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The effect of summertime shelf break upwelling on nutrient flux in southeastern United States continental shelf waters

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ABSTRACT

Gulf Stream-induced upwelling at the shelf break of the South Atlantic Bight (SAB) presents water which, in summer, can intrude onto the continental shelf. In July 1979, an XBT survey of the continental shelf revealed such an intrusion of cold water off St. Augustine, Florida.

From weekly mappings, it was determined that Gulf Stream water <22.5°C covered 3280 km^2 and occupied 38 km^3 shoreward of the 42 m isobath. Using temperature and nitrate distributions and the T°C:NO^3 relationship, we determined that 3200 metric tons of nitrate-nitrogen were advected into the study area. Net nitrate-nitrogen fluxes were 32 μmoles · m^{-2} · sec^{-1} across the 42 m isobath and 30 μmoles · m^{-2} · sec^{-1} across the 30 m isobath.

The advection of nitrate-enriched water into the photic zone caused a dramatic increase in phytoplankton biomass. The decreasing nitrate concentrations correlated with chlorophyll increases indicating phytoplankton production was mainly at the expense of nitrate advected into the area. Prior to the intrusion, production was likely supported by regenerated nutrients.

Summertime intrusions supply an estimated 2.9×10^4 mtons NO_3-N · yr^{-1} to the middle shelf area of the southern SAB and are thus a major source of nitrogen to that area.

1. Introduction

The phenomenon of upwelled water intruding onto the continental shelf of the southeastern United States (Fig. 1) was first recognized by Green (1944). Based on data from several years, obtained at coastal stations between Charleston, South Carolina and Key West, Florida, he determined that surface water temperatures were anomalously low during July and August. These anomalies, most pronounced near Daytona Beach, were attributed to the onshore movement of subsurface water of the Florida Current. Warmer resident surface water in summer is transported offshore by prevailing southerly winds.

Taylor and Stewart (1959) confirmed that decreases in summer water temperature were most pronounced in the Daytona Beach area and found that in some summers the anomaly may extend from Fernandina Beach south to West Palm Beach. Periods when colder water was present were coincident with winds conducive to upwelling and with intervals of lowered sea level.

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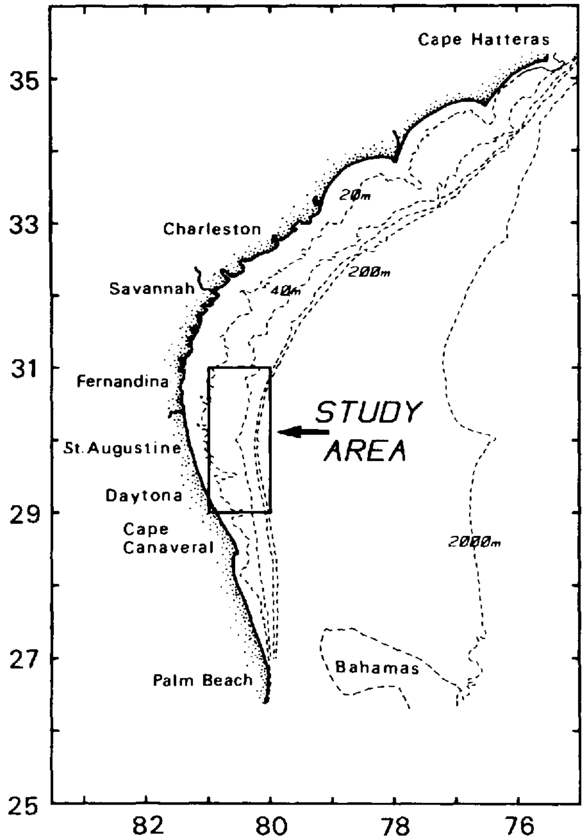

Figure 1. The continental land mass and shelf of the southeastern U.S. The South Atlantic Bight (SAB) is from Cape Hatteras to Cape Canaveral. The area of the present study is indicated.

In other parts of the southeastern United States shelf waters, similar observations were made. In Onslow Bay, North Carolina, Bumpus (1955) observed "the intrusion of cold, highly saline water across the shelf on the bottom." Stefánsson *et al.* (1971) documented several intrusions of cold, high nutrient water into Onslow Bay during the summers of 1965 to 1967. They proposed that "the near bottom intrusions are at least partly wind-controlled and therefore favored by southerly or southwesterly winds . . ." which prevail in the summer.

The geographic link between processes described for Florida and North Carolina shelf regions was provided by Atkinson (1977). Drawing on data from the South Atlantic Bight (SAB), the continental shelf area between Cape Hatteras, North Carolina and Cape Canaveral, Florida, he demonstrated that cold Gulf Stream water could intrude beneath shelf water along the entire region. He also showed that given the proper conditions—the presence of upwelled water at the shelf break and favorable (i.e., south to southwest) winds—bottom intrusions occur when the density of the resident shelf water is less than that of the intruding water. The first condition, upwelling at the shelf break, is related to offshore meanders of the Gulf Stream axis (Webster, 1961; Atkinson, 1977). These motions, although favored and enhanced by the offshore Ekman transport expected with south to southwesterly winds, are not necessarily wind-dependent (Webster, 1961; Blanton, 1971) and apparently occur year-round at periods of one to two weeks. The second condition, favorable winds, suggests that bottom intrusions are most likely to occur in summer when south to southwesterly winds prevail in the SAB and shelf water density is lower than at other times of the year.

Phytoplankton blooms develop rapidly within nutrient-rich, subsurface summer intrusions (Dunstan and Atkinson, 1976; Atkinson *et al.*, 1978; Paffenhöfer *et al.*, 1980; Yoder *et al.*, 1983). During summer, primary production averages close to 2 g $C \cdot m^{-2} \cdot day^{-1}$ within intrusions that reach the 30–40 m isobaths. "New production" (*in sensu* Dugdale and Goering, 1967) is 50% or more of the total, and nitrate is depleted within about 10–14 days. At the peak of the phytoplankton bloom within the intrusion, chlorophyll *a* concentration is more than 10 times that of the overlying surface mixed layer (Yoder *et al.*, 1983; Yoder, unpublished).

The object of research reported here was to determine the effect of intruding upwelled Gulf Stream water on the chemistry and biology of the southern SAB (Fig. 1). We show that the intrusion of nutrient-rich Gulf Stream water is the most significant source of nitrate to shelf waters. We also show that cross-shelf intrusions are probably wind-related. This paper reports the results of thesis work done by one of the authors (O'Malley, 1981).

2. Materials and methods

a. Sampling rationale. Seven weekly cruises of three to five days duration were conducted onboard the R/V *Blue Fin* (Cruise BF 7934) during July and August 1979. From previous experience it was determined that this would be sufficient time to locate and sample bottom intrusions. Table 1 lists the sequence of sampling events, methods of data collection, and distances between stations.

To determine when and where a bottom intrusion penetrated into the study area, a quasi-synoptic survey of middle to outer shelf temperature distribution was obtained each week. The shelf was thoroughly surveyed the first week to establish shelf water temperatures at the beginning of the study. Ten east-west transects were run between the 30 and 45 m isobaths at ten nautical mile (18.5 km) north-south intervals.

During subsequent weeks, bottom temperature distributions along the 30 and 45 m isobaths were determined and an east-west hydrographic transect was run at latitudes reported in Table 1. If a bottom intrusion was indicated, its limits, defined by temperature, were mapped and a hydrographic transect was run along the latitude line at which the lowest temperature was observed. A typical cruise track is shown in

Table 1. Sampling events: Cruise BF 7934, summer 1979.

