. Sherry<sup>1</sup>

Department of Biology, University of Oregon, Eugene

Adriana Huyer

College of Ocean and Atmospheric Sciences, Oregon State University, Corvallis

**Abstract.** In July 1993 we collected hydrographic data and information on chlorophyll distribution on the continental shelf north of Cape Hatteras and across the shelf break at Cape Hatteras. The data show that a warm, transparent mixed layer lies over much colder, euphotic, chlorophyll-rich bottom water on the shelf. This layer has temperature and salinity properties characteristic of the Middle Atlantic Bight (MAB) cold pool, a distinctive mass of cold bottom water formed when cold water from the Gulf of Maine and Scotian Shelf is isolated from surface water by vernal warming and seasonal stratification [Houghton *et al.*, 1982]. The constant density of this chlorophyll-rich water ( $\sigma_\theta = 25.0\text{--}25.6$ ) combined with a strong chlorophyll gradient along the  $25 \sigma_\theta$  isopycnal at the shelf break indicates that chlorophyll advected off the shelf at Cape Hatteras in July 1993. TS diagrams further indicate that cold pool water, and the chlorophyll it contained, mixed into upper levels of the Gulf Stream. Thus the MAB may contribute to the nutrient budget of Atlantic surface waters through a long loop of circulation that transports deep water from the Labrador Sea to Cape Hatteras.

### Introduction

The fate of primary production in the Middle Atlantic Bight (MAB) has been the subject of intense debate and scientific inquiry for several decades, primarily in response to evidence that much of the spring bloom of the MAB is exported off the shelf [Walsh *et al.*, 1981; Malone *et al.*, 1983]. Two major experiments designed to document off-shelf transport of organic carbon showed that most primary production on the MAB shelf is oxidized in the water column and/or shelf sediments [Rowe *et al.*, 1988; Biscaye *et al.*, 1988, 1994; Falkowski *et al.*, 1988, 1994; Kemp, 1994; Wirick, 1994]. Since remineralization of nutrients accompanies oxidation of organic material, these results do not resolve the shelf/slope nutrient balance which actually determines whether or not continental margins are important sources of organic matter to the slope and deep sea [Marra *et al.*, 1990; Walsh, 1991, 1994]. Rapid recycling could support both high rates of on-shelf productivity and respiration and high off-shelf fluxes of organic matter. In this context it is important to determine the fate of new nutrients entering the MAB.

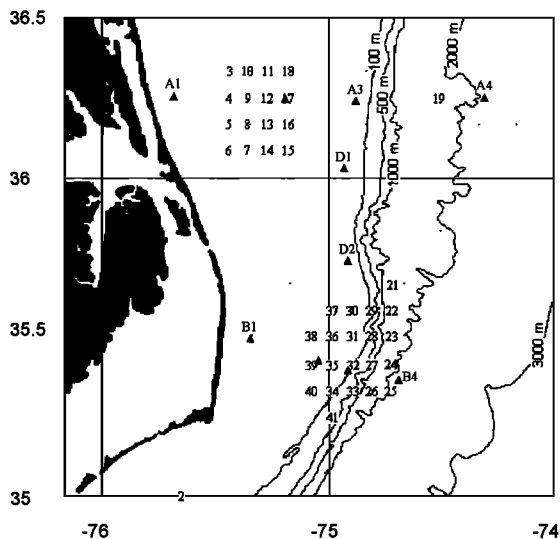
Intermittent intrusions of nutrient-rich slope water and exchange of MAB shelf water with slope water are two of the main sources of nutrients in the MAB [Flagg *et al.*, 1994; Walsh *et al.*, 1987]. A third major source of new nutrients for the MAB is cold, nutrient-rich slope water that apparently originates in the Labrador Sea and enters the MAB from the Scotian Shelf and Gulf of Maine [Bigelow, 1933; Chapman *et*

*al.*, 1986; Chapman and Beardsley, 1989; Walsh *et al.*, 1987]. Vernal warming isolates cold shelf water to form the “cold pool” of the MAB, a distinctive mass of bottom water which spreads along the shelf and shelf break from Hudson Canyon to Cape Hatteras during the summer [Houghton *et al.*, 1982]. Net current flow in the MAB is to the southwest. This flow converges with northward flow from the SAB at Cape Hatteras where the close approach of the Gulf Stream leads to mixing of shelf, slope, and Gulf Stream water [Churchill and Cornillon, 1991a, b; Gawarkiewicz *et al.*, 1992; Churchill *et al.*, 1993].

Because of the convergence of flow at Cape Hatteras, organic matter in the water which reaches Cape Hatteras must either exit the shelf in water which is mixed into the Gulf Stream and slope water, be deposited locally in sediments, or be oxidized locally. Oxidation would result in net release of CO<sub>2</sub> at Cape Hatteras and off-shelf transport of remineralized nutrients. Since water leaving the shelf at Cape Hatteras is likely to be enriched in either organic material or inorganic nutrients or both, when compared to the upper levels of the Gulf Stream and slope water, this region represents a potentially important source of nutrient enrichment for the Gulf Stream and, through Gulf Stream transport, more oligotrophic water offshore.

The Cape Hatteras region is a primary study site for the ongoing Ocean Margins Program (OMP), an interdisciplinary, multiinstitution investigation of the fate of organic matter at continental margins [Jahnke and Verity, 1994]. Preliminary cruises for this program were conducted in 1993 and 1994 to help identify temporal and spatial scales that would adequately describe shelf and shelf-edge processes. In July 1993 we collected hydrographic data and information on the chlorophyll distribution on the continental shelf north of Cape Hatteras and across the shelf break at Cape Hatteras. Intensive sampling was carried out in a region of the midshelf where scales

<sup>1</sup>Now at Department of Oceanography, University of British Columbia, Vancouver, Canada.



**Figure 1.** Location of conductivity-temperature-depth (CTD) stations made from R/V *Cape Hatteras*, July 14–18, 1993, with bathymetric contours showing the position of the shelf break. Stations 1 and 2 were sampled en route to the study area; station 1 (not shown) was located at 34°44.59N and 76°03.60 W. Stations 3–18 are in the “midshelf grid”; stations 21–41 are in the “shelf-break grid.” Station 20 was located at the same position as station 12. Positions of the Minerals Management Service/Science Applications International Corporation (MMS/SAIC) moorings are noted with solid triangles.

of variability were expected to be low and at the shelf break where the historical axis of the Gulf Stream is closest to the Carolina shelf. Here we report the distribution of water mass properties and chlorophyll in both regions and discuss the data which indicate that bottom water with characteristics of the cold pool was a site of primary production on the shelf. We also provide evidence that this water mixed with Gulf Stream water at the shelf break, transporting the chlorophyll it contained off the shelf and into slope waters.

## Methods

### Study Area

Observations were made at 41 stations sampled from the R/V *Cape Hatteras* during July 15–18, 1993 (Figure 1). Sea conditions were fairly calm throughout the cruise; wind speeds recorded while on station ranged from 3 to 18 knots (1.5 to 9.3 m/s), with a median value of 9 knots (4.6 m/s). All but three stations were included in one of two station grids, within which stations were located at intervals of 5 min of latitude and longitude. The northern grid or “midshelf” grid was located in the midshelf region and was situated over relatively flat topography ~100 km north of Cape Hatteras and ~40 km west of the shelf break (Figure 1). Station depth ranged from 28 to 42 m, with an average of 33 m (s.d. = 4 m,  $n = 16$ ). The grid was sampled in a radiator-like pattern beginning shortly before noon on July 15 at the northwest corner and ending in the northeast corner around 2200 hours on July 15. The southern grid, or “shelf-break grid,” was situated over the outer shelf and extended across the shelf break just north of Cape Hatteras (Figure 1). This grid included eight shelf stations (stations 30, 31, 35–40) with bottom depths between 32 and 50 m, five shelf-break stations (stations 28, 29, 32, 34, 41) with bot-

tom depths between 149 and 600 m, and eight slope stations with bottom depths exceeding 1000 m (stations 21–27, 33). This grid was also sampled in a radiator-like pattern beginning at the northeast corner at ~0800 hours on July 17 and ending in the southwest corner at 0345 on July 18. The position of the southern grid was within the zone where maximum benthic deposition off Cape Hatteras is thought to occur (L. Benninger, personal communication, 1993).

### Data Collection and Processing

A Sea-Bird Electronics 9/11 conductivity-temperature-depth (CTD) system, equipped with a Sea Tech fluorometer and Sea Tech transmissometer (660-nm source), was used to measure water properties to within 3–5 m of the bottom, or to 500 m, whichever was most shallow. The raw 24-Hz CTD data from the underwater unit were averaged in the deck unit to produce a 4-Hz data file, which was processed through the Sea-Bird SeaSoft software to remove spikes and correct for the thermal mass of the conductivity cell; data were averaged into 1-dbar pressure bins, and salinity and density ( $\sigma_\theta$ ) were calculated for each 1-dbar bin. Salinity data from the CTD were spot-checked against water samples run on an Autosol precision salinometer; the mean difference (0.008 psu) of nine pairs was less than the standard deviation (0.012 psu), so we did not correct the CTD data for this small negative bias. Water transparency was estimated at selected stations using a 0.5-m oceanographic Secchi disk. Light transmission data from the Sea Tech transmissometer on the CTD show a strong negative correlation with the in situ fluorometer reading (i.e., Figure 5 below) and are not discussed separately.

### Calibration of In Situ Fluorometer

Water samples for measurement of chlorophyll concentration in discrete samples were collected from Niskin bottles tripped at various depths and stations across the shelf and shelf break (Table 1). Calibration stations ran along the diagonal of each grid and samples were collected from each of these stations at four or more depths (Table 1). Dawn occurred at approximately 0500 local time and sunset occurred at approximately 2015 local time. Thus calibration stations were collected in both daylight and nighttime hours (Table 1; Figure 2). Samples were filtered through Whatman glass microfiber filters (grade: GF/F), and chlorophyll was extracted by freezing the filter in 1 mL distilled water. After freezing, samples were diluted with 9 mL of 100% acetone and placed at 4°C in the dark for 24 hours. Chlorophyll concentration in the samples was then determined fluorometrically using a Turner Designs AU-10 fluorometer, correcting for phaeopigments [Parsons *et al.*, 1992]. At the midshelf grid, phaeopigments were 30% (s.d. = 4%,  $n = 20$ ) of fluorometrically determined pigments (chlorophyll + phaeopigment), and phaeopigments averaged 42% (s.d. = 32%,  $n = 43$ ) in the calibration data set overall. High values (>60% of total pigments) were only found in samples from >200 m (Table 1). Before the cruise the AU-10 was calibrated with a dilution series of standard spinach chlorophyll (Sigma).

