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Enhanced chlorophyll at the shelfbreak of the Mid-Atlantic Bight and Georges Bank during the spring transition

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Abstract

In 8 yr (1979–1986) of Coastal Zone Color Scanner (CZCS) imagery, we find annual enhancement of chlorophyll at the shelfbreak of the Mid-Atlantic Bight (MAB) and Georges Bank during the spring transition from well-mixed to stratified conditions. Spatial and temporal extents of enhancement vary interannually, and expression is intermittent intraannually. This feature can span the entire MAB and southern flank of Georges Bank (~1,100 km) and can be expressed for as long as 10 weeks (mid-April to late June). Pigment concentrations within the feature average more than two times that of adjacent shelf and slope waters. Enhanced shelfbreak chlorophyll consistently coincided with the shelf-slope front and often extended inshore of the surface outcrop of the front a few to ~10 km. In all years except 1986, it coincided with seaward entrainment of shelf water by Gulf Stream warm-core rings (WCRs) or meanders. Shelfbreak chlorophyll enhancement was most pronounced during 1980. Using satellite and in situ observations, we found that during 1980, it coincided with the shelf-slope front for 10 weeks, and, unlike the spring bloom, it was dominated by the nanophytoplankton (<20 μm) size fraction. During the peak of the 1980 occurrence, four WCRs simultaneously interacted with shelf water, and chlorophyll enhancement inshore of one WCR coincided with a slope-water intrusion onto the shelf. Empirical orthogonal function (EOF) decomposition of CZCS images for late March–June 1980 showed that shelfbreak enhancement was strongly pronounced in an EOF that accounted for $>10\%$ of the variance about the mean. This annual biological feature, brought to light in satellite ocean color imagery, is an important aspect of the shelf-slope ecology of the MAB and Georges Bank.

The continental shelf ecosystem of the MAB and Georges Bank (Fig. 1) is among the most productive in the world (O'Reilly and Bush 1984; O'Reilly et al. 1987). Understanding variability in oceanic primary production has been greatly augmented by synoptic distributions of phytoplankton pigment concentrations derived from satellite remote sensing. The first instrument for remote sensing of ocean color, the CZCS, yielded almost 8 yr of imagery between fall 1978 and summer 1986 (Hovis 1980; Feldman et al. 1989). CZCS imagery of this region has been used to study the spring bloom (Brown et al. 1985; Eslinger and Iverson 1986; Walsh et al. 1987*a*; Gregg and Walsh 1992), spatial and temporal modes of variation in pigment distributions (Eslinger et al. 1989), WCR processes (Garcia-Moliner and Yoder 1994), absorption by chromophoric dissolved organic matter (Hoge et al. 1995), and transport of acid wastes dumped in shelf water (Elrod 1988). Here, we use CZCS-derived pigment concentrations (CZCS-Chl) and other satellite and in situ data to examine fundamental attributes of annual chlorophyll enhancement at the shelfbreak.

The Slope Sea resides between Gulf Stream and shelf waters (Fig. 1). The front between shelf and slope waters is biologically important. The shelf-slope front persists year around, extending from bottom to surface during winter but only between bottom and the seasonal thermocline during summer (Beardsley and Flagg 1976; Wright 1976; Mooers et al. 1978; Lynn and Csanady 1984; Houghton et al. 1988). Phytoplankton bloom relatively early at the shelfbreak during winter/spring, where shoaling of the mixed layer by the front locally increases light exposure (Marra et al. 1982; Malone et al. 1983). Phytoplankton production is enhanced at the shelfbreak during the stratified season when shelf water transported offshore is upwelled along frontal isopycnals (Malone et al. 1983; Marra et al. 1990). An abrupt change in depth of the deep chlorophyll maximum at the shelfbreak

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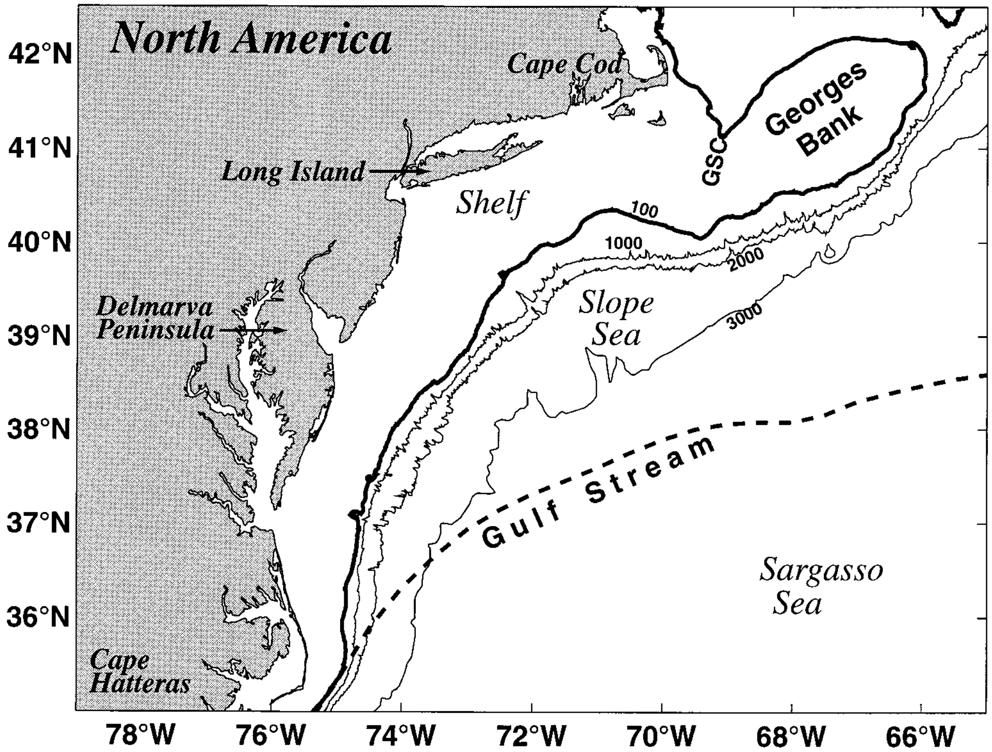

Fig. 1. Map of the study region. The Mid-Atlantic Bight (MAB) extends from Cape Hatteras to Georges Bank, the division being Great South Channel. The 100-m isobath defines the approximate location of the shelfbreak and the outline of Georges Bank. All land reference points mentioned in the text are labeled. The mean position of the Gulf Stream north wall, determined from 12 yr of satellite sea surface temperature imagery (Gilman 1988), is shown as the thick dashed line.

during summer is attributed to convergent frontal circulation (Houghton and Marra 1983). The front extends north of Georges Bank to the Nova Scotian shelfbreak, where phytoplankton biomass is enhanced at the front during periods of stratification as well as during periods of intense vertical mixing (Fournier 1978; Fournier et al. 1979, 1984). Because the front influences lateral exchange between shelf and slope waters, researchers have studied its role in influencing the fate of biogenic and anthropogenic materials, including phytoplankton, pollutants, and fish larvae (Walsh 1988; Myers and Drinkwater 1989; Milliman 1994).

While frontal processes important to phytoplankton growth have been studied during the winter/spring bloom and stratified periods, they have not been well studied during the transitional period between the well-mixed conditions of winter and the strongly stratified conditions of summer. This is a critical period for changes in hydrography, vertical mixing, and exchange between shelf and slope waters. Increasing insolation and freshwater input and decreasing wind stress during the spring promote the development of stratification, eventually obliterating the shelf-slope front above the seasonal thermocline. Interleaving of the two water masses increases (Voorhis et al. 1976; Flagg et al. 1994), and they become connected along isopycnal surfaces, facilitating exchange (Gordon and Aikman 1981; Houghton et al. 1988). Nutrient depletion develops in the upper ~20–30 m of the shelf by ca. May (Ketchum et al. 1958; Walsh et al. 1978, 1987*b*), and stratification suppresses the vertical mixing that can replenish nutrients. This forces a transition from light limitation of phytoplankton growth to nutrient limitation (Malone et al. 1983). During this transition in physical and chemical conditions, the phytoplankton assemblage changes from netphytoplankton (>20 μm) to nanophytoplankton (<20 μm) dominance throughout the water column of the middle and outer shelves (O'Reilly and Zetlin 1998). Our purposes here are to define, within the context of this transitional period, fundamental attributes of the annual shelfbreak chlorophyll enhancement and to consider processes that may force its development.

