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Nutrients and chlorophyll at the shelf break off the southeastern United States during the Genesis of Atlantic Lows Experiment: Winter 1986

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Abstract. The outer shelf and upper slope off Charleston, South Carolina, were the site of oceanographic and meteorological measurements during the winter of 1986. The purpose of the study was to test ideas about front formation, heat transport, and stratification during cold air outbreaks. An ancillary part of the study was the observation of nutrients and chlorophyll concentrations. The observations extended across the shelf and sometimes crossed the Gulf Stream front. The results show slightly elevated nitrate concentrations in outer shelf waters ($1-2 \mu M$ NO_3) with chlorophyll concentrations in the $1-1.8 \mu g$ L^{-1} range. When effects of Gulf Stream frontal eddies are eliminated, the estimated wintertime wind-driven transport of nutrients from the deep ocean to the shelf is comparable to that observed during spring and summer. Thus significant onshore nutrient transport can occur throughout the year in this region.

Introduction

Continental shelves are among the most biologically productive regions in the world ocean. Most of the nutrients that support this production come from the deeper adjacent ocean [*Riley*, 1967]. Many research efforts in the past decade addressed the process of nutrient transport to shelf waters along the ocean's western boundary. However, most of these studies were during the spring and summer seasons, when stratification is high and wind stress is low. Unfortunately, sampling in the spring and summer seasons misses the winter season, when many biologically important processes occur (e.g., Atlantic menhaden spawning [*Judy and Lewis*, 1983]). More recently, *Checkley et al.* [1988] suggested that menhaden have evolved to reproduce during specific winter conditions at the shelf break. There is also indirect evidence of nutrient input to the shelf waters. Observations of high levels of biological activity during wintertime off South Carolina imply nutrient input from the Gulf Stream [*Deibel*, 1985], and analysis of Coastal Zone Color Scanner imagery shows high surface chlorophyll concentrations over the shelf break off North and South Carolina in the wintertime [*McClain et al.*, 1988]. There also are few reported observations of nutrients from there during winter season conditions. This paper presents new observations of nutrients and chlorophyll in outer shelf waters off South Carolina during winter.

The observations described in this paper were part of the Genesis of Atlantic Lows Experiment (GALE). GALE's main goal was the testing of models of front formation, stratification, and heat transport that occur during cold air outbreaks. Shipboard observations were made off Charleston, South Carolina, during a 20-day period in late January 1986 (Figure 1). The study area was influenced by the Gulf Stream and the Charleston Gyre. The Gulf Stream flows along the shelf break and upper slope, strongly affecting the outer shelf currents. Because of sloping isopycnals, nutrient-rich water is present as shallow as 50-100 m depth over the slope. The Charleston Gyre is a quasi-stationary cyclonic eddy in the Gulf Stream between 32 and 33°N (Figure 1). It is caused by a low relief ridge, the Charleston Bump, between 400 and 500 m depth [*McClain and Atkinson*, 1985]. The gyre causes southward currents over the outer shelf and upper slope to its west, in contrast to the usual northward Gulf Stream induced currents.

Other papers give the meteorological [*Bane and Osgood*, 1989; *Blanton et al.*, 1989] and physical oceanographic conditions [*Lee et al.*, 1989; *Atkinson et al.*, 1989] during GALE. The key findings from these papers relevant to this paper are that stratification and heat content of outer shelf waters depend on cooling

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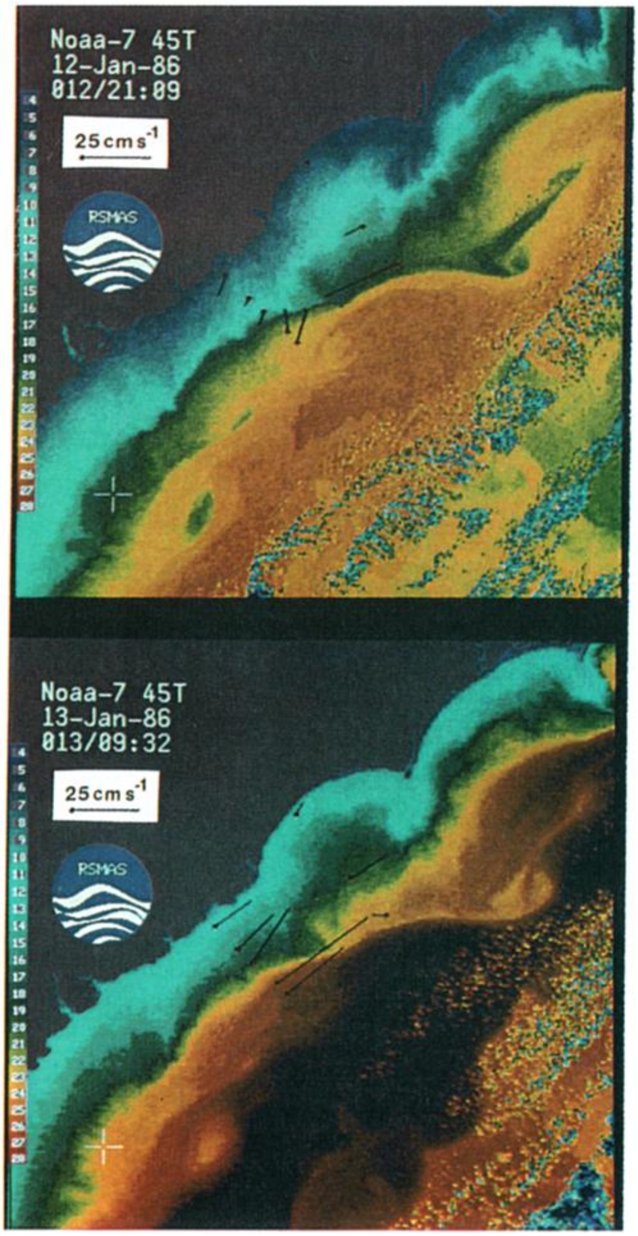

Plate 1. Sea surface temperature on January 12 and 13, 1986. Near-surface currents measured at the Genesis of Atlantic Lows Experiment (GALE) moorings at the time of each image are superimposed. The 25 cm s^{-1} velocity scale also corresponds to 50 km of distance.

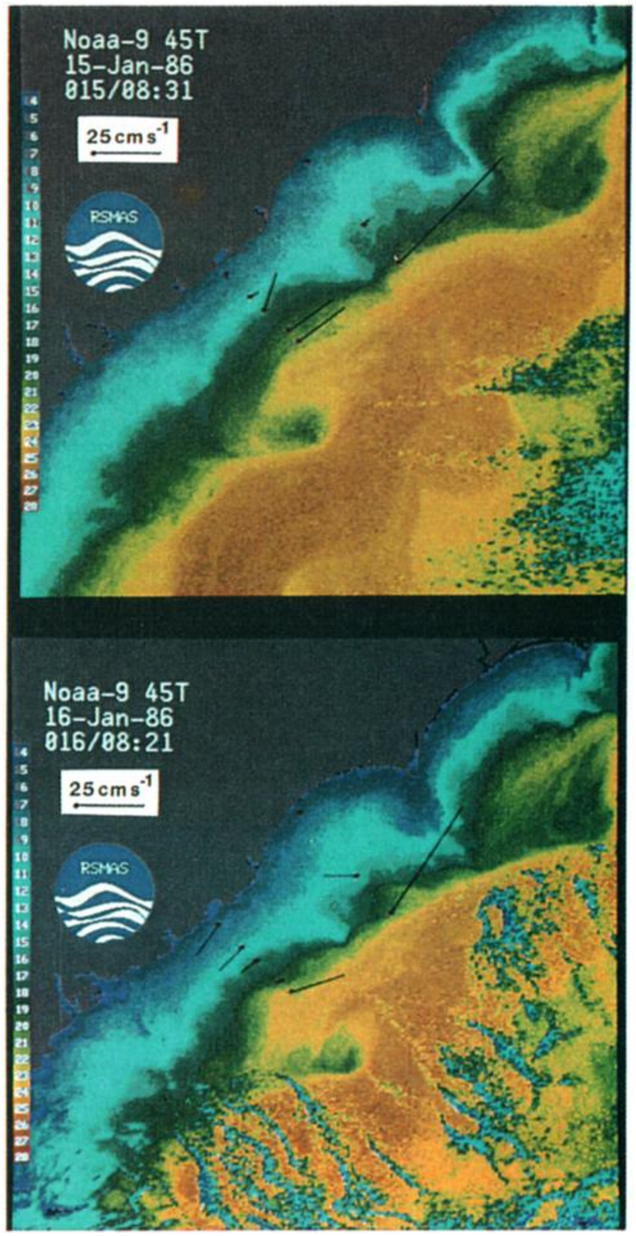

Plate 2. Sea surface temperature on January 15 and 16, 1986. Near-surface currents measured at the GALE moorings at the time of each image are superimposed.

and strong wind events. These events cause onshore flow of warm, buoyant Gulf Stream waters at rates similar to flow caused by onshore movement of Gulf Stream meanders and eddies. In this paper we examine the effects of these physical processes on the distribution of nutrients over the outer continental shelf and present rough estimates of onshore nutrient transport, which are then interpreted in terms of historical estimates for other seasons.