Chlorophyll fluorescence, derived from the 1-m bin-averaged in situ fluorometer readings at the depths where samples for extracted chlorophyll were taken, was calibrated by linear regression against the chlorophyll measurements made on the AU-10 fluorometer (Figure 2). Chlorophyll data discussed below represent in situ fluorescence measurements con-

**Table 1.** Station Data for Samples Used to Calibrate In Situ Fluorometer

Station	Date	Local Time	Latitude	Longitude	Depth	Volume Filtered, mL	Acid Ratio	Chl <i>a</i> , mg m <sup>-3</sup>		Phaeo, mg m <sup>-3</sup>		Phaeo % of Total	In Situ Fluorescence
								$\bar{x}$	s.d.	$\bar{x}$	s.d.		
1	July 14	1519	34°44.59	76°03.60	16	15	1.86	0.28	0.02	0.11	0.02	28.7	-0.03
					24	15	1.71	0.54	0.02	0.38	0.04	41.1	0.16
2	July 14	2012	35°00.05	75°39.95	21	15	1.72	0.28	0.02	0.18	0.05	39.8	0.03
					21	15	1.83	0.23	0.03	0.10	0.01	31.3	0.03
					<i>Midshelf Grid Stations</i>								
3	July 15	1110	36°19.96	75°16.45	5	100	1.83	0.27	0.02	0.12	0.01	31.3	-0.06
					10	100	1.83	0.47	0.01	0.21	0.00	31.2	0.02
					16	100	1.85	0.94	0.01	0.38	0.02	29.0	0.14
					28	100	1.82	3.62	0.15	1.68	0.12	31.7	1.12
9	July 15	1712	14.43	11.64	5	100	1.82	0.26	0.01	0.12	0.01	32.2	-0.08
					15	100	1.81	1.68	0.03	0.81	0.08	32.4	0.18
					20	100	1.85	5.47	0.10	2.21	0.13	28.8	1.22
					27	100	1.88	5.90	0.06	2.19	0.15	27.1	1.49
13	July 15	2030	09.96	06.41	5	100	1.85	0.24	0.01	0.10	0.01	29.0	-0.05
					10	100	1.83	0.87	0.04	0.38	0.00	30.6	0.13
					15	100	1.82	0.92	0.19	0.42	0.10	31.4	0.14
					31	100	1.90	4.25	0.08	1.43	0.08	25.2	0.69
15	July 15	2211	05.06	01.39	6	100	1.86	0.45	0.02	0.18	0.01	28.2	0.01
					10	100	1.88	0.63	0.00	0.23	0.02	26.9	0.16
					20	100	1.93	4.98	0.04	1.44	0.04	22.5	0.73
					40	100	1.91	5.23	0.18	1.66	0.10	24.1	0.99
19	July 16	1620	36°14.71	74°31.52	30	100	1.82	0.75	0.03	0.35	0.05	32.0	0.21
					100	100	1.56	0.06	0.00	0.07	0.00	53.8	-0.01
					200	100	1.23	0.02	0.00	0.08	0.01	80.3	-0.05
					250	100	1.22	0.02	0.01	0.08	0.00	80.3	-0.25
					<i>Shelf-Break Grid Stations</i>								
21	July 17	0748	35°39.21	74°42.68	42	100	1.83	1.76	0.11	0.78	0.06	30.8	0.38
25	July 17	1248	19.16	42.83	21	100	1.90	0.15	0.01	0.05	0.01	25.3	0.02
					51	100	1.86	0.30	0.01	0.12	0.01	28.3	0.05
					70	100	1.81	0.42	0.00	0.20	0.01	32.1	0.07
					91	100	1.65	0.53	0.02	0.44	0.04	45.5	0.13
					120	100	1.57	0.25	0.01	0.28	0.02	52.7	0.07
					201	100	1.41	0.06	0.01	0.12	0.01	66.7	0.00
27	July 17	1512	24.07	47.97	20	100	1.88	0.16	0.00	0.06	0.01	27.3	0.01
					70	100	1.68	0.49	0.01	0.38	0.01	43.6	0.07
					90	100	1.57	0.25	0.01	0.29	0.01	53.3	0.08
					120	100	1.48	0.16	0.00	0.24	0.02	59.8	-0.06
31	July 17	1839	29.08	52.93	200	100	1.38	0.02	0.01	0.05	0.01	70.0	0.11
					6	100	1.93	0.14	0.01	0.04	0.00	23.1	-0.01
					18	100	1.76	0.24	0.00	0.14	0.01	36.4	0.06
					23	100	1.76	0.34	0.01	0.20	0.02	37.1	0.09
37	July 17	2325	34.04	58.08	35	100	1.74	0.87	0.04	0.53	0.03	37.9	0.31
					5	100	1.82	0.14	0.02	0.07	0.01	32.0	0.02
					12	100	1.78	0.18	0.00	0.10	0.00	34.9	0.03
					30	100	1.76	2.06	0.06	1.17	0.02	36.3	0.59
					41	100	1.87	1.79	0.22	0.67	0.06	27.1	0.28

verted to chlorophyll *a* concentrations using this regression. A diurnal pattern of fluorescence quenching during periods of high irradiance would lead to a clustering of our daytime data points above the regression line in Figure 2. Diurnal changes in fluorescence yield do not appear to bias our fluorometer calibration. This is not surprising since, as described below, most of the chlorophyll in the water masses we were studying occurred as subsurface patches or layers.

#### Remote Sensing

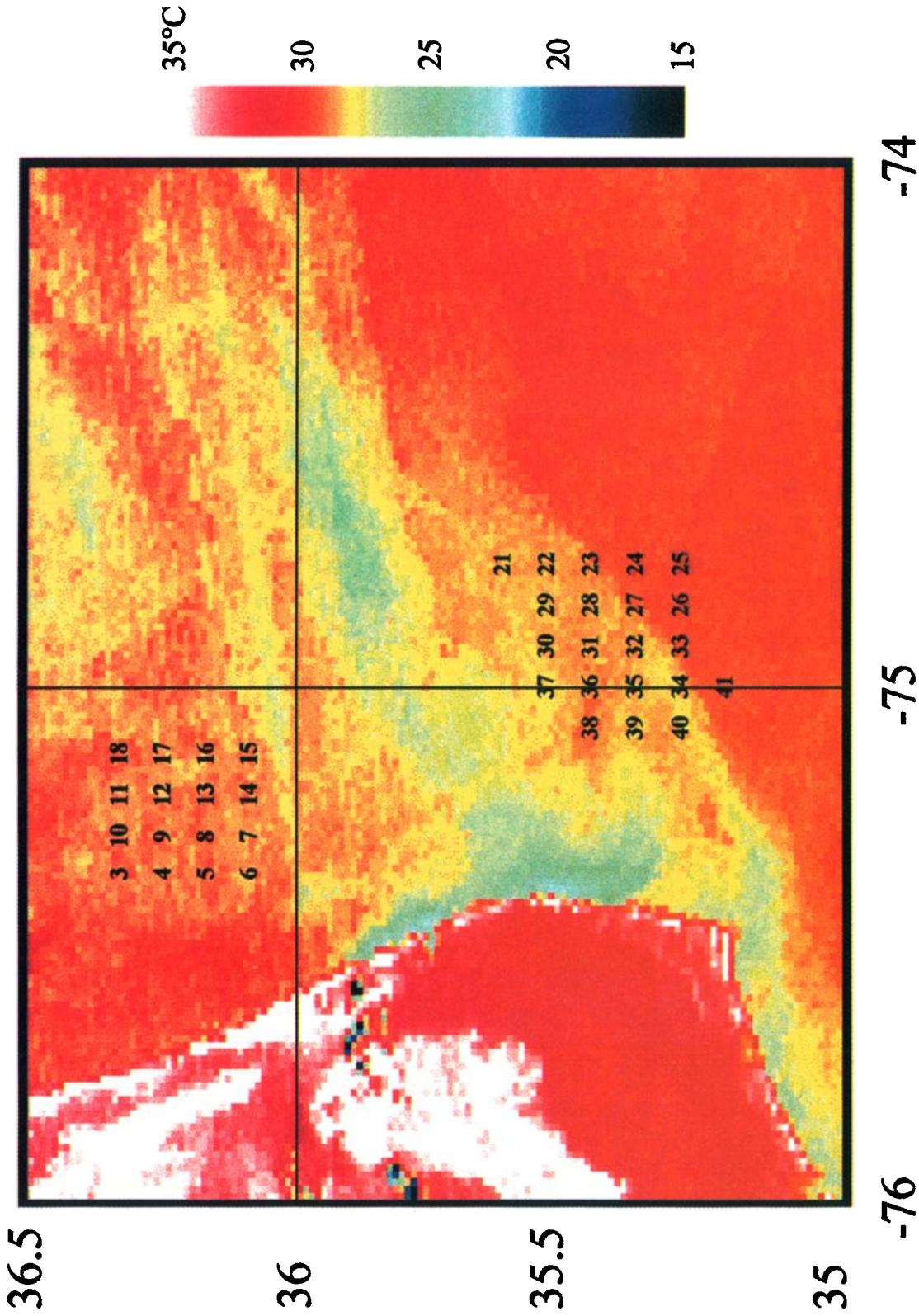
Advanced very high resolution radiometer (AVHRR) satellite images from the study region were obtained courtesy of the National Oceanic and Atmospheric Administration (NOAA) CoastWatch and processed with NOAA's CCoast software ( $\beta$  version). Plate 1 is a 1.4-km pixel, daytime, nonlinear split window sea surface temperature (SST) image from a NOAA

high-resolution picture transmission pass at 2041 UT, July 14, 1993.