Week	Station designation	Time (GMT) h/d/m	Middle shelf temperature distribution	Cross shelf section (Lat)	Station interval (km)
1	PI-P98	1.4/6/7-15.1/7/7	towed T/D* sensor and XBT** grid		~5.6 east-west 18.5 north-south
2	1–39	3.8/11/7-16.2/11/7	towed T/D sensor		~5.6
	40–44	16.7/11/7-4.4/12/7		XBT/bottle cast (30°25′N)	18.5
3	100–163	18.2/16/-15.2/17/7	towed T/D sensor		
	164–172	16.0/17/7-5.0/18/7		CTD/bottle cast and XBT (30°25′N)	9.3
	173–180	13.5/18/7-23.8/18/7		CTD/bottle cast and XBT (29°50′N)	9.3
4	201–290	19.5/23/7-21.8/24/7	towed T/D sensor and XBT		~5.6
	292–300	2.0/25/7-17.0/25/7		CTD/bottle cast and XBT (30°05′N)	9.3

Table 1. (Continued)

5	302–367	18.3/30/7-15.3/1/8	XBT grid		9.3 east-west 18.5 north-south
	370–374	1.1/2/8-8.7/2/8		CTD/bottle cast (30°00′N)	14.8
6	400–436	17.6/6/8-23.0/7/8	XBT grid		9.3 east-west
	438–443	13.5/8/8-21.6/8/8		CTD/bottle cast (30°00′N)	9.3
	444–456	23.3/8/8-12.9/9/8	XBT		9.3 east-west 9.3-18.5 north-south
	457–458	13.3/9/8-23.0/9/8		middle shelf CTD/bottle cast (30°00′N)	
7	500–529	21.0/13/8-23.1/14/8	XBT grid		9.3 east-west 18.5 north-south
	530–538	2.4/15/8-6.8/16/8		XBT/bottle cast (30°10′N)	9.3
	539–541	12.0/16/8-22.6/16/8		Middle shelf; XBT/bottle cast (30°15′N)	

*Temperature/Depth
**Expendable Bathythermograph

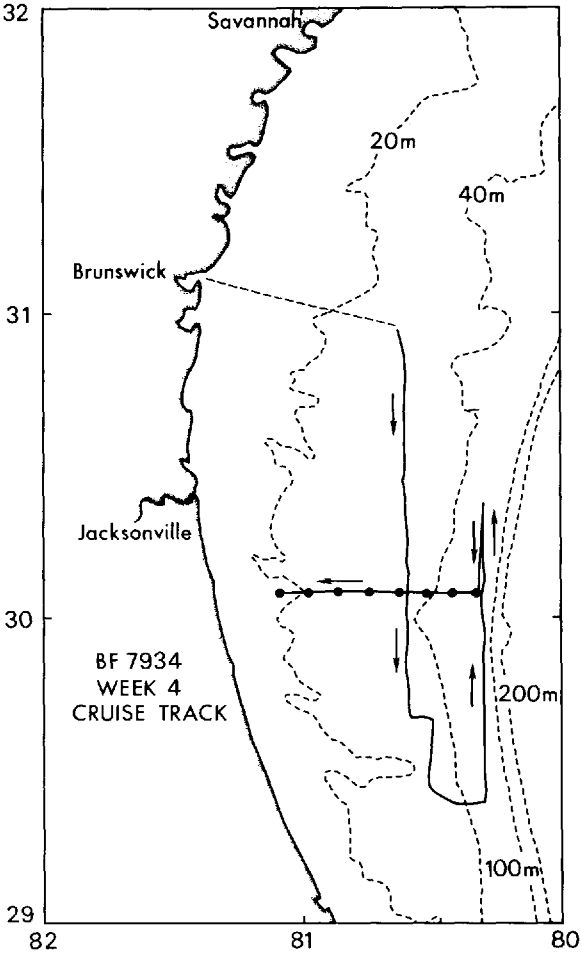

Figure 2. Cruise track of R/V *Blue Fin*, week 4, 24–25 July 1979. Dots indicate hydrographic stations along latitude 30°05′N.

Figure 2. To develop various time series studies at mid-shelf, the central transect station was occupied and sampled morning and evening on the last day of weeks 6 and 7.

b. Sampling procedures. During the cruise a variety of instruments was used. A towed depth/temperature probe and 200 m expendable bathythermographs were used for underway temperature observations. Vertical profiles of temperature and salinity were obtained at fixed stations using a CTD/Rosette system or bottles on the wire. Standard techniques were used in all cases. For further detail concerning methods see O'Malley (1981).

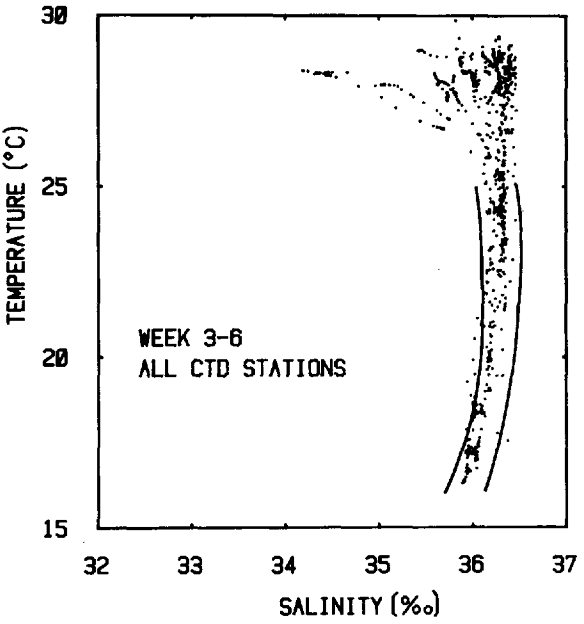

Figure 3. Temperature/salinity relationship of all CTD stations; Cruise BF 7934. The T/S envelope delineated is from Wennekens (1959) and is characteristic of Continental Edge Water.

3. Results

a. The identification of upwelled Gulf Stream Water. It is essential to characterize "upwelled Gulf Stream Water" in terms of the parameters measured before presenting and discussing the results of this study. A plot of all T/S data (Fig. 3) indicates that waters colder than 25°C were typical of the Gulf Stream.

At temperatures above 25°C, salinities ranged from 34.1‰ to 36.4‰. There was no sharp distinction between Gulf Stream Water and coastal water (Fig. 3) which is runoff-modified Gulf Stream Water. However, salinities >36.1‰ at temperatures >25°C are characteristic of the Gulf Stream (Stefánsson *et al.*, 1971).

