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Gulf Stream Frontal Eddy Influence on Productivity of the Southeast U.S. Continental Shelf

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Weekly period meanders and eddies are persistent features of Gulf Stream frontal dynamics from Miami, Florida, to Cape Hatteras, North Carolina. Satellite imagery and moored current and temperature records reveal a spatial pattern of preferred regions for growth and decay of frontal disturbances. Growth regions occur off Miami, Cape Canaveral, and Cape Fear due to baroclinic instability, and decay occurs in the confines of the Straits of Florida between Miami and Palm Beach, between 30° and 32°N where the stream approaches the topographic feature known as the Charleston bump and between 33°N and Cape Hatteras. Eddy decay regions are associated with elongation of frontal features, offshore transport of momentum and heat, and onshore transport of nutrients. Onshore transport of new nitrogen from the nutrient-bearing strata beneath the Gulf Stream indicates that frontal eddies serve as a "nutrient pump" for the shelf. New nitrogen flux to the shelf due to Gulf Stream input could support new production of 7.4×10^{12} g C yr^{-1} or about 8 million tons carbon per year if all nitrate were utilized. Calculations indicate that approximately 70% of this potential new production is realized, yielding an annual new production for the outer shelf of 4.3×10^{12} g C.

INTRODUCTION

It is now well known that biological production in the South Atlantic Bight (SAB) is strongly influenced by interaction between the Gulf Stream and adjacent shelf waters. Upwelling in frontal eddies and summer bottom intrusions can advect nutrients into the euphotic zone of the upper slope and shelf [*Lee et al.*, 1981; *Lee and Atkinson*, 1983; *Lee and Pietrafesa*, 1987; *Atkinson et al.*, 1987]. This transport of new nutrients from the thermocline of the Gulf Stream provides a major food source for a succession of biological responses [*Yoder et al.*, 1983, 1985; *Paffenhofer et al.*, 1987*b*; *Ishizaka*, 1990*a*, *b*, *c*]. In this paper we discuss the regional aspects of the physical and biological processes from a synthesis of outer shelf current and temperature measurements, and we show a spatial and seasonal pattern of carbon production related to the dynamics of Gulf Stream frontal eddies. We then use this information to estimate seasonal carbon cycles and annual carbon production from Gulf Stream nutrient sources.

BACKGROUND

Satellite Imagery

Satellite advanced very high resolution radiometer (AVHRR) thermal imagery (Plate 1) typically shows that wavelike meanders and eddies are consistent features of the Gulf Stream cyclonic front along the length of the southeast U.S. outer continental shelf. These features appear to amplify north of the Straits of Florida between 27° and 30°N and again between 32° and 33°N. Dissipation appears to occur between 30° and 32°N and again between 33° and 36°N.

The first amplification region is just north of the Straits of Florida where the shelf begins to widen and the Bahama Bank falls off sharply into the 800-m depths of the Blake Plateau, relaxing the physical constraints of the channel. In this region, eddy dimensions can more than double in size in just a few days, reaching 100–200 km in the downstream direction, while the features remain coupled to the parent offshore meanders, with cross-stream scales of 30–50 km [*Lee et al.*, 1981; *Bane and Brooks*, 1979; *Lee and Atkinson*, 1983].

A second amplification region occurs between 32° and 33°N, just downstream of the Charleston bump, a topographic anomaly of the slope extending seaward into the Gulf Stream [*Brooks and Bane*, 1978; *Pietrafesa et al.*, 1978]. Downstream dimensions of eddies in this region can reach 300 km [*Legeckis*, 1979], and meanders with 100-km offshore displacements can occur. The meanders propagate to the north at an average speed of about 40 cm s^{-1}, with wave lengths of 100–250 km and periods of 2–14 days [*Legeckis*, 1979; *Bane and Brooks*, 1979; *Brooks and Bane*, 1981; *Bane et al.*, 1981; *Olson et al.*, 1983]. Perturbation of the Gulf Stream flow by the Charleston bump is believed to be the cause of the larger meanders and eddies between the "bump" and Cape Hatteras [*Pietrafesa et al.*, 1978; *Brooks and Bane*, 1978; *Bane and Brooks*, 1979; *Legeckis*, 1979; *Olson et al.*, 1983; *Bane*, 1983; *Singer et al.*, 1983]. Immediately downstream of the "bump" the Gulf Stream under-

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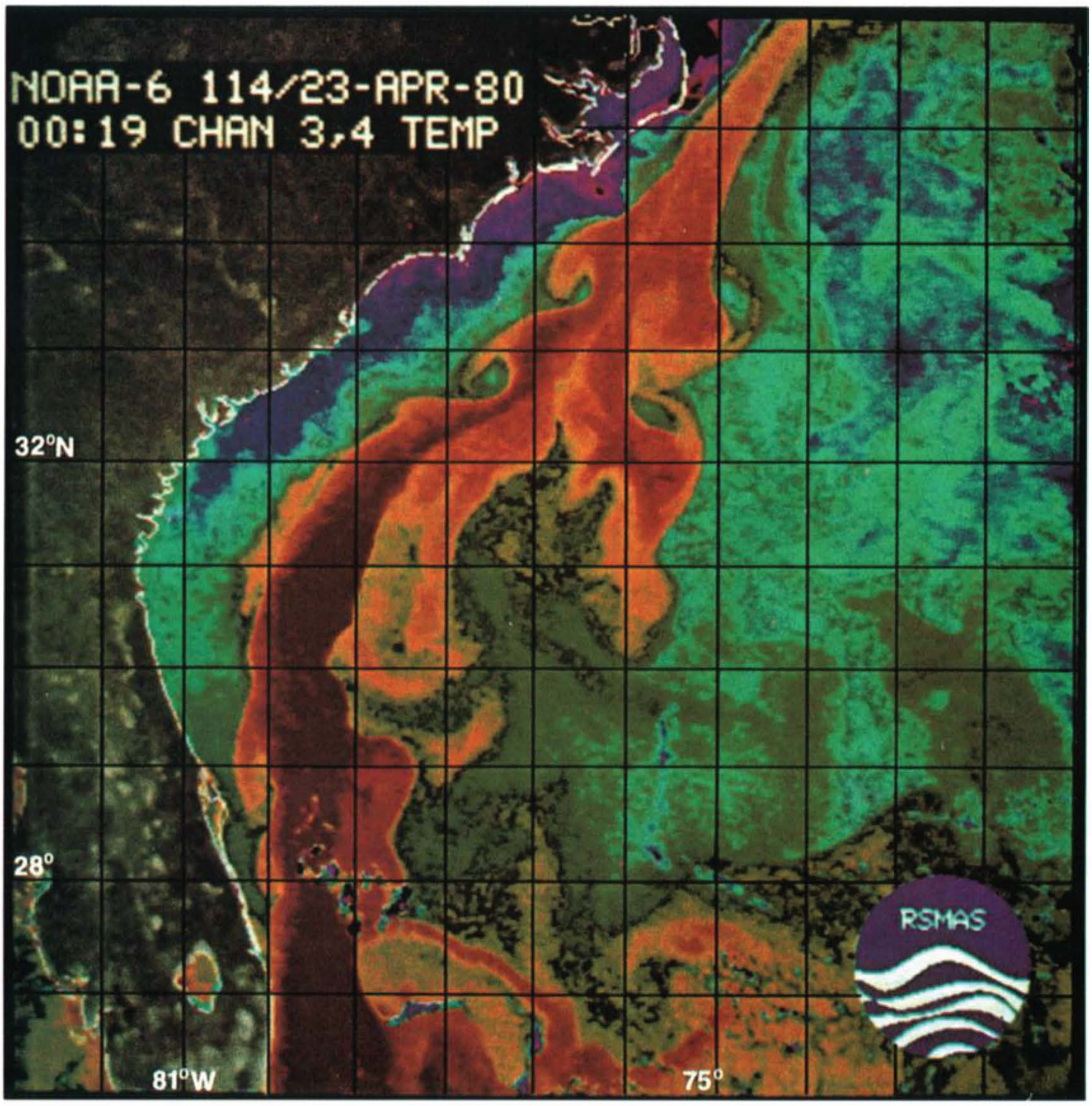