Methods

The hydrographic line running southeast from Charleston (hereafter referred to as the GALE section) was sampled about every 2 days (Figure 1). Consideration of storm frequency determined the spatial and temporal sampling scales. Sampling along the line included continuous measurements of surface temperature and salin-

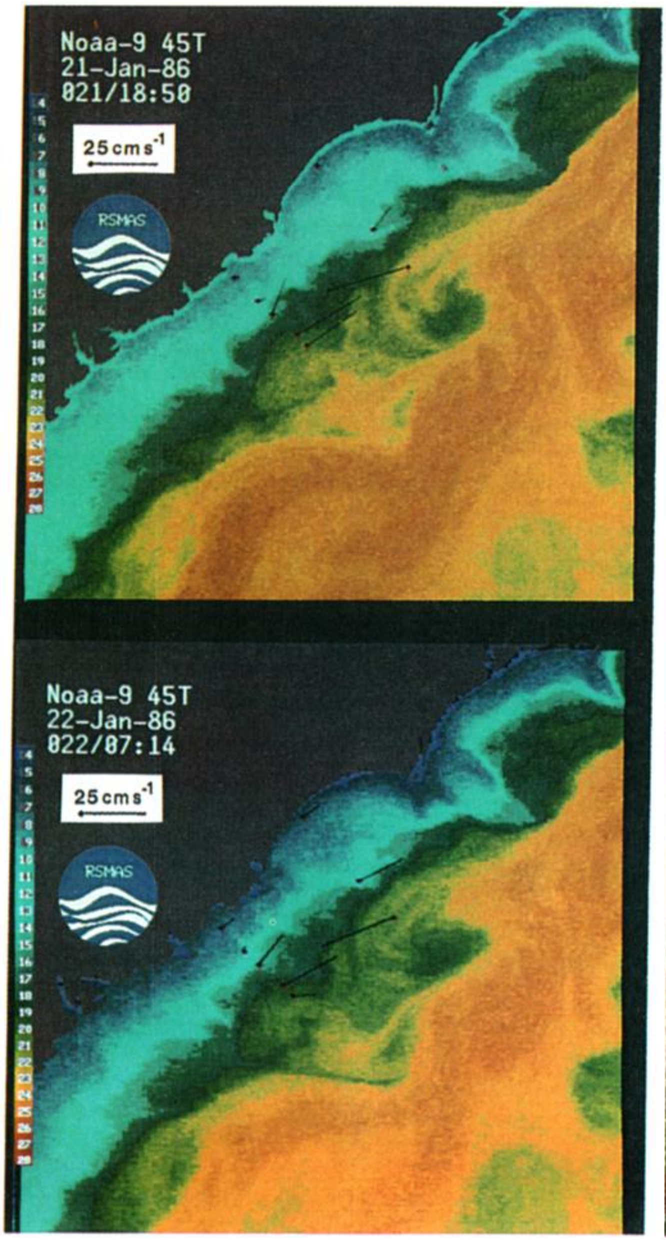

Plate 3. Sea surface temperature on January 21 and 22, 1986. Near-surface currents measured at the GALE moorings at the time of each image are superimposed.

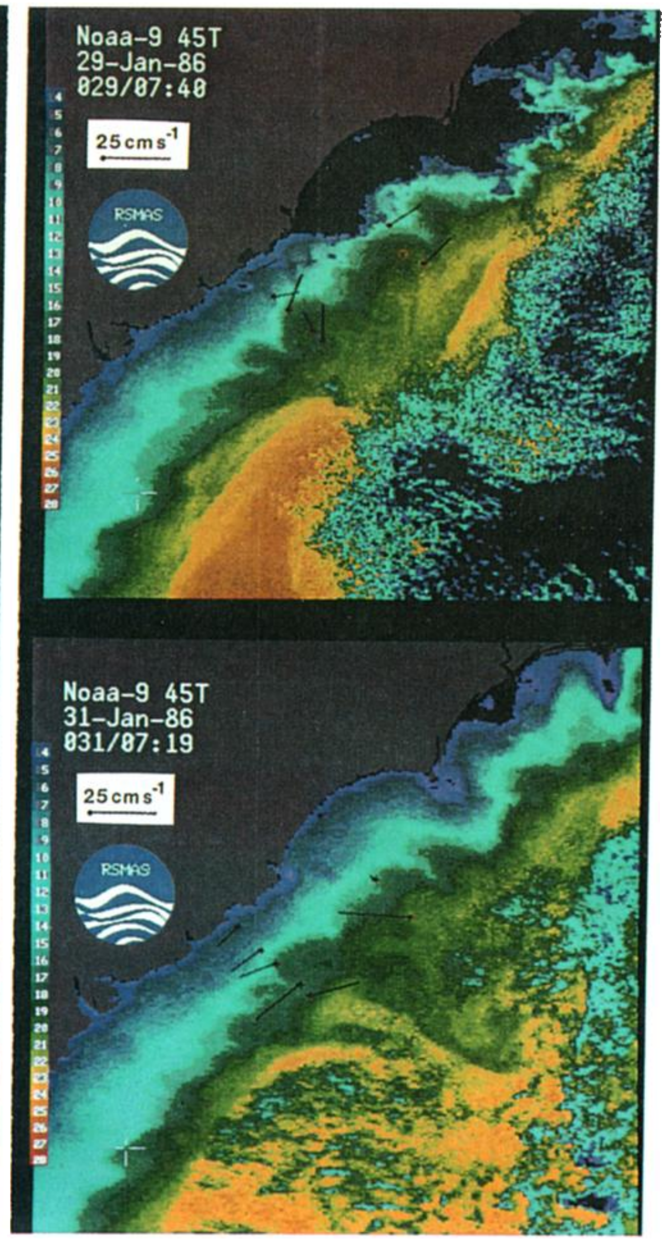

Plate 4. Sea surface temperature on January 29 and 31, 1986. Near-surface currents measured at the GALE moorings at the time of each image are superimposed.

ity and conductivity-temperature-depth (CTD) measurements at closely spaced stations. A Neil Brown Mark III was used for CTD measurements, and a General Oceanics rosette equipped with Niskin bottles attached to the CTD collected water samples. Water samples were frozen immediately after sampling and were later analyzed for nitrate, phosphate, and silicate using the colorimetric methods described by *Parsons et al.* [1984] and modified for use with an Alpkem rapid flow analyzer.

Wind stress values were measured at the Savannah Navigational Light Tower (marked SNLT in Figure 1 [*Blanton et al.*, 1989]). Wind vectors were rotated 45° clockwise to conform with local topography. Winds from buoys in the area correlated well with SNLT winds, but the buoy winds were stronger [*Blanton et al.*, 1989]. The buoy wind measurements started on January 15, after the hydrographic measurements began.

Currents at the 40-m isobath were measured with vector-measuring current meters. Vector-averaging current meters were used at the 72-m isobath. The data were filtered with a 40-hour low-pass Lanczos filter kernel that removed variance associated with tidal and inertial motions. All vectors were rotated 45° to conform to local topography (see *Lee et al.* [1989] for details). Advanced very high resolution radiometer (AVHRR) imagery were obtained from NASA and processed using the University of Miami software package.