The T/S characteristics of continental shelf water changed dramatically during the study. Figure 4 a–d shows T/S relationships at mid-shelf (~40 m) stations in weeks 3 through 6. In week 4, water temperatures were >24°C while in week 5, minimum water temperatures were <20°C. Clearly, from week 4 to 5, upwelled Gulf Stream Water had intruded onto the continental shelf. Figure 4d shows that upwelled water was present during week 6.

b. The effect of wind. Weather observations at Jacksonville, Florida (U.S. Department of Commerce, 1979), ~140 km from the center of our study area, were used to test the hypothesis that the intrusion event was wind-induced. Figure 5a shows that

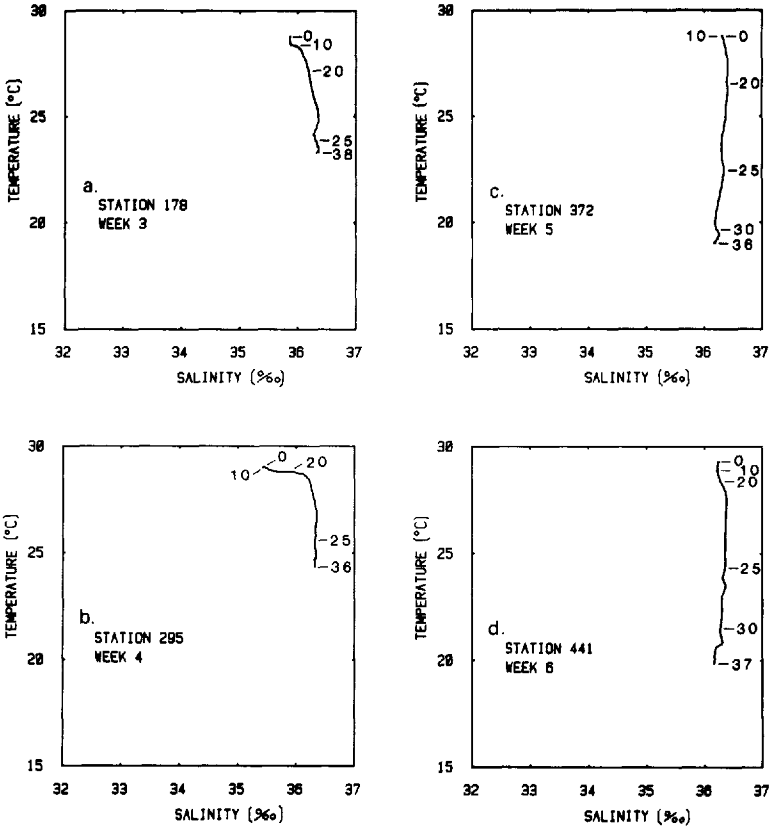

Figure 4. T/S relationship of mid-shelf (~40 m) stations; (a) week 3, (b) week 4, (c) week 5, and (d) week 6. Depth in meters is indicated.

winds were variable until July 20 with sustained northwestward winds from July 21 until July 26. Winds then shifted to generally northward to northeastward until August 13 except during a brief period of westward winds from August 5 through August 7. Winds were generally southwestward from August 15 until the end of the study.

To illustrate the coupling of wind events to water movements, the north-south (v) and east-west (u) components of the wind stress (τ) were calculated from daily resultant wind speeds and direction (Fig. 5b). Northward winds are conducive to offshore Ekman transport of coastal water and the bottom intrusion of upwelled water. There were no sustained northward winds through July 19 and hydrographic observations through week 3 did not indicate a bottom intrusion. Except for a brief reversal on July 28, northward winds prevailed from July 20 until August 13, and upwelled Gulf Stream Water was observed on the continental shelf during that entire period except week 4.

The presence of upwelled water at the shelf break is necessary for a bottom intrusion

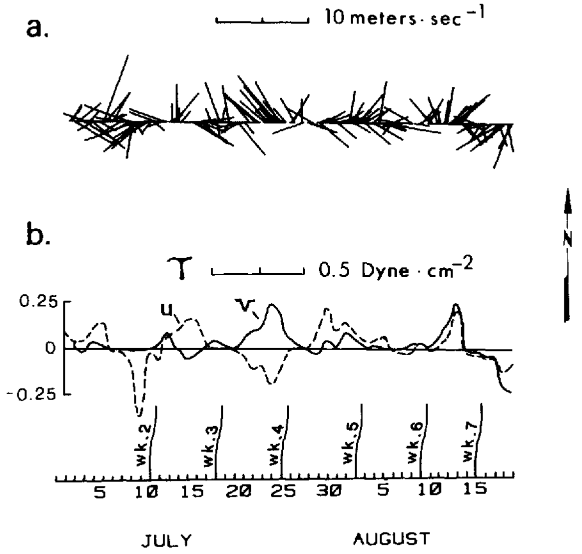

Figure 5. Jacksonville, Florida wind data; (a) wind speed and direction at six-hour intervals, (b) *u* (— — — —) and *v* (————) components of wind speed and direction. Components of wind stress generated from daily resultant wind speed and direction.

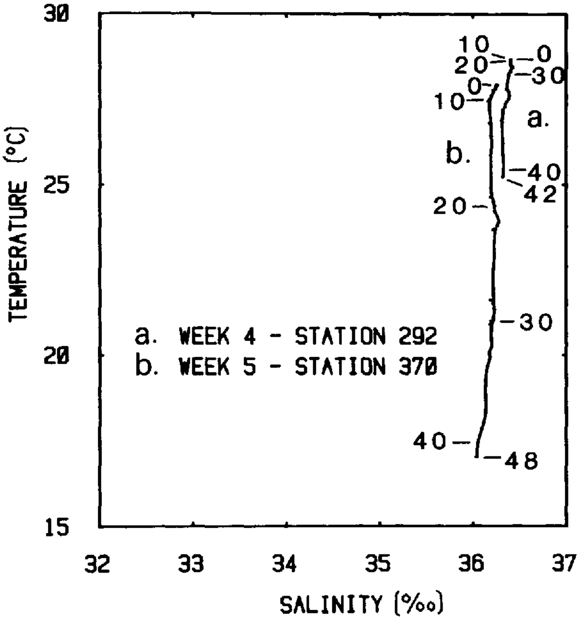

Figure 6. T/S relationship at the outer shelf station of the week 4 and week 5 hydrographic transects. Depth in meters is indicated.

Table 2. Ranges of water column temperature, nitrate, and total chlorophyll at middle shelf stations of week 2 through week 4; Cruise BF 7934.

	Week 2		Week 3		Week 4	
	MIN	MAX	MIN	MAX	MIN	MAX
T(°C)	25.2	28.3	23.3	28.8	23.0	29.0
NO_3(μM)	<0.2	0.2	<0.2	1.0	<0.2	1.8
Tot Chl (μg/L)	0.1	0.4	0.2	1.6	0.1	0.6

to occur (Atkinson, 1977). During week 4, this condition was not met. The minimum temperature at the outer shelf was >25°C, and the T/S relationship (Fig. 6) was characteristic of the core of the Gulf Stream (Stefánsson *et al.*, 1971). In week 5, the surface temperatures and salinities observed at the outer shelf were lower than in week 4. Temperatures <20°C at the outer shelf station demonstrated that an eastward movement of the Gulf Stream from week 4 to week 5 resulted in upwelling, thus confirming the observations of Atkinson (1977).

A second intrusion event was observed in week 7, apparently in response to strong northward winds between August 9 and August 12 (Fig. 5b). Evidence that a second intrusion occurred is developed later.

c. Hydrographic conditions: Week 1–Week 4. Bottom intrusions of Gulf Stream Water <22.5°C were not observed in week 1 through week 4. Bottom temperatures of middle continental shelf waters were >22.5°C. High temperatures, low nitrate, and total chlorophyll concentrations were characteristic of water resident on the continental shelf during that time (Table 2). Vertical distributions in week 4 were generally typical of those in earlier weeks (Fig. 7).

d. Hydrographic conditions: Week 5–Week 7. A bottom intrusion of Gulf Stream Water occurred in week 5. Upwelled water (<22.5°C) intruded ~30 km onto the middle shelf when water temperatures at the outer shelf were <15°C (Fig. 8a). In week 6, the leading edge of the intrusion had moved 10 km farther shoreward and minimum water temperature in the now well-defined "core" of the intrusion was <16°C (Fig. 8b). By week 7, upwelled water had penetrated more than 50 km from the outer shelf and stranded water (<18°C) covered an area >500 km^2 (Fig. 8c).