Plate 1. Satellite advanced very high resolution radiometer thermal image of the Gulf Stream in the SAB for 0019 UT on April 23, 1980 (prepared by O. Brown and R. Evans of Rosenstiel School of Marine and Atmospheric Science, University of Miami).

goes a quasi-persistent eastward displacement from the shelf edge causing a cold, cyclonic "Charleston gyre" to form shoreward of the stream off Long Bay [*Bane*, 1983; *Singer et al.*, 1983].

In the Straits of Florida, surface temperature gradients are weak and spatial scales are small, making detection of frontal eddies by satellite imagery difficult. However, in situ current meter records and shipboard thermal surveys [*Lee*, 1975; *Lee and Mayer*, 1977] indicate that a third growth region occurs in the vicinity of Miami, Florida, where eddies with diameters of 10–30 km are embedded in frontal meanders with wavelengths of 75–122 km. Northeast of Cape Hatteras, Gulf Stream meanders are no longer restricted by the continental shelf, as along the southeast United States, and the well-known warm- and cold-core "rings" develop.

Weekly Period Frontal Eddies and Meanders

Gulf Stream meanders were first observed off Onslow Bay by *Webster* [1961]. They were later shown to be northward traveling waves [*Legeckis*, 1979; *Bane and Brooks*, 1979] whose "crest" was represented by an onshore meander position (westward displacement of the Gulf Stream) and whose "trough" was the offshore position of the meander. Upwelling occurs in the wave troughs between the offshore displaced front and the shelf break and is believed to support the formation of cold, cyclonic eddies that travel to the north with the parent wave [*Lee et al.*, 1981; *Lee and Atkinson*, 1983; *Brooks and Bane*, 1983]. Cyclonic circulation in an eddy interacts with the leading wave crest and entrains a warm streamer or filament around the west side of the eddy that results in a contortion of the Gulf Stream surface thermal front into a series of "shingle" shapes [*Von Arx et al.*, 1955] or folded wave patterns [*Legeckis*, 1979]. This is the characteristic sea surface temperature (SST) pattern of an eddy-meander combination seen in satellite thermal imagery of the Gulf Stream (Plate 1).

Cyclonic, cold-core eddies are observed embedded in the Gulf Stream front in the Florida Strait region (Figure 1*a*)

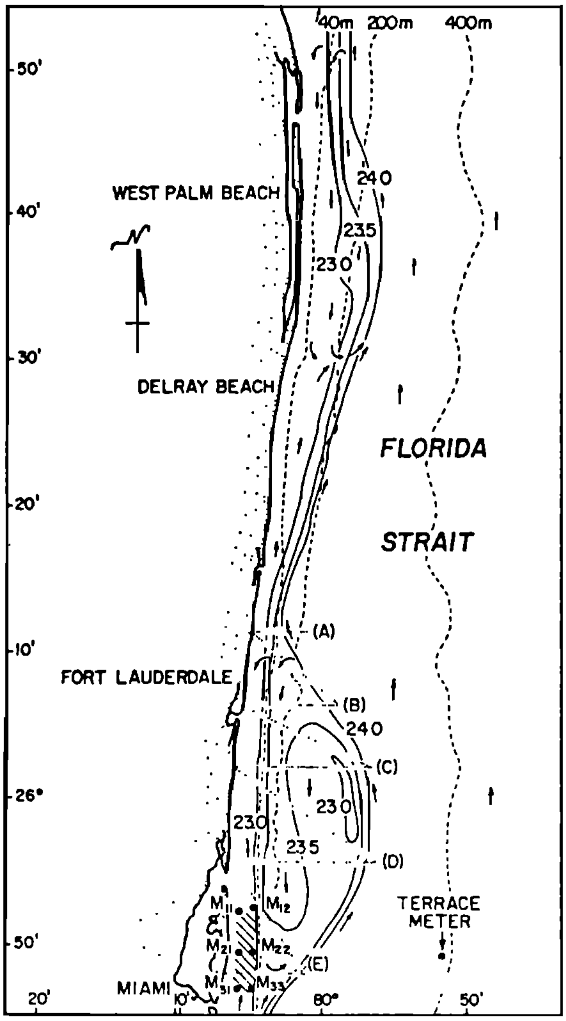

Fig. 1*a*. Composite map of surface temperature for February 20 to 23, 1973. Dots indicate the ship track; letters (A)–(E), temperature sections; solid blackened circles, current meter moorings; and arrows, observed current direction (Figure 15 of *Lee and Mayer* [1977].)