Chlorophyll fluorescence was measured in situ using a Q fluorometer interfaced to the CTD system. At each CTD station at least two discrete water samples were taken, one from the surface (less than 10 m) and one

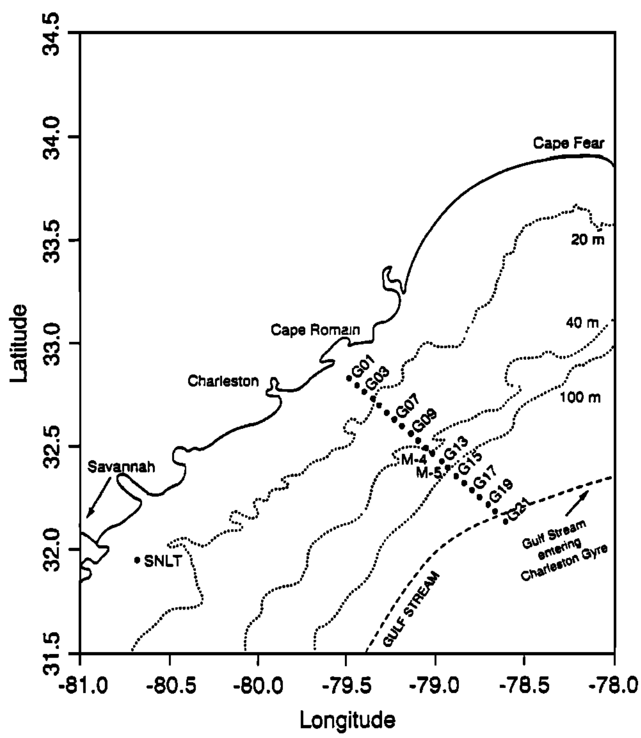

Figure 1. The Genesis of Atlantic Lows Experiment (GALE) observation area off South Carolina. Hydrographic stations, current meter locations (4 and 5), and the Savannah Navigational Light Tower (SNLT) are shown. Mean path of the Gulf Stream is also indicated.

from the chlorophyll maximum. Replicate 100 mL samples were filtered through GF/A glass fiber filters and frozen immediately for later extraction in 90% acetone according to the methods of *Holm-Hansen et al.* [1965] and *Lorenzen* [1966] using a Turner Designs (model 10) fluorometer calibrated with pure chlorophyll a. The Q fluorometer data were converted to chlorophyll from a postcruise calibration using the extracted values.

Observations

Sea Surface Temperature from AVHRR

Lee et al. [1989] discuss the AVHRR imagery for the study period (Plates 1-4). The Gulf Stream flows around the Charleston Gyre [*McClain and Atkinson*, 1985], and a warm filament wraps cyclonically around the cold core of the gyre. A third feature is the difference between the shelf currents that follow the wind and outer shelf currents that are affected by the Gulf Stream and are moving northward. The passage of a frontal eddy is also noted.

January 12, 1986. The Gulf Stream front lies between the third and fourth moorings offshore, where current direction changes from southward to northward. Winds were southward (Figure 2). A frontal eddy is about 100 km south of the GALE section.

January 13, 1986. This sea surface temperature (SST) image in Plate 1 shows the gyre in the same position. The warm filament around the gyre seems to be moving southward, but because this is a daytime image, temperatures are naturally higher. Surface currents at the outer two moorings increased, possibly due to the northward winds (Figure 2) that also caused middle and inner shelf currents to reverse direction.

January 15, 1986. The Gulf Stream flows over the Charleston Bump, and the eddy that was over the gyre has moved downstream off Onslow Bay. Outer shelf currents on the northern mooring section have reversed and are very strong because of the impingement of the Gulf Stream. Outer shelf currents at the GALE section have weakened, and the frontal eddy has moved closer.

January 16, 1986. The Gulf Stream continues to flow over the Charleston Bump, and outer shelf currents are northward and strong at both mooring sections. The frontal eddy has moved directly off the GALE section, causing warm water to flood over the outer mooring. Shelf currents continue to follow the variable wind field (Figure 2), which has again turned southward.

January 21-22, 1986. The passage of the frontal eddy appears to have set up the Charleston Gyre again. Outer shelf currents look similar to the original situation on January 12. The Gulf Stream takes an eastward turn well south of the GALE section.

January 29, 1986. Although the region directly seaward of the outer mooring is obscured by clouds, the Gulf Stream appears to remain deflected offshore south of the GALE section and to converge toward the shelf break north of the northern mooring section. Thus it remains in a strong gyre mode, and flow is eastward away from the GALE section. Outer shelf currents are weak and variable.

January 31, 1986. The intense cold air outbreak caused cooling over the shelf, and currents were southward over all but the most outer part of the shelf.

Wind Stress and Currents

The presence of nutrients over the outer shelf must depend on some combination of wind and Gulf Stream forcing since there are no other significant sources. Figure 2 contains plots of wind stress at SNLT and top and bottom cross-shelf currents at mooring 4 on the 40 m isobath and mooring 5 on the 75-m isobath. During the hydrographic observations there were six southward (marked S1-S6) and six northward (marked N1-N6) wind events (Figure 2, bottom). The effect of wind on cross-shelf transport can be identified by the presence of surface and bottom Ekman layers moving in opposite directions due to a frictional equilibrium response [*Lee et al.*, 1989]. Such layers were observed during events S1, N1, N2, N4, and S4 at mooring 4 on the 45 m isobath and events S1, N1, S2, N4, S4, and N6 at mooring 5 on the 75 m isobath. The passage of Gulf Stream frontal eddies and the setup of the Charleston Gyre also cause significant cross-shelf flows [*Lee et al.*, 1989]. The key observation is that onshore flow, either in the upper or lower layer, often occurred during wind

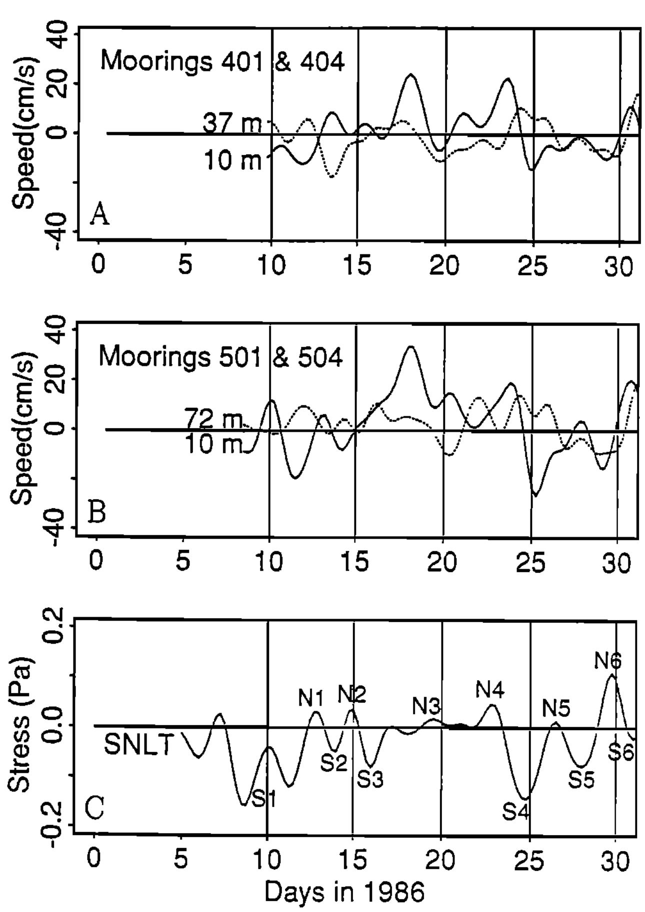

Figure 2. Cross-shelf currents at mooring 4 (top), 5 (middle), and along-shelf wind stress at SNLT (bottom). Northward (N) and southward (S) wind events are indicated.

events. The mean flow was onshore during the entire current meter mooring observation period (January 10 to March 24) at the 40-m isobath at all depths and onshore at middepths at the 75-m isobath [*Lee et al.*, 1989].

Hydrographic Structures and the Distribution of Nutrients and Chlorophyll

During the GALE observations, hydrographic structure varied considerably because of wind, cooling, and Gulf Stream motions. The temporal variability of temperature (Figures 3a and 3b) is closely related to that of nitrate (Figures 3c and 3d). On January 10 (C01) the structure was simple; the Gulf Stream front surfaced just east of the shelf break (Figures 3a and 3b). (The Gulf Stream front is generally considered to be the region where lateral temperature gradients are greatest; however, under strong wind conditions this definition can fail. For the purposes of the present discussion, the front corresponds to approximately the 20°C isotherm.) By January 12 (C02) a cold dome feature appeared in the temperature field over the upper slope, 92 km offshore. A small frontal eddy, barely noticeable in the AVHRR imagery (Plate 1) may have caused the dome [*Lee et al.*, 1989]. Winds had been southward for 4 days, and Ekman flow was established in the upper water column over the outer shelf. After January 12 (C02), winds weakened and became variable and the hydrographic structure over the upper slope never returned to the "classic" structure seen on the January 10 (C01). The surface expression of a substantial cold dome located seaward of the hydrographic section on January 16 is evident (Plate 2). However, the corresponding temperature section shows that this feature had little influence on conditions at the shelf break. This is consistent with the general lack of onshore flow during the preceding few days (Figure 2), when one would expect an advancing cold core frontal eddy to pump deep waters to the shelf break. The Charleston Gyre was reforming, and this frontal eddy was too far offshore to directly influence cross-isobath transport on the outer shelf.

