1984

Review of Upwelling Off the Southeastern United States and Its Effect on Continental-Shelf Nutrient Concentrations and Primary Productivity

Larry P. Atkinson
latkinso@odu.edu

James A. Yonder

Thomas N. Lee

Original Publication Citation

Atkinson, L. P., Yoder, J. A., & Lee, T. N. (1984). Review of upwelling off the southeastern United States and its effect on continental-shelf nutrient concentrations and primary productivity. *Rapports et procès-verbaux des réunions, 183*, 70-78.

Rapp. P.-v. Réun. Cons. int. Explor. Mer, 183: 70–78. 1984.

Review of upwelling off the southeastern United States and its effect on continental-shelf nutrient concentrations and primary productivity

Larry P. Atkinson and James A. Yoder

Skidaway Institute of Oceanography
P.O. Box 13687, Savannah, Georgia 31416, USA

Thomas N. Lee

University of Miami
Rosenstiel School of Marine and Atmospheric Sciences
4600 Rickenbacker Causeway, Miami, Florida 33149, USA

Gulf Stream induced upwelling occurs along the length of the southeastern United States continental shelf break. Upwelling events are produced by northward propagating Gulf Stream frontal meanders and eddies and travel northwards with these features. Meanders and eddies occur throughout the year in a period band of 2–14 days; however, resultant upwellings can affect the shelf quite differently. During fall, winter, and spring, upwelling is restricted to the outer shelf by cross-shelf density distributions, but in the summer upwelled water may penetrate across as a subsurface intrusion if aided by upwelling-favorable winds. If water does penetrate across the shelf, it may become stranded, detached from its deep-water Gulf Stream source, and may reside on the shelf for many weeks. The mass of nitrate within stranded water masses has been observed to be over 2500 metric tonnes nitrate-nitrogen covering an area of 2500 km^2.

Gulf Stream upwelling-induced nutrient inputs dominate all other sources to the South Atlantic Bight (SAB) and have a profound effect on phytoplankton production. During the fall, winter, and spring, high phytoplankton coincides with outer shelf upwelling, while in the summer production also occurs in the lower layer over the inner and middle shelf. Over one-half the phytoplankton production is considered "new" production.

Introduction

The continental shelf of the southeastern United States extends from Cape Canaveral, Florida, to Cape Hatteras, North Carolina (Fig. 1). The shelf varies in width from less than 50 km off Cape Canaveral and 30 km off Cape Hatteras to a maximum of 120 km off Savannah, Georgia. The bathymetry generally follows the coastline with cuspate bays formed between the shoals off Capes Fear, Lookout, and Hatteras. Depths over the shelf are quite uniform with typical relief less than 2 m, although in the vicinity of the sparse rock outcrops relief may reach 5 m. In contrast to other continental shelves, there are no basins or sills. The shelf break is at about 55 m.

A distinctive aspect of the southeastern United States shelf is the proximity of the Gulf Stream, which flows northwards along the shelf break. The western edge of the Gulf Stream generally lies within ±15 km of the shelf break south of 32°N latitude (Bane and Brooks, 1979). Between 32° and 33°N a topographic feature known as the "Charleston Bump" forces an offshore flow of the Gulf Stream (Brooks and Bane, 1978; Pietrafesa *et al.*, 1978; Legeckis, 1979). Downstream of the "Bump" enlarged east–west meanders displace the Gulf Stream front up to 100 km from the shelf break (Legeckis, 1979; Bane and Brooks, 1979). Northward-propagating Gulf Stream frontal disturbances in the form of meanders and eddies exert considerable control over the oceanography of the adjacent shelf waters. Current meter and temperature records from the shelf edge south of the Charleston Bump show large-amplitude subtidal current and temperature fluctuations with periods of 5–10 days that are produced by these propagating frontal disturbances (Lee *et al.*, 1981; Lee and Atkinson, 1983). Figure 2 shows the effect of a frontal eddy on the sea surface temperature. The cold upwelling core, between 29° and 30°N and about 80°W, is embedded in the Gulf Stream front. A warm streamer of Gulf Stream water curls cyclonically around the cold

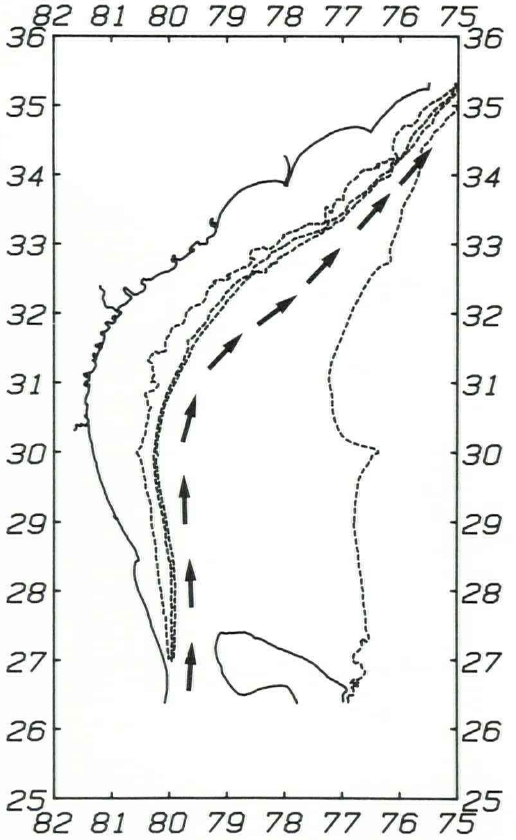

Figure 1. The southeastern United States continental shelf. Mean position of Gulf Stream is indicated.

upwelling core. The occurrence of a frontal eddy produces a cyclonic perturbation of the flow field with upwelling of deeper, cooler, and nutrient-rich Gulf Stream water onto the outer shelf. Long-term current meter records indicate that these eddy-induced velocity and temperature fluctuations tend to occur every 5 to 10 days throughout the year (Lee and Atkinson, 1983).