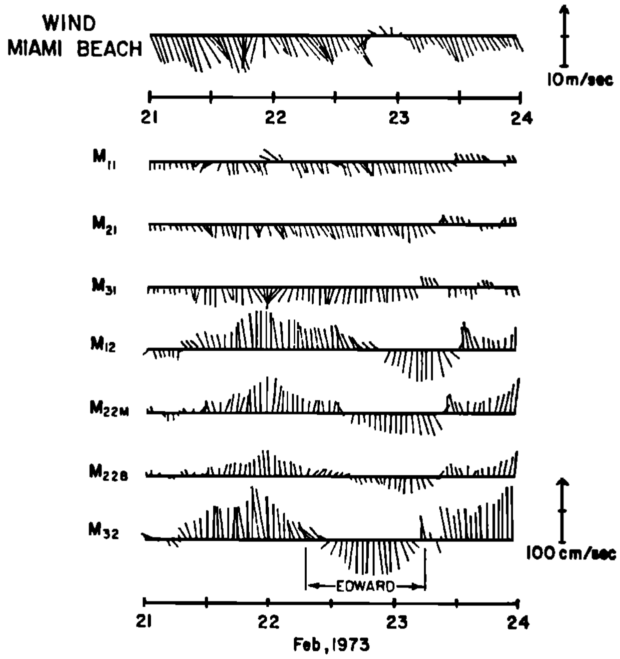

Fig. 1*c*. Time series of hourly current and wind vectors during the passage of the frontal eddy shown in Figure 1*a* (Figure 16 of *Lee and Mayer* [1977].)

along the Florida-Georgia outer shelf (Figure 2*a*) and along the North Carolina outer shelf (Figure 3). These eddies occur during periods when the meander is in an offshore position and have horizontal dimensions equivalent to the meander. They move to the north at the same speed as the meander and appear to grow as the meander develops. They occur on the average of about one per week and have a lifespan of about 1 to 3 weeks. Upwelling in the cold core of frontal eddies uplifts the density structure of the front approximately 10 m d^{-1} in the upper 200 m and transports nutrients into the euphotic zone for biological uptake over the outer shelf throughout the year [*Lee and Atkinson*, 1983] (Figures

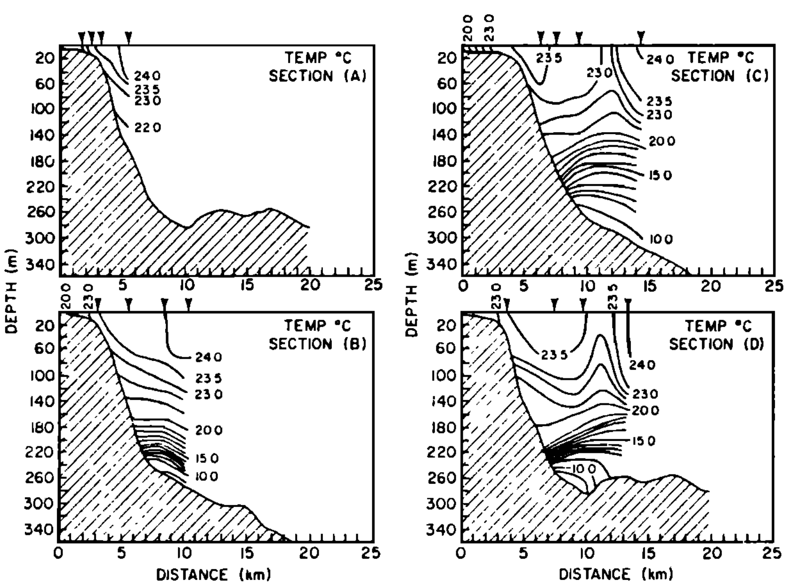

Fig. 1*b*. Temperature sections through frontal eddy shown in Figure 1*a*. Arrows indicate expendable bathythermograph (XBT) stations (Figure 17 of *Lee and Mayer* [1977].)

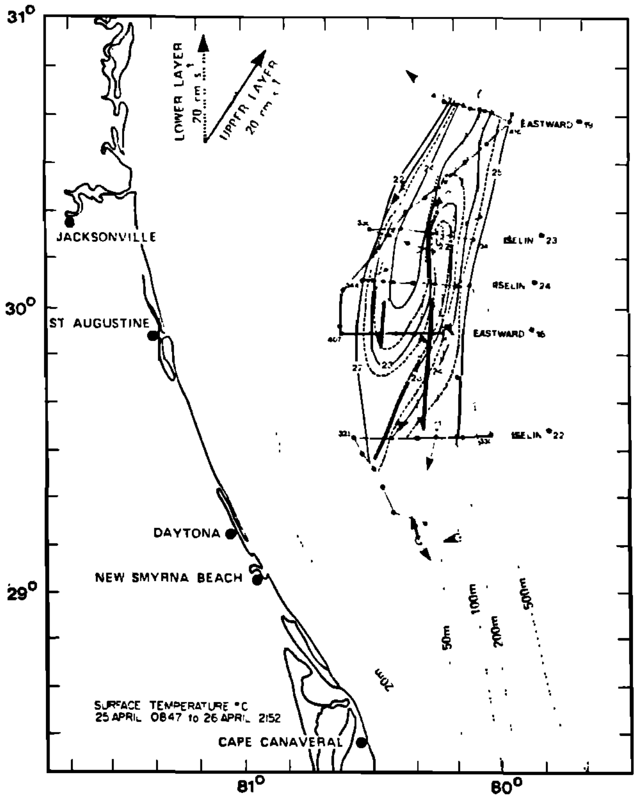

Fig. 2*a*. Ship-measured surface temperature on April 25 (0847) to April 26 (2152), with daily averaged current vectors for April 26. (Figure 21 of *Lee and Atkinson* [1983].)

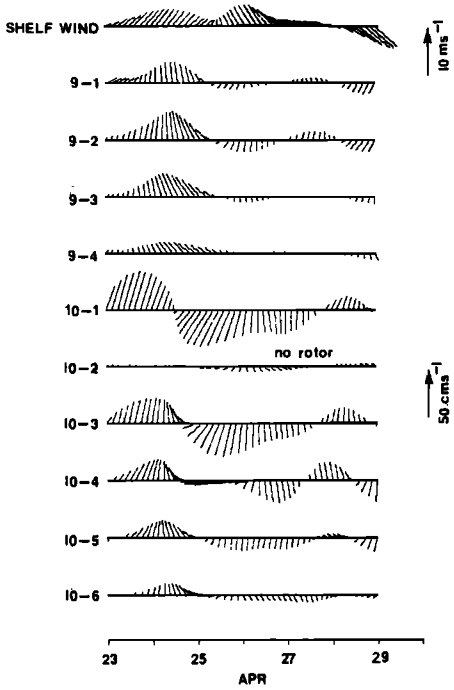

Fig. 2*c*. Time series of 40-hour low-pass wind vectors and 40-hour to 2-week band-pass-filtered currents during passage of the frontal eddy in Figure 2*a*. (Figure 23 of *Lee and Atkinson* [1983].)

1*b*, 2*b*, and 3). During summer the eddy-induced upwelling can extend to midshelf or inner shelf regions as a subsurface intrusion if additional upwelling and onshore bottom flows occur at the same time from upwelling favorable winds [*Atkinson et al.*, 1987; *Lee and Pietrafesa*, 1987; *Lorenzzetti et al.*, 1987].