Another feature observed in the hydrography was the offshore movement of the Gulf Stream front and cooling of waters over the upper slope (Plates 1 and 4). The cooler upper slope temperatures occurred because of upwelling, mixing, and heat loss to the atmosphere [*Bane and Osgood*, 1989]. In addition, such cooling, turbulent mixing of middle shelf waters, and offshore flow in the bottom Ekman layer could have caused cascading. The salinity section on January 10 (Figure 4) showed 36.1-36.2 practical salinity units (psu) water from the shelf over the upper slope near 36.4 psu Gulf Stream water. On January 30 (C11) a bottom layer of 36.2 psu water extended over the shelf break in a manner consistent with cascading.

The hydrographic structures (Figures 3a, 3b, and 4) influence the distribution of nutrients. Nutrients correlate with temperature in this oceanic region if there are no nonconservative processes at work such as cooling, mixing, or biological processes. Clearly, all three of these were occurring over the outer shelf and the shallow layers of the upper slope, but at depth the relationship still holds (Figure 5). Nutrient concentrations were bimodal below 22°C. High concentrations tended to conform to Blake Plateau water, suggesting the water ascended from the deeper Gulf Stream to the upper slope and outer shelf. The other mode was near-zero nutrient concentrations in some shelf waters colder than 22°C. One exception was the higher silicate concentrations found in waters colder than 15°C. These waters were inshore near river mouths that were a silica source. From 22°C to 18°C, nitrate concentration increased from about 1 to 10 μM; thus small variations in upwelling or deep mixing would have a large effect on upper slope and outer shelf nutrient concentrations.

Nitrate concentrations over the outer shelf and slope increase as waters over the slope ascend (Figures 3c and 3d). Phosphate and silicate distributions were well correlated with nitrate distributions. Nitrate concentrations were low above 40 m depth on January 12, with only a few scattered values in the 0.1– to 0.4 – μM range over the upper slope and outer shelf. By Janu-

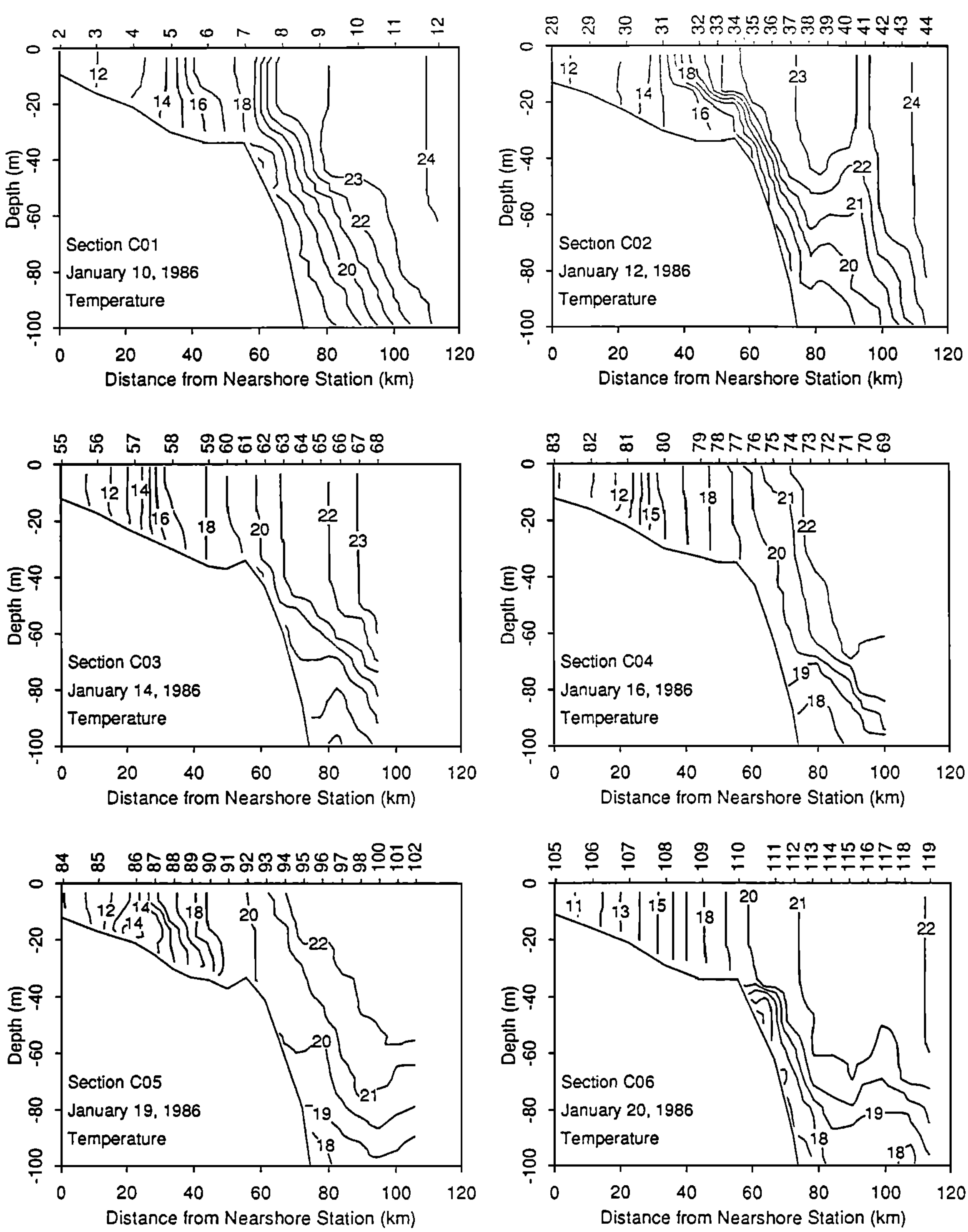

Figure 3a. Temperature sections (in degrees Celsius).

ary 14, concentrations were still low above 40 m, but scattered values between 0.2 and 1.2 μM were observed over the upper slope and outer shelf. By January 16 the situation was similar, but upper slope and outer shelf concentrations had increased further, and by January 19 the $2-\mu M$ isopleth extended from the Gulf Stream front up to the surface over the outer shelf. Concentrations over the outer shelf and upper slope increased. On January, 20 only limited water samples were taken and distributions are unknown. However, on January 22, scattered high concentrations were again found over the shelf, with maximum concentrations of 3.3 μM versus maximum concentrations of 2.5 μM on January 19. On January 24, samples were again limited but peak concentrations remained similar. On January 29, only surface samples were taken but maximum concentrations remained high over the upper slope and outer shelf. These data suggest that nutrient-rich water in-