Maximum water temperature at the outer shelf during week 7 was >25°C indicating an onshore meander of the Gulf Stream. This meander may have caused the 18°C water to separate from its deep offshore source.

Although weekly observations are too infrequent to yield meaningful intrusion velocities, it is obvious that the movement of the intrusion was north and west (Fig. 8a–c).

Vertical temperature sections on the shelf, before and during the two intrusion events, are shown in Figure 9a-d. From week 4 through week 7, surface water

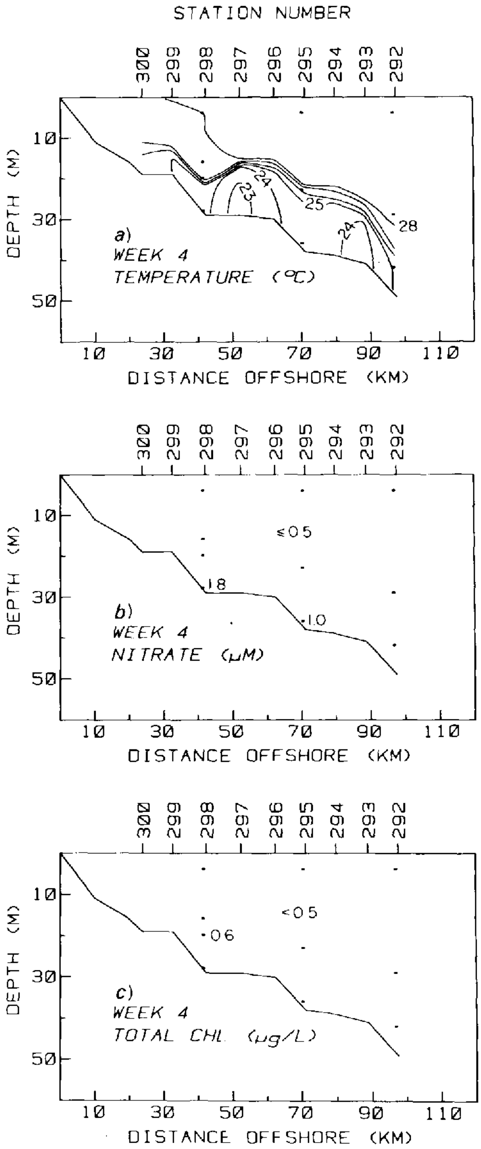

Figure 7. Vertical distributions of; (a) temperature, (b) nitrate, and (c) total chlorophyll *a*; 25 July 1979, Latitude 30°05′N.

temperatures remained almost constant (~28 – 29°C), but vertical temperature differences varied from ~5°C in week 4 to >10°C in succeeding weeks. This increased vertical stratification was caused by the intrusion of upwelled water beneath the thermocline. Minimum water temperatures during weeks 5–7 were <17°C.

Figure 10a–d shows the effect of the intrusion on the vertical distribution of nitrate.

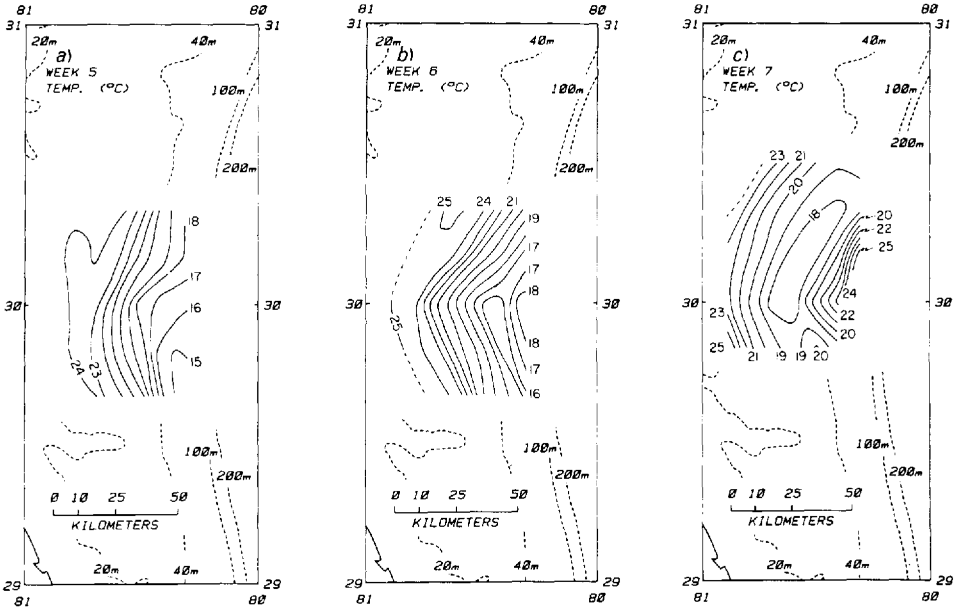

Figure 8. Horizontal distribution of bottom temperature on the continental shelf; (a) week 5, 31 July 1979, (b) week 6, 7 August 1979, and (c) week 7, 14 August 1979.

In week 4, the shelf was essentially depleted of nitrate while in week 5, near-bottom nitrate concentrations >9 μM were at stations 380 and 371, with concentrations of >1 μM below the thermocline from the middle to the outer shelf. In week 6, nitrate concentration was >10 μM at the intrusion core.

Based on nitrate deficit data developed later (Fig. 13), it was determined that the cross-shelf transect of week 7 intersected a new intrusion. Maximum nitrate concentrations were >14 μM.

In week 4, before the intrusion, total chlorophyll *a* concentration was generally <0.5 mg · m^{-3} across the entire shelf (Fig. 11a). In weeks 5 and 6, after the input of nutrients to the euphotic zone, total chlorophyll *a* concentrations were consistently >0.5 mg · m^{-3} and usually >1.0 mg · m^{-3} in upwelled water. Maximum chlorophyll concentrations were 10.8 and 2.9 mg · m^{-3} in weeks 5 and 6, respectively.

During week 7, in the freshly upwelled water, chlorophyll *a* concentrations ranged from >3 mg · m^{-3} on the middle shelf to <0.5 mg · m^{-3} at the outer shelf.

e. Temperature-nitrate relationship. Nitrate concentration is linearly related to temperature in Gulf Stream Water between temperatures of ~15 to 22.5°C (Stefánsson *et al.*, 1971; Stefánsson and Atkinson, 1971; Atkinson *et al.*, 1978). Off the shelf, the <22.5°C isotherm is generally deeper than 75 m (Wennekens, 1959),