A schematic representation of a fully developed Gulf Stream frontal eddy-meander field, identifying the various features, is shown in Figure 4. The approach of a meander crest displaces the front shoreward, toward the outer shelf. This results in strong northward currents and increased

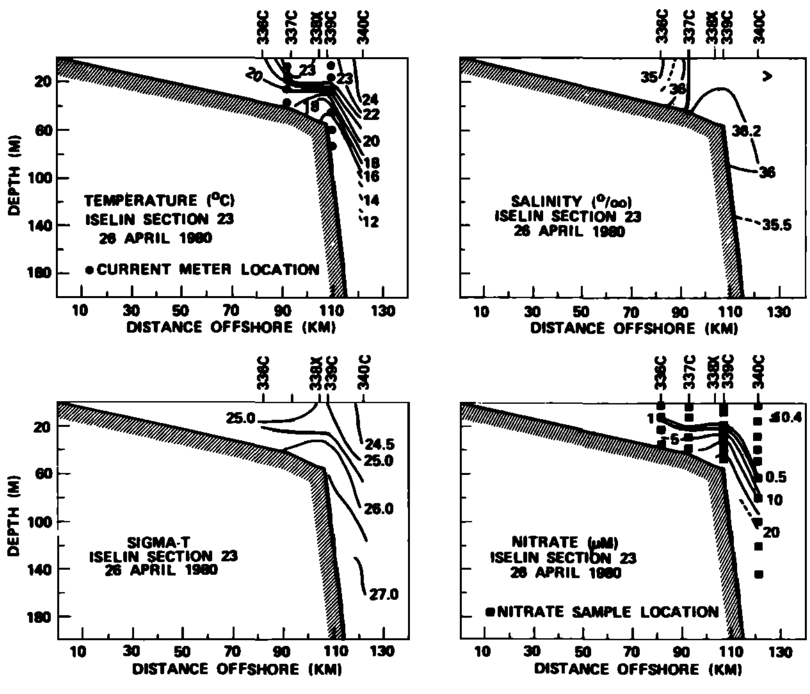

Fig. 2*b*. Temperature, salinity, density, and nitrate sections across the frontal eddy of Figure 2*a*, *Iselin* section 23. (Figure 22 of *Lee and Atkinson* [1983].)

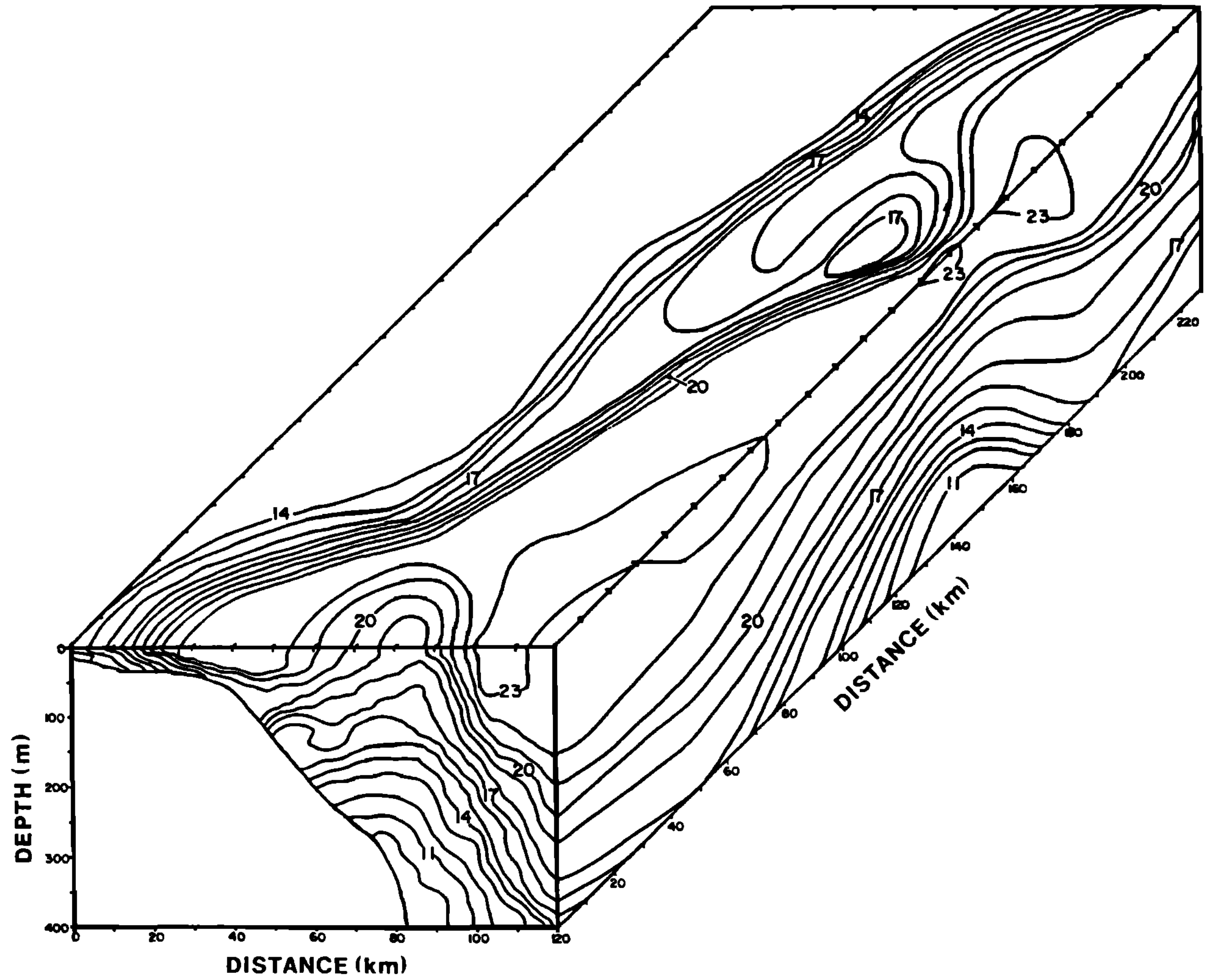

Fig. 3. An extensive, oblique view of the thermal structure of meanders off Cape Fear and Onslow Bay, February 11, 1979, constructed from XBT sections. (Figure 11*a* of *Bane et al.* [1981].)

temperatures throughout the water column from the outer shelf and slope (Figures 1*c* and 2*c*). A meander trough moves the front seaward, away from the shelf break, causing decreasing northward current speeds, current reversals, and decreasing temperatures.