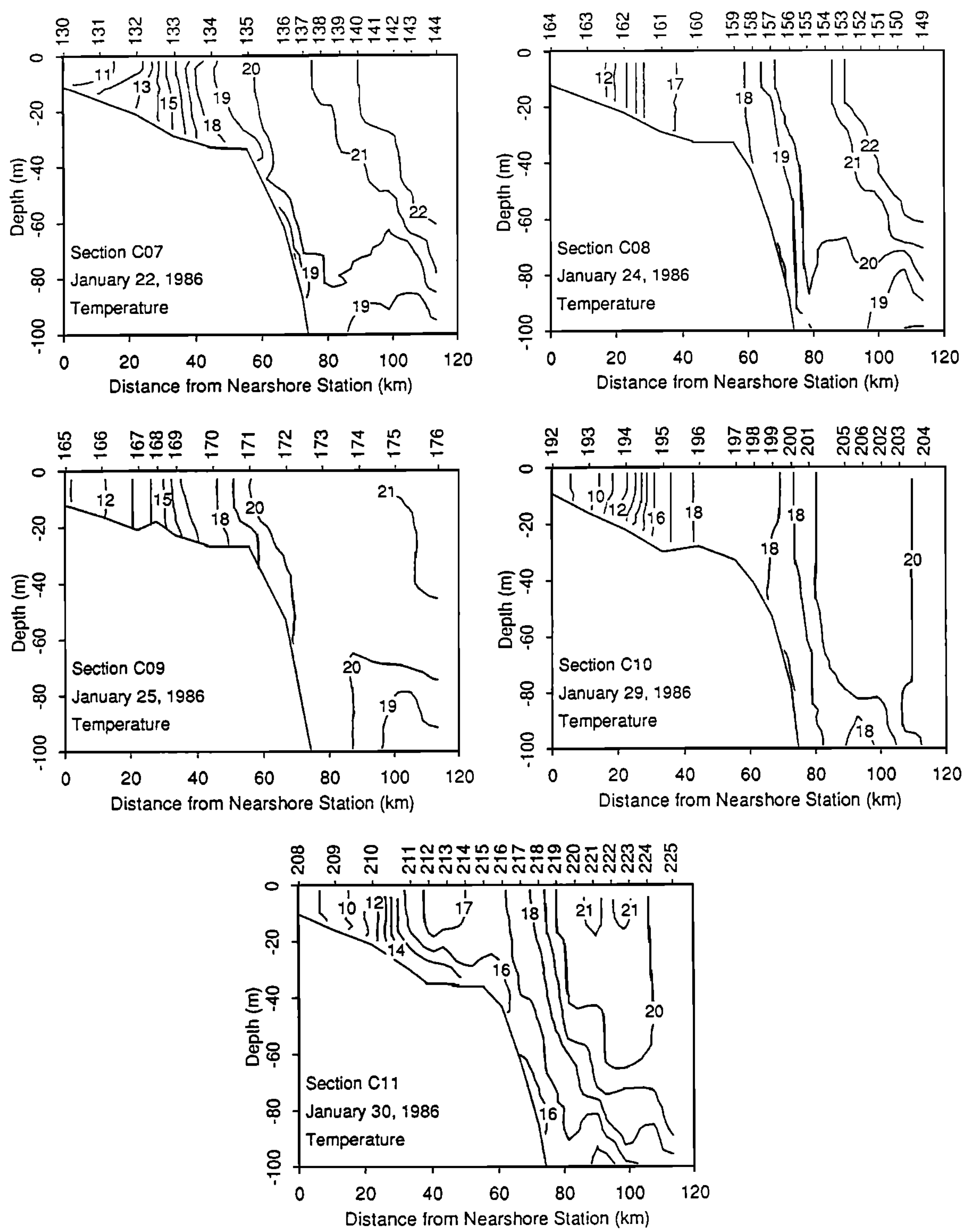

Figure 3b. Additional temperature sections (in degrees Celsius).

vaded the upper slope and outer shelf between January 16 and 19 and persisted in the area until January 29.

The advection of nutrients into the euphotic zone over the shelf break should eventually cause elevated chlorophyll concentrations (Figure 6). Concentrations over the outer shelf coincided with or were offshore of the 18° isotherm, sometimes forming a coherent mass as seen in the 1.6 – 1.8 $\mu g\ L^{-1}$ chlorophyll concentrations over the shelf break in section C01. The coincidence of the 18° isotherm that marks the onshore extent of higher nutrient concentrations with elevated chlorophyll concentrations shows the relationship between nutrient intrusions and chlorophyll.

On January 10 (C01), nearshore chlorophyll concentrations were 2.5 $\mu g\ L^{-1}$; over the middle shelf, concentrations were about 1.0 $\mu g\ L^{-1}$; and over the outer shelf

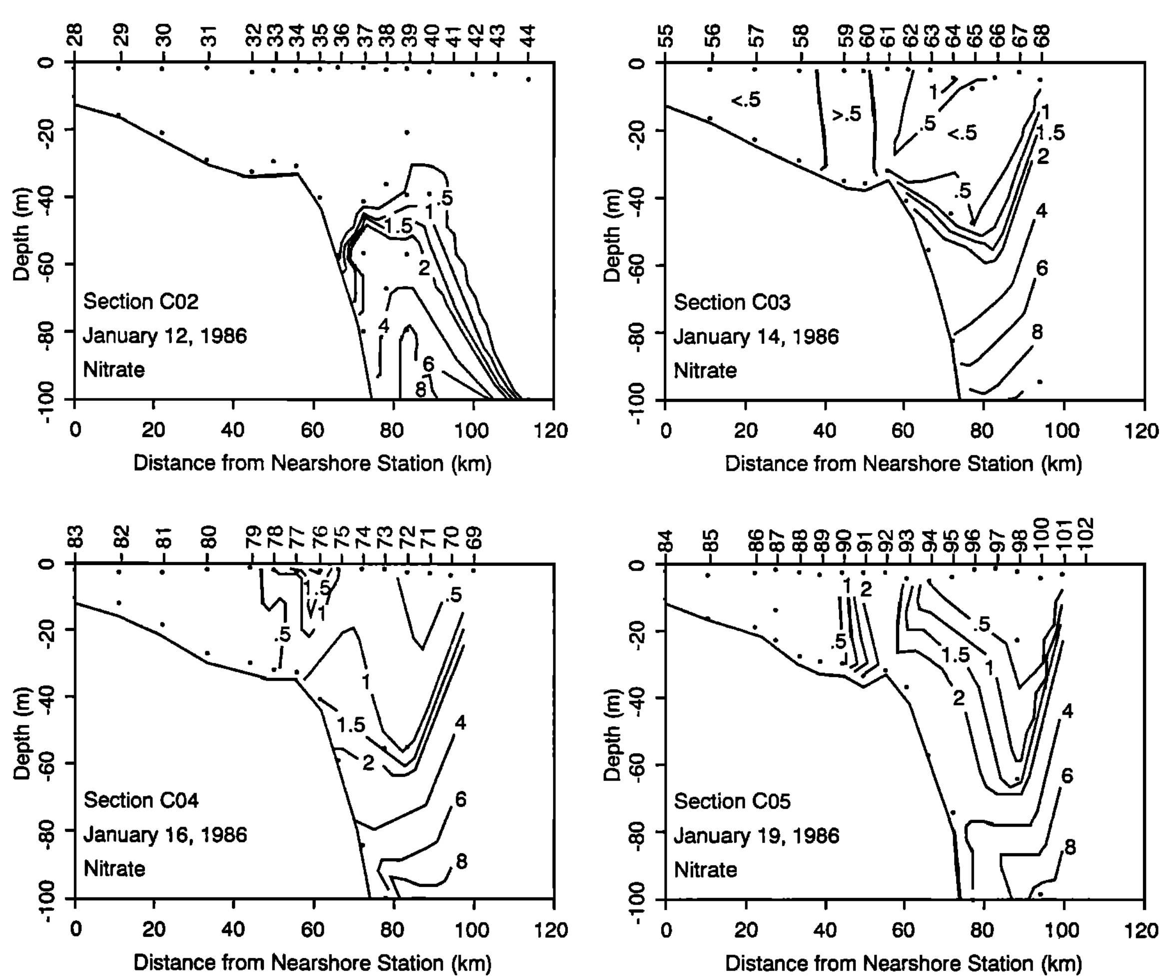

Figure 3c. Nitrate sections, with concentrations in micromoles.

and shelf break, maximum values reached 1.8 $\mu g\ L^{-1}$. Southward winds set up an onshore surface Ekman layer and an offshore near-bottom Ekman layer. By January 12 (C02), winds were still southward and Ekman flow persisted. Chlorophyll concentrations generally decreased, and the outer shelf middepth maximum shifted to the bottom at the shelf break. High chlorophyll concentrations advanced down the upper slope, causing concentrations at 60 m to increase from 0.6 to 1.2 $\mu g\ L^{-1}$. The onshore flow of nutrient- and chlorophyll-poor offshore surface water displaced high-chlorophyll shelf break surface water shoreward. There the water cooled, sank, and moved offshore in the bottom Ekman layer. This resembles previous reports of cascading in the area [*Yoder and Ishimaru*, 1989]. Between January 12 (C02) and 14 (C03), winds switched to northward and then southward, and currents changed accordingly. The chlorophyll distribution changed dramatically. The bottom maximum disappeared, and concentrations above 1 $\mu g\ L^{-1}$ extended across the middle and outer shelf and upper slope. Presumably, the outer shelf mixed and chlorophyll moved offshore in the surface Ekman layer, while the onshore bottom Ekman layer moved low-chlorophyll water onshore. Between January 16 (C04) and 19 (C05), winds were southward and weakening, then turned northward. Yet because of the passage of a frontal eddy, cross-shelf flow was offshore at all depths [*Lee et al.*, 1989]. By January 19, bottom flow switched to onshore at both moorings. Chlorophyll peak concentrations moved onshore and decreased. By January 20 (C06), bottom currents were onshore at both moorings and surface currents were onshore at mooring 4 (40 m). Chlorophyll concentrations decreased to 1 $\mu g\ L^{-1}$ or less over the whole outer shelf, and this trend continued until the fluorometer was damaged in heavy seas on January 24.