## Results

#### Remote Sensing

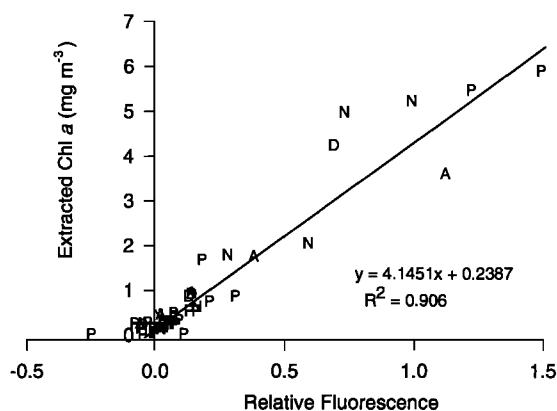
The best satellite image of SST near the time of our cruise is a daytime pass on July 14, 1995 (Plate 1), which shows warm water throughout the study region. Very warm water (29°–31°C), presumably associated with the Gulf Stream, fills the southeastern corner of the study area and creates a sharp temperature front across the southeast corner of the shelf-break grid (Plate 1). Lower surface temperatures (25°–27°C) were seen in an eastward tending tongue between the two grids. Satellite-derived SST within the midshelf grid were



**July 14, daytime**

**Image courtesy of NOAA CoastWatch**

Plate 1. Station grids superimposed on a daytime advanced very high resolution radiometer satellite image of sea surface temperature for July 14, 1993. Image courtesy of National Oceanic and Atmospheric Administration (NOAA) CoastWatch.



**Figure 2.** Regression of extracted chlorophyll values from Table 1 against in situ fluorometer readings at the depth of discrete samples. D, samples collected within 1 hour of sunset; N, samples collected at night (at least 1 hour after sunset and before sunrise); P, samples collected after local apparent noon but less than 1 hour before sunset; A, samples collected after sunrise and before local apparent noon.

nearly uniform and similar to those in the northwest half of the shelf-break grid.

#### Midshelf Grid

There is little evidence for persistent horizontal gradients in the upper 15 m of the northern (midshelf) grid, although vertical stratification is strong (Figures 3 and 4). A warm, relatively fresh surface mixed layer occupies the upper 8–10 m (Figures 3 and 4). The surface layer is very transparent with chlorophyll concentrations  $<0.5 \text{ mg m}^{-3}$  throughout the layer (Figures 3 and 4). Secchi depths in the midshelf grid ranged from 18 m, determined at night under ship's lights, to 24 m, determined at midday.

The mixed layer is separated from cold bottom water by a strong thermocline between 8 and 15 m (Figures 3 and 4). The water below 20 m is nearly uniform in both temperature and salinity which range from  $7.7^\circ$  to  $10^\circ\text{C}$  and 32.4 to 32.9 practical salinity units (psu), respectively. There is a slight horizontal gradient in the bottom water, which tends to be colder and more saline on the eastern side of the grid (Figure 3). Chlorophyll concentrations are slightly higher within the thermocline than in the surface layer and increase sharply below the thermocline. The most dramatic feature of the on-shelf grid is the high chlorophyll content of the bottom water (Figure 4). Nearly all the chlorophyll in the water column at the mid-shelf grid is contained within this thick ( $\sim 15 \text{ m}$ ) bottom layer which contains the densest water observed on the shelf in either grid ( $\sigma_\theta = 25.31 \pm 0.16$  at 20 m ( $n = 16$ ),  $25.30 \pm 0.20$  at 25 m ( $n = 16$ ), and  $25.39 \pm 0.16$  at 30 m ( $n = 11$ ); values are mean  $\pm$  s.d.; Figure 4).

Within the bottom water, chlorophyll concentrations increased with increasing depth to a point slightly above the bottom. Typical vertical profiles for an individual station are shown in Figure 5; across the grid, maximum chlorophyll concentrations ranged from 3 to  $8.6 \text{ mg m}^{-3}$ , and the depth at which maximum values were observed ranged from 21 to 35 m, with an average depth of 26 m. As with temperature and salinity, there was a slight horizontal gradient, with generally lower chlorophyll values observed at the westernmost stations.

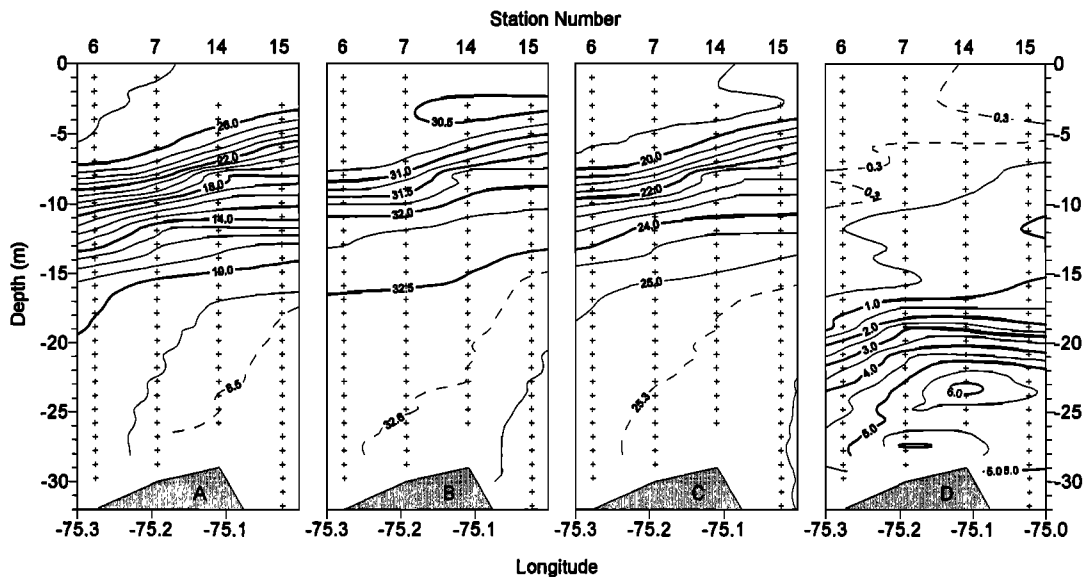
#### Shelf-Break Grid

Mixed layer temperatures from CTD data collected in the shelf-break grid July 17–18 agree well with the satellite SST observed July 14 but show that the temperature front moved further north into the station grid during the intervening period (compare Plate 1 and Figure 6). This shift in the position of the temperature front was also apparent in partially cloud-covered AVHRR images available for July 16 and 17. Together with surface salinity, which is  $>35.5$  psu throughout the southern and northeastern part of the grid (Figure 6), these data suggest that most of the southeastern half of the cross-shelf grid was experiencing direct Gulf Stream influence at the time of our cruise. This interpretation was confirmed by data from current meter arrays maintained by the Minerals Management Service (MMS) of the U.S. Department of the Interior for extended periods including mid-February to late August, 1993 [Science Applications International Corporation, (SAIC), 1994]. Three of the MMS moorings were inside our shelf-break grid (Figures 1 and 6). Between July 15 and 20, 1993, 40-hour low-pass filtered currents were  $80\text{--}100 \text{ cm s}^{-1}$  to the northeast at 30 m at mooring B3 located in about 60 m of water and  $150\text{--}170 \text{ cm s}^{-1}$  to the northeast at 100 m at mooring B4 located in approximately 2000 m of water.

Horizontal property distributions show a thermohaline front running diagonally across the grid at the interface between very warm, salty Gulf Stream water present throughout the water column in the southeast corner of the cross-shelf grid and relatively cool, fresh water present in the north and northeast quadrants of the grid (Figure 6). The front is most apparent in bottom water, which is cooler and fresher than overlying surface water (Figure 6). Outer-shelf bottom water is similar to the midshelf bottom water, though not as cold ( $10.5^\circ\text{C}$ ; compare  $8^\circ\text{C}$ ) and fresh (33.7; compare 32.7 psu). Outer-shelf surface water was slightly warmer (by  $<1^\circ\text{C}$ ) and much more saline than surface water in the midshelf grid: at 5 m, salinity was  $<31$  psu at all stations in the midshelf grid (Figures 3 and 4) and  $>34$  psu at all of the stations in the shelf-break grid (Figure 6).

East-west transects through the shelf-break grid (Figures 7–10) show a definite north-south gradient in water properties over the upper slope and outer shelf. Along the southern boundary ( $35^\circ 19' \text{ N}$ ), all of the water is relatively warm and very saline compared to the waters within the midshelf grid (compare Figures 7 and 8 to Figures 3 and 4; see also Figure 12). More northerly sections show progressively more evidence of cool ( $<12^\circ\text{C}$ ) low-salinity ( $<35$  psu) water over the upper slope, just seaward of the shelf break. The salinity of bottom water (or water at 100 m for slope stations) was  $<33$  psu at all of the midshelf grid stations (Figures 3 and 4) and  $>34$  psu at all but five of the stations in the shelf-break grid (Figure 6). Stations where bottom or 100 m salinities were  $<35$  psu were concentrated along the most northern transect of the grid (Figures 6 and 8) and, at these stations, bottom temperatures were also low, ranging from  $10.5^\circ$  to  $12.7^\circ\text{C}$  (Figures 6 and 7). This is in contrast to bottom (or 100 m) temperatures  $>17^\circ\text{C}$  in the rest of the grid (Figure 6).

Chlorophyll concentrations were lower at the shelf-break grid than at the midshelf grid and did not exceed  $4 \text{ mg m}^{-3}$  anywhere in the grid (Figure 9). Surface waters had very low chlorophyll content throughout the grid. The highest chlorophyll concentrations occurred in bottom water at shelf stations



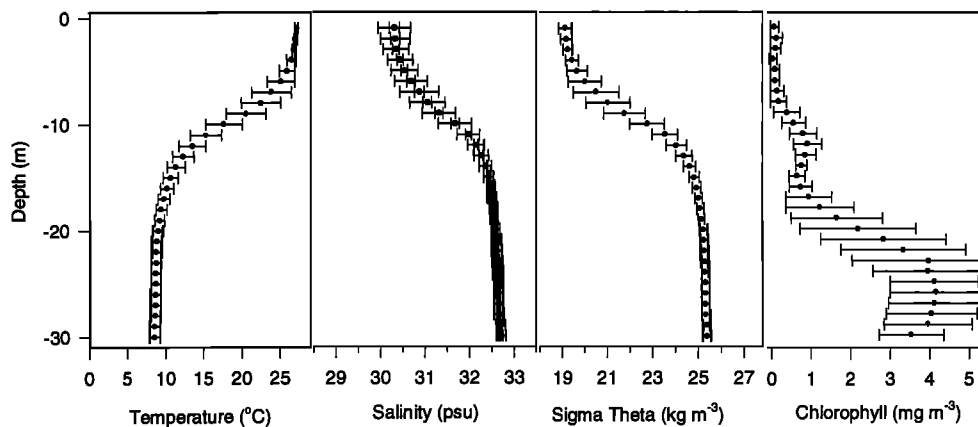
**Figure 3.** West-to-east sections of (a) temperature, degrees; (b) salinity, practical salinity units; (c) density anomaly, kilograms per cubic meter; and (d) chlorophyll, milligrams per cubic meter, at the southern end of the midshelf grid (stations 6, 7, 14, 15, along 36°05'N). Other sections through the midshelf grid are similar.

and between 40 and 80 m at shelf-break stations. Patches of elevated chlorophyll concentration in bottom water at the outer shelf stations of this grid appear to be contiguous with patches of high chlorophyll in slope water.