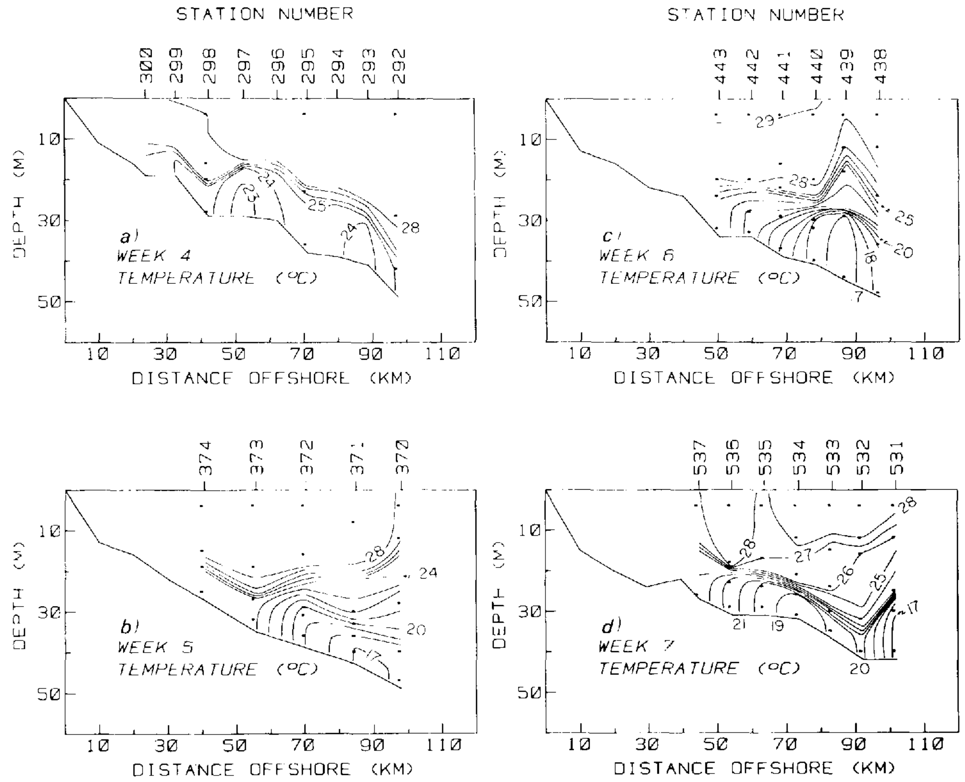

Figure 9. Vertical distribution of temperature; (a) week 4, 30°05′N Latitude, (b) week 5, 30°00′N Latitude, (c) week 6, 30°00′N Latitude, and (d) week 7, 30°10′N Latitude. Dots indicate water sampling depths.

where nitrate uptake by phytoplankton is limited by low irradiance levels. The T-NO_3 regression analyses of bottom waters <22.5°C demonstrated that, in freshly upwelled waters, a linear relationship is maintained after water is upwelled into the euphotic zone. Low nitrate at stations 372, 441 and 534 (Fig. 10) indicated that considerable nitrate had been used after the water was advected into the euphotic zone. Because the leading edge of the intrusion was just shoreward of these stations, the bottom T-NO_3 pairs were omitted from the analysis. The bottom T-NO_3 pair at station 541 was omitted because at the time of sampling, the intrusion was stranded on the continental shelf and therefore cut off from the Gulf Stream.

The results of the T-NO_3 regression analyses of all other bottom samples <22.5°C (Fig. 12) yielded the relationship:

$$NO_3\,(\mu M) = 38.21 - 1.67\,T\,(^{\circ}C) \qquad (1)$$

The correlation coefficient was −0.92. This expression compares favorably with

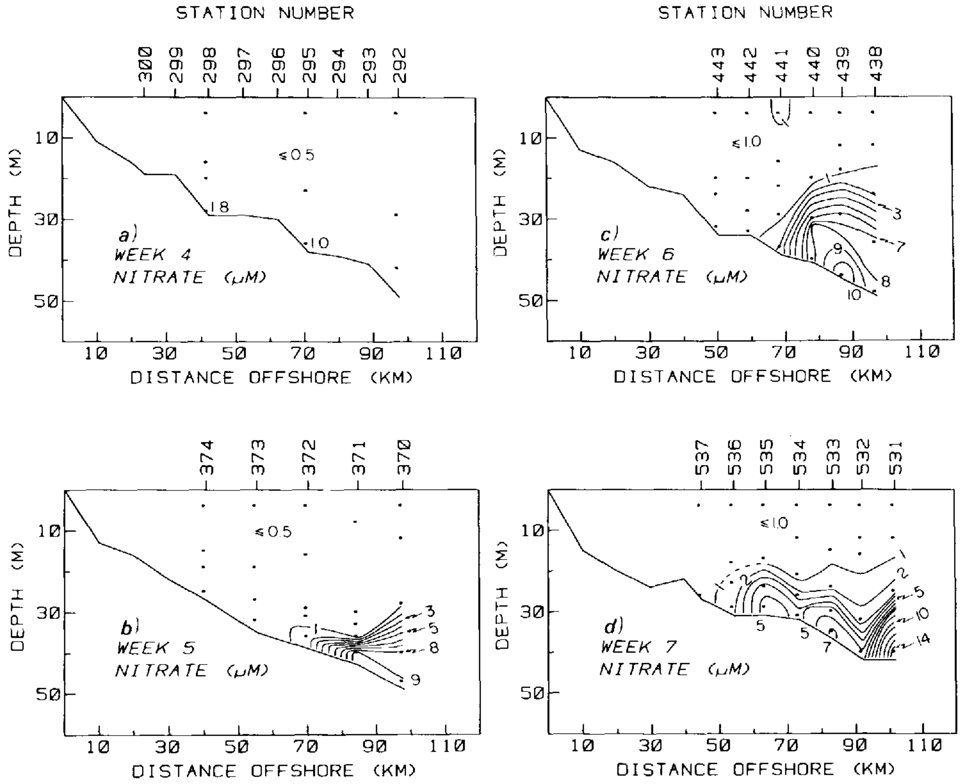

Figure 10. Vertical distribution of nitrate; (a) week 4, (b) week 5, (c) week 6, and (d) week 7. Latitudes as in Figure 8.

[NO_3 = 38.33 − 1.67 T] for Gulf Stream Water intruded into Onslow Bay, North Carolina, during the summers of 1975 and 1976 (Atkinson *et al.*, 1982). The close agreement and the high T-NO_3 correlation justified estimating the initial concentrations in upwelled waters from the observed temperatures.

f. The nitrate deficit. T-NO_3 relationships were also used to estimate the nitrate deficit, which is defined as the difference between calculated and observed nitrate [NO_3 deficit = NO_3 calculated − NO_3 observed]. The deficit is a measure of uptake by phytoplankton (Atkinson *et al.*, 1978).

During weeks 5 through 7, the nitrate deficit generally increased from offshore to onshore in a given week, an expected result because the inshore upwelled water had been on the shelf longer.

Two separate intrusions were encountered during week 7. Except at station 534 there had been no appreciable nitrate uptake (Fig. 13c). Thus, the cross-shelf transect must have been through recently upwelled water, i.e., a new intrusion. The older