Numerical model results indicate that eddy growth occurs due to baroclinic instability throughout the SAB [*Orlanski and Cox*, 1973; *Luther and Bane*, 1985; *Chao and Kao*, 1987; *Boudra et al.*, 1988; *Oey*, 1988]. In the Straits of Florida, perturbations of velocity and density fields can be generated by flow over topography and by local along-channel wind forcing [*Düing et al.*, 1977; *Johns and Schott*, 1987; *Lee and Williams*, 1988; *Schott et al.*, 1989]. *Boudra et al.* [1988] used an isopycnic coordinate model to show that the growth of Florida Current perturbations was due primarily to baroclinic instability and resulted in meanders with wave properties that matched observations. Fluctuations of volume transport of ±3 to $\pm 5 \times 10^6$ m^3 s^{-1} and changes in the slope of isopycnal surfaces accompany these disturbances on time scales of about 1 week. The perturbed velocity and density fields are advected northward out of the confines of the Straits of Florida by the mean flow of the Gulf Stream [*Zantopp et al.*, 1987; *Lee and Williams*, 1988].

Explosive growth of frontal perturbations takes place immediately downstream of the straits and downstream of the Charleston bump, near Cape Fear. *Oey* [1988] used a three-dimensional, nonlinear, time dependent model to show that the growth of finite amplitude disturbances is dependent on $(L_0/R_0)(h_0/H)$ where L_0 is the cross-stream distance from the slope to the Gulf Stream axis, R_0 is the Rossby radius of deformation, h_0 is the upper layer depth, and H is the basin depth. Oey's analysis indicates that increased growth rates are primarily related to L_0, which increases north of the Straits of Florida and downstream of the Charleston bump. Decreased growth rates are related to h_0/H, which decreases sharply in the greater depths off Cape Lookout and Cape Hatteras, and also L_0, which decreases as the Gulf Stream converges on the Charleston bump. *Oey* [1988] shows good agreement between observations and modeled frontal eddy-meander phase speeds (~40 cm s^{-1} toward north), wavelengths 100 to 200 km, asymmetric spatial structure, forward upwelling and backward downwelling regions, warm filaments, growth rate (3–7 days) and energy conversions in the regions upstream and downstream of the Charleston bump.

The amplification of disturbances off Cape Fear appears to be clearly related to perturbations that were either generated

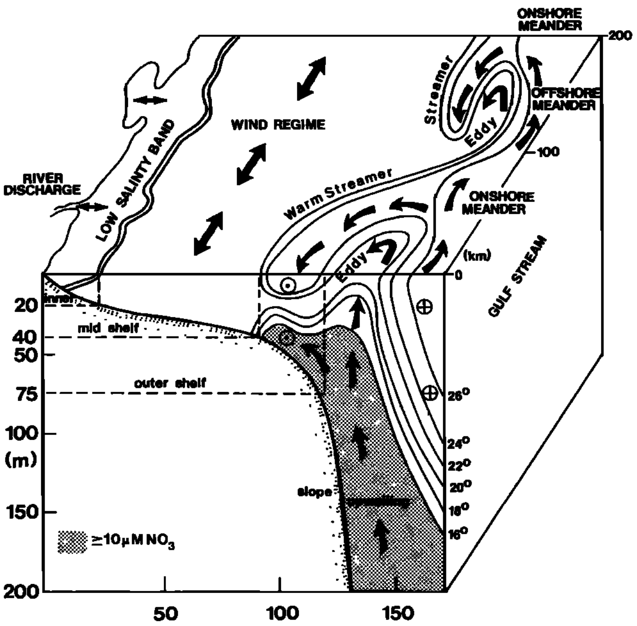

Fig. 4. Schematic of Gulf Stream frontal eddies and meanders together with shelf flow regimes on the SAB.

or enhanced by interaction of the Gulf Stream flow with the topography of the Charleston bump. *Lee et al.* [1989] showed that the Gulf Stream position off Long Bay (immediately downstream of the Charleston bump) has two preferred modes: onshore, with the front following the shelf break and weekly period frontal eddies interacting directly with the shelf waters of Long Bay, and offshore, when the Gulf Stream front can be located 100 km seaward of the shelf break. *Lee et al.* [1989] show that the transition to the offshore mode is rapid, requiring only about 1 week, and occurs together with the rapid growth of enlarged frontal eddies. These eddies travel with the Gulf Stream frontal waves on a convergent course toward Cape Hatteras, where they elongate and shear apart over the steeper and deeper slope region off Cape Lookout and Cape Hatteras. Interestingly, the Gulf Stream can remain in the offshore mode off Long Bay for 1 to 3 months [*Bane and Dewar*, 1988; *Lee et al.*, 1991] with a cold, cyclonic gyre (the Charleston gyre [*Singer et al.*, 1983; *Bane*, 1983]) spun up between the shelf and the offshore displaced Stream. Enlarged frontal eddies continue to shed from the gyre–Gulf Stream interaction as small vorticies are advected offshore and around the common gyre–Gulf Stream front and detach with the front on its northeasterly course toward Cape Hatteras.

Biological Production

Phytoplankton and bacterioplankton production of the middle and outer shelf is controlled principally by the upwelling-intrusion events associated with the Gulf Stream frontal processes just described. Productive phytoplankton blooms develop within upwelled waters on the outer shelf during all seasons of the year (results summarized by Yoder [1985, 1991]). During warmer months of the year (May through October), phytoplankton blooms also occur within upwelled waters that penetrate to the middle shelf as subsurface intrusions. Under these conditions, blooms are subsurface but still highly productive because of the clear surface water [*Yoder et al.*, 1985; *Paffenhofer et al.*, 1987*a*]. For example, during summer 1981, primary production averaged 1.9 g C m^{-2} d^{-1} for 40 days in middle shelf waters affected by large intrusions [*Yoder et al.*, 1985].

Since long time series of biological measurements are not available for southeastern shelf waters, seasonal, annual and interannual effects of Gulf Stream–induced upwelling on productivity of this region must be based on models, satellite imagery, and extrapolation of limited field data sets. The approach used in this paper is to combine the observations of biological response for a few individual upwelling events with long-term current and temperature records that show the frequency and intensity of the events.

DATA SOURCES AND METHODS

Statistical analyses of spatial variability of the Gulf Stream cyclonic frontal zone from satellite IR images are combined with cross-front estimates of momentum and heat flux to show the existence of preferred regions for eddy growth and decay. Standard deviations of cross-stream displacements of the Gulf Stream front are reproduced from *Bane and Brooks* [1979] and shown in Figure 5 together with net momentum $\overline{u'v'}$ and heat flux $\overline{u'T'}$ estimates derived from a combination of historical and recent data sets obtained within the frontal zone (Table 1). The range of values listed represents the change over depth of the time average (net) fluxes. The fluctuating current components are rotated into cross-