The upwelling process is clearly shown in a series of near synoptic cross-shelf sections made from Savannah (32°N) south to Ormond Beach (29°N) (Fig. 3). Off Savannah the Gulf Stream was close to the shelf break and nutrient concentrations were relatively low over the shelf, while to the south upwelling was evident. Water temperature decreased to 15°C over the outer shelf, and a large dome feature with high nutrient concentrations was observed. High nutrient concentrations did not reach the surface as might be observed in a classical upwelling situation, but the high concentrations were well within the euphotic zone (1 % light at 50 m). Qualitatively we observe a zone of shelf-break upwelling propagate northwards, causing variations in nutrient concentrations. This, of course, must be quantified.

Deeper waters in the Gulf Stream have a reliable nutrient/temperature relationship where, in the case of nitrate, the empirical relationship is:

$$[NO_3] = 53 - 2{\cdot}6\ T \qquad (1)$$

for temperatures below 20°C. Because nutrients correlate well with temperature, we have been able to use temperature records to determine changes in nitrate with time at current meter locations. We can then calculate nitrate flux, using the relationship

$$\overline{u'NO_3'} = \overline{(u-\bar{u})(NO_3-\overline{NO_3})} \qquad (2)$$

where u is the daily mean onshore/offshore velocity component. NO_3 is the daily mean nitrate concentration calculated from temperature, and the overbar represents a time average. A negative $\overline{u'NO_3'}$ corresponds to a net onshore nitrate flux. Using data obtained between December 1976 and April 1977, we determined an eddy-induced nitrate flux of $-8{\cdot}5$ µmoles $m^{-2}\ s^{-1}$. We converted this to a mean annual nitrate flux by considering the alongshore length of upwelling events and their frequency. The result was a calculated upwelling-induced flux of 55 000 t nitrogen/year. This compares to riverine input of 12 600 t and atmospheric input of 7 500 t N. Recent recalculations of the shoreward nitrate flux using more extensive current meter and hydrographic data indicate a yearly flux in excess of 190 000 t nitrogen per year (Lee and Atkinson, 1983). These quantities are summarized in Figure 4.

Our discussion so far has been limited to onshore nitrogen flux at the shelf break. During stratified conditions, which occur from June to September (Atkinson *et al.,* 1983), dense water upwelled at the shelf break can penetrate across the shelf, usually as a response to wind-driven Ekman flow (Atkinson, 1977; O'Malley, 1981). Upwelled nutrient-rich waters may then reach the inner shelf and remain in the euphotic zone for days or weeks (O'Malley, 1981). This process is enhanced off northeast Florida where upwelling-favorable winds are more frequent than elsewhere along the southeastern U.S. (Green, 1944; Taylor and Stewart, 1959), and diverging isobaths can amplify upwelling (Blanton *et al.,* 1981). Such an upwelling event was observed off northeast Florida in the summer of 1979. Prior to the upwelling event the cross-shelf distribution of properties was similar to that shown in Figure 5. Temperatures were above 23°C and nitrate and chlorophyll were low. One week later upwelled water (< 22·5°C) intruded ~30 km onto the middle shelf, and the water temperature at the outer shelf was less than 15°C (Fig. 6). In the following two weeks (Fig. 6 b, c) the intrusion moved 10 km farther shoreward and minimum water temperature in the intrusion core was less than 16°C. By week 7, upwelled water had penetrated more than 50 km from the outer shelf, and stranded water of less than 18°C covered an area of greater than 500 km². The stranding was caused by an apparent onshore meander of the Gulf Stream between weeks 6 and 7 that resulted in warmer shelf-break bottom temperatures.