Methods

Image processing—Using the browse archive (Feldman et al. 1989), we examined all CZCS imagery to identify >2,000 images having pigment data. We acquired these images at full resolution (~1 by 1 km) from the National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center and processed them from level 1 (top of atmosphere radiance) to level 3 (standard map projection) pigment imagery (Feldman et al. 1989) using the ''clear water'' atmospheric correction algorithm (Gordon and Clark 1981) and a three-band pigment algorithm (Clark 1981). Aerosol optical thickness ratios (ϵ), required for atmospheric correction of CZCS imagery, were derived interactively for all scenes that met the correction algorithm criteria. This ϵ database was combined with two others from adjacent regions of the North American east coast, one derived from CZCS imagery of the South Atlantic Bight (Ryan and Yoder 1996) and the other from the Gulf of Maine (Bisagni et al. 1997). Because the use of mean ϵ calculated from all three regions optimized accuracy and precision of CZCS pigment estimates in the Georges Bank–Gulf of Maine region (Bisagni et al. 1997; ECOAST ϵ in their table 2a), these mean ϵ were used to process all imagery. Adjacent scenes from the same day were composited to yield 1,114 daily images, 323 within the transitional months of April–June. If images required navigation correction, they were shifted to fit the coastline as determined by the map projection. Since CZCS-Chl can be contaminated by cloud reflectance (Mueller 1988), all data within 10 pixels downscan of cloud pixels were masked. Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST) imagery was obtained from archives at the University of Rhode Island (URI) Graduate School of Oceanography (Sea Surface Temperature Satellite Image Archive 1998). Our map projection for both CZCS and AVHRR imagery has a pixel resolution of ~2 by 2 km.

Image analysis—All CZCS images were examined to determine the annual temporal limits of shelfbreak chlorophyll enhancement, the range of its spatial scale, and when it was most strongly expressed each year. To determine the magnitude of the enhancement relative to background, we sampled all occurrences of this feature and its immediately adjacent shelf and slope waters. The sampling procedure consisted of taking 5- by 5-pixel (~10 by 10 km) averages at evenly spaced intervals along the entire length of the feature in three subdomains: within, adjacent shelf, and adjacent slope. These domains were sampled across the shelfbreak only where water masses could be distinguished, i.e., excluding filaments of shelf water drawn into the Slope Sea by WCRs. Because of differences in size of the feature and extent visible (cloud cover), the number of samples obtained for each image and subdomain was variable; this ranged from 5 to 15. For each image, means were calculated from all samples within each subdomain. Of the 53 images that exhibited shelfbreak chlorophyll enhancement, only 37 could be well sampled (i.e., an image may exhibit the structure, verified in proximate imagery, but be inadequate for sampling all three domains because of cloud cover). To calculate overall means, samples from the 37 images were pooled by subdomain. Because CZCS pigments are approximately lognormally distributed (Denman and Abbott 1988; Campbell 1995), the geometric mean was calculated. Means were compared by *t*-tests. For pairs of means having unequal variances (determined by *F*-tests), Welch's *t*-test was used (Afifi and Azen 1972).

To determine if shelfbreak chlorophyll enhancement was evident in a multiyear (1979–1986) composite, we calculated 20-d means of CZCS-Chl for the transitional months, April–June. To define the association between the pigment enhancement and oceanic features, we examined paired CZCS and AVHRR imagery. In considering association with the shelf-slope front, we examined 2 consecutive yr of paired imagery, 1979 and 1980 (mapped imagery available at the time of analysis). In considering association with WCRs, we examined paired imagery for 1979 and 1980 and annually published reports of WCR paths for 1979–1986. These reports (Fitzgerald and Chamberlin [1982–1984]; Price and Celone [1984]; Celone and Price [1985]; Price [1985]; Price and Barton [1986, 1987]) are based on National Oceanic and Atmospheric Administration (NOAA) frontal analysis charts and AVHRR imagery. Lastly, in examining association with Gulf Stream water (non-WCR) at the shelfbreak in years other than 1979 and 1980, we examined the URI 5.5-km AVHRR archive (available online: *see* DODS [1998]) and hydrographic observations from the National Ocean Data Center (NODC).

Focus on the 1980 spring transition—The shelfbreak pigment enhancement during 1980 had a particularly large spatial and temporal scale and was sampled in situ during a survey of the NOAA/National Marine Fisheries Service (NMFS) Marine Resources Monitoring Assessment and Prediction program (MARMAP; Sherman 1980). We examined its development during 1980 with CZCS and AVHRR imagery and in situ pigment and hydrographic observations. To objectively define the feature and examine its contribution to the total variance during the 1980 spring transition, we decomposed a time series of log-transformed CZCS-Chl into the temporal mean and EOFs. To generate the input time series, we calculated 20-d-average images between 20 March and 28 June (days 80–180). This temporal bin was required to fill the domain of interest (midshelf to midslope; 32,742 pixels) with a representative mean. The seaward limit was the 3,000-m isobath (Fig. 1). Because of the complex shelf topography, we used a midshelf chlorophyll contour from mean CZCS-Chl (all years) to define the shoreward boundary of the domain. Given the large number of spatial points, we used singular value decomposition to calculate the EOFs (Kelly 1988).

Results

Spatial attributes—Shelfbreak pigment enhancement is evident in 1979–1986 mean CZCS-Chl for 1–20 May (Fig. 2a); this is the time of the year when the feature is most strongly pronounced in daily imagery. It is most evident south of New England (between arrows on Fig. 2a), primarily seaward of the 100-m isobath, and is less evident off the Delmarva Peninsula. Synoptic pigment distributions show some of the variability of the feature (Fig. 2b–d). The image from 10 May 1980 (Fig. 2b) shows the enhancement at its maximum observed spatial extent, spanning ~1,100 km along the entire MAB shelfbreak and southern flank of Georges Bank. At this time, four WCRs were interacting with shelf water between the southern MAB and easternmost Georges Bank. WCR 2 had been near its 10 May location for ca. 1 month, interacting with shelf water. WCR 3 interacted with Georges Bank and drew a filament of shelf water into the Slope Sea. The filament is the wide band of pigment-rich water delineated by a box on Fig. 2b; it is south of the shelfbreak enhancement that followed the outline of Georges Bank. The image from 13 June 1983 (Fig. 2c) shows the