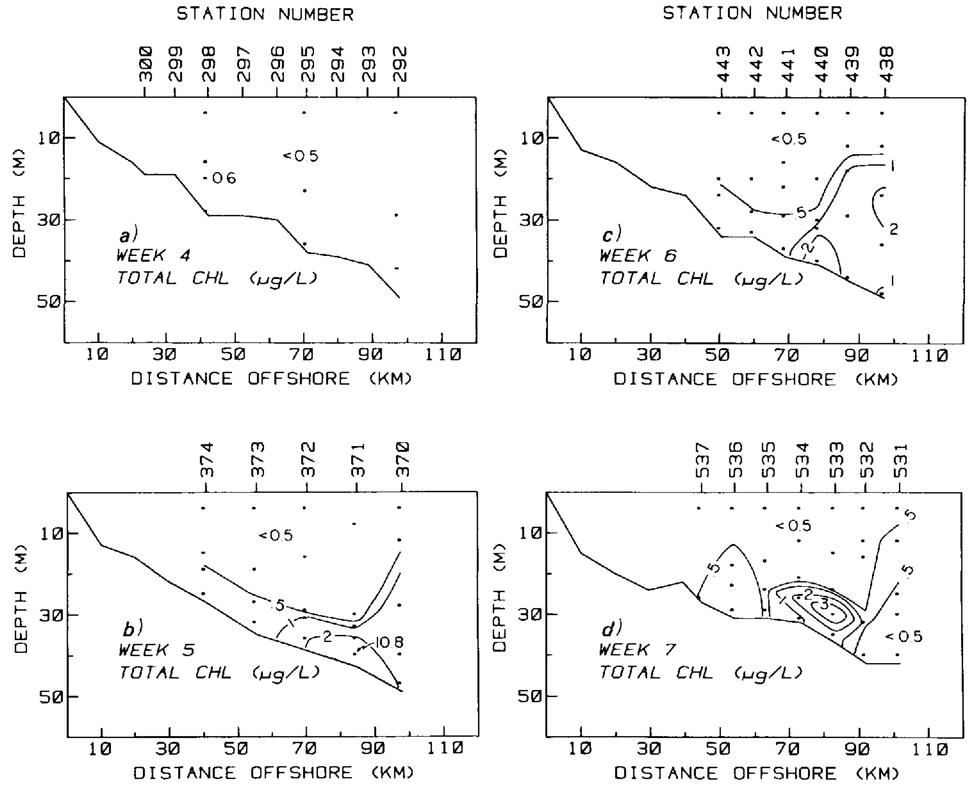

Figure 11. Vertical distribution of total chlorophyll *a*; (a) week 4, (b) week 5, (c) week 6, and (d) week 7. Latitudes as in Figure 8.

intrusion was the stranded <18°C water observed during week 7 (Fig. 7c). At central stations within the stranded intrusion, 40% or more of the nitrate was depleted.

g. The biological effect of the intrusion. Temporal changes in vertically integrated (thermocline to the bottom) NO_3-N, DON, PN, NH_4-N, total chlorophyll *a* and the NO_3-N deficit at the middle shelf demonstrate the biological effect of the intrusion (Fig. 14). Prior to the intrusion event (week 4), NO_3-N at the middle shelf was very low (ca. 0.1 g · m^{-2}), the largest N pool was DON (greater than 2 g · m^{-2}), and total chlorophyll *a* was less than 5 mg · m^{-2}. The intrusion reached the middle shelf during week 5, but NO_3-N was still low. However, the large NO_3 deficit (ca. 0.75 g · m^{-2}) suggests that phytoplankton removed a significant amount of NO_3 as the upwelled water progressed from the outer shelf.

The middle shelf samples of week 6 were taken from the cold core of the intrusion. By week 6 both NO_3-N and total chlorophyll *a* reached maximum observed values (greater than 1.5 g · m^{-2} and 50 mg · m^{-2}, respectively). However, the NO_3 deficit

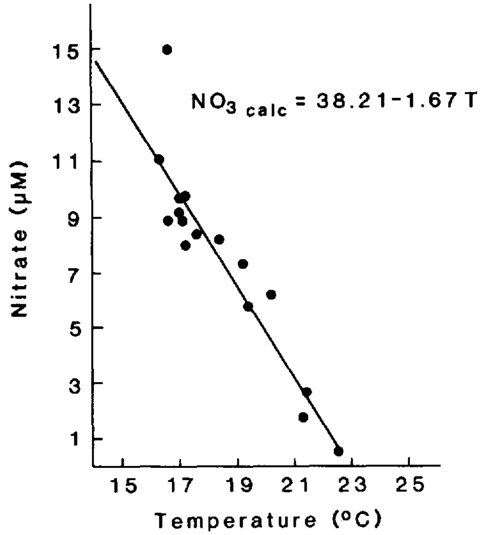

Figure 12. Regression analysis of observed bottom nitrate versus temperature; Cruise BF 7934.

was less than the previous week indicating that nutrient-rich water continued to be upwelled and advected to the middle shelf. During week 7, total chlorophyll *a* and NO_3-N were less than for week 6. However, the NO_3 deficit was about the same as week 6, again suggesting that upwelled water continued to advect into the middle shelf between weeks 6 and 7.

NH_4-N did change significantly from week 4 to week 7 and was low relative to other N species. NH_4 is taken up by phytoplankton much faster than NO_3, and thus the amount of NH_4 in the water does not necessarily reflect the significance of NH_4 as a N source for phytoplankton.

To relate chlorophyll *a* to field measurements of PN requires assumptions concerning PN:Chl *a* ratios of phytoplankton. Diatoms generally dominate subsurface intrusions (Bishop *et al.*, 1980; Paffenhöfer *et al.*, 1980; Yoder *et al.*, 1983). Phytoplankton were not enumerated during our study, but intrusion chlorophyll *a* was linearly correlated with particulate Si ($r = 0.92$, $n = 12$) during weeks 4–6 suggesting that diatoms were an important component of the phytoplankton taxa. Diatoms growing on NO_3 at relatively low irradiance levels (less than 60 ly · dy^{-1}, 400–700 nm) and at temperatures above 15°C have mean PN:Chl *a* ratios of ca. 6 (Yoder, 1979; Verity, 1981). This ratio was used to compare the NO_3 deficit with estimated phytoplankton N during weeks 5, 6, and 7. The NO_3 deficits for weeks 5, 6, and 7 should have yielded 117, 45, and 45 mg · m^{-2} of chlorophyll *a*, respectively. For weeks 5 and 7, observed chlorophyll *a* was only about 10% and 60%, respectively, of that predicted from the NO_3 deficit. Only during week 6 were observed chlorophyll *a* levels (ca. 50 mg · m^{-2}) close to the prediction (45 mg · m^{-2}). This shows that "missing"

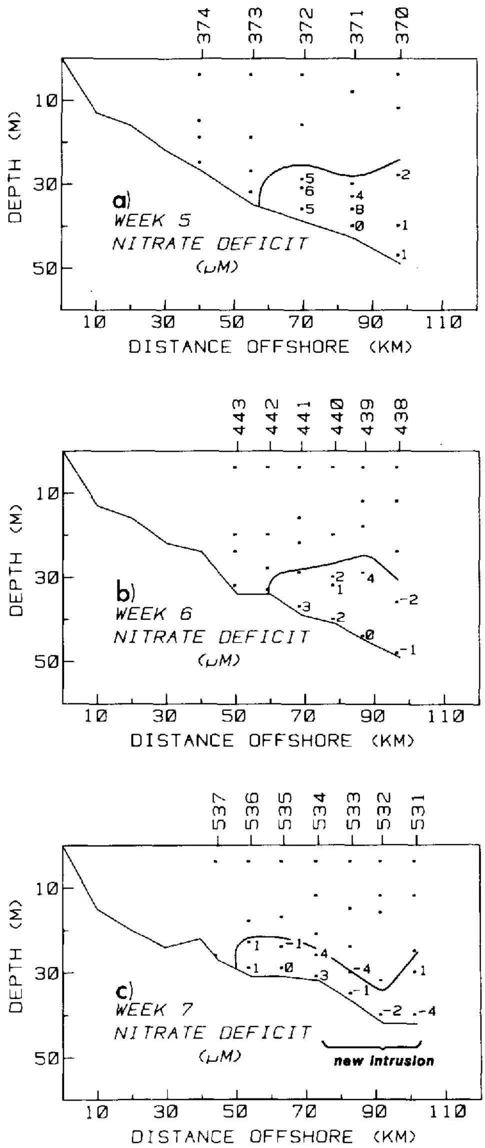

Figure 13. Vertical distribution of the nitrate deficit (see text) in <22.5°C water; (a) week 5, (b) week 6, and (c) week 7. The 22.5°C isotherm is plotted in each figure. Values are rounded to the nearest integer.