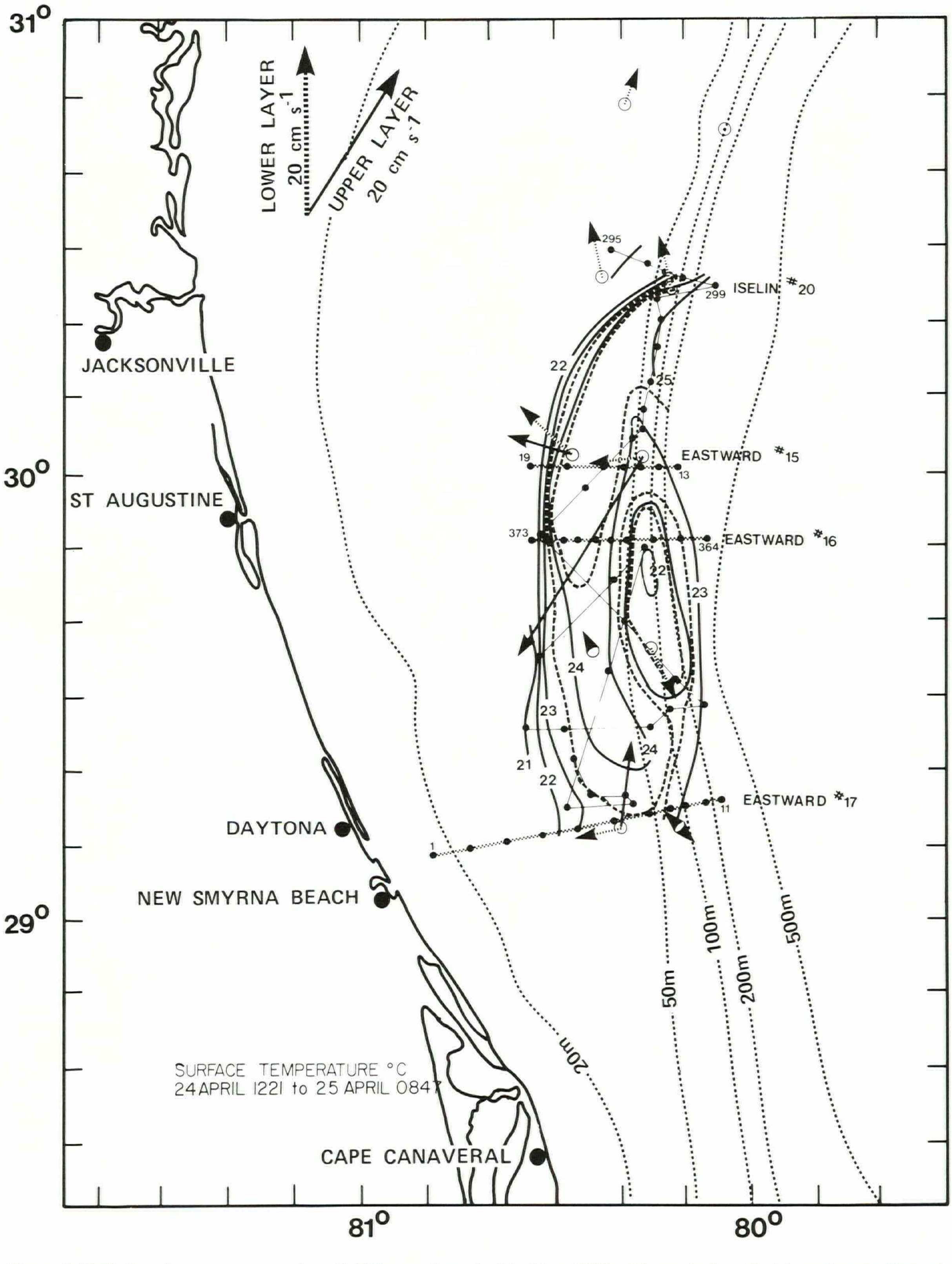

Figure 2. Typical surface temperatures in a Gulf Stream frontal eddy. Note 22°C cold core in frontal eddy and warm filament moving cyclonically around it. Upper and lower layer currents are indicated. Data are from a large-scale experiment in the spring of 1980.