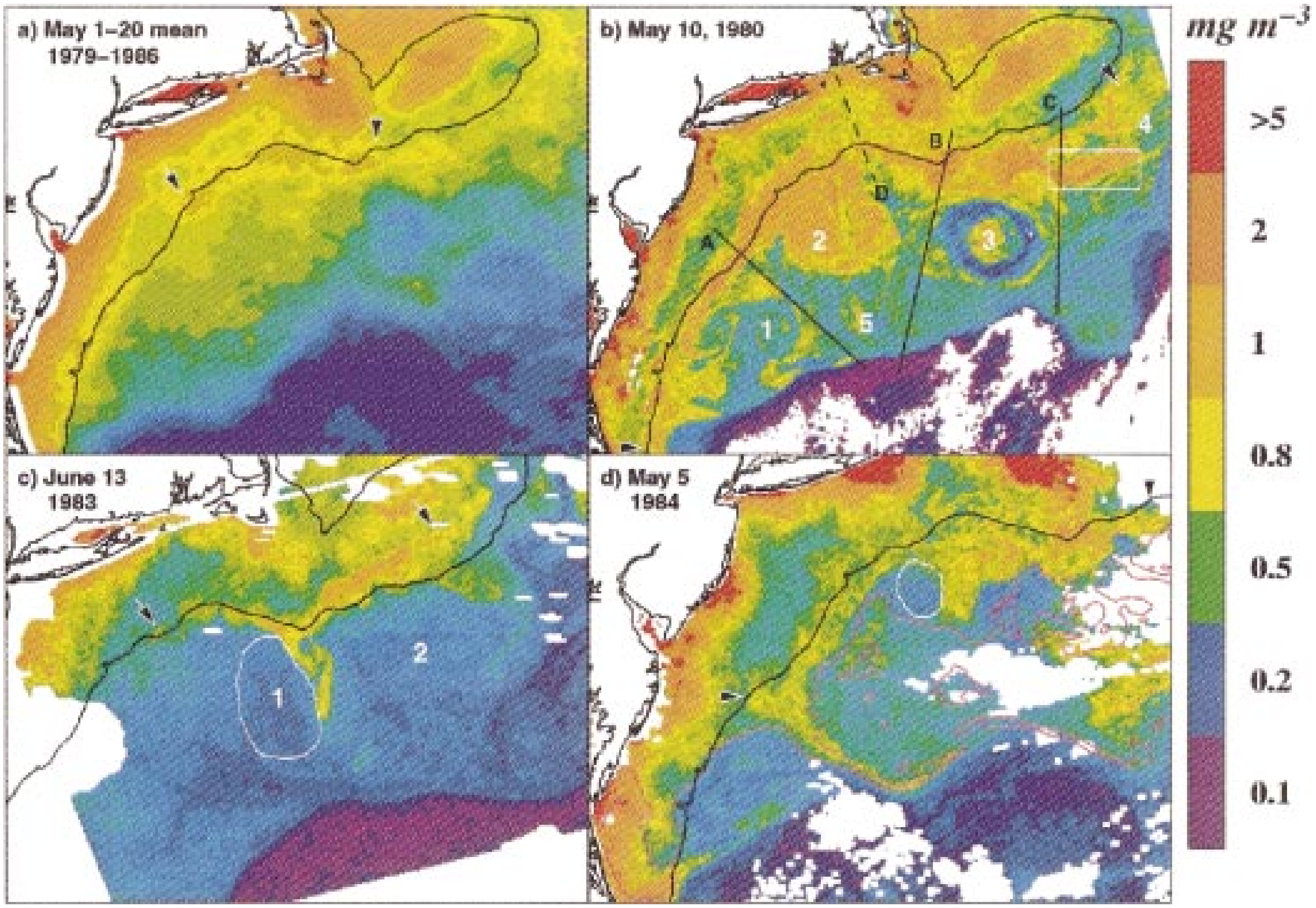

Fig. 2. Coastal Zone color Scanner (CZCS) images of the MAB showing the shelfbreak pigment enhancement; use Fig. 1 for reference locations. (a) mean CZCS-Chl for 1–20 May, all years ($n = 64$ images). (b–d) synoptic pigment distributions of the region when the shelfbreak enhancement was present. In each image, arrows indicate the approximate alongshelf endpoints of the enhancement, and the 100-m isobath is shown in black. White numbers on b and c mark the approximate centers of warm-core rings (WCRs), except 4 on b, which marks the NW perimeter of a WCR. WCR positions were determined from CZCS and AVHRR imagery. (b) CZCS-Chl and AVHRR SST from the solid transect lines labeled A–C are shown in Fig. 3; in situ hydrographic and pigment observations from the transect labeled D (dashed line) are shown in Fig. 4; the white box delineates a large shelf-water filament drawn seaward by WCR 3. (c) The outline of the surface signature of WCR 1, digitized from a same-day AVHRR SST image, is shown as the white oval adjacent to the shelfbreak. (d) The magenta contour is the 13.5° isotherm from same-day AVHRR, emphasizing offshore transport of shelf water, and the white oval defines the perimeter (digitized from an AVHRR image) of an anticyclonic eddy at the shelfbreak.

feature inshore of two WCRs that drew shelf water into the Slope Sea (the relatively high pigment water E-NE of the WCRs). The image of 5 May 1984 (Fig. 2d) shows shelfbreak chlorophyll enhancement in the presence of offshore transport of shelf water by frontal processes of both the Gulf Stream and shelf-slope front. The 13.5° isotherm (magenta contour on Fig. 2d) illustrates offshore flows of shelf water at three locations: (1) off Delmarva where shelf water was advected >500 km east along the Gulf Stream front, (2) east of an anticyclonic eddy at the shelf-slope front (~60 km in diameter; outlined in white), and (3) south of Great South Channel at another disturbance of the shelf-slope front. This pigment field structure was also pronounced in CZCS imagery of 27 April. (For a thorough description of the physical oceanography of the Gulf Stream meander and its associated mixing, *see* Churchill et al. [1993].)

Shelfbreak chlorophyll enhancement showed close spatial association with the shelf-slope front. In 1979 and 1980, CZCS-Chl enhancement always coincided with the front and often extended shoreward (a few to ~10 km) of the surface outcrop of the front. This generalization is based on observations outside the immediate WCR–shelfbreak contact zone. For example, consider CZCS-Chl and AVHRR SST from along the three transects shown in Fig. 2b (solid lines labeled A–C). Along all three transects, shelfbreak CZCS-Chl enhancement coincided with the frontal temperature gradient (Fig. 3). Along transect A, between WCRs 1 and 2 (Fig. 2b), the enhancement extended ~30 km cross-shelf and was aligned very closely with the front (Fig. 3). Along transect B, between WCRs 2 and 3 (Fig. 2b), the frontal temperature gradient extended over the full 80-km width of the enhancement (Fig. 3). Along transect C, between WCRs 3

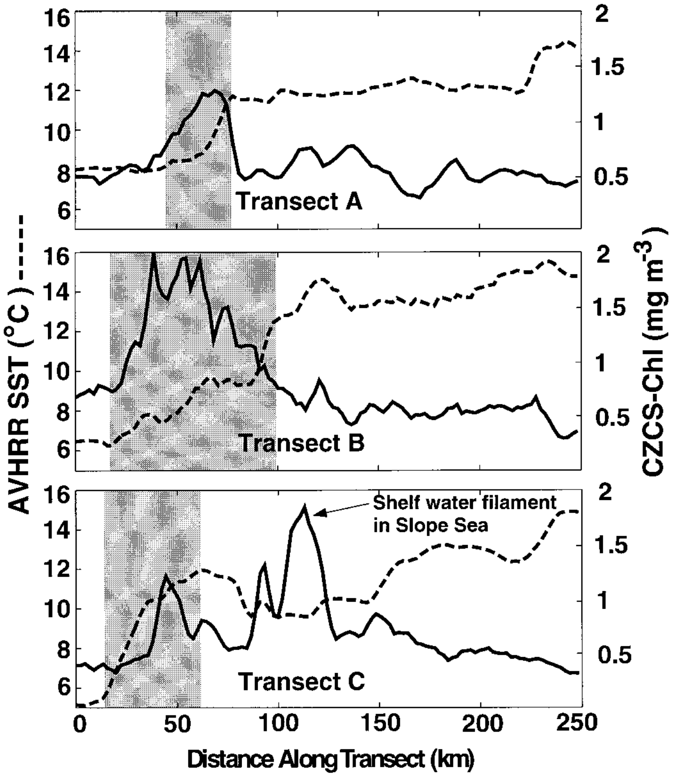

Fig. 3. CZCS-Chl and AVHRR SST from along transect lines shown in Fig. 2b. The shaded region in each indicates the approximate range of the frontal temperature gradient. Along each transect, shelfbreak chlorophyll enhancement coincided with the frontal temperature gradient. Along transect C, the stronger pigment peak is in a filament of shelf water drawn into the Slope Sea by WCR 3. Distance shown is limited to the first 250 km from the shoreward origin of each transect.

and 4 (Fig. 2b), shelfbreak enhancement extended ~20 km cross-shelf within the frontal zone (Fig. 3; centered near 50 km). South of the shelfbreak enhancement was a pigment-rich filament of shelf water drawn into the Slope Sea by WCR 3. This filament is delineated by the box in Fig. 2b and is visible as the trough of cold water <10°C from ~90 to 125 km, coincident with the highest CZCS-Chl (Fig. 3).

In all years, shelfbreak chlorophyll enhancement coincided with the presence of Gulf Stream water at the shelfbreak, most frequently as WCRs drawing shelf water seaward (44 of 54 images). In all WCR cases, offshore entrainment of shelf water was evident in imagery (CZCS and/or AVHRR). Enhanced CZCS-Chl often extended along the shelfbreak SW of the WCRs (e.g., Fig. 2c). On four occasions, enhancement extended hundreds of kilometers along the shelfbreak between two WCRs, and on two occasions, enhancement extended NE of a WCR and followed a wavelike pattern along the shelfbreak.