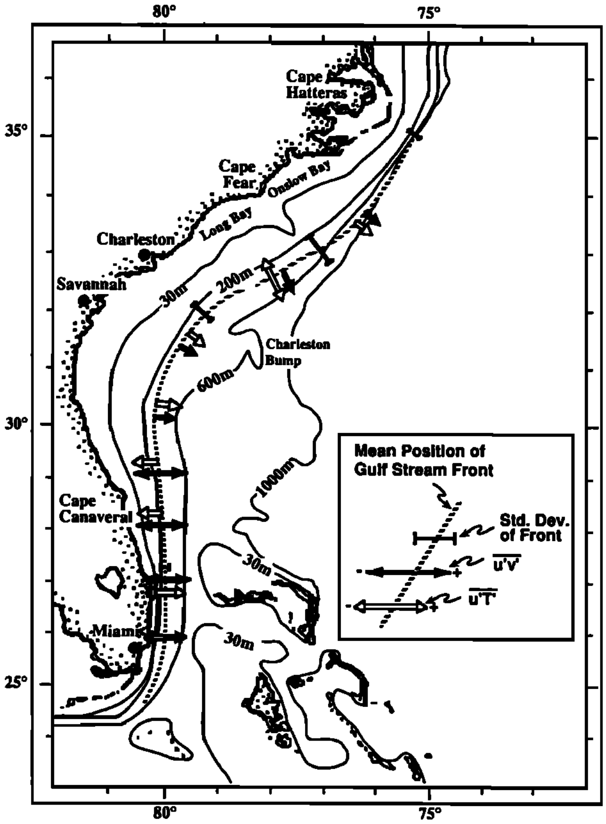

Fig. 5. Net fluxes of momentum $\overline{u'v'}$ and heat $\overline{u'T'}$ across the Gulf Stream cyclonic front together with the mean and standard deviation of frontal positions (frontal positions from Figures 1 and 2 of *Hood and Bane* [1983]), term estimates, and data sources given in Table 1.

TABLE 1. Cross-Stream Flux of Momentum and Heat and Energy Transfer Within the Gulf Stream Cyclonic Frontal Zone

Location	$\overline{u'v'}$, cm^2 s^{-2}	$\overline{u'T'}$, cm s^{-1} °C	$\overline{u'v'}\,(\partial v/\partial x)$, $\times 10^{-4}$ cm^2 s^{-3} (KE′ ⇄ KE)	$g\overline{u'\rho'}\,(\partial\bar{\rho}/\partial x)\,\lvert\partial\bar{\rho}/\partial z\rvert^{-1}$, $\times 10^{-4}$ cm^2 s^{-3} (PE′ ⇄ PE)	Stability	Time Period	Data Type	Source	Current Vector Rotation
26°N	50 to 100	−2 to −10	50 →	50 ←	unstable	Summer 1974	dropsonde	*Brooks and Niler* [1977]	0°
27°N	10 to 70	1 to 8	20 to 40 →	5 to 15 →	stable	1982–1984	Current meters, STACS	*Schott et al.* [1988]	0°
	8 to 20	0.2 to 0.6	4 to 12 →	2 to 4 →	stable	Dec. 1983 to Aug. 1984	EOF 12-day mode	*Johns and Schott* [1987]	0°
	3 to 9	0.2 to 0.8	2 to 4 →	2 to 4 →	stable	Dec. 1983 to June 1984	EOF 5-day mode	*Johns and Schott* [1987]	0°
	−200 to +120	−2 to +6	±60 ⇄	±30 ⇄	mixed	April 1982 to July 1984	Pegasus STACS	*Leaman et al.* [1987]	0°
	200 to 400	20 to 50	→	→	stable	March–Aug. 1984	current meter, FACTS-I	*Lee et al.* [1986]	0°
	−200	−0.4 to +7	←	⇄	unstable	Oct. 1984 to March 1985	current meter, FACTS-II	*Lee et al.* [1986]	0°
	−300 to −100	−1.4 to +3.5	←	⇄	unstable	March–June 1985	current meter, FACTS-III	*Lee et al.* [1986]	0°
27°30′N	−175 to −90		←		unstable	March–Aug. 1984	current meter, FACTS-I	*Lee et al.* [1986]	0°
28°N	30 to 100		→		stable	March–Aug. 1984	current meter, FACTS-I	*Lee et al.* [1986]	−5°
	−50 to +30	−1.1 to −0.3	⇄	←	unstable	Oct. 1984 to March 1985	current meter, FACTS-II	*Lee et al.* [1986]	−5°
29°N	−20 to +130		⇄	←	mixed	March–Aug. 1984	current meter, FACTS-I	*Lee et al.* [1986]	−10°
	−50 to +2	−2.5 to −0.7	⇄	←	unstable	Oct. 1984 to March 1985	current meter, FACTS-II	*Lee et al.* [1986]	−10°
	−90 to +45	−8 to +0.8	⇄		unstable	March–June 1985	current meter, FACTS-III	*Lee et al.* [1986]	−10°
30°N	30 to 50		→		stable	March–Aug. 1984	current meter, FACTS-I	*Lee et al.* [1986]	0°
	50 to 100	−1.1 to −0.6	→	←	unstable	Oct. 1984 to March 1985	current meter, FACTS-II	*Lee et al.* [1986]	0°
	70 to 200	2 to 6	50 →	60 →	stable	Feb.–June 1980	current meter, GABEX-I	*Lee and Atkinson* [1983]	0°
	30 to 600	1 to 15	12 →	10 →	stable	June–Oct. 1981	current meter, GABEX-II	*Lee and Pietrafesa* [1987]	0°
31°30′N	300 to 800	2 to 9	20 to 200 →	10 to 20 →	stable	Feb. 1983 to Aug. 1984	current meter, Blake Plateau	*Lee* [1986]	+17°
32°30′N	50 to 370	−10 to 20	20 to 30 →	−7 to −2 ←	unstable	Feb. 1983 to Aug. 1984	current meter, Blake Plateau	*Lee* [1986]	+39°
33°30′N	115 to 413	−1 to 13	30 to 100 →	10 to 50 →	stable	Feb. 1983 to Aug. 1984	current meter, Blake Plateau	*Lee* [1986]	+38°

Currents were rotated into an isobath coordinate system; the rotation angle is given in the right-hand column. The range of values in each column represents the variation over depth of the time averages. Abbreviations are as follows: FACTS, Florida Atlantic Coast Transport Study; GABEX, Georgia Bight Experiment; STACS, Subtropical Atlantic Climate Studies.

isobath (u') and along-isobath (v') directions, with v' generally aligned with the mean frontal orientation. The rotation angles used are given in Table 1. The fluctuating temperature is given by T'. The overbar represents a time average. The shortest averaging period was 3 months for the historical dropesonde data and 4 months for current meter data obtained during spring 1985 (Table 1). The remaining data sets were all 6 months or longer in duration, which is normally sufficient to reach stable mean conditions. However, the omission of these two shorter data sets would have little influence on the main conclusions regarding spatial patterns. Arrows represent the sign or direction of the flux, positive offshore or against the gradient in the cyclonic front, and negative onshore or with the gradient. The magnitudes and vertical ranges of these fluxes are given in Table 1. There was no attempt to attach magnitudes to the arrows owing to the large number of different types of data sources used with differing record lengths, time of measurement and vertical extent. The common feature of the data sets is they all provide estimates of the net flux of momentum and heat within the cyclonic frontal zone for the interior portion of the water column, i.e., away from the surface and bottom Ekman layers.