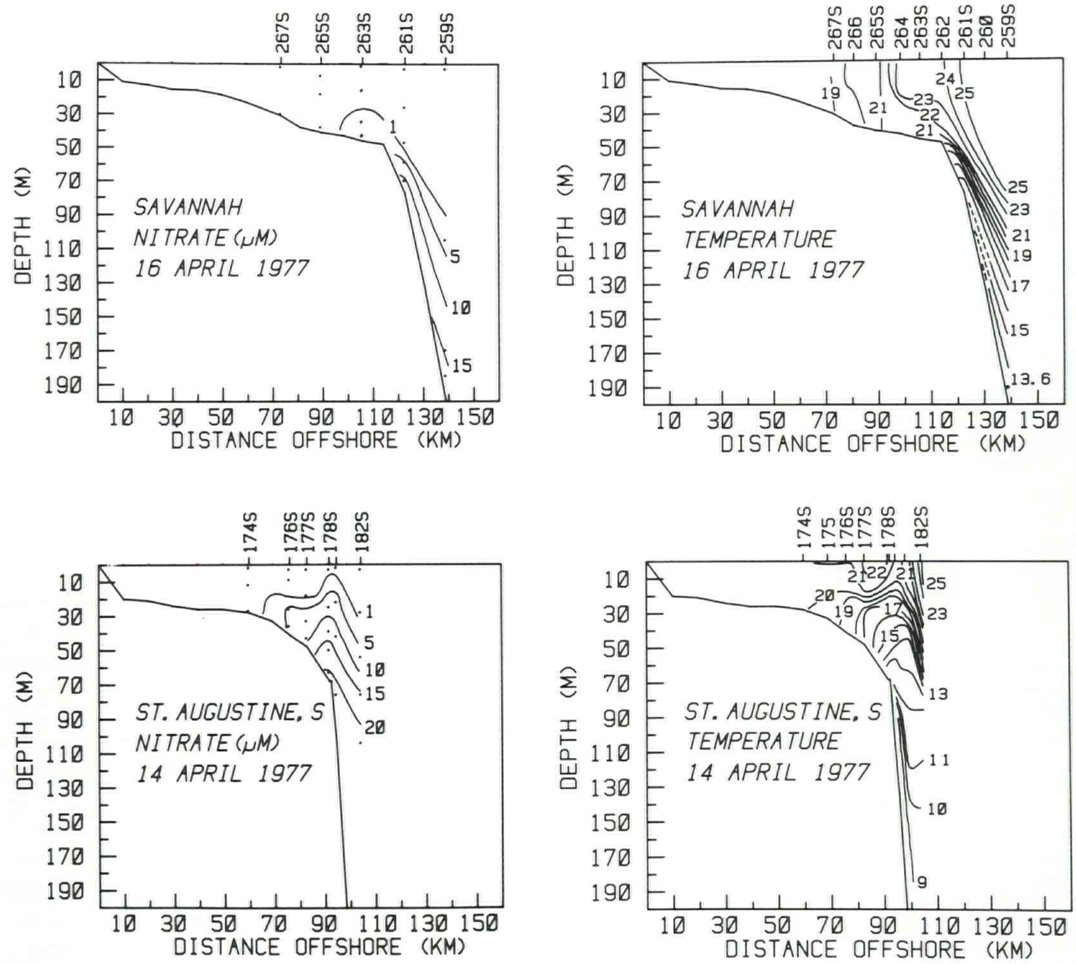

Figure 3. Cross-shelf sections of temperature and nitrate off Savannah where the Gulf Stream is close to the shelf break and off St. Augustine where a frontal eddy is over the shelf break and upwelling occurs.

The cross-shelf distributions for weeks 4–7 are shown in Figures 7 a–d, 8 a–d, and 9 a–d. The intrusion event occurred between weeks 4 and 5 when 17°C water was advected over the outer shelf. During week 6 the intrusion shifted onshore and by week 7 it was isolated from a new intrusion at the shelf edge where <17°C was observed. Nitrate concentrations correlated with the colder waters; however, the stranded mid-shelf intrusion (see station 439, week 6, and station 535–534, week 7) had lower nitrate concentrations by week 7, no doubt due to phytoplankton assimilation. The new intrusion at the outer shelf in week 7 carried high nitrate concentrations and low chlorophyll. Phytoplankton had not yet developed in the intrusion.

The stranded intrusions we have observed carry 2000–3000 t of nitrate-nitrogen and cover approximately 2000 km^3 (O'Malley, 1981). When an intrusion is stranded, nitrate concentrations are reduced to near zero within a week or two.

The effect of shelf-break upwelling on plant produc-

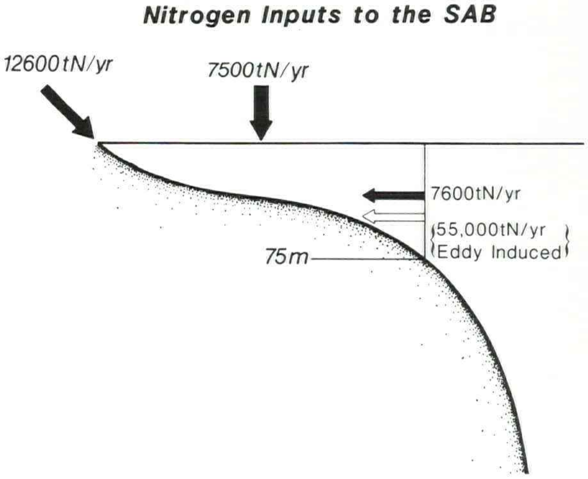

Figure 4. Schematic diagram of annual nitrogen input to the Georgia shelf as computed by Haines (1974). Values are in tonnes nitrogen per year. Eddy flux measurements are shown in brackets. (Figure from Lee *et al.*, 1981).

tion has recently been summarized by Yoder *et al.* (1981). Their study indicates that when shelf waters are not stratified, upwelling causes productive phytoplankton blooms on the outer shelf. Phytoplankton production averages about 2 g C m^{-2} day^{-1} during upwelling events, and "new" production is 50 %, or more, of the total (Dugdale and Goering, 1967). When shelf waters are stratified and upwelled waters penetrate well onto the shelf as a subsurface intrusion, phytoplankton production averages about five times higher than in the nutrient-depleted overlying mixed layer. Phytoplankton within the intrusion can deplete upwelled nitrate in about 7–10 days, after which no further net increase in phytoplankton biomass is observed.

Current meter records show that upwelling in the Gulf Stream frontal disturbances occurs roughly 50 % of the time on the outer shelf during November–April (shelf not stratified), leading us to estimate that seasonal primary production in these upwelled waters is 175 g C m^{-2} 6 $mos.^{-1}$ of which at least 50 % is "new" production. More than 90 % of production occurs during upwelling at the outer shelf, and thus Gulf Stream induced upwelling is the dominant process affecting primary productivity of the outer shelf. Our seasonal estimates of outer shelf plant production are, respectively, two and ten times higher than previous estimates that did not account for upwelling by Gulf Stream disturbances.