Table 1. Earliest and latest times of CZCS-Chl shelfbreak enhancement, based on 54 images that exhibited this structure.

Year	Earliest	Latest	Minimum time span* (days)
1979	21 Apr	14 June	55
1980	15 Apr	25 June	72
1981	27 Apr	11 June	46
1982	15 Apr	9 June	56
1983	28 Apr	30 June	64
1984	27 Apr	5 May	9
1985	28 Apr	2 June	36
1986	12 Apr	19 May	38

* Time spans are minimum because of the limitations of satellite coverage. Coverage was particularly scant in 1984.

In four of the years, shelfbreak chlorophyll enhancement coincided with non-WCR processes. (1) During 1979, in addition to a strong association with WCRs, enhancement also developed during mid-June along ~100 km of the southern flank of Georges Bank, immediately inshore of a Gulf Stream intrusion (extension of a northward meander, verified with in situ salinity). A large volume of shelf water had been transported seaward south of the meander/intrusion during this cross-frontal exchange. (2) During 1980, again in addition to strong association with WCRs, enhancement developed along the shelfbreak north of Gulf Stream entrainment of shelf water at Cape Hatteras. (3) During 1984, enhancement developed along >500 km of the shelfbreak in association with offshore transport of shelf water along the Gulf Stream front and two shelf-slope frontal disturbances (as described above for Fig. 2d). (4) During 1986, enhancement developed inshore of Gulf Stream water that flowed hundreds of kilometers along the shelfbreak after being entrained across the Slope Sea by a WCR. We found no evidence of seaward transport of shelf water for this occurrence.

Temporal attributes—The earliest day of the year on which CZCS imagery showed shelfbreak pigment enhancement was 12 April and the latest, 30 June (Table 1). The longest time span from earliest to latest observation within a year was 72 d, in 1980. Generally, the pigment enhancement within the feature was stronger earlier in the season; the signal tended to be more muted later, when stratification is more developed. Overall, it was most strongly expressed during early to mid-May.

Magnitude relative to background—Mean CZCS-Chl within the shelfbreak enhancement was always significantly greater ($P < 0.01$) than that of adjacent shelf and slope waters. The overall ($n = 37$) shelfbreak mean, 1.18 mg m^{-3}, averaged more than twice that of adjacent shelf (0.57) and slope (0.40) waters. Within individual images, shelfbreak CZCS-Chl ranged from 1.3 to 6 times greater than in adjacent waters.

The 1980 spring transition—The best satellite coverage of the shelfbreak pigment enhancement was during 1980, when the feature persisted at least 10 weeks (Table 1) and extended more than 1,100 km alongshelf during its peak (Fig. 2b). All CZCS and AVHRR same-day image pairs for this 10-week period showed that the pigment enhancement was at the front (e.g., Fig. 3); thus, it was a frontal feature for its duration.

Shelfbreak chlorophyll enhancement was sampled in situ

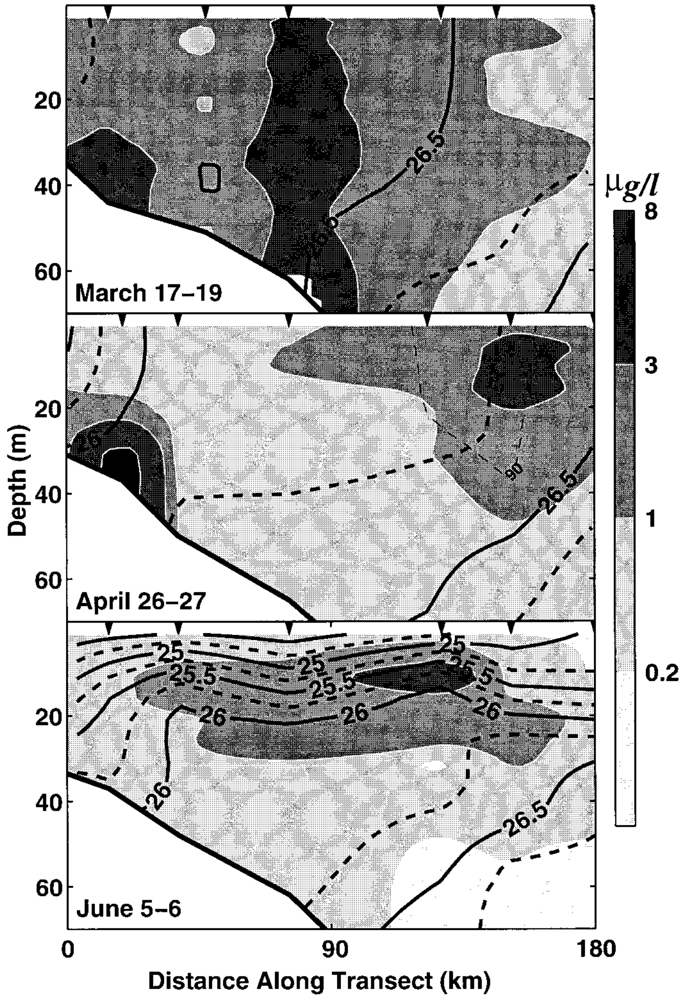

Fig. 4. Total pigments (chlorophyll *a* + phaeophytin *a*; shaded map with scale) and density (contoured σ_t) from MARMAP transect D shown as a dashed line in Fig. 2b. Locations of profiles are shown at the top of each plot. Shelfbreak pigment enhancement is evident in the 26–27 April observations. The thin dashed contour on the plot of 26–27 April is the 90% nanophytoplankton contour. All observations were obtained from NOAA/NMFS; phytoplankton data are from O'Reilly and Zetlin (1998).

during 1980. The sequence of vertical sections of pigments and density shown in Fig. 4 are from transect D (shown as a dashed line in Fig. 2b). The center of the shelf-slope front in this region generally coincides with the 26.5-σ_t isopycnal (Mooers et al. 1978). During mid-March (Fig. 4a), the front extended from surface to bottom, the water column was well mixed over the shelf, and pigments were vertically homogeneous, with maxima near midshelf and in the lower half of the water column nearshore. These conditions are typical of the winter/spring bloom period (Walsh et al. 1978; Malone et al. 1983; O'Reilly and Zetlin 1998). By late April (Fig. 4b), shelfbreak enhancement was present over the upper $\sim$50 m; its full seaward extent was not resolved. Size fractionation of the phytoplankton samples showed that this feature was dominated by the nanophytoplankton ($<$20 μM) size fraction (90% contour on Fig. 4b). Also at this time, settling out of winter/spring bloom biomass had produced a pigment-rich layer over the lower water column of the inner shelf. The warming and freshening of shelf water between mid-March and the end of April is evident in the offshore displacement and change in slope of the 26.25 and 26.5 isopycnals and the appearance nearshore of isopycnals $<$26.25. By early June (Fig. 4c), stratification was well developed, and a subsurface pigment maximum had formed, centered near 10-m depth, inshore of where the shelfbreak enhancement had been 5 weeks earlier. This subsurface pigment maximum was coincident with a local shoaling of isopycnals (25.25–26). Nutrient concentrations increase below the pycnocline under stratified conditions, which suggests that the location of the subsurface maximum was related to nutrient availability. Shelfbreak enhancement was not discernible in CZCS imagery at this time, but it was detected by the CZCS during mid- to late June.

The EOF decomposition of 1980 CZCS-Chl clearly illustrates the importance of shelfbreak enhancement during that year. More than 90% of the variability in the 1980 CZCS time series was captured in the first three EOFs (Fig. 5). The first EOF, containing $\sim$60% of the variance, describes the overall pattern of the bloom during the spring transition. It is dominated by blooms seaward of the 100-m isobath from ca. mid-April to mid-May. The second EOF, containing $\sim$23% of the variance, accounts for some of the extreme high and low CZCS-Chl patterns. For example, the distinct negative circular feature near the center of the domain defines the influence of WCR 2, in which pigment concentrations were relatively low early in the time series and relatively high thereafter. Similarly, positive regions show where the bloom was particularly strong during late March through mid-April. The third EOF, containing $\sim$11% of the variance, describes the structure of the shelfbreak pigment enhancement. Orientation of the highest and lowest values closely follows the shelfbreak topography, except where pigment-rich filaments were drawn into the Slope Sea during early May (at the southern and northern extremes of the band of positive values in EOF 3). This entrainment by WCRs is illustrated in Fig. 2b, SW of WCR 1 and NE of WCR 3. EOF 3 shows that the MAB and Georges Bank were out of phase with regard to shelfbreak chlorophyll enhancement. Combined with its amplitude time series, this EOF indicates that the shelfbreak along the southern flank of Georges Bank was in bloom before and after the peak blooming of the MAB shelfbreak. Daily CZCS imagery shows WCR entrainment of shelf water from Georges Bank and intense blooming along its shelfbreak during late April and late May, as indicated by EOF 3.