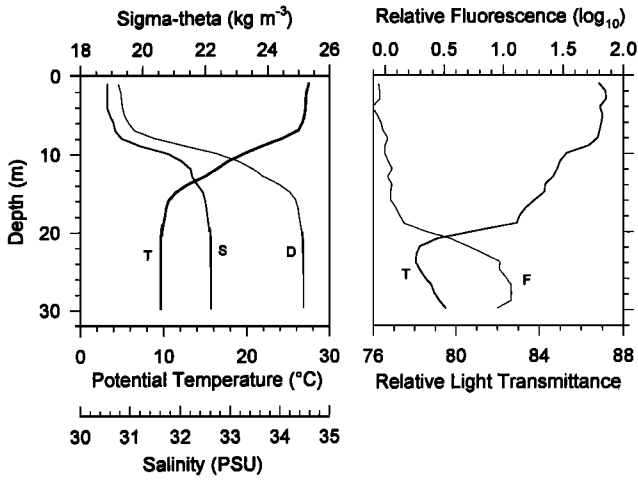
Density contours also suggest continuity across the shelf break in the northern half of the shelf-break grid (Figure 10). In the transects along 35° 34' N and along 35° 29' N, water with a density ( $\sigma_\theta$ ) between 25.0 and 25.5 kg m<sup>-3</sup> lies near the bottom over the shelf (Figure 10) and continues beyond the shelf break, forming a horizontal layer between 45 and 80 m over the continental slope (Figure 10). In transects along 35° 24' N and 35° 19' N, isopycnals with  $\sigma_\theta$  between 23.5 and 24.5 kg m<sup>-3</sup> follow the bottom contours of the shelf, continue beyond the shelf break, and form horizontal layers between 30 and 60 m over the slope. In the two southern transects, isopycnals with  $\sigma_\theta$  between 25.0 and 25.5 kg m<sup>-3</sup> do not occur on the shelf, and they occur slightly deeper at slope stations than

they did at the two northern transects (e.g., 60–100 m as compared to 45–80 m; see Figure 10).

While the depth of the chlorophyll maximum at stations in the shelf-break grid ranged from 21 to 98 m,  $\sigma_\theta$  at the depth of the chlorophyll maximum was relatively invariant ( $\bar{x} = 24.9$ , s.d. = 0.4,  $n = 19$  stations). Water this dense was not observed at stations 35, 36, and 39, which were located on the shelf in the southern two transects of the shelf-break grid, although extrapolation between stations 31 and 38 suggests that water with a density anomaly as great as 25 kg m<sup>-3</sup> probably occurred at station 36 below our deepest sampling depth of 34 m (station depth ~37 m; Figure 10). At these, as at other shelf stations in the grid, the chlorophyll maximum occurred in the bottom water and  $\sigma_\theta$  ranged from 23.5 to 24.8 at the chlorophyll maximum. When chlorophyll concentration is plotted on the 24.5, 25.0, and 25.5 isopycnal surfaces, a gradient of concentration can be seen extending diagonally across the grid, with



**Figure 4.** Vertical profiles of average water properties at stations 3–18 in the midshelf grid; error bars are  $\pm 1$  standard deviation calculated from all observations at each depth; only a few stations were deeper than 33 m ( $N = 16$  between 4 and 26 m and  $N \geq 8$  at all depths  $\leq 33$  m).



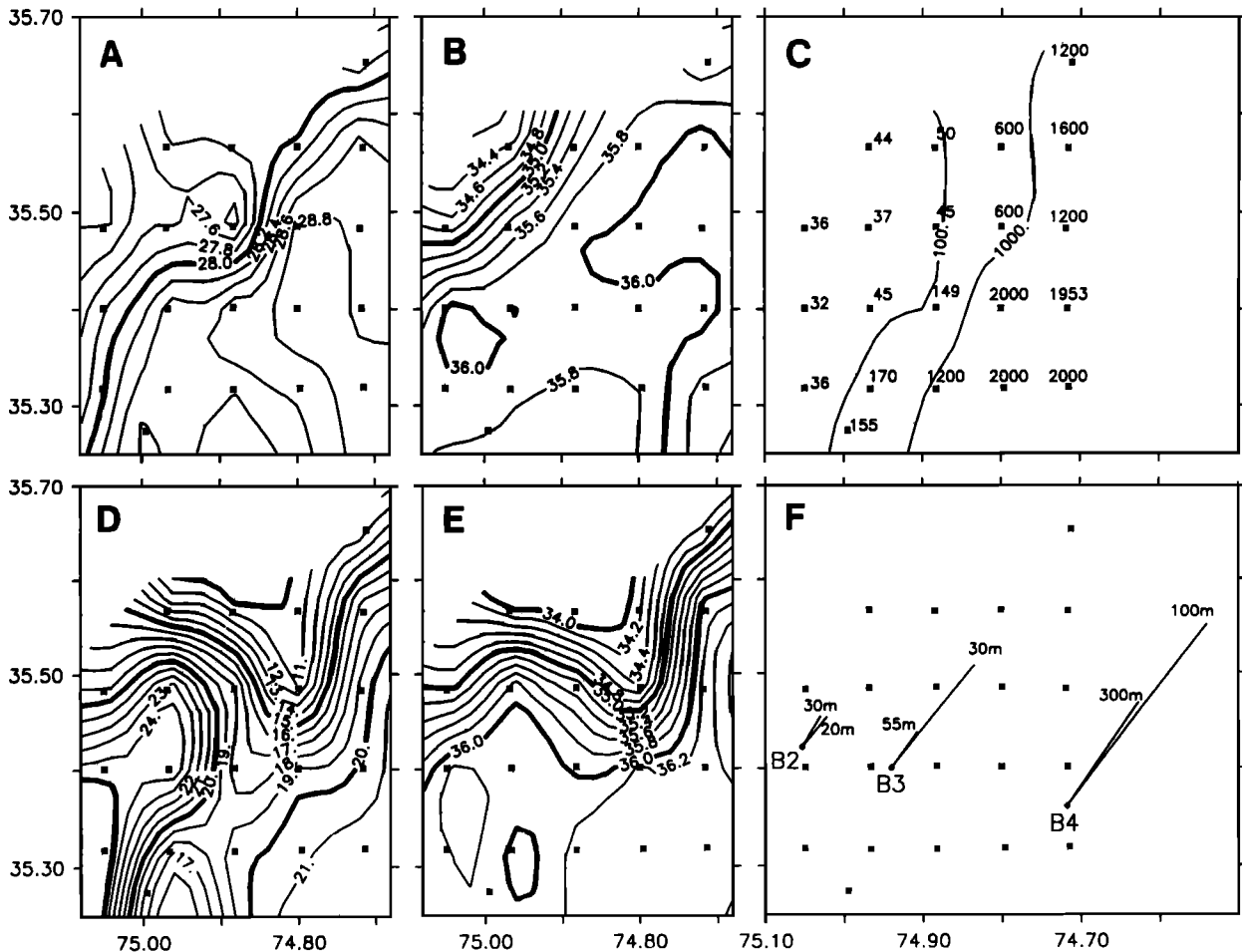
**Figure 5.** Observed CTD profiles of temperature (T, left panel), salinity (S), density anomaly (D), fluorometer voltage (F), and light transmission (T, right panel) at station 6, located at 36° 04.9'N, 75° 16.6'W, over the 32-m isobath, made at 1754 UT, July 15, 1993. These profiles are typical of stations in the midshelf grid.

high values in the north and west (Figure 11). These surfaces are inclined, shoaling in the north and west.

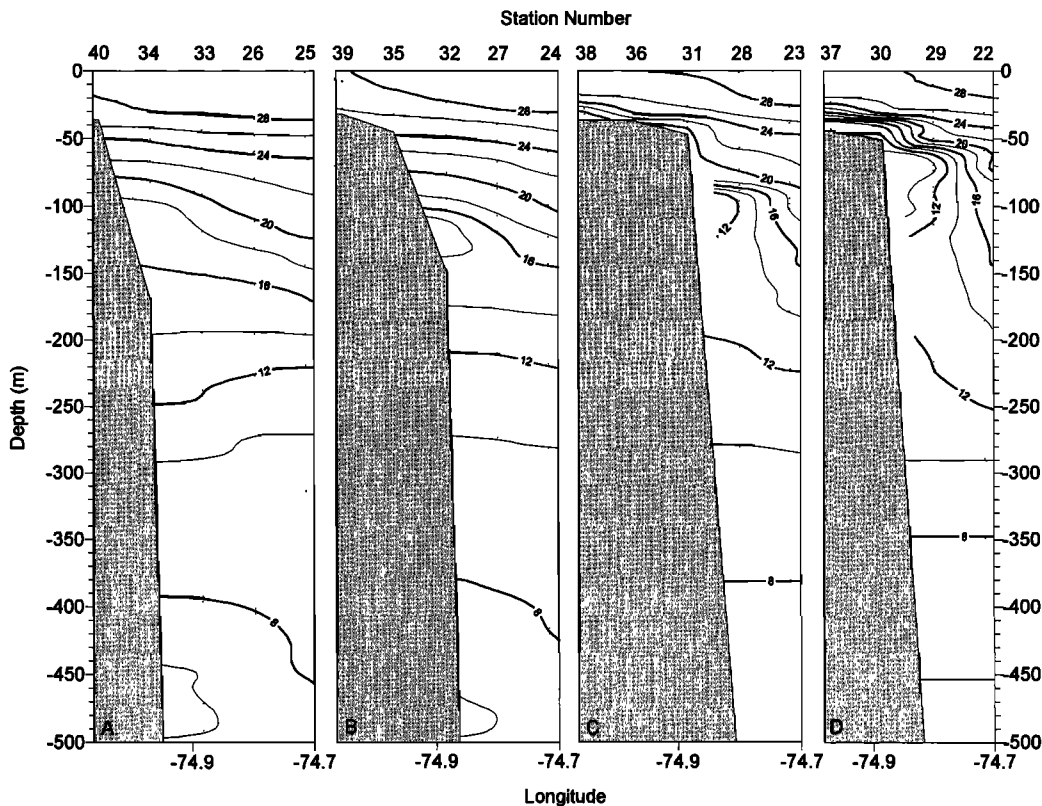
**θ-S Analysis**

Potential temperature-salinity characteristics of all data points from all stations for both grids are plotted in Figures 12a–12c. Four end-members can be identified: warm (25°C), relatively fresh (29.5–30.5 psu) water found only in the surface layer in the midshelf grid; cold (7°–10°C) water with salinity between 32.0 and 32.8 psu found primarily at deeper depths in the midshelf grid but also at some stations in the shelf-break grid; high salinity (35.0–35.1 psu), low-temperature (4.8°–7°C) water found only at depths >300 m at stations on the continental slope (stations 21–28 and station 33); and warmer (>15°C) high-salinity (35.7–36.3 psu) water found only at stations in the cross-shelf grid. Chlorophyll values exceed 1 mg m<sup>-3</sup> at some points associated with all of these water masses except the warm relatively fresh water (<30.5 psu) which comprised the surface water of the midshelf grid (Figure 12d).