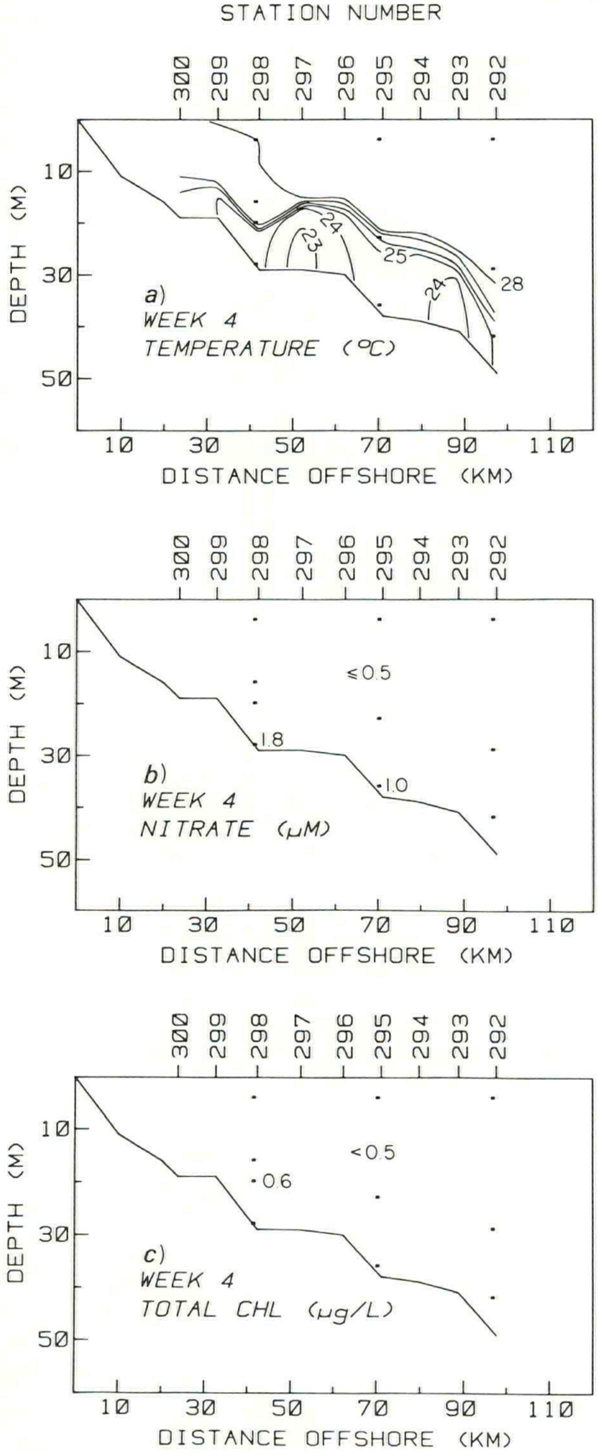

Figure 5. Cross-shelf distribution of temperature, nitrate, and chlorophyll. Week 4 of study, 25 July 1979; 30°05′N; prior to intrusion. (Figure from O'Malley, 1981).

Acknowledgements

The research reported in this paper was supported by the United States Department of Energy (Contracts DE-AS09-76EV00889, DE-AS09-76EV00936, and DE-AS05-76EV05163) and Minerals Management Services (prime contract AAT 851-CT1-25 to Science Applications Inc., of Raleigh, North Carolina). We would like to thank Patrick O'Malley, William Chandler, Steve Bishop, and James Singer for technical assistance.

References

Atkinson, L. P. 1977. Modes of Gulf Stream intrusion into the South Atlantic Bight shelf waters. Geophys. Res. Lett., 4 (12): 583–586.

Atkinson, L. P., Lee, T. N., Blanton, J. O., and Chandler, W. S. 1983. Climatology of the southeastern United States continental shelf waters. J. Geophys. Res., 88 (C8): 4705–4718.

Bane, J. M., Jr., Brooks, D. A. 1979. Gulf Stream meanders along the continental margin from the Florida Straits to Cape Hatteras. Geophys. Res. Lett., 6: 280–282.

Blanton, J. O., Atkinson, L. P., Pietrafesa, L. J., and Lee, T. N. 1981. The intrusion of Gulf Stream water across the continental shelf due to topographically induced upwelling. Deep-Sea Res., 28 (4 A): 393–405.

Brooks, D. A., and Bane, J. M., Jr. 1978. Gulf Stream deflection by a bottom feature off Charleston, South Carolina. Science, 201: 1225–1226.

Dugdale, R. C., and Goering, J. J. 1967. Uptake of new and regenerated forms of nitrogen in primary production. Limnol. Oceanogr., 12 (2): 196–206.