The peak of the 1980 enhancement was near 10 May (Fig. 2b). One week later, the feature was still pronounced over the entire region (Fig. 6a). Seaward entrainment of shelf water by the WCRs was still vigorous. Hydrographic observations were made across the enhancement where a WCR was adjacent to the shelfbreak. While the shelfbreak and WCR were rich in pigment, there was a distinct minimum in CZCS-Chl at the front between the two (Fig. 6a–c). Intrusion of relatively warm slope or WCR water cooccurred with the shelfbreak enhancement (Fig. 6d). This intrusion coincided with entrainment of shelf water into the Slope Sea

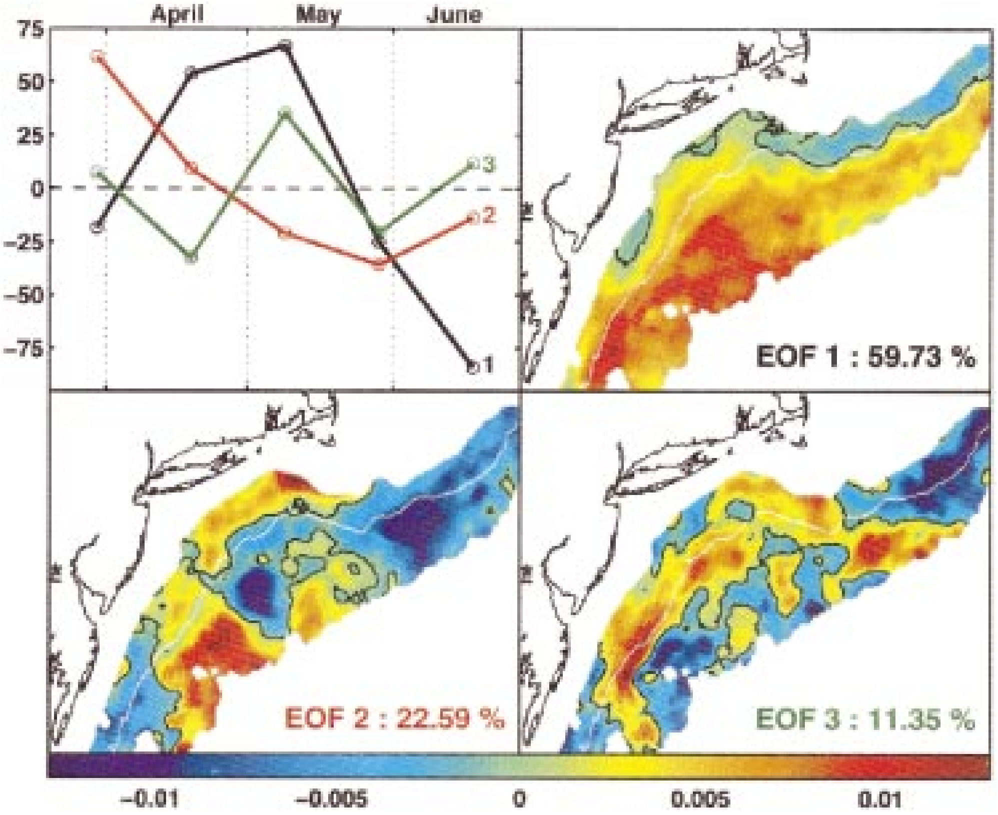

Fig. 5. The first three empirical orthogonal functions (EOFs) of the log-transformed 1980 CZCS-Chl time series (5 × 32,742), together containing >90% of the variance. The scale for all three EOFs is shown at the bottom, and the zero line of each EOF is contoured in black. The white line is the 100-m isobath. Amplitudes for all three EOFs are shown in the upper left plot; points represent the center of each 20-d averaging period.

by the WCR and its adjacent cyclone, as evident in the CZCS image (Fig. 6a) and in a thermal section taken 1 d later.

Discussion

Annual enhancement of phytoplankton chlorophyll at the shelfbreak of the MAB and Georges Bank is distinct from the well-known winter/spring bloom on the shelf. The winter/spring bloom normally occurs during March–April (Malone et al. 1983; O'Reilly and Zetlin 1998), whereas shelfbreak chlorophyll enhancement can occur as late as the end of June. During 1980, its constituent phytoplankton were primarily those that dominate shelf water following the winter/spring bloom. The conditions under which shelfbreak enhancement occurs are also distinct from the conditions of the winter/spring bloom. The shelf-water column in winter is well mixed and nutrient rich, and stratification is needed to overcome light limitation of phytoplankton growth. The winter/spring bloom depletes near-surface nutrients, and increasing stratification during the spring transition suppresses the vertical mixing that can replenish nutrients. Shelfbreak chlorophyll enhancement thus develops during a period when vertical mixing or upwelling is needed to overcome nutrient limitation of phytoplankton growth in near-surface waters. Because satellite-derived pigment concentrations are representative of the upper optical depth, <10 m in these waters, upwelling or mixing to near-surface waters is required for enhancement to be detected by remote sensing.

Shelfbreak chlorophyll enhancement was associated with the shelf-slope front. The front has a strong influence on phytoplankton growth at the shelfbreak before and after the spring transition. Under light-limited conditions of winter, the spring bloom begins relatively early at the shelfbreak because the front shoals the mixed layer and allows earlier stratification (Marra et al. 1982; Malone et al. 1983). Under nutrient-limited conditions of summer, disturbance of the front by winds or WCRs can upwell deep-shelf nutrients along frontal isopycnals that shoal in the offshore direction (Malone et al. 1983; Marra et al. 1990). Although this causes shelfbreak chlorophyll enhancement during the strongly stratified conditions of summer, enhancement is below the depth to which satellite remote sensing can detect. Considering the earlier blooming of phytoplankton at the front during spring, nutrients would be depleted there earliest without mechanisms of replenishment. Thus, the causative mechanisms for shelfbreak chlorophyll enhancement during the spring transition must involve frontal structure and dynamics.

The importance of the shelf-slope front to phytoplankton processes along the Scotian Shelf is well known (Fournier 1978; Fournier et al. 1979; Herman and Denman 1979; Fournier et al. 1984). Although this front does not extend into