Water of salinity between 33 and 35 psu was only observed in the shelf-break grid and only at stations 21, 28–32, 37, and 38 in the northern half of this grid (Figure 12). At all of these



**Figure 6.** Distributions of near-surface and subsurface temperature (degrees Celsius) and salinity (practical salinity units) in the shelf-break grid, with separate panels showing bottom depths and average currents: (a) temperature and (b) salinity at 5 m; (c) bottom depths in meters of CTD stations; (d) temperature and (e) salinity at 100 m, or at maximum depth if less than 100 m; (f) average currents at MMS/SAIC moorings within the grid for the 1-week period beginning 0000 UT, July 12, 1993, scaled so that 5 cm s<sup>-1</sup> = 1 km; the longest vector represents a speed of 133 cm s<sup>-1</sup>.



**Figure 7.** West-to-east sections of temperature (degrees Celsius) through the shelf-break grid; sections are shown in order from south to north: (a) along  $35^{\circ}19'N$  (stations 40, 34, 33, 26, 25), (b) along  $35^{\circ}24'N$  (stations 39, 35, 32, 27, 24), (c) along  $35^{\circ}29'N$  (stations 38, 36, 31, 28, 23), and (d) along  $35^{\circ}34'N$  (stations 37, 30, 29, 22).

stations, there is a portion of the  $\theta$ - $S$  curve in which temperature increases linearly with salinity, from water with low values of  $\theta < 12^{\circ}C$ ,  $S < 35$  psu to waters of variable high temperature ( $20^{\circ}$ - $25^{\circ}C$ ) but nearly constant salinity ( $\sim 36.1$  psu). These straight line segments indicate two-point conservative mixing between the cooler, fresher waters and warm, salty waters. The values at the cool end of these straight line segments occur near a straight line joining the  $\theta$ - $S$  characteristics of the bottom water seen over the midshelf ( $\theta \sim 8^{\circ}C$ ,  $S \sim 32.7$  psu,  $\sigma_{\theta} \sim 25.3$   $kg\ m^{-3}$ ) with the  $\theta$ - $S$  characteristics of water at a depth of 200 m over the upper slope ( $\theta \sim 12^{\circ}C$ ,  $S \sim 35.5$  psu,  $\sigma_{\theta} \sim 26.8$   $kg\ m^{-3}$ ). Some of these cool, fresh values were observed in the bottom water over the outer shelf (e.g., stations 30, 37). Others occurred as local extrema in stations over the upper slope (stations 21, 28, 29). Samples in which chlorophyll concentrations were  $>1$   $mg\ m^{-3}$  either occurred in deep slope water, in midshelf bottom water, or in water where there was a strong indication of two- or three-point mixing of midshelf bottom water with one or more sources of Gulf Stream water (Figure 12d).

A layer of very cool, relatively fresh water, lying between layers of Gulf Stream water is apparent between 40 and 80 m at station 21, which was located on the continental slope slightly north of the other stations in the shelf-break grid (Figure 13e). Chlorophyll concentrations in this layer are among the highest observed in the cross-shelf grid and greatly exceed the chlorophyll concentrations above and below the intrusion (chlorophyll  $<0.15$   $mg\ m^{-3}$  at 10 m,  $2.9$   $mg\ m^{-3}$  at 46 m, and  $0.19$  at 100 m). Two-point mixing between the intruded water and overlying Gulf Stream surface water is apparent in the  $\theta$ - $S$

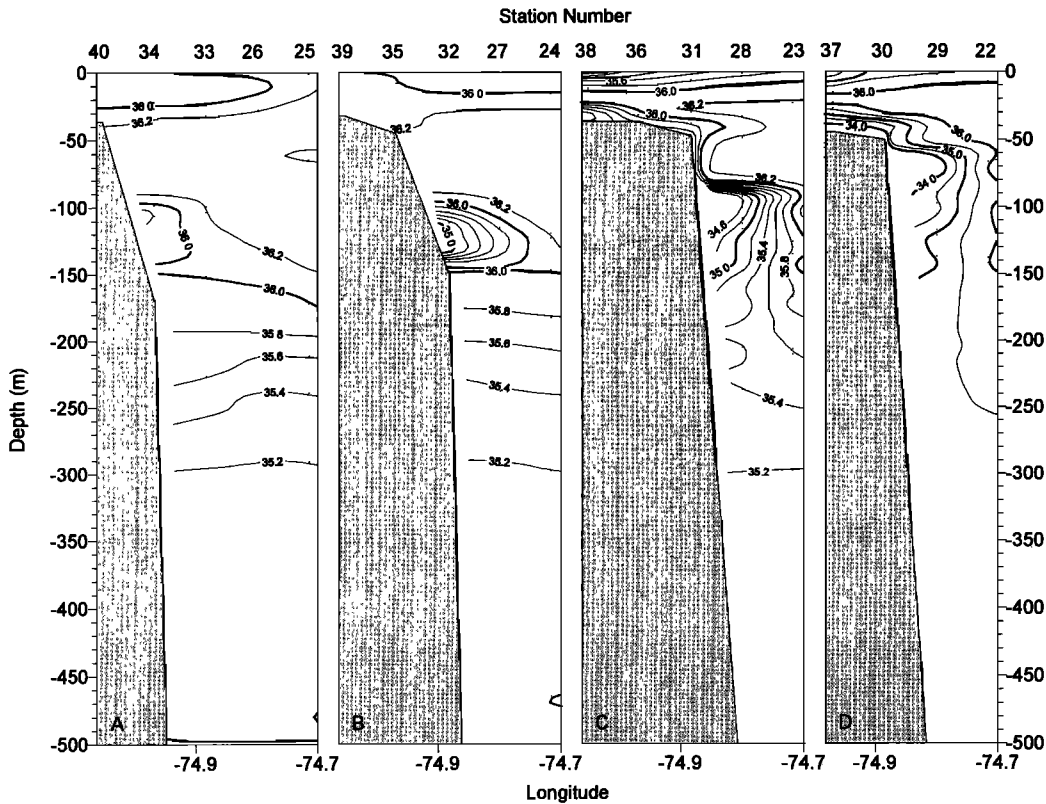
diagram for station 21; this is cross-isopycnal mixing apparently facilitated by wind-driven turbulence in the surface layer. Mixing of the intruded water with deeper Gulf Stream water below the intrusion is also apparent in Figure 13a; most of this mixing occurs along the  $26\ \sigma_{\theta}$  isopycnal. In both instances of mixing between the intruded water and Gulf Stream water, chlorophyll values are  $>1$   $mg\ m^{-3}$  in water which contains a strong component of intruded water (Figure 13a).

## Discussion

### Shelf Bottom Waters Near Cape Hatteras

The cold, chlorophyll-rich water observed as a layer of bottom water on the midshelf has properties similar to that of the Mid-Atlantic Bight cold pool. This is a benthic water mass which is formed as summer stratification isolates the surface water from cold subsurface water that has entered the MAB from the Gulf of Maine [Bigelow, 1933; Ketchum and Corwin, 1964]. Extensive data sets from a cross-shelf moored array and surveys spanning the entire MAB in 1979 [Houghton et al., 1982] and the southern MAB in 1971 and 1972 [Boicourt, 1973] show that the coldest cold pool water ( $5^{\circ}$ - $6^{\circ}C$  in July) is located on the outer shelf and slope of the northeastern MAB. As this water is advected slowly to the south, the cold pool waters undergo general warming. In 1979 the cold pool was still clearly defined south of Hudson Canyon where temperatures on the outer shelf were between  $8^{\circ}$  and  $10^{\circ}C$  in July [Houghton et al., 1982], and in 1971 and 1972 the cold pool was easily recognized on the outer shelf (depths  $>50$  m) as far south as  $36^{\circ}20'N$  [Boicourt, 1973]. In June 1988 the cold pool





**Figure 8.** West-to-east sections of salinity (practical salinity units) through the shelf-break grid; sections are shown in the same order as in Figure 7.

could be identified on the midshelf and outer shelf in a cross-shelf transect off the northern Delmarva peninsula [Biscaye *et al.*, 1994]. Salinity associated with the coldest cold pool waters in July 1979 was between 32.5 and 33 psu [Houghton *et al.*, 1982], identical to that of the bottom water of our midshelf grid. Water of similar salinity, but not quite as cold as the bottom water we observed at our mid-shelf grid, formed a bottom layer on the inner shelf north of Cape Hatteras in July 1971 and July 1972 [Boicourt, 1973].

The only other source of cold bottom water for the shelf off Cape Hatteras would be deep slope water. Gulf Stream meanders that eject water onto the shelf north of Cape Hatteras are common [Churchill and Cornillon, 1991a], but 10°C water that could be intruded from the slope or Gulf Stream would be of higher salinity ( $S > 35.0$  psu) than the bottom water we observed in the midshelf grid ( $S < 33.0$  psu). The combination of temperature and salinity properties and the slight gradient toward colder, saltier water from west to east within the layer (Figure 3) are consistent with spreading of the cold pool slightly further south in the MAB in 1993 than in 1979 or 1980 [c.f. Houghton *et al.*, 1982; Falkowski *et al.*, 1983] and further west than in 1971 or 1972 [Boicourt, 1973].