It seems that the persistent southward wind event around January 10 (C01) caused transport of nutrients into outer shelf waters to stimulate phytoplankton growth. The chlorophyll concentrations peaked over the outer shelf, coincident with the 18°C isotherm, and elevated nutrient concentrations. The southward wind event on January 16 had little effect on chlorophyll, possibly because of the presence of the frontal eddy that reduced onshore nutrient transport. The southward wind event on January 25 may have had a delayed effect, but we have no data to confirm it.

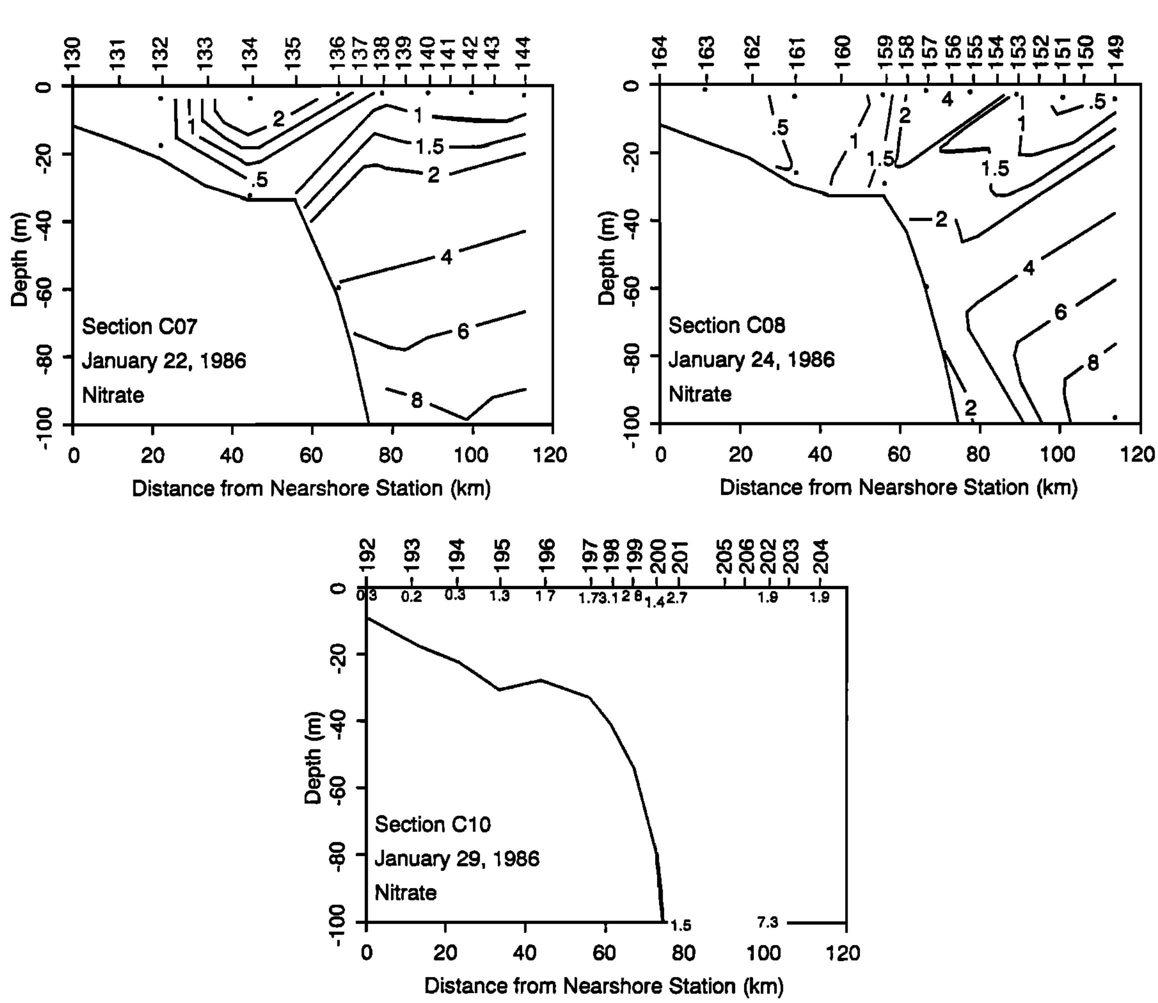

Figure 3d. Additional nitrate sections, with concentrations in micromoles.

Mass of Nutrient and Chlorophyll Over the Outer Shelf

The observations just presented show elevated nutrient and chlorophyll concentrations over the outer shelf. The change in these concentrations was quantified using data from stations G07, G09, G10, G11, and G12 (Figure 1 and Table 1). These stations were inshore of the 40 m isobath (mooring 4) and represent the outer shelf. Figure 7 shows the integration volume, mooring locations, and typical thermal structure. Vertical and horizontal integration of the observations within the domain yielded the total nutrient and chlorophyll mass in the defined shelf area. For the few cases when concentrations were not available for a grid station, values were

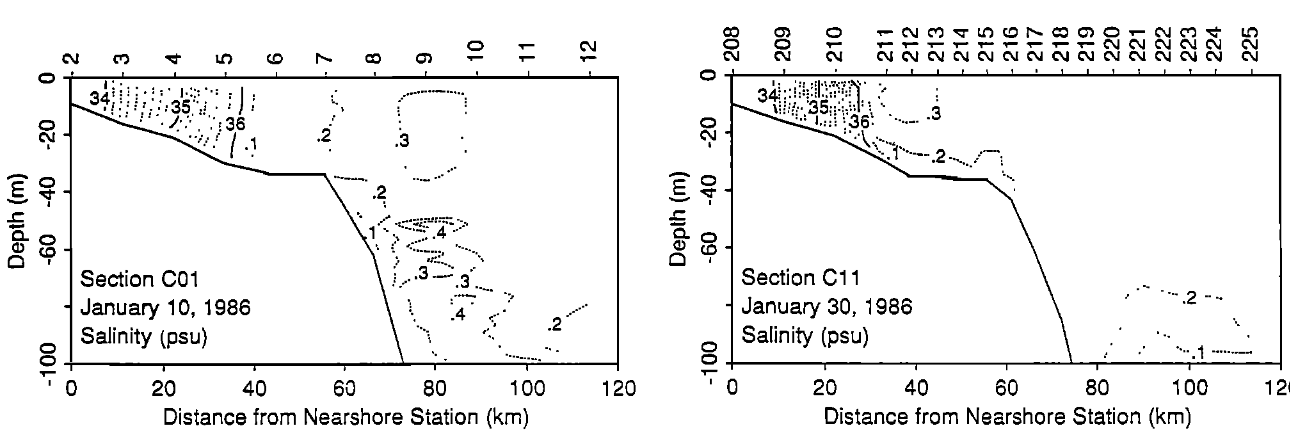

Figure 4. Salinity sections for January 10 (C01) and January 30 (C11).

obtained by horizontal interpolation prior to integration. The actual nitrate and chlorophyll observations are noted in Figures 3c, 3d and 6. Table 2 summarizes the results as does Figure 8. The error in the integrations is difficult to assess. Chlorophyll was measured