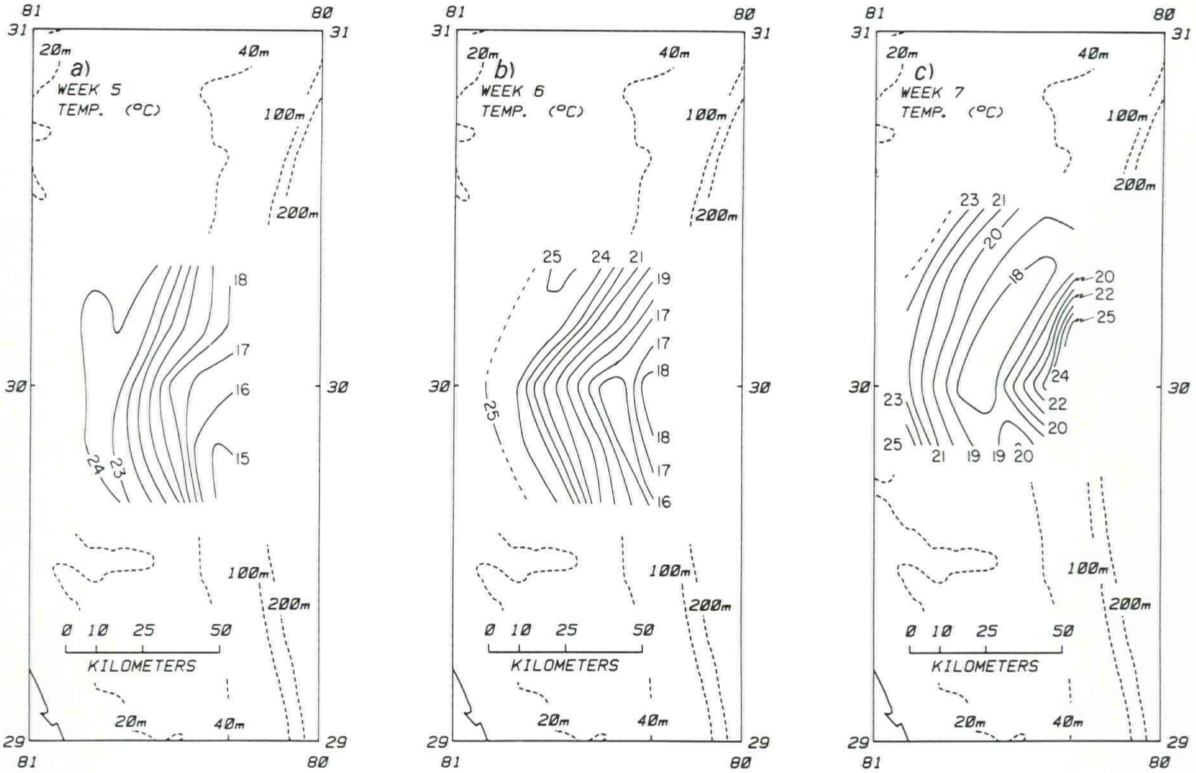

Figure 6. Horizontal distribution of bottom temperature on the continental shelf off north Florida and Georgia: a) week 5 of study, 31 July 1979; b) week 6 of study, 7 August 1979; c) week 7 of study, 14 August 1979. (Figure from O'Malley, 1981).

Green, C. K. 1944. Summer upwelling, northeast coast of Florida. Science, 100: 546–547.

Haines, E. B. 1974. Processes affecting production in Georgia coastal waters. Ph.D. dissertation, Duke University, Durham, North Carolina, USA, 118 pp.

Lee, T. N., and Atkinson, L. P. 1983. Low frequency current and temperature variability from Gulf Stream frontal eddies and atmospheric forcing along the southeast U.S. outer continental shelf. J. Geophys. Res., 88 (C8): 4541–4567.

Lee, T. N., Atkinson, L. P., and Legeckis, R. 1981. Detailed observations of a Gulf Stream frontal eddy on the Georgia continental shelf, April 1977. Deep-Sea Res., 28 (4): 347–378.

Legeckis, R. 1979. Satellite observations of the influence of bottom topography on the seaward deflection of the Gulf Stream off Charleston, South Carolina. J. Geophys. Res., 9 (3): 483–497.

O'Malley, P. G. 1981. The effect of summertime shelf break upwelling on nutrient flux in southeastern United States continental shelf waters. M.S. thesis, Georgia Institute of Technology, Atlanta, Georgia, USA, 52 pp.

Pietrafesa, L. J., Atkinson, L. P., and Blanton, J. O. 1978. Evidence for deflection of the Gulf Stream by the Charleston Rise. Gulf Stream, IV (9): 3–7.

Taylor, C. B., and Stewart, H. B. 1959. Summer upwelling along the east coast of Florida. J. Geophys. Res., 64 (1): 33–40.

Yoder, J. A., Atkinson, L. P., Lee, T. N., Kim, H., and McClain, C. 1981. Role of Gulf Stream frontal eddies in forming phytoplankton patches on the outer southeastern U.S. shelf. Limnol. Oceanogr. 26 (6): 1103–1110.

NOTE: Figures 7–9, see pp. 76–78.