During our survey the cold pool water in the midshelf grid contained high concentrations of chlorophyll. The low estimated contribution of phaeopigments to total fluorometrically derived pigment concentration at stations in the midshelf grid (Table 1) indicates that the chlorophyll we measured was present in healthy cells. Although high concentrations of accessory pigments could cause artifacts in the determination of phaeopigment concentration [Gibbs, 1979; Trees *et al.*, 1985], the presence of photosynthetically competent cells was con-

firmed by examining plankton samples collected in the midshelf grid. Phase contrast and epifluorescence microscopy revealed abundant planktonic diatoms with intact chloroplasts in the bottom water (*Leptocylindrus danicus*, *Corethron* sp., and *Skeletonema costatum*).

Since the transmissometer data cannot be used to infer irradiance levels at a given depth because the instrument measures changes in beam attenuation rather than diffuse attenuation (R. Zaneveld, Oregon State University, personal communication, 1996), it is unfortunate that we were unable to measure irradiance directly. However, we can infer that the chlorophyll-rich bottom water was within the euphotic zone from the 24-m daytime Secchi Disk reading we obtained. As is apparent from Figure 4, the Secchi depth was at least 4 m deeper than the transition from the relatively transparent upper layer of the water column to the less transparent chlorophyll-rich bottom water. Using the relation  $K_d = 1.44/Z_{sd}$ , where  $K_d$  is the diffuse attenuation coefficient and  $Z_{sd}$  is the Secchi depth [Kirk, 1994], we calculate a very conservative estimate of 0.06 for  $K_d$  in the transparent surface layer and of 0.24 for  $K_d$  in the chlorophyll-rich layer. The latter value is based on a presumed "Secchi depth" of at least 6 m within the chlorophyll-rich layer since the observed Secchi Disk depth involved round-trip travel of light through at least 8 m in the chlorophyll-rich layer and 40 m in the surface water. Combined, these values lead to the prediction that irradiance at 30 m was roughly 2.7% of surface values and that irradiance at 33 m is close to 1% surface irradiance. The combined Secchi Disk data, chlorophyll data, and microscopic observations support our interpretation that chlorophyll in the bottom water resulted from in situ production. It also appears that the sed-

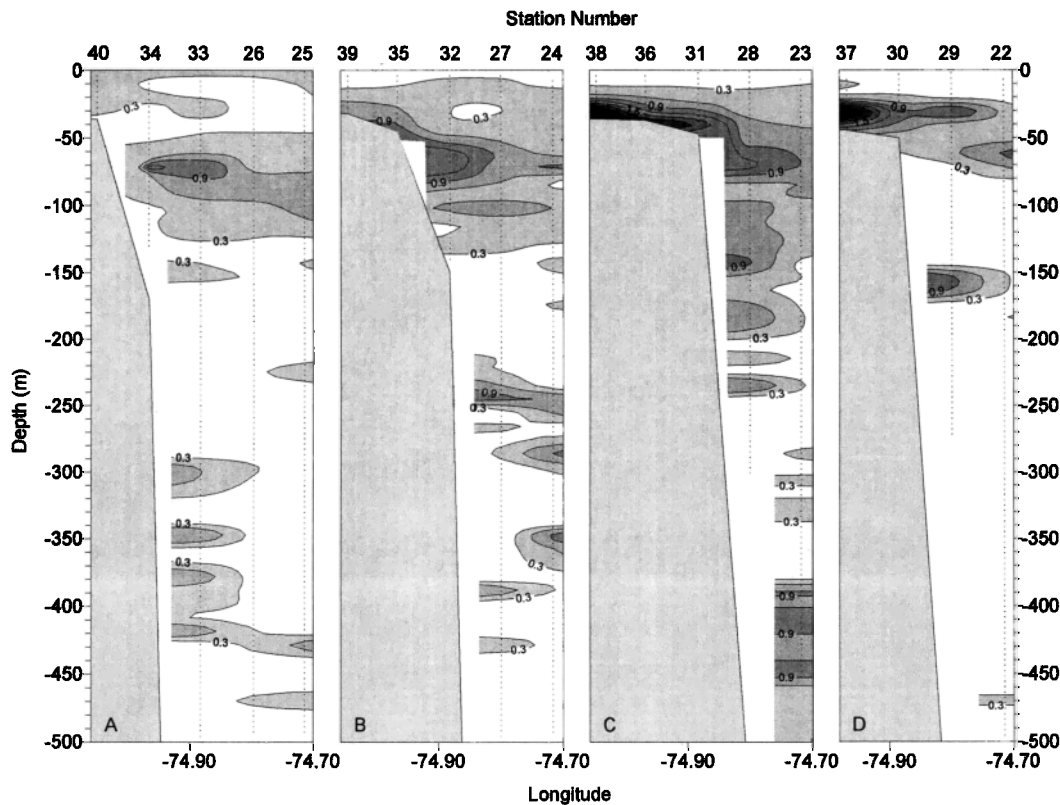


Figure 9. West-to-east sections of chlorophyll (milligrams per cubic meter) through the shelf-break grid; sections are shown in the same order as in Figure 7.

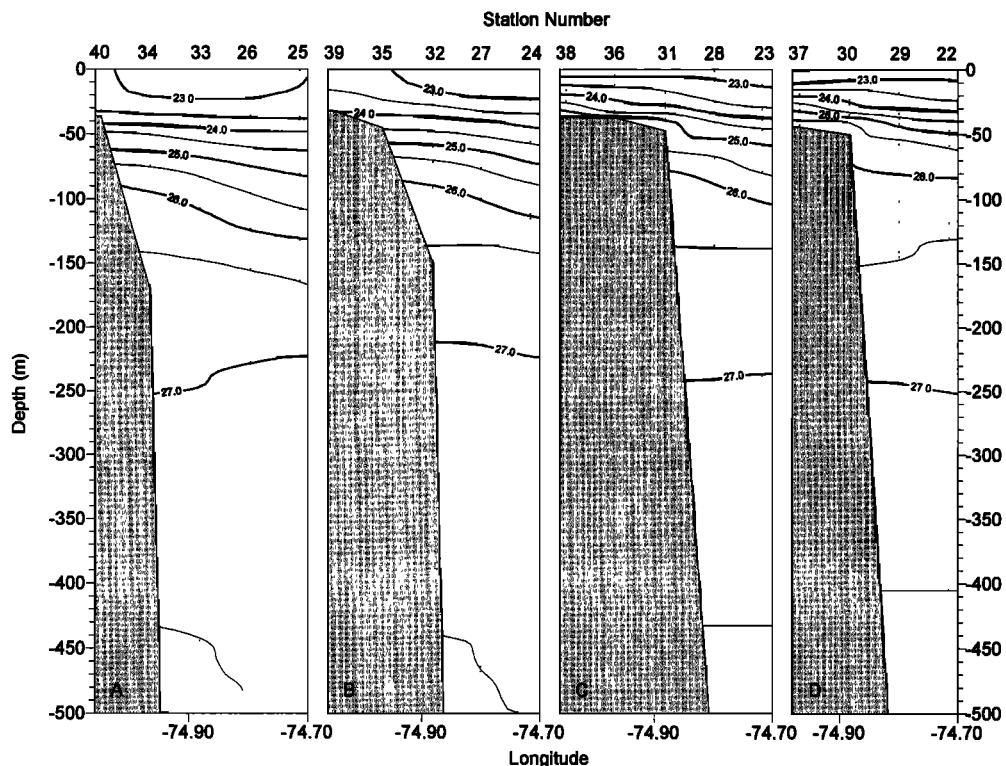
iment surface was probably within the euphotic zone, at least in the western half of the midshelf grid where total depth was less than 33 m.

There is more variety in the benthic waters of the outer shelf than the midshelf. At stations 35, 39 and 40, in the southeastern corner of the shelf-break grid (Figure 1 and Plate 1), warm, salty Gulf Stream surface water fills the entire water column over the shelf: even the deepest samples have temperatures  $>24^{\circ}\text{C}$  and salinities  $>36$  psu. These stations tend to have low concentrations of chlorophyll at all depths. At stations 30, 31, 36, 37, and 38, in the northwestern corner of the grid, warm salty Gulf Stream surface waters at middepth or in the surface layer lie over a cooler, fresher bottom layer; bottom water at these stations is warmer and fresher than cold pool water, but cold pool influence is apparent from comparison of the  $\theta$ - $S$  diagrams from these stations (e.g., Figures 13b–13d) with the  $\theta$ - $S$  diagram for the midshelf grid (Figures 12a and 12b). At some stations, e.g., 37 and 38, the deep water is a mixture only of undiluted cold pool water and Gulf Stream surface waters; that is, the deep  $\theta$ - $S$  characteristics lie on the mixing line joining the cold pool and Gulf Stream surface water types. At other stations, e.g., station 36, the deep water is a mixture of three water types: Gulf Stream surface water, cold pool water, and cold, saline, upper slope water ( $\theta \sim 12^{\circ}\text{C}$ ,  $S \sim 35.5$  psu,  $\sigma_{\theta} \sim 26.8$ ). The outer-shelf stations in which the bottom water shows significant cold pool influence tend to have high ( $\geq 2$  mg  $\text{m}^{-3}$ ) chlorophyll values in the bottom water, intermediate chlorophyll values (1–2 mg  $\text{m}^{-3}$ ) at the interface between bottom water and overlying Gulf Stream water, and low chlorophyll values in surface Gulf Stream water (e.g., Figures 13b, 13c, and 13d).