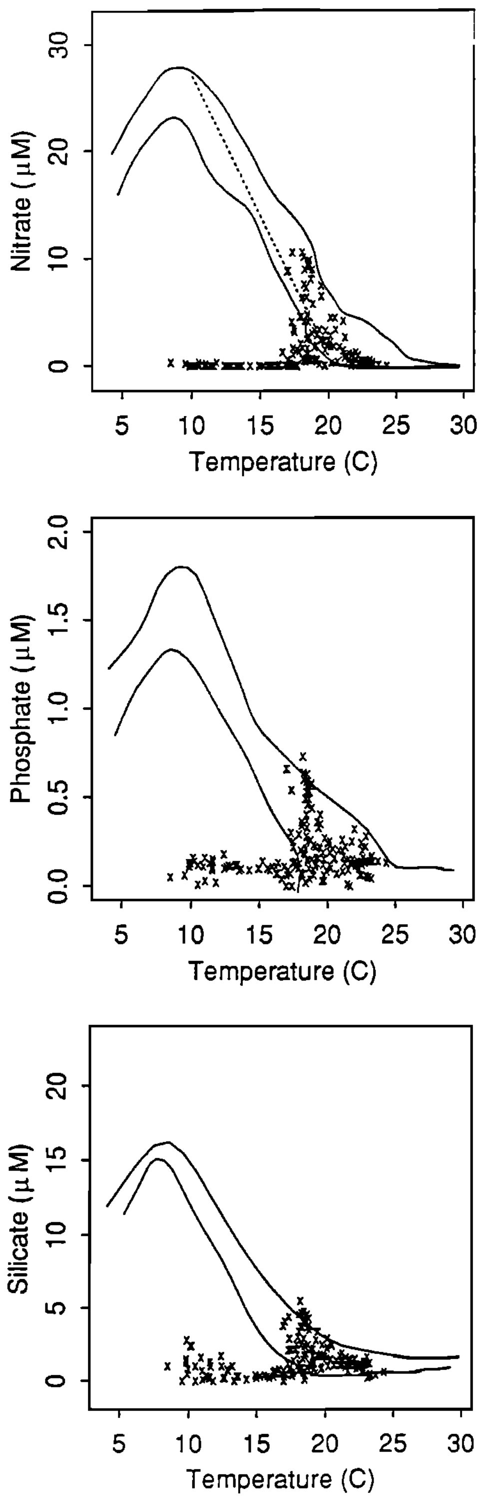

Figure 5. Plots of nitrate, silicate, and phosphate versus temperature. The two solid lines envelope normal temperature/nutrient values from the Blake Plateau. The straight line in the nitrate plot is the relationship used in the nitrate transport calculations.

Table 1. Volumes of the Computational Domain Assuming a 1-m Alongshore Width

Grid Station	Depth at Stations, m	Depth between Stations, m	Distance between Stations, km	Volume, $x10^5 m^3$
7	29.7			
		31.5	11.1	3.5
9	33.4			
		34.6	5.5	1.9
10	35.8			
		34.8	5.5	1.9
11	33.9			
		38.1	5.6	2.1
12	42.3			

two ways, and the integrated values (in situ values only shown in section figures), on average, differ by about 100 g or 10%.

The trends in Figure 8 show an overall rise in nutrients during the sampling period that was interrupted by two times of decrease, one small and one large. The overall rise suggests there was a continuous input of nutrients into the observation area, which agrees with current measurements made at the time. A rise in chlorophyll was observed when nutrients decreased. Currents at mooring 4 (Figure 2) were onshore in either the upper, lower, or both layers during the whole time period except for two brief periods on days 15.9–16.0 and 16.8–18.2 and a longer period from day 23.2 to 24.2.

The first brief period of offshore flow around day 16.0 may have caused the slight decrease in N and Si observed on day 16.3. The large decrease observed on day 24.3 was no doubt related to the offshore flow in both layers observed on day 23.2 to 24.2. Nutrients would be depleted in the offshore moving water either because the water was originally low in nutrients or phytoplankton had grown and reduced the nutrient concentrations. Since in both cases, chlorophyll increased when nutrients decreased, the later reason can be true but the former cannot be ruled out.

Comparing the molar ratios of the nutrient concentrations reveals something of the processes occurring. Under normal circumstances, newly upwelled water at the shelf edge should have an N:P ratio of 16:1. Table 2 shows that the ratio was in the three following ranges: near zero, 3 – 10, and > 600. First, we note that the nutrient concentrations being divided are quite small, and we are at the lower end of concentrations, where the relationship could be expected to hold. The very high ratios are not significant since the values are in the analytical noise level. Nevertheless, the ratio was near 16:1 during the times of presumed influx of new water containing nutrients. That the ratio was less than 16:1 indicates the water was not "pure," but some regeneration of P had occurred. The high value on January 24 may represent limiting P; some N still remains after phytoplankton growth. In summary, the N:P molar

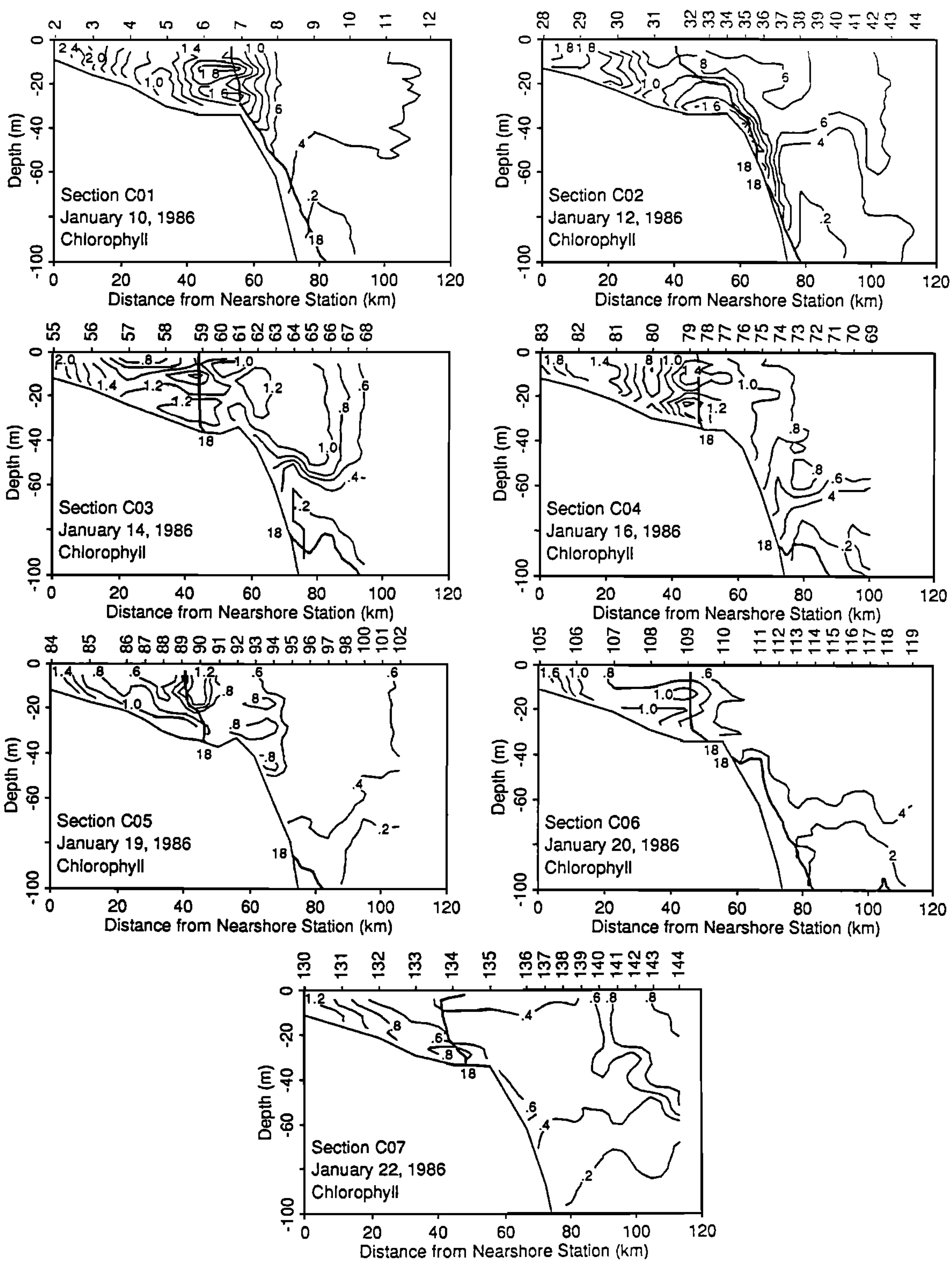

Figure 6. Cross-shelf sections of chlorophyll. Chlorophyll data were averaged over 5 m. The 18°C isotherm is shown as a thick line for reference.

ratios were slightly lower than expected Redfield levels during times of nutrient influx, while at other times they were very low or high, possibly because of the low initial concentrations, phytoplankton growth, and the problem of ratios affected by numbers based on analysis of very low nutrient concentrations.