NO_3 would at least account for the phytoplankton biomass present in the intrusion and suggests that during week 5 and 7, a high percentage (40–90%) of phytoplankton biomass synthesized during the intrusion bloom was no longer present in the water column. High abundances of small, fast-reproducing zooplankton were observed during this study (Paffenhöfer *et al.*, 1984). In general, however, grazing pressure on

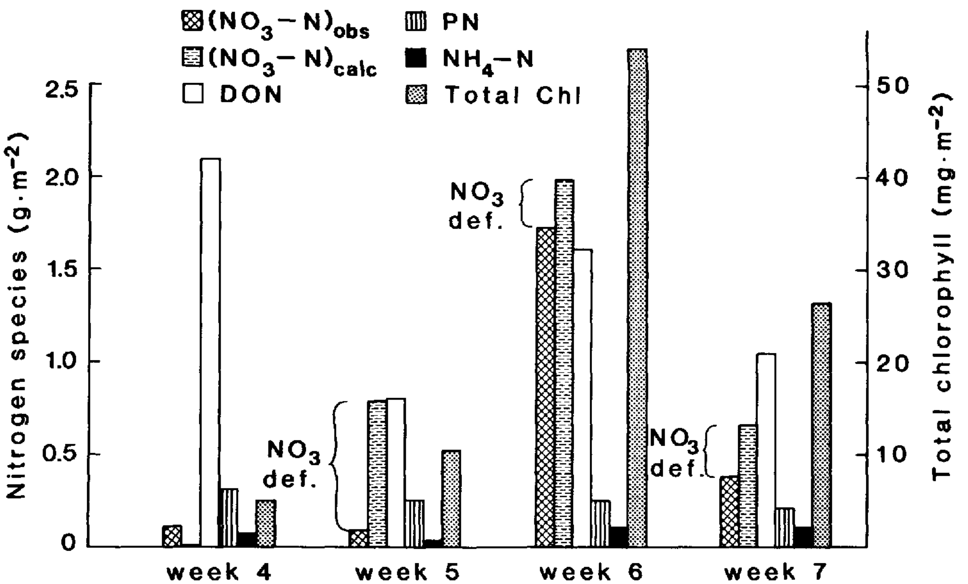

Figure 14. Variation with time of biogeochemically important nitrogen species and total chlorophyll *a* at the middle shelf; week 4 through week 7.

the dominant peaks of the particle spectra was limited during weeks 5–7 (Paffenhöfer *et al.*, 1984). Thus, sinking of nonbuoyant diatom particles may have been an important process in removing phytoplankton-N from intruded waters.

h. Quantitative estimates of mass flux. The XBT grids of week 5 through week 7 yielded a quasi-synoptic three-dimensional distribution of temperature for each of the weeks. The bottom area covered by nitrate-enriched upwelled water (i.e., <22.5°C) was determined by planimetry. The volume of the intrusion was estimated by multiplying the area by the mean thickness of upwelled water at all stations seaward of the 22.5°C isotherm (Table 3). The calculated intrusion volume in week 7 was 38 km^3. The volume of continental shelf waters from Brunswick, Georgia, to Cape Canaveral, Florida, is about 550 km^3.

i. Quantitative estimates of intrusions related nitrate flux. To estimate the nitrate flux onto the shelf we made use of the temperature field derived from quasi-synoptic XBT mapping cruises during weeks 5, 6, and 7 and the known relationships between temperature and nitrate concentration (Eq. 1). The area, volume and mass of nitrate in the subsurface intrusions observed during those three weeks are shown in Table 3. During week 4 no water less than 22.5°C was observed on the shelf; thus, the mass of nitrate was zero. Between weeks 4 and 5 there was a dramatic increase; then, through week 7, the amount slowly increased. The onshore nitrate flux across the 46 m isobath

Table 3. Area and volume of upwelled intruded water (<22.5°C) in the study area and calculated nitrate-nitrogen masses associated with intruded water; Cruise BF 7934.

	Week 4	Week 5	Week 6	Week 7
area (km^2)	0	2250	2200	3280
volume (km^3)	0	27	29	38
NO_3-N (metric tons)	0	2490	2910	3200
Estimated Flux (μM NO_3 m^{-2} sec^{-1})				
Across 46 m isobath		------70------	------32------	
Across 30 m isobath				------30------

was calculated by assuming the nitrate mass on the shelf passed through an area 98 km long and 46 m deep. Between week 4 and 5 the nitrate flux was 70 μmoles, NO_3-N m^{-2} sec^{-2}. During the whole intrusion event, weeks 4 through 7, 3200 mtons nitrate nitrogen were advected into shelf waters. Assuming a 21 day event duration and a 3200 mton total mass advected and the same dimensions as before, we calculate a flux of 32 μmoles NO_3-N m^{-2} sec^{-1} for this one event.

The flux of nitrate across the 30 m isobath was calculated to be 30 μmoles NO_3-N m^{-2} sec^{-1} between weeks 6 and 7.

4. Discussion

Our purpose in determining the nitrate-nitrogen flux and mass associated with a bottom intrusion was to estimate the importance of intrusions to the nitrogen budget of the continental shelf. Various approaches to the problem of determining nitrate-nitrogen masses have been taken. Haines (1974) assumed an average nitrogen content of 15 μM in intruded water, that an intrusion occurs 100 days per year, and that there is a 2% per day exchange of intruded water with shelf water yielding an annual nitrogen input to Georgia coastal waters of 7600 mtons g · yr^{-1}. Dunstan and Atkinson (1976), recognizing the event nature of bottom intrusions, estimated that the average event transported 12,300 mtons of inorganic nitrogen onto the shelf. They assigned an average nitrate content of 10 μM in intruded water and an intrusion volume of about 10% of the shelf volume.

Lee *et al.* (1981) approached the same problem by determining nitrate flux through a 1 m^2 column at the shelf break. Calculations, based on current meter-derived temperature time series and appropriate expressions for the temperature versus nitrate relationship, yielded a net onshore nitrate flux of 22.2 μmoles NO_3-N · m^{-2} · sec^{-1} over a seven-day event at the shelf break off St. Augustine, Florida. 2500 mtons nitrogen was transported onto the outer shelf during that event. Atkinson *et al.* (1982), using a similar technique, reported a net onshore flux into the middle shelf (~40 m) region on Onslow Bay, North Carolina, of 3.4 μmoles NO_3-N · m^{-2} · sec^{-1} for a 13-day event. About 170 mtons of nitrogen were advected into Onslow Bay as a result of that event.

The approach taken here is different in that it provides the first estimate of the mass of nitrate-nitrogen which was resident on the continental shelf, as derived from temperature distributions. The nitrate flux determined was that necessary to emplace that observed mass. The results of the net flux and mass calculations from this and the other studies are shown in Table 4.

To extrapolate results from the present study to determine the importance of bottom intrusions to the nitrogen budget of the SAB required an estimate of how representative conditions were of a "typical" summer intrusion. Bottom intrusions occur in response to north wind stress. The daily resultant north stress during the observed intrusion event ranged from zero to 0.25 dynes · cm^{-2} averaging ~0.04 dynes · cm^{-2} (Fig. 5b). Monthly mean wind fields for the SAB from 1945 through 1963 show that average north wind speed in July was ~2m · sec^{-1} at the middle and outer shelf (Weber and Blanton, 1980) converting to a stress of ~0.08 dynes · cm^{-2}, or twice that we found. No attempt is made here to quantitatively relate northward stress to intrusion volume. However, if we assume that greater northward stress results in larger intrusion volumes, the nitrate-nitrogen mass and flux we determined underestimates a "typical" summer intrusion. Nevertheless, by using a proper intrusion frequency and nitrate-nitrogen mass volumes, a realistic, although conservative, estimate of the importance of summer intrusions to the nitrogen budget of the SAB can be derived.