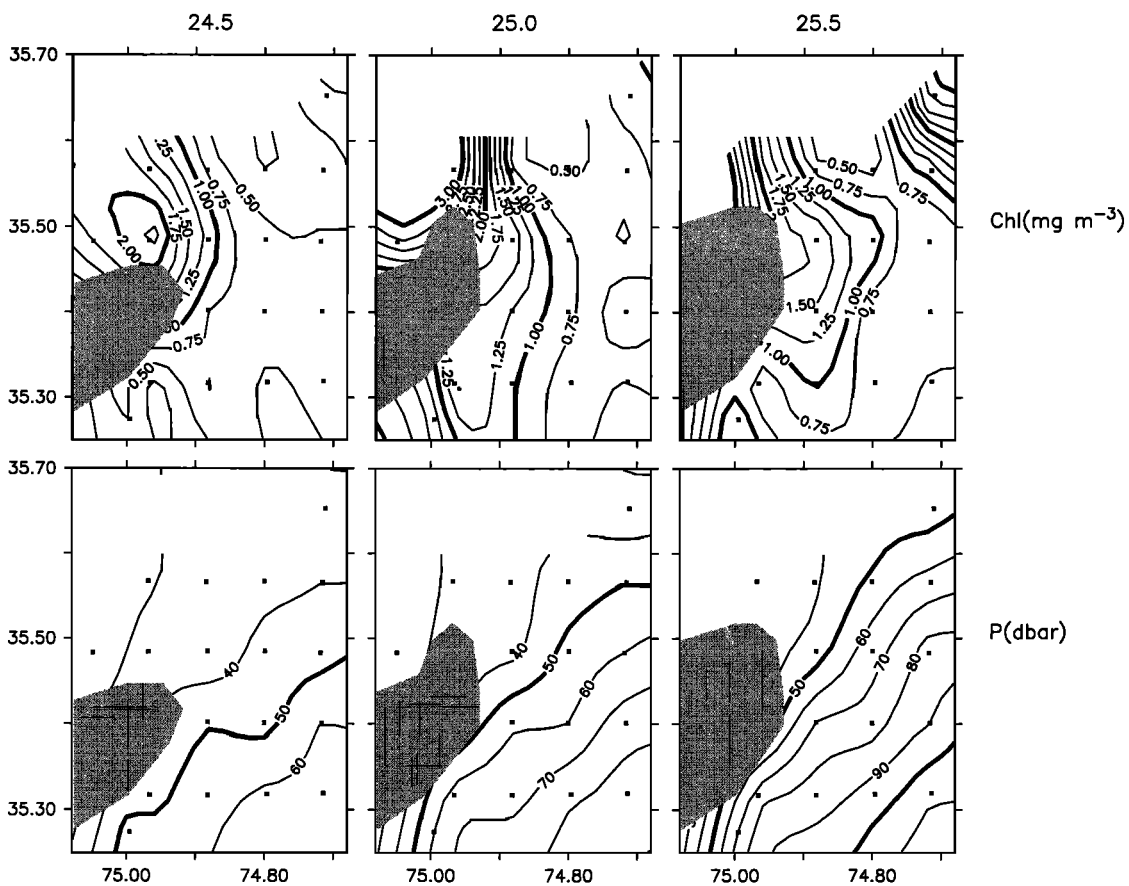
### Shelf-Break Transport and Mixing

As noted above, bottom water found over the outer shelf in the northern transects of the shelf-break grid, though not quite as cold ( $10.5^{\circ}\text{C}$ ; compare  $8^{\circ}\text{C}$ ) or fresh (33.7; compare 32.7 psu), is similar to the cold pool water in the midshelf grid (Figures 4 and 6). The cool, relatively fresh water seen in the shelf-break grid may be contiguous with the water mass we sampled as bottom water in the midshelf grid, or it may represent fragments of that water mass. As would be expected if midshelf cold pool water were transported to the shelf break by southeastward flow, chlorophyll concentrations are relatively high in the cooler, relatively fresh water at the shelf break, compared to concentrations in other water masses found on the outer shelf and slope (Figures 7 and 9). Along the  $25 \sigma_{\theta}$  isopycnal, which corresponds to the density of the midshelf cold pool, chlorophyll concentrations at the shelf-break grid also show a clear gradient from high values on the shelf in the northwest to low values over the slope in the southeast (Figure 11). This is also consistent with transport of cold pool water from the midshelf regions north of Cape Hatteras to the shelf break by the prevailing southward shelf currents. We therefore interpret the cooler, less saline water in the shelf-break grid, and the chlorophyll it contains, as being of shelf origin.

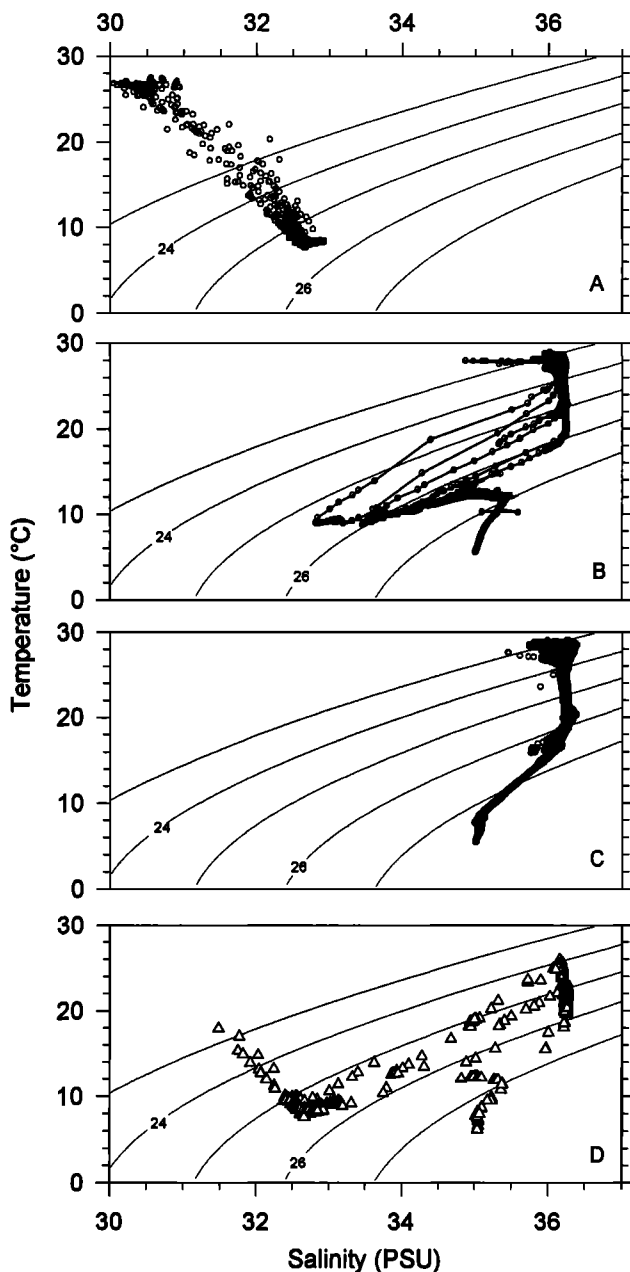
Some of these cool, fresh values are found in the bottom water on the outer shelf; others are seen as local extrema in stations over the upper slope (e.g., stations 21, 28, and 29) and indicate interleaving of waters transported off the shelf with ambient Gulf Stream waters. Figure 13 shows that the salinity minimum at station 21, the most northern station of the shelf-break grid, occurs at 40 m, about the bottom depth of the outer



**Figure 10.** West-to-east sections of density anomaly ( $\sigma_{\theta}$ , kilograms per cubic meter) through the shelf-break grid; sections are shown in the same order as in Figure 7.



**Figure 11.** (top) Chlorophyll on the 24.5, 25.0, and 25.5  $\text{kg m}^{-3}$  isopycnal surfaces and (bottom) the depth of these isopycnals. The shaded region in each panel represents areas where bottom water was less dense than the isopycnal of interest. The densest water was found at the bottom at stations 35, 39, and 40 and had  $\sigma_{\theta}$  values of 24.3, 24.3, and 23.8  $\text{kg m}^{-3}$  and chlorophyll concentrations of 1.38, 0.95, and 0.34  $\text{mg m}^{-3}$  at each station, respectively.



**Figure 12.** Potential temperature-salinity characteristics of water at all stations in three groups: (a) shelf water (stations 2–18, midshelf grid); (b) stations 21, 28–32, 37, and 38, predominantly over the outer shelf, (c) Gulf Stream water (stations 22–27, 33–36, 39–41, predominantly in the southern half of the shelf-break grid. (d) The  $\theta$ - $S$  characteristics of water with chlorophyll concentrations greater than  $1.0 \text{ mg m}^{-3}$  at all stations in either grid are also shown.

shelf, and contains water with chlorophyll content and hydrographic characteristics that are nearly the same as the midshelf cold pool. A similar salinity minimum layer was observed at two adjacent upper slope stations (stations 29 and 28), indicating that this intrusion of shelf water into the Gulf Stream extended at least 20 km alongshore. There was a definite gradation of  $\theta$ - $S$  characteristics immediately above the extremum, with progressively less cold pool and more Gulf Stream influence southwestward along the continental slope. It seems likely

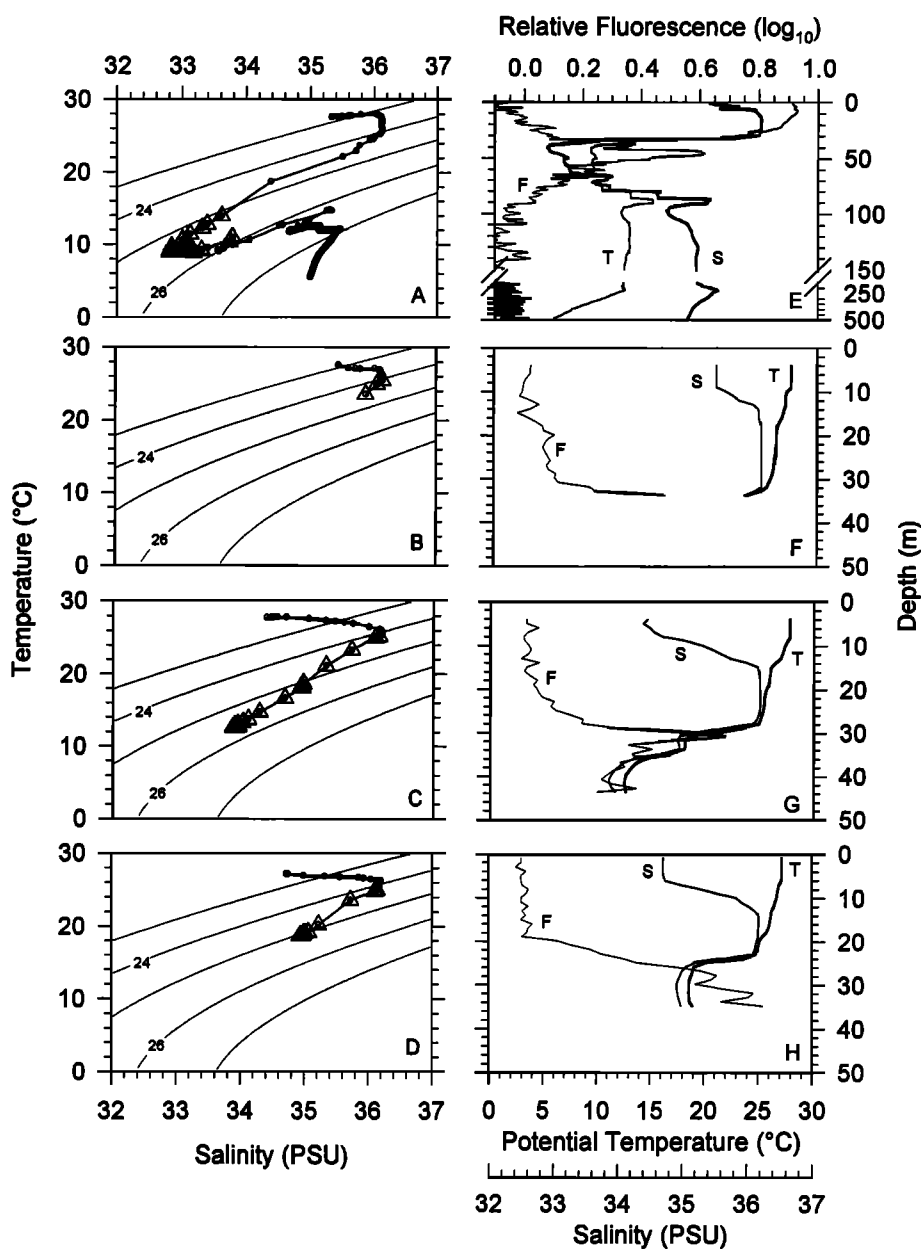
that a large extrusion of shelf water was subsequently overridden by Gulf Stream surface water.