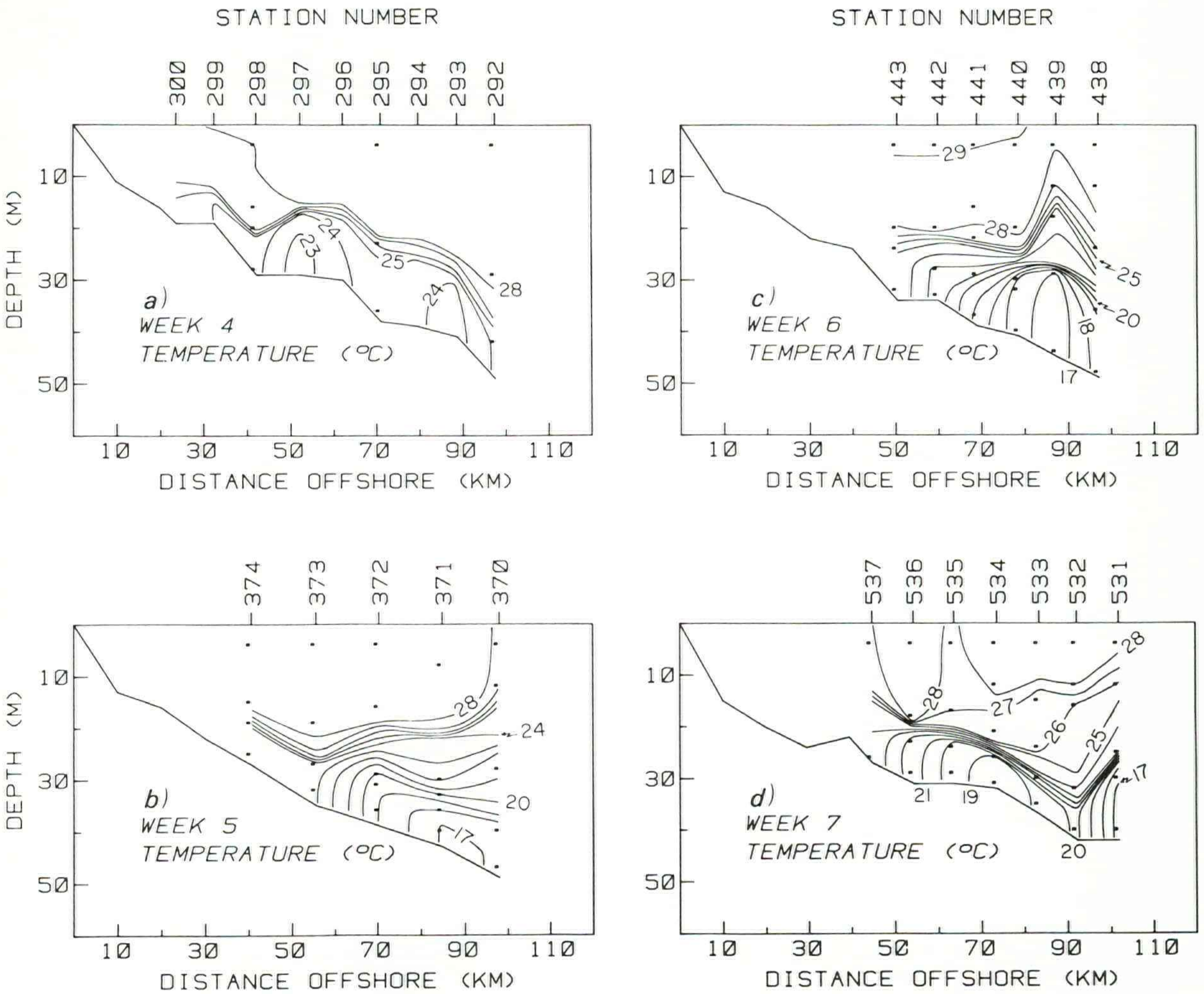

Figure 7. Vertical distribution of temperature: a) week 4, 30°05′N; b) week 5, 30°00′N; c) week 6, 30°00′N; and d) week 7, 30°10′N. Dots indicate water sampling depths.