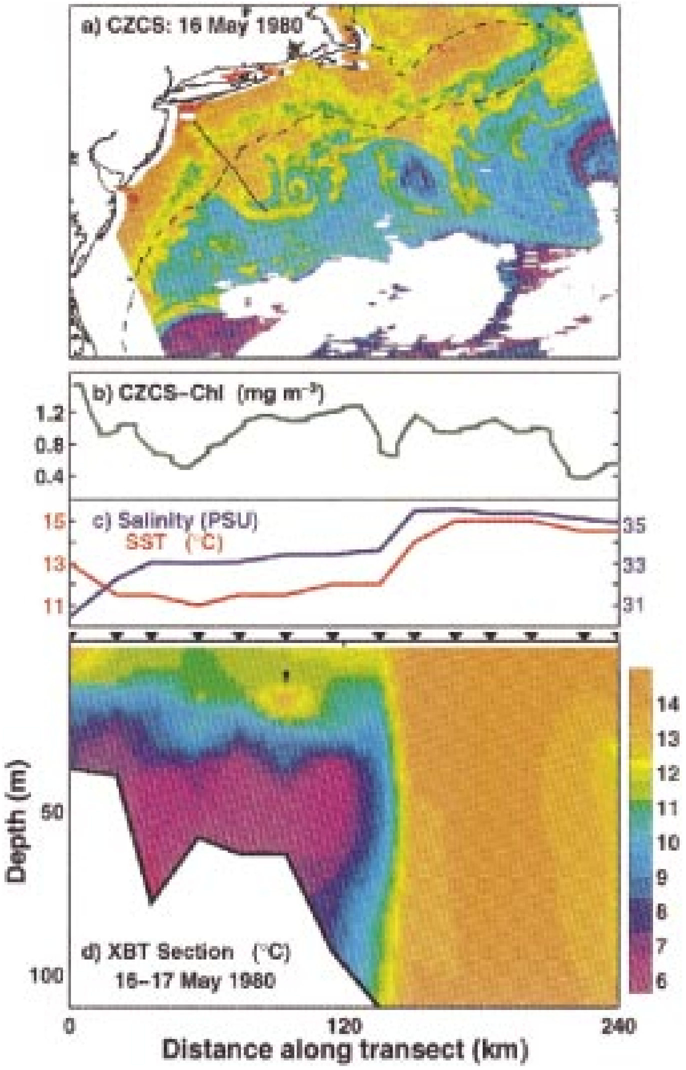

Fig. 6. (a) CZCS image from 16 May 1980, 6 d after the image shown in Fig. 2b (*see Fig. 2 for color scale*). The black line shows the location of a cross-shelf/slope transect, along which were measured surface temperature and salinity and vertical thermal structure on 16–17 May. (b, c) CZCS pigment concentrations, surface salinity, and surface temperature from along the transect. (d) Vertical thermal structure from XBT survey along the transect; arrow marks intrusion of slope and/or WCR water.

the neighboring South Atlantic Bight, the importance of Gulf Stream (Yoder et al. 1981, 1983) and midshelf (Ryan and Yoder 1996) fronts to phytoplankton processes and satellite-observed chlorophyll distributions is documented.

One important dynamic feature of the shelf-slope front is its high-velocity geostrophic jet, evident in mean flow (Aikman et al. 1988) and in fine-scale synoptic sampling (Gawarkiewicz et al. 1996). It flows approximately parallel to local isobaths from Georges Bank toward Cape Hatteras. Nutrients or phytoplankton upwelled or vertically mixed at the shelfbreak and phytoplankton that grow in response to shoaled nutrients can be rapidly transported SW along the shelfbreak in the frontal jet. This may explain the frequently observed extension of shelfbreak chlorophyll enhancement SW of WCRs.

Extension of shelfbreak enhancement somewhat inshore of the surface outcrop of the front is interesting to consider in relation to the climatological position of the frontal jet and the development of SST during the spring transition. A climatology of the shelfbreak front shows that the frontal jet is inshore of the surface outcrop of the front (Linder and Gawarkiewicz 1998), consistent with the observed extension of chlorophyll enhancement inshore of the front. EOF analysis of AVHRR SST observations of this region during the spring transition shows slower seasonal warming along the shelfbreak than in adjacent shelf and slope waters (Everson et al. 1997). This slower warming is inshore of where the surface outcrop of the front is most consistently observed. The authors suggest mixing or vertical motion locally modifying seasonal warming. Advection, heat flux, and shear within the frontal jet could influence both the seasonal warming rate and phytoplankton distributions.

The fundamental process consistently related to shelfbreak chlorophyll enhancement was seaward displacement of shelf water, and the most frequent dynamic basis for this was WCR entrainment. The largest observed spatial scale and longest duration of enhancement, during 1980, coincided with the most WCR entrainment of shelf water within the period 1979–1985 (Garfield and Evans 1987). The CZCS imagery we presented shows four WCRs simultaneously interacting with shelf water during the peak of the 1980 shelfbreak chlorophyll enhancement. Coincidence with shelf-water entrainment along the Gulf Stream front was evident during 1979, 1980, and 1984. Also, during 1984, seaward flow of shelf water was related to disturbances of the shelf-slope front, which involved an anticyclonic eddy. Enhancement of chlorophyll and primary production at the shelf-slope front during summer has been associated with similar frontal eddy formation (Marra et al. 1990). Although offshore flow east of the anticyclonic eddy might suggest that entrainment by the eddy was causative, it has been proposed that such frontal eddies result from offshore transport (Houghton et al. 1986); shelf water flowing offshore between density surfaces that converge would turn anticyclonically to conserve potential vorticity. Although variable in dynamics, seaward displacement of shelf water emerges as the most fundamental process related to shelfbreak chlorophyll enhancement during the spring transition.

How could displacement of shelf water across isobaths result in chlorophyll enhancement oriented along isobaths? Association of this feature with the shelf-slope front provides the probable answer. Because frontal isopycnals shoal in the offshore direction, shelf water flowing offshore would upwell along isopycnals. Before shelf and slope waters become strongly stratified, frontal isopycnals extend closer to the surface and are more steeply sloped, and onshore displacement of the front by a WCR or Gulf Stream meander would increase frontal slope. For example, density sections across the shelfbreak south of Nantucket Shoals (Wright 1983) show that the slope of the front was ~3× greater with a ring adjacent to the shelfbreak on 27 April 1979 than it had been 1 month earlier, when no WCR was present and springtime stratification was weaker. Thus, entrainment has greater po-

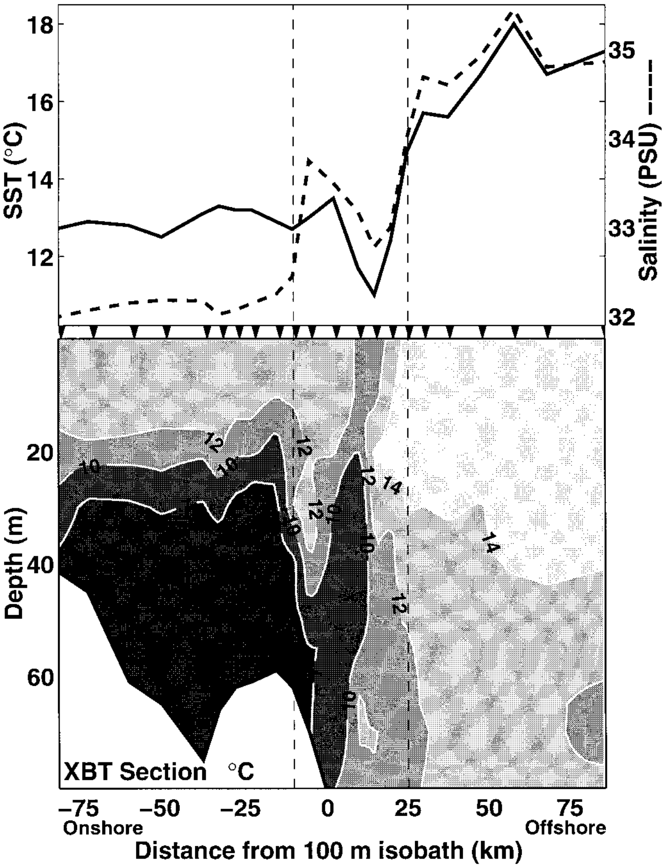

Fig. 7. Surface salinity, surface temperature, and vertical thermal structure on 16–17 June 1982 from along the same ship transect as that shown in Fig. 6a. The vertical dashed lines mark the region of interleaving of shelf and slope waters (warmer, more saline water inshore of colder, fresher water). No CZCS pigment observations were near in time to these hydrographic observations. Note the apparent upwelling of thermocline water to the surface.

tential for upwelling nutrients during the spring transition than during summer, and the presence and dynamics of Gulf Stream WCRs and meanders at the shelfbreak would enhance this potential. Additionally, alongshelf orientation of chlorophyll enhancement would be promoted by alongshelf advection of chlorophyll and/or nutrients in the frontal jet.

We observed intrusion of slope and/or WCR water onto the shelf inshore of the shelfbreak chlorophyll enhancement during 1980. WCRs commonly force exchange of shelf and slope waters during the annual period May–October (Churchill et al. 1986). In this exchange, slope water moves onshore above shelf water moving offshore. It is similar to the annual development during the spring transition of interleaving between shelf and slope waters at the front (Voorhis et al. 1976), a process that can occur in the absence of a WCR. Thermal observations across the shelfbreak show that this interleaving can upwell shelf water from the thermocline to the surface (Fig. 7). Although we infer that upwelling of shelf water along frontal isopycnals during offshore flow is the most probable dynamic basis for the annual shelfbreak chlorophyll enhancement, exchange of shelf and slope waters through this interleaving may be involved. Phytoplankton enhancement along the Scotian shelfbreak has been associated with interleaving of shelf and slope waters (Herman and Denman 1979).