Examination of the change in N, P, and Si over the sampling period yields nutrient transport values. Over the whole time period, N, P, and Si increased by 1700, 79, and 860 M, respectively. Since the frontal eddy located seaward of the section on January 16 (Plate 2) did not actively influence conditions at the shelf break,

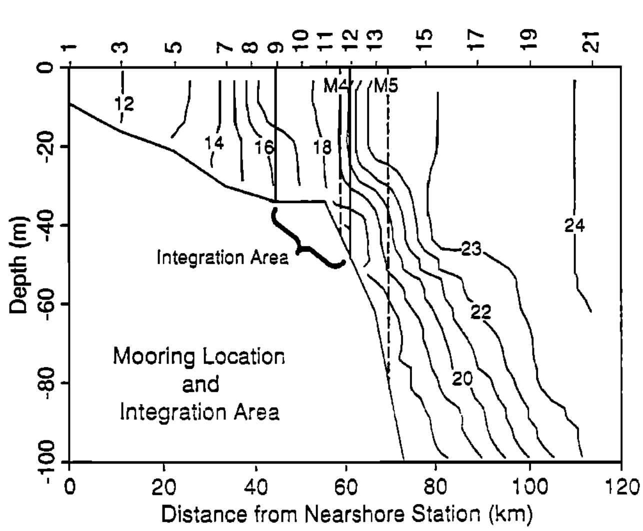

Figure 7. Location of moorings 4 and 5 at the 40- and 75-m isobath and the integration boundaries for nutrient mass integration. A typical temperature section is shown for reference.

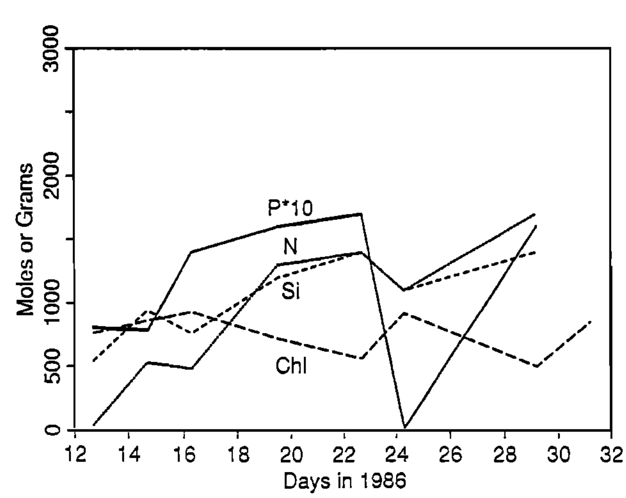

Figure 8. Variations in nitrate, phosphate, silicate, and chlorophyll masses over the outer shelf during GALE, showing the amount of nutrient or chlorophyll in a 1-m-wide section over the outer shelf (see Figure 7). Units are moles for nutrients and grams for chlorophyll. Phosphate mass was multiplied by 10 to preserve the scale.

we follow the methods of *Lee and Atkinson* [1983] to compute onshore transport. We assume that all the nutrient passed onshore during a 16.5-day period through an area 1 m in width at the shelf break with an average depth of 42.3 m (the average depth of the outer station) and find that the transports are 28, 1.3, and 14 μM m^2 s^{-1}. If the transport were calculated over a shorter specific time period (e.g., between January 12 and 22), the rates would be higher. These transport values are very similar to those obtained for frontal eddies and summer intrusions.

The data can also be used to relate the decrease of nutrients to the increase of chlorophyll during January 22–24. Little along-isobath variability on the shelf occurred at the time (Plate 3). This along-isobath homogeneity implies that although currents were predominately along isobath, little of the chlorophyll variability on the GALE section is due to along-isobath advection of water parcels containing varying levels of chlorophyll . Thus the productivity rate can be calculated as follows: The increase in chlorophyll was 360 g over the 1.8 day period in the 940,000 m^3 volume. By assuming a conservative 100:1 (by weight) carbon to chlorophyll ratio, the carbon increase would be 36,000 g C, or an estimated areal production of 300 g C m^{-2} yr^{-1}, a high rate of productivity characteristic of estuarine or highly productive shelf areas [*Platt and Sathyendranath*, 1988]. This yearly rate is calculated only to provide a frame of reference since the value is only based on a short-timescale episode.

Table 2. Summary of Nutrient and Chlorophyll Integrations

Section	Date	P	N	Si	Chl	N/P	N/Si
2	12.7	81	38	540	760	0.5	0.1
3	14.7	78	530	940	860	6.8	0.6
4	16.3	140	480	760	930	3.4	0.6
5	19.5	160	1300	1200	720	8.0	1.1
7	22.7	170	1400	1400	560	8.6	1.0
8	24.3	1.6	1100	1100	920	694.	1.0
10	29.2	160	1700	1400	560	10.4	1.2
11	31.2				850		

See Figure 3a-3d for data from the sections. Date refers to decimal day in 1986 representing the midpoint of time when data were taken. Phosphate, nitrate, and silicate values are moles in the cross-shelf section (see Table 1 for volume of section). Chlorophyll is in grams in the cross-shelf section (data are from in vitro measurements). Molar ratios are given by N/P and N/Si.

Discussion

Comparison to Summer Intrusions

During the summer a combination of northward wind stress, frontal eddy passage, and offshore Gulf Stream position causes cold, nutrient rich water to ascend to the shelf edge. This water then penetrates shoreward to the coast. Measurements during several summers show that approximately $10^4 - 10^5$ t nitrogen enter the shelf waters each summer by this process [*Atkinson et al.*, 1987]. Instantaneous transport was $20 - 350$ μM m^{-2} s^{-1} [*Atkinson et al.*, 1987]. The total summer season transport is about the same as the winter onshore transport we observed, although the instantaneous transport may be significantly less.

Seasonal comparisons must be made carefully because of the very different nature of the processes and their location. Both the frontal eddy and summer intrusion studies were made in the area between Cape

Canaveral and Savannah, well south of the GALE study area. This is an area of net onshore flow compared to the GALE area [*Lee et al.*, 1991], and thus a winter study off Florida would be required to make accurate comparisons. Nevertheless, it seems that comparable amounts of nutrients are involved in the different processes.

Sources of Nutrients

The source of the nutrients observed over the upper slope and outer shelf clearly comes from the deeper water since there are no other waters on the shelf containing nutrients at any significant concentration. The processes that may cause nutrients to ascend to shelf break depths are (1) frontal eddies, (2) deep mixing, and (3) Ekman type upwelling. As already discussed, frontal eddies were present during the observations, thus they may have caused some observed enrichment. Ekman upwelling is also possible since there was a weak relation between amounts or concentrations of nitrate and wind stress. Deep mixing because of the intense winds and cooling may be a significant source of nutrients.

The possibility of deep mixing over the upper slope was evaluated by assessing potential energy. The potential energy anomaly of the water column over the upper slope was about 100 J m^{-3} or 10,000 J m^{-2}, assuming a 100 m depth. If we assumed that mixing occurred over 3 days, then 40 mW m^{-2} of mixing power was required. Winds and cooling can provide this. For example, a typical 20 m s^{-1} wind or 1000 W m^{-2} cooling rate both equal about 20 mW m^{-2}. Thus extreme winter storm events probably have enough power to mix the upper parts of slope water and elevate nutrient concentrations in shallower outer shelf and upper slope waters. Lesser storms or ones not accompanied by cold air outbreaks do not.

Conclusions

The observations presented in this paper show sporadic nutrient transport into outer shelf waters off Charleston, South Carolina, from the Gulf Stream during the winter. The nutrient levels may result from deep mixing during winter storms, together with wind- and eddy-induced upwelling. The amounts moved into shelf waters by wind events are similar in magnitude to those observed during the passage of frontal eddies in the spring and intrusions during the summer. This suggests that onshore nutrient transport can occur during all seasons. The onshore flow may be either during one event, wind or frontal eddy, or over a whole season. Regardless, the outer shelf ecosystem receives new nitrogen. Since the frequency of the transport process is partly at the wind scale, there will be considerable interannual variability. The importance of these observations is that significant biological production can occur during the winter in these temperate shelf waters. Since this is a time some fish species spawn over the outer shelf, we must better understand the dominant physical processes as well as the biological response.

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