Such an expulsion of water from the shelf into the open ocean is the result of strong convergence of the alongshore flow near Cape Hatteras. Figure 6 shows that currents during our survey were strongly northeastward at the shelf break within our grid ( $\sim 30 \text{ cm s}^{-1}$  at 55 m,  $75 \text{ cm s}^{-1}$  at 30 m at B3; see legend for Figure 6), while the core of the Gulf Stream lay over the outer continental slope. Meanwhile, shelf-break currents were much weaker ( $\sim 2 \text{ cm s}^{-1}$  to the southeast at 55 m,  $\sim 10 \text{ cm s}^{-1}$  to the southeast at 30 m) at another shelf-break mooring (D2, at  $35.72 \text{ N}$ ,  $74.93 \text{ W}$ ) just north of the array in our shelf-break grid [SAIC, 1994]. Such strong alongshore convergence must be balanced by an increase in the offshore velocity at the shelf break; that is, shelf waters are advected offshore across the shelf break. The 6-month averages (February–August 1993) from MMS/SAIC moorings near our midshelf grid (A2 and A3 along  $36^{\circ}14.7\text{N}$  at  $75^{\circ}12.4\text{W}$  and  $74^{\circ}54.4\text{W}$ , respectively) show bottom water flow to the southeast at  $\sim 12$ – $18 \text{ cm s}^{-1}$ , indicating approximately 4–6 day transit time from our midshelf grid to the shelf break. Six-month average current velocity and direction at the shelf-break moorings (B3, B4, and D4) are similar to those observed at the time of our survey but not as strong [SAIC, 1994]. Thus conditions favored mixing of cold pool water into the Gulf Stream at Cape Hatteras during most of the summer of 1993.

Opportunities for mixing of shelf water transported to Cape Hatteras with the upper levels of the Gulf Stream are frequent, and mixing of cold pool water with the Gulf Stream may partially explain the loss of cold pool signature observed in temperature data collected between  $36^{\circ}$  and  $37^{\circ}\text{N}$  at the shelf break in the summer of 1980 [Falkowski et al., 1983]. The historical axis of the west wall of the Gulf Stream comes very close to the shelf break at Cape Hatteras. During July and August, Gulf Stream displacement from the historical axis as it moves north and east from Cape Hatteras is most frequently to the northwest [Tracey and Watts, 1986], providing extended contact with outer shelf and slope water before the Gulf Stream moves offshore. Low-temperature ( $8^{\circ}$ – $10^{\circ}\text{C}$ ) water of low salinity (33–34 ppt) in the upper 200 m of the Gulf Stream north of Cape Hatteras is a well-known phenomenon; this water was first identified as being of shelf origin by Ford et al. [1952]. Additional studies have shown that large volumes of shelf water are often found in the Gulf Stream north of Cape Hatteras [Fisher, 1972; Kupferman and Garfield, 1977; Churchill et al., 1989; Churchill and Cornillon, 1991b], and Boicourt was the first to propose that the specific origin of the water might be the cold pool [Boicourt, 1973]. Lillibridge et al. [1990] provide the only data besides ours which include information about the biological content of water entrained into the Gulf Stream at Cape Hatteras. In their study, conducted in October 1985, phytoplankton communities in cool, fresh layers in the Gulf Stream were dominated by neritic diatoms, suggesting to them that these layers had their origins on the inner shelf.

#### Implications for Material Flux From the Continental Shelf

The cold pool is a site of new production throughout the summer [Harrison et al., 1983], and some of this production may leave the shelf in the northern MAB where chlorophyll-rich cold pool water is contiguous with slope water of similar density [Falkowski et al., 1983; Houghton et al., 1988]. At these points, energetic barriers to advection of organic matter off the



**Figure 13.** Potential temperature-salinity characteristics and vertical profiles of water properties at stations where mixing of chlorophyll-rich cold pool water and Gulf Stream water was apparent. Station 21 (top panels) is located in 1200 m of water at the northeastern corner of the shelf-break grid; the lower panels are shelf stations in the shelf-break grid where bottom water shows cold pool influence (stations 36 (Figures 13b and 13f), 37 (Figures 13c and 13g), and 38 (Figures 13d and 13h)). Data points enclosed in a triangle indicate water in which chlorophyll concentration was  $>1 \text{ mg m}^{-3}$ . F is in situ fluorescence, S is salinity, and T is temperature.

shelf would be low, but unlike the situation we observe the Gulf Stream is too far offshore to provide a mechanism of transport into the open ocean. In contrast, entrainment of shelf water into the Gulf Stream at Cape Hatteras will result in rapid transport of the entrained water to the open ocean where the organic matter and nutrients it contains may have a significant influence on Gulf Stream biogeochemistry. Entrainment of shelf water into the Gulf Stream at Cape Hatteras may be one of the more significant loss terms in the shelf nutrient budget. However, because the water is entrained into surface layers and is unlikely to reach more than 200-m depth, advected organic matter could easily be oxidized in the epipelagic. Thus

incorporation of shelf water into the Gulf Stream at Cape Hatteras is more likely to be important as a source of nutrients to the upper levels of the Gulf Stream than as a sink for organic carbon.

It is difficult to quantify the input of organic nutrients to the Gulf Stream at Cape Hatteras from our data set, but at station 21, more than 60% of the chlorophyll in the upper 200 m of the Gulf Stream is found in the entrained cold pool water (compare  $87.3 \text{ mg chl m}^{-2}$  integrated over the upper 200 m to  $56.41 \text{ mg chl m}^{-2}$  integrated over the depth interval between 40 and 80 m where cold pool water intruded into the stream; Figure 13). Using a carbon chlorophyll conversion value of 47 (mg/

mg) [Cho and Azam, 1990; Li et al., 1992], assuming Redfield proportions for C:N:P (molar ratios of 106:16:1) [Harris, 1986], and comparing conditions at station 21 to those at station 25 where the Gulf Stream appears to be undiluted by shelf water, entrainment of the cold pool into the Gulf Stream at station 21 represents an addition of approximately 33 mM nitrogen  $m^{-2}$  and 2 mM  $m^{-2}$  phosphorus as particulate organic matter. If this material were remineralized and dispersed evenly throughout the upper 100 m, this single intrusion event would increase local concentration of inorganic nitrogen in the euphotic zone by 0.5  $\mu M$ .

The deep chlorophyll observed at nearly 400 m at station 23 is probably not from the shelf near Cape Hatteras. Since the shelf is approximately 50 m deep at the shelf break in this region, organic matter entrained into the Gulf Stream at the shelf break would travel much further north in the stream before it would have time to sink to such great depths. Organic matter associated with blooms on the outer shelf of the SAB, however, could have had time to sink to 400 m. Since these blooms are generally caused by westward meanders of the Gulf Stream and occur frequently in the summer [Yoder et al., 1981; Atkinson, 1985], this chlorophyll may reflect entrainment of shelf-edge blooms of the SAB into the Gulf Stream before it reaches Cape Hatteras.

## Conclusions

The cold pool is a well-known summertime feature on the outer shelf of the southern MAB. We provide new data which show the presence of the cold pool on the inner shelf of the southern MAB in July 1993 and confirm that the cold pool is entrained into the Gulf Stream at Cape Hatteras. There is a gradient of chlorophyll concentration along density surfaces which are contiguous between shelf bottom water and Gulf Stream water over the slope. On the slope and outer shelf the highest chlorophyll concentrations are associated with water having  $\theta$ -S properties which indicate mixing between the cold pool and Gulf Stream. Both sets of observations support our conclusion that organic matter of shelf origin mixed into the Gulf Stream at Cape Hatteras where it could be rapidly advected into the open ocean.

The degree to which continental shelf environments export organic matter to the deep sea is not necessarily a function of the proportion of total primary production that is exported. In a large ecosystem like the MAB, nutrients may be recycled many times before they are ultimately lost from the system through benthic deposition or export; the export rate may be nearly as high as is possible but still only a small fraction of total primary production. Under these conditions the significance of export flux is best estimated from the fraction of inorganic nutrients entering the shelf that ultimately leave as dissolved or particulate organic material. The cold pool of the MAB is an important reservoir for new nitrogen entering the system from the Scotian Shelf, from the Gulf of Maine, and through exchange with slope water. We have provided evidence that the ultimate fate of some of organic matter produced in the cold pool of the MAB is entrainment into the Gulf Stream at Cape Hatteras. Historical data on the position of the Gulf Stream, the regular occurrence of the cold pool in the southern MAB, and the frequent presence of cool shelf water in the Gulf Stream north of Cape Hatteras indicate this is a common phenomenon and a potentially important mech-

anism by which the MAB shelf influences the biogeochemistry of the open ocean.

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A. Huyer, College of Ocean and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331.

N. D. Sherry, Department of Oceanography, University of British Columbia, Vancouver, British Columbia, V6T 124 Canada.

A. M. Wood, Department of Biology, University of Oregon, Eugene, OR 97403. (e-mail: miche@darkwing.uoregon.edu)

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