One other process of potential significance was suggested in the CZCS imagery. Shelfbreak chlorophyll enhancement on two occasions extended NE of a WCR in a wavelike pattern. The wavelength was consistent with that described for frontal waves generated by horizontal shear between opposing WCR and shelfbreak flows (Ramp et al. 1983; Ramp 1986). The waves extend from the surface to ~100-m depth, they occur in the MAB during the spring transition, and they eventually break and mix water across the front. The amplitude of these waves is ~20 km, they propagate toward the NE, and they grow in amplitude before breaking. Considering a mean frontal slope of ~10^{-3} (Beardsley and Flagg 1976), the vertical scale of mixing across the front when the waves break would be ~20 m.

Chlorophyll enhancement during the spring transition was evident in a multiyear mean of satellite-derived chlorophyll and was most pronounced seaward of the 100-m isobath. The annual cycle of euphotic zone primary production in MAB shelfbreak waters off Long Island (between the 80- and 1,000-m isobaths) exhibits a broad maximum during March–June, in contrast to a sharp March peak in middle shelf water (Malone et al. 1983). Endurance of maximum production at the shelfbreak may be related to the same processes that force chlorophyll enhancement. The volume of shelf water above the front, seaward of the shelfbreak, constitutes ca. half of the total shelf-water volume (Wright and Parker 1976). This part of the shelf-water mass was not considered in shelf-to-slope export of spring bloom biomass during the Shelf Edge Exchange Processes (SEEP) II Experiment, but its central importance to carbon budgets was emphasized (Wirick 1994). Carbon fixed by phytoplankton seaward of the shelfbreak can be exported to slope water by sinking through the shelf-slope front. Thus, a better understanding of the spatial and temporal scale of this annual chlorophyll enhancement is important to understanding not only MAB/Georges Bank ecology but also shelf carbon budgets.

References

Afifi, A. A., and S. P. Azen. 1972. Statistical analysis: A computer oriented approach. Academic Press.

Aikman, F. III, H. W. Ou, and R. W. Houghton. 1988. Current variability across the New England continental shelf-break and slope. Cont. Shelf Res. **8:** 625–651.

Beardsley, R. C., and C. N. Flagg. 1976. The water structure, mean currents, and shelf-water/slope-water front on the New England continental shelf, p. 209–225. *In* J. C. J. Nihoul [ed.], Continental shelf dynamics. Siege de la Societe Univ.

Bisagni, J. J., J. E. O'Reilly, A. H. Barnard, and C. M. Wolfteich. 1997. Determination of optimum aerosol thickness ratios for atmospheric correction of coastal zone color scanner data in the Georges Bank–Gulf of Maine region. Cont. Shelf Res. **17:** 635–654.

Brown, O. B., R. H. Evans, J. W. Brown, H. R. Gordon, R. C. Smith, and K. S. Baker. 1985. Phytoplankton blooming off the U.S. east coast: A satellite description. Science **229:** 163–167.

Campbell, J. W. 1995. The lognormal distribution as a model for bio-optical variability in the sea. J. Geophys. Res. **100:** 13237–13254.

Celone, P. J., and C. A. Price. 1985. Anticyclonic warm-core Gulf Stream rings off the northeastern United States during 1982. Ann. Biol. (Copenhagen) **39:** 19–23.

Churchill, J. H., P. C. Cornillon, and G. W. Milkowski. 1986. A cyclonic eddy and shelf-slope water exchange associated with a Gulf Stream warm-core ring. J. Geophys. Res. **91:** 9615–9623.

———, E. R. Levine, D. N. Connors, and P. C. Cornillon. 1993. Mixing of shelf, slope and Gulf Stream water over the continental slope of the Middle Atlantic Bight. Deep-Sea Res. **40:** 1063–1085.

Clark, D. K. 1981. Phytoplankton algorithms for the Nimbus-7 CZCS, p. 227–238. *In* J. F. R. Gower [ed.], Oceanography from space. Plenum Press.

Denman, K. L., and M. R. Abbott. 1988. Time evolution of surface chlorophyll patterns from cross spectrum analysis of satellite color images. J. Geophys. Res. **93:** 6789–6798.

DODS. 1998. The Distributed Oceanographic Data System. Graduate School of Oceanography, Univ. of Rhode Island [online]. Available: http://dods.gso.uri.edu/DODS/home/home.html.

Elrod, J. A. 1988. CZCS view of an oceanic acid waste dump. Remote Sens. Environ. **25:** 245–254.

Eslinger, D. L., and R. L. Iverson. 1986. Wind effects on Coastal Zone Color Scanner chlorophyll patterns in the U.S. Mid-Atlantic Bight during spring 1979. J. Geophys. Res. **91:** 12985–12992.

———, J. J. O'Brien, and R. L. Everson. 1989. Empirical orthogonal function analysis of cloud-containing Coastal Zone Color Scanner images of northwestern North American coastal waters. J. Geophys. Res. **94:** 10884–10890.

Everson, R., P. Cornillon, L. Sirovich, and A. Webber. 1997. An empirical eigenfunction analysis of sea surface temperatures in the Western North Atlantic. J. Phys. Oceanogr. **27:** 468–479.

Feldman, G., and others. 1989. Ocean color: Availability of the global data set. EOS Trans. **70:** 634–635, 640–641.

Fitzgerald, J. L., and J. L. Chamberlin. 1982. Anticyclonic warm-core Gulf Stream rings off the northeastern United States during 1979. Ann. Biol. (Copenhagen) **36:** 44–51.

———, and ———. 1983. Anticyclonic warm-core Gulf Stream rings off the northeastern United States during 1980. Ann. Biol. (Copenhagen) **37:** 41–47.

———, and ———. 1984. Anticyclonic warm-core Gulf Stream rings off the northeastern United States during 1981. Ann. Biol. (Copenhagen) **38:** 29–33.

Flagg, C. N., R. W. Houghton, and L. J. Pietrafesa. 1994. Summertime thermocline salinity maximum intrusions in the Mid-Atlantic Bight. Deep-Sea Res. II **41:** 325–340.

Fournier, R. O. 1978. Biological aspects of the Nova Scotian shelf-break front, p. 69–77. *In* M. J. Bowman and W. E. Esaias [eds.], Oceanic fronts in coastal processes. Springer.

———, M. Van Det, N. B. Hargreaves, J. S. Wilson, T. A. Clair, and R. Ernst. 1984. Physical factors controlling summer distributions of chlorophyll *a* off southwestern Nova Scotia. Limnol. Oceanogr. **29:** 517–526.

———, ———, J. S. Wilson, and N. B. Hargreaves. 1979. Influence of the shelf-break front off Nova Scotia on phytoplankton standing stock in winter. J. Fish. Res. Board Can. **36:** 1228–1237.

Garcia-Moliner, G., and J. A. Yoder. 1994. Variability in pigment concentration in warm-core rings as determined by Coastal Zone Color Scanner satellite imagery from the Mid-Atlantic Bight. J. Geophys. Res. **99:** 14277–14290.

Garfield, N., and D. L. Evans. 1987. Shelf water entrainment by Gulf Stream warm-core rings. J. Geophys. Res. **92:** 13003–13012.

Gawarkiewicz, G., T. G. Ferdelman, T. M. Church, and G. W. Luther III. 1996. Shelfbreak frontal structure on the continental shelf north of Cape Hatteras. Cont. Shelf Res. **16:** 1751–1773.

Gilman, C. S. 1988. A study of the Gulf Stream downstream of Cape Hatteras, 1975–1986. M.S. thesis, Univ. of Rhode Island.

Gordon, A. L., and F. Aikman III. 1981. Salinity maximum in the pycnocline of the Middle Atlantic Bight. Limnol. Oceanogr. **26:** 123–130.

Gordon, H. R., and D. K. Clark. 1981. Clear water radiances for atmospheric correction of Coastal Zone Color Scanner imagery. Appl. Opt. **20:** 4175–4180.