The calculation of nitrate flux at the shelf break depends on the linear relationship between nitrate and temperature for newly upwelled waters [*O'Malley et al.*, 1978]. Nitrate concentrations in Gulf Stream thermocline waters off the SAB can be estimated by the relationship

$$[\mathrm{NO_3}] = 53.0 - 2.6T$$

where $[\mathrm{NO_3}] = 0$ for $T > 20°\mathrm{C}$. Given this relationship, nitrate flux ($\overline{u'NO_3{}'}$) can be determined from current and temperature time series. This technique has been used previously by *Lee et al.* [1981] and *Lee and Atkinson* [1983].

RESULTS AND DISCUSSION

Preferred Regions of Eddy Growth and Decay

Cross-front momentum and heat flux. The mean position of the Gulf Stream front tends to follow the 200-m isobath from the Straits of Florida to about 32°N, where it is displaced offshore owing to the offshore turning of the stream by bottom steering of the flow over the Charleston bump (Figure 5). North of about 33°N the mean front converges shoreward as the Gulf Stream approaches Cape Hatteras. The amplitude of onshore-offshore meanders of the front shows a similar pattern, with standard deviations increasing steadily from the Straits of Florida to the Charleston bump, then increasing sharply downstream of the bump, followed by a decrease at Cape Hatteras.

Since meanders and frontal eddies are seldom symmetrical in shape, but rather are elongated and skewed (Figures 1–3, Plate 1), their passage causes strong instantaneous and net fluxes of momentum $\overline{u'v'}$ and heat $\overline{u'T'}$ over the outer shelf and slope as observed in Eulerian measurements.

Cross-front momentum fluxes tend to be positive at Miami and all locations north of 30°N and to be variable from 27° to 29°N where the Gulf Stream emerges from the Straits of Florida. Cross-front heat fluxes are negative in the regions where rapid eddy growth is observed, i.e., off Miami, Cape Canaveral, and Cape Fear, and positive in the regions where eddy and meander scales decrease, i.e., between 30° and 32°N and off Onslow Bay. The only exception is off Long Bay, where both negative and positive heat flux occurred. This variability may be caused by the large east-west shifts of the Gulf Stream that occur in this area, causing the mooring to be located within the cyclonic front only part of the time.

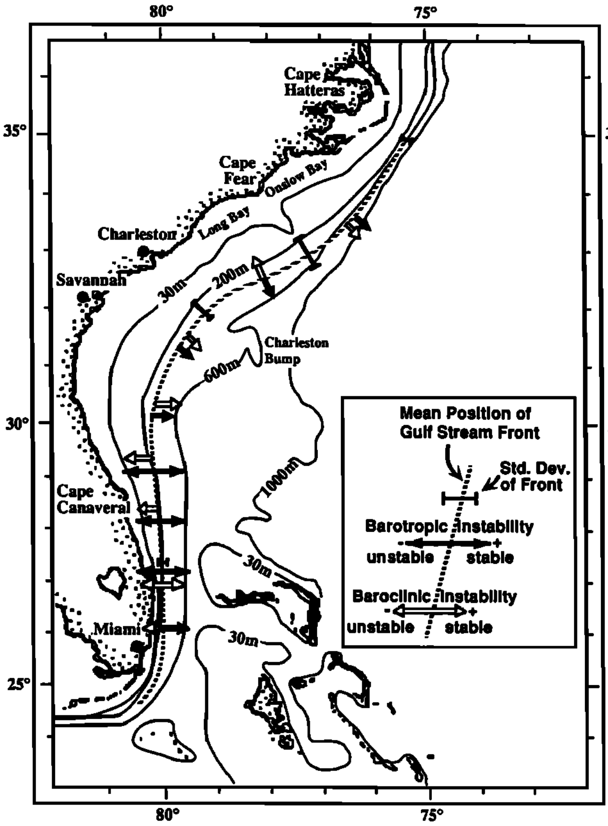

Fig. 6. Estimates of energy transfer terms $\overline{u'v'}\ \partial\bar{v}/\partial x$ (negative or onshore for barotropic instability), $\overline{u'\rho'}\partial\bar{\rho}/\partial x|\partial\bar{\rho}/\partial z|^{-1}$ (negative or onshore for baroclinic instability), term estimates, and data sources given in Table 1 (frontal positions from Figures 1 and 2 of *Hood and Bane* [1983]).

Baroclinic instability. Since cross-stream gradients of downstream current and temperature are both positive within the Gulf Stream's cyclonic front, the sign of the flux terms also provides an estimate of the direction of energy transfers between perturbation kinetic energy (KE′) and potential energy (PE′) of the fluctuations with the mean flow and density fields as determined by the commonly computed barotropic and baroclinic instability terms [*Brooks and Niiler*, 1977; *Hood and Bane*, 1983; *Dewar and Bane*, 1985; *Johns and Schott*, 1987; *Leaman et al.*, 1986]:

$$\overline{u'v'}\,\frac{\partial \bar{v}}{\partial x} < 0$$

$$g\,\overline{u'\rho'}\,\frac{\partial \bar{\rho}}{\partial x}\left|\frac{\partial \bar{\rho}}{\partial z}\right|^{-1} < 0$$

The direction of energy transfer as computed by these terms is shown in Figure 6. Negative values imply energy flux to the perturbations (unstable) and are shown by onshore arrows. Positive values imply energy flux to the mean (stable) and are shown by offshore arrows. The magnitudes of the energy transfers are given in Table 1 for those data sets that were usable for this purpose. Energy exchange estimates indicate preferred regions for baroclinic instability of the frontal zone in the vicinity of Miami, Cape Canaveral, and Cape Fear, which supports earlier conclusions drawn from satellite IR images (Plate 1). At the northern end of the Straits of Florida (27°N), both stable and unstable modes can occur within the frontal zone, but this is replaced by a strong tendency for baroclinic instability to dominate in the growth region north of the straits. Apparently frontal perturbations grow rapidly after the Gulf Stream emerges from the confines of the Straits of Florida and again after the flow impinges upon the Charleston bump and turns offshore. The amplification is supported by a transfer of potential energy from the mean density field to the perturbation, which is converted into perturbation kinetic energy and then fed back to the mean flow, thus completing the energy cycle of the baroclinic instability process [*Orlanski*, 1969; *Orlanski and Cox*, 1973].