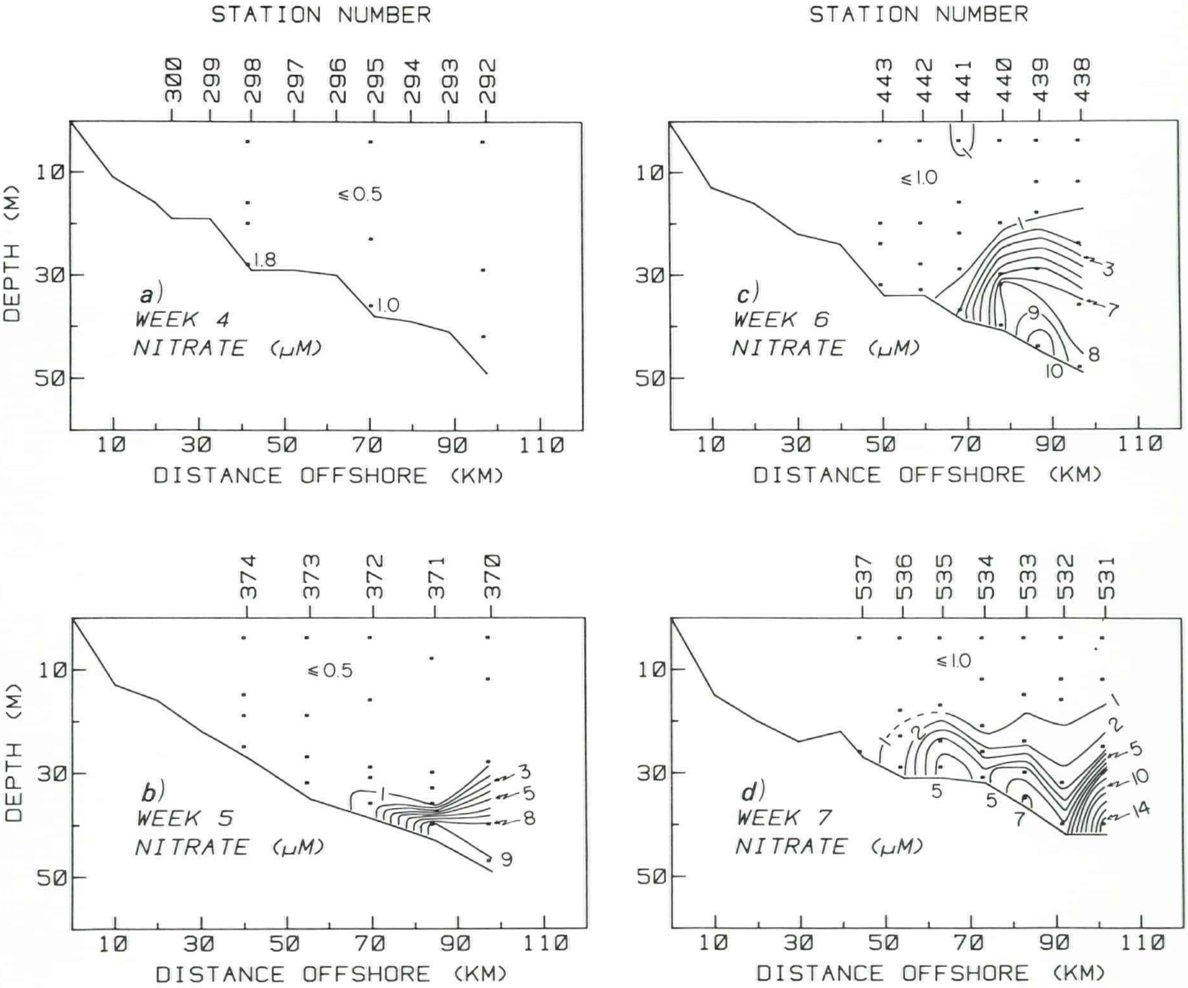

Figure 8. Vertical distribution of nitrate: a) week 4; b) week 5; c) week 6; d) week 7.

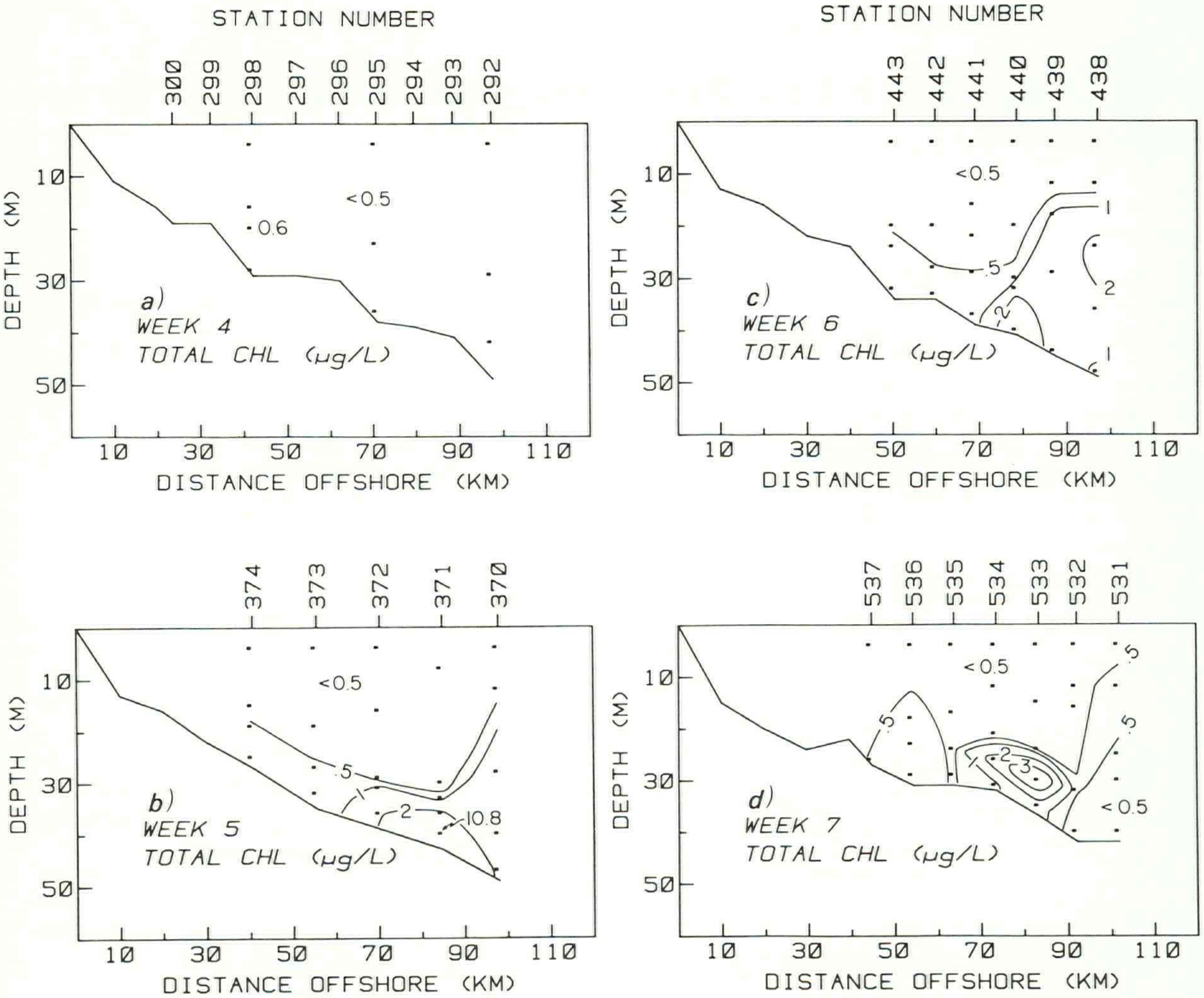

Figure 9. Vertical distribution of total chlorophyll: a) week 4; b) week 5; c) week 6; and d) week 7.