Gregg, W. W., and J. J. Walsh. 1992. Simulation of the 1979 spring bloom in the Mid-Atlantic Bight: A coupled physical/biological/optical model. J. Geophys. Res. **97:** 5723–5743.

Herman, A. W., and K. L. Denman. 1979. Intrusions and vertical mixing at the shelf/slope water front south of Nova Scotia. J. Fish. Res. Board Can. **36:** 1445–1453.

Hoge, F. E., M. E. Williams, R. N. Swift, J. K. Yungel, and A. Vodacek. 1995. Satellite retrieval of the absorption coefficient of chromophoric dissolved organic matter in continental margins. J. Geophys. Res. **100:** 24847–24854.

Houghton, R. W., F. Aikman III, and H. W. Ou. 1988. Shelf-slope frontal structure and cross-shelf exchange at the New England shelfbreak. Cont. Shelf Res. **8:** 687–710.

———, and J. Marra. 1983. Physical/biological structure and exchange across the thermohaline shelf/slope front in the New York Bight. J. Geophys. Res. **88:** 4467–4481.

———, D. B. Olson, and P. J. Celone. 1986. Observation of an anticyclonic eddy near the continental shelf break south of New England. J. Phys. Oceanogr. **16:** 60–71.

Hovis, W. A. 1980. Nimbus-7 Coastal Zone Color Scanner: System description and initial imagery. Science **210:** 60–63.

Kelly, K. A. 1988. Comment on ''Empirical Orthogonal Function Analysis of Advanced Very High Resolution Radiometer Surface Temperature Patterns in Santa Barbara Channel'' by G. S. E. Lagerloef and R. L. Bernstein. J. Geophys. Res. **93:** 15753–15754.

Ketchum, B. H., R. F. Vaccaro, and N. Corwin. 1958. The annual cycle of phosphorous and nitrogen in New England coastal waters. J. Mar. Res. **17:** 282–301.

Linder, C. A., and G. Gawarkiewicz. 1998. A climatology of the shelfbreak front in the Middle Atlantic Bight. J. Geophys. Res. **103:** 18405–18424.

Lyne, V. D., and G. T. Csanady. 1984. A compilation and description of hydrographic transects of the Mid-Atlantic Bight shelf-break front. WHOI Technical Rep. 84-19. Woods Hole Oceanographic Institution.

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

Marra, J., R. W. Houghton, D. C. Boardman, and P. J. Neale. 1982. Variability in surface chlorophyll *a* at a shelf-break front. J. Mar. Res. **40:** 575–591.

———, ———, and C. Garside. 1990. Phytoplankton growth at the shelf-break front in the Middle Atlantic Bight. J. Mar. Res. **48:** 851–868.

Milliman, J. D. [ed.] 1994. Shelf edge exchange processes in the southern Mid-Atlantic Bight: SEEP II. Deep-Sea Res. II **41:** 2–3.

Mooers, C. N. K., C. N. Flagg, and W. C. Boicourt. 1978. Prograde and retrograde fronts, p. 43–58. *In* M. J. Bowman and

W. E. Esaias [eds.], Oceanic fronts in coastal processes. Springer.

MUELLER, J. L. 1988. Nimbus-7 CZCS: Electronic overshoot due to cloud reflectance. Appl. Opt. **27:** 438–440.

MYERS, R. A., AND K. DRINKWATER. 1989. The influence of Gulf Stream warm core rings on recruitment of fish in the northwest Atlantic. J. Mar. Res. **47:** 635–656.

O'REILLY, J. E., AND D. A. BUSH. 1984. Phytoplankton primary production on the northwestern Atlantic shelf. Rapp. P-V. Reun. Cons. Int. Explor. Mer **183:** 255–268.

———, AND C. ZETLIN. 1998. Monograph on the seasonal, horizontal, and vertical distribution of phytoplankton chlorophyll *a* in the northeast U.S. continental shelf ecosystem. NOAA Technical Rep. 139, Fishery Bulletin, National Marine Fisheries Service.

———, ———, AND D. A. BUSCH. 1987. Primary production, p. 221–233. *In* R. H. Backus and D. W. Bourne [eds.], Georges Bank. MIT Press.

PRICE, C. A. 1985. Anticyclonic warm-core Gulf Stream rings off the northeastern United States during 1984. NAFO SCR Doc. 85/19.

———, AND K. W. BARTON. 1986. Anticyclonic warm-core Gulf Stream rings off the northeastern United States during 1985. NAFO SCR Doc. 86/77.

———, AND ———. 1987. Anticyclonic warm-core Gulf Stream rings off the northeastern United States during 1986. NAFO SCR Doc. 87/14.

———, AND P. J. CELONE. 1984. Anticyclonic warm-core Gulf Stream rings off the northeastern United States during 1983. NAFO SCR Doc. 84/18.

RAMP, S. R. 1986. The interaction of warm core rings with the shelf water and shelf-slope front south of New England. Ph.D. thesis, Univ. of Rhode Island.

———, R. C. BEARDSLEY, AND R. LEGECKIS. 1983. An observation of frontal wave development on a shelf-slope/warm core ring front near the shelfbreak south of New England. J. Phys. Oceanogr. **13:** 907–912.

RYAN, J. P., AND J. A. YODER. 1996. Long-term mean and event-related pigment distributions during the unstratified period in South Atlantic Bight outer margin and middle shelf waters. Cont. Shelf Res. **16:** 1165–1183.

SEA SURFACE TEMPERATURE SATELLITE IMAGE ARCHIVE. 1998. The University of Rhode Island Graduate School of Oceanography [online]. Available: http://rs.gso.uri.edu/avhrr-archive/archive.html.

SHERMAN, K. 1980. MARMAP, a fisheries ecosystem study in the Northwest Atlantic: Fluctuations in ichthyoplankton–zooplankton components and their potential for impact on the system, p. 9–37. *In* F. P. Diemer, F. J. Vernberg, and D. Z. Mirkes [eds.], Advanced concepts in ocean measurements for marine biology. Univ. of South Carolina Press.

VOORHIS, A. D., D. C. WEBB, AND R. C. MILLARD. 1976. Current structure and mixing in the shelf-slope water front south of New England. J. Geophys. Res. **81:** 3695–3708.

WALSH, J. J. [ED.]. 1988. Shelf edge exchange processes of the Mid-Atlantic Bight. Cont. Shelf Res. **8:** 5–7.

———, D. A. DIETERLE, AND W. E. ESAIAS. 1987*a*. Satellite detection of phytoplankton export from the Mid-Atlantic Bight during the 1979 spring bloom. Deep-Sea Res. **34:** 675–703.

———, T. E. WHITLEDGE, F. W. BARVENIK, C. D. WIRICK, S. O. HOWE, W. E. ESAIAS, AND J. T. SCOTT. 1978. Wind events and food chain dynamics within the New York Bight. Limnol. Oceanogr. **23:** 659–683.

———, ———, J. E. O'REILLY, W. C. PHOEL, AND A. F. DRAXLER. 1987*b*. Nitrogen cycling on Georges Bank and the New York shelf: A comparison between well-mixed and seasonally-stratified waters, p. 234–246. *In* R. H. Backus and D. W. Bourne [eds.], Georges Bank. MIT Press.

WIRICK, C. D. 1994. Exchange of phytoplankton across the continental shelf-slope boundary of the Middle Atlantic Bight during spring 1988. Deep-Sea Res. II **41:** 391–410.

WRIGHT, W. R. 1976. The limits of shelf water south of Cape Cod. J. Mar. Res. **34:** 1–14.

———. 1983. Nantucket Shoals Flux Experiment data report I. Hydrography. NOAA Technical Memo. NMFS-F/NEC 23. U.S. Department of Commerce.

YODER, J. A., L. P. ATKINSON, S. S. BISHOP, E. E. HOFMANN, AND T. N. LEE. 1983. Effect of upwelling on phytoplankton productivity of the outer southeastern United States continental shelf. Cont. Shelf. Res. **1:** 385–404.

———, ———, T. N. LEE, H. H. KIM, AND C. R. MCCLAIN. 1981. Role of Gulf Stream frontal eddies in forming phytoplankton patches on the outer southeastern shelf. Limnol. Oceanogr. **26:** 1103–1110.

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