Factors considered in estimating the frequency of bottom intrusions are the presence of upwelled water at the shelf break, the density of the upwelled water relative to the shelf water, and the concurrence of intrusion-favorable winds with periods of shelf break upwelling (Atkinson, 1977).

Upwelled water is presented at the shelf break because of offshore meanders of the Gulf Stream front (Atkinson, 1977) which apparently occur year-round with periods of one to two weeks (Webster, 1961; Lee *et al.*, 1981). It is assumed here that shelf break upwelling occurs twice monthly. Similar frequencies have been used by Dunstan and Atkinson (1976) and Lee *et al.* (1981) in estimating nitrogen inputs to the continental shelf. However, not every occurrence of shelf break upwelling results in a bottom intrusion because density and wind conditions may not be met.

Historical oceanographic data (Atkinson *et al.*, 1983) indicate that in the middle and inner shelf region of the study area, surface water σ_t is ~25 in April and <25 through November so that upwelled water with a σ_t value of 25 could form a bottom intrusion during that period. Upwelled Gulf Stream Water at 22.5°C and 36.2 ‰ has a σ_t value of ~25.

When the conditions of wind and density are met and denser upwelled water intrudes beneath the shelf water, the result is a stratified water column. To demonstrate stratification caused by intrusions, differences in σ_t from the bottom to the surface were determined from historical National Oceanographic Data Center file at Skidaway Institute of Oceanography. Figure 15 shows density differences by month at inner and middle shelf areas that we studied. The middle shelf region is most stratified

Table 4. Nitrate-nitrogen mass and flux results of this and other studies.

Study	Location	NO_3-N mass (mtons)	NO_3-N flux (μmoles · m^{-2} · sec^{-1})	Depth (m)	Event duration
Haines (1974)	Southeastern U.S. Continental Shelf	7600 · yr^{-1}		Shelf Break	100 d · yr^{-1}
Dunstan & Atkinson (1976)	Southeastern U.S. Continental Shelf	12,300		Shelf Break	
Lee *et al.* (1983)	Southeastern U.S. Continental Shelf	2,500	22.2	55	7 days
Atkinson *et al.* (1983)	Onslow Bay, N.C.	170	3.4	40	13 days
This study	Southeastern U.S. Continental Shelf	3,200 (46 m isobath)	32	46	21 days
		700 (30 m isobath)	30	30	7 days

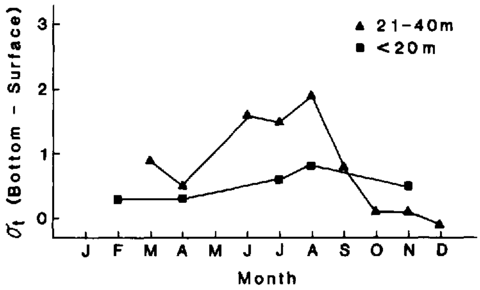

Figure 15. Differences of bottom from surface σ_t by month based on five or more observations in the inner and middle shelf areas between Latitudes 29N and 31N.

during June, July, and August. By October, the water column is mixed vertically. Thus, the density conditions for bottom intrusions are usually met in the middle shelf area from April through November, but bottom intrusions can occur only from April through September. It can be argued that wind-driven mixing can break down the stratified water column in October. However, surface salinities in October are usually lower than in September suggesting that in October there is no mixing with high salinity Gulf Stream Water from a bottom layer.

The concurrence of shelf break upwelling with winds having a north stress component is the third condition necessary for a bottom intrusion to occur. Average monthly wind patterns over the SAB (Weber and Blanton, 1980) for 19 years indicate that in the middle shelf region there is a positive v component of wind stress only in months during which bottom intrusions were indicated by density stratification (Fig. 15). Southerly winds dominate during the summer while April and May are transition months from winter to the summer regimes. Periods of north wind stress would be more transient in those months. In September, easterly flow predominated but there was a small positive v stress component. It is assumed here, therefore, that wind conditions favorable for intrusions are always met in June, July, and August but are met only one-half the time in April, May, and September.

The frequency of bottom intrusions can be estimated from the above considerations. Upwelling at the shelf break can occur twice monthly. Shelf water density is less than that of upwelled 22.5°C Gulf Stream Water between April through November, but density stratification on the middle shelf indicates that bottom intrusions occur only from April through September. Shelf break upwelling and north wind stress are concurrent twice monthly in the summer and once monthly in the spring and fall. Thus, bottom intrusions are predicted about nine times a year.

Using the calculated nitrate-nitrogen mass of 3200 mtons per intrusion and an estimated bottom intrusion frequency of nine per year yields an annual nitrate-nitrogen input to the middle shelf region of the southern SAB of 2.9×10^4 mtons $NO_3N \cdot yr^{-1}$. River and atmospheric sources annually contribute 1.3×10^4 and $0.8 \times$

10^4 metric tons of N, respectively, to the Georgia Bight (Haines, 1974). N flux from Georgia and South Carolina salt marshes may be as high as 12×10^4 metric tons per year (Turner, 1981). A direct comparison of the N sources given above, however, is complicated by several factors. First, our estimate of intrusion flux of N applies to the middle shelf (ca. 20–40 m isobaths) south of Brunswick, Georgia (see Fig. 2). Most of the freshwater inflow into southeastern shelf waters occurs from Brunswick north as is most of the area covered by salt marshes. Secondly, the form of N is very different. Most of the N exported from salt marshes is DON or PN (Haines, 1979; Kjerfve and McKellar, 1980) and a large fraction may be refractory material that does not enter the food chain on the southeastern shelf. Finally, primary production on the inner shelf (0-20 m isobaths) of the Georgia and South Carolina coasts is very high (ca. 300 g $C \cdot m^{-2} \cdot year^{-1}$) (Haines and Dunstan, 1975). Even if one assumes that all N entering the shelf from river and marsh sources is available to phytoplankton, the amount required to support inner shelf primary production is at least 3 times more than the amount coming to the shelf from rivers and marshes (Yoder, in preparation). This implies that N entering the inner shelf from rivers and marshes in a form (e.g., NO_3, NO_2, NH_4, urea) that can be readily utilized by phytoplankton is taken up by inner shelf phytoplankton before it reaches the middle shelf (Bishop *et al.*, 1980; Yoder *et al.*, 1981). Thus, bottom intrusions are a major, if not the only major, source of "new" N for phytoplankton on the middle shelf region of the southern SAB.

5. Summary

Our observations of summertime bottom intrusions during 1979 led to the following conclusions:

- The two observed bottom intrusions of upwelled water apparently occurred in response to north wind stress.
- Pre-intrusion hydrographic conditions on the continental shelf were characterized by high water temperatures, low nitrate concentrations, and low total chlorophyll concentrations.
- Upwelled water of <22.5°C covered an area of 3280 km^2 on the continental shelf and occupied a volume of 38 km^3.
- The intrusion of upwelled Gulf Stream Water resulted in the advection of 3200 mtons of nitrate-nitrogen into the study area. The net flux necessary to emplace that mass was 32 $\mu moles \cdot m^{-2} \cdot sec^{-1}$ across the shelf break. The net flux across the 30 m isobath was 30 $\mu moles \cdot m^{-2} \cdot sec^{-1}$.
- The advection of nitrate-enriched water onto the continental shelf resulted in a dramatic increase in phytoplankton biomass as reflected in total chlorophyll *a* concentrations.

— Phytoplankton production was likely supported by *in situ* regeneration of nutrients prior to the intrusion and dominated by "new" nitrate during the intrusion.

— The summertime intrusion process is a major source of nitrogen to southeastern United State continental waters.

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