Two stable regions are indicated in Figure 6, from 30° to 32°N and from about 33°N to Cape Hatteras, where the frontal perturbations give up both their eddy kinetic and potential energy to the mean flow and density fields, respectively. Satellite imagery (Plate 1) shows that within these stable regions, frontal eddies tend to elongate to a point that they are no longer easily identifiable and apparently become stranded on the outer shelf where they are sheared apart from the main body of the Gulf Stream.

Nitrate flux. The direction of the net cross-stream nitrate flux within the Gulf Stream cyclonic front can be determined from the net heat flux estimates (Figure 5). Since temperature and nitrate are inversely correlated [*O'Malley et al.*, 1978] the sign of the nitrate flux will be opposite to that of the heat flux (Figure 7). Therefore the mean transport of nitrogen across the shelf edge is offshore in areas of preferred eddy growth and onshore in regions of preferred eddy decay, i.e., stable regions characterized by fully developed eddies that begin to elongate and shear apart over the outer shelf. A clear example supporting the regional characterization of these features is obvious in the satellite-derived surface thermal patterns shown in Plate 1. Upwelling in the mature eddy occurs within the northern, or front, half of the feature, where the flow is onshore as a result of the cyclonic circulation of the vortex. This results in an onshore transport of nutrient rich waters onto the shelf and a negative nitrate flow. In the eddy decay regions the shoreward transported nitrate strands over the outer shelf as the eddy shears apart from the Gulf Stream front. Therefore in the stable regions of eddy decay there is a net shoreward flux of nitrate averaged over the length of the feature, i.e., averaged at a fixed mooring site over the time it takes an eddy to pass, which is typically about 3–5 days. The new nitrogen brought to the outer shelf can be totally consumed in about 2 weeks by grazing phytoplankton (primarily diatoms) [*Yoder et al.*, 1983], which can lead to zooplankton blooms [*Paffenhofer et al.*, 1987*b*].

Frontal Eddies as Gulf Stream Nutrient Pumps

The thermocline of the subtropical North Atlantic contains large quantities of nitrate nitrogen that fuels new carbon production when transported into the euphotic zone. Nitrate concentrations of 10 and 20 μM extend across the North Atlantic subtropical gyre at depths of about 500 and 700 m, respectively [*Roemmich and Wunsch*, 1985]. *Pelegri and Csanady* [1991] refer to a "nutrient stream" formed by an intense core of along-stream nitrate flux centered at about 500 m in the Gulf Stream. They find that along-isopycnal inflow of new nutrients from the subtropical gyre can triple the nutrient transport between the Florida Strait and the Mid-Atlantic Bight (MAB). Geostrophic uplifting of the thermocline on the western side of the gyre in the Gulf Stream brings the 10- and 20-μM nitrate concentrations to within about 100 and 200 m of the surface, respectively. Unlike the MAB, where the Gulf Stream is separated from the shelf by the slope sea [*Csanady*, 1990], in the SAB the Gulf Stream interacts directly with the shelf waters through the process of baroclinic instability that leads to the growth of frontal eddies and meanders. *Csanady* [1990] showed that baroclinic instability is the primary mechanism for supplying nitrate to the MAB shelf from the "nutrient bearing strata" (NBS) beneath the Gulf Stream. However, this is the last stage of a complicated sequence of events connecting the NBS to the shelf. First, the Gulf Stream nutrients must be transported across the slope sea by the formation and advection of warm core rings. Csanady's exchange model for the MAB then involves baroclinic instability of the outer shelf front formed by interaction of shelf and slope water (warm core rings) to extrude "boluses" in the surface (offshore) and bottom (onshore) layers to complete the mass transfer.

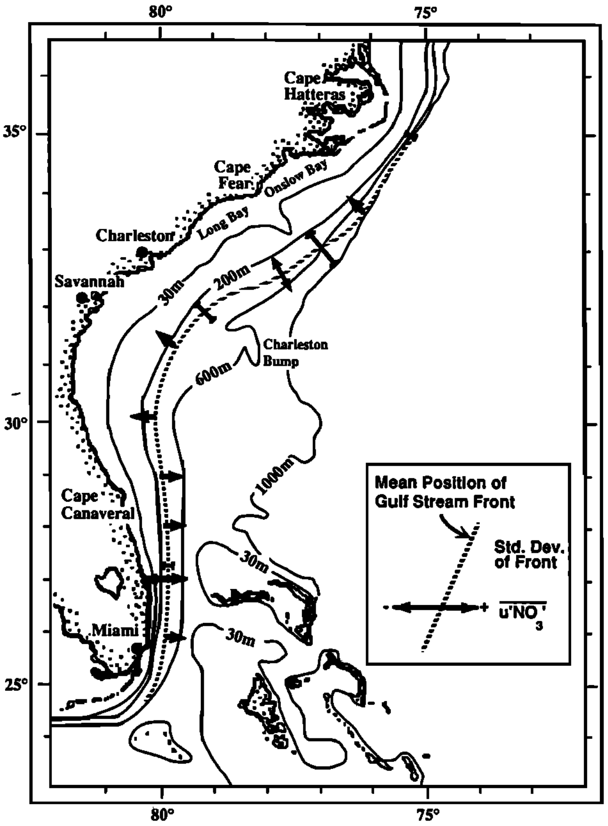

Fig. 7. Nitrate flux across the Gulf Stream cyclonic front together with the mean and standard deviation of frontal positions (frontal positions from Figures 1 and 2 of *Hood and Bane* [1983]), term estimates, and data sources given in Table 1.

A shelf edge exchange model for the SAB is shown in Figure 4. The Gulf Stream flows along the shelf edge over the alongshore extent of the SAB, except in the area off Long Bay where the stream is displaced offshore for periods of 1 to 3 months [*Bane and Dewar*, 1988; *Lee et al.*, 1989; *Lee et al.*, 1991]. Frontal eddies extend across the outer shelf, causing direct interaction of the stream with shelf waters. Upwelling and onshore transport in the cold core of frontal eddies pumps new nutrients from the NBS directly onto the outer shelf and into the euhotic zone in a cold, subsurface intrusion. *O'Malley et al.* [1978] found a linear, negative correlation between "new nitrate" from the NBS and temperature for temperatures less than 20°C. *Lee and Atkinson* [1983] used this correlation to compute nitrate flux profiles at the shelf break from moored current and temperature time series. They found the vertically averaged net nitrate flux at the shelf break (75 m) for the eddy event shown in Figure 2 to be onshore at $-115\ \mu M\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$, and for the total 4-month record it was onshore at $-65\ \mu M\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$. They concluded that since frontal eddies occurred about half the time and the 4-month nitrate flux was about half of that for the event, then eddies represent the dominant source of new nitrogen to the outer shelf. *Yoder et al.* [1983] found phytoplankton (diatom) blooms in the frontal eddy's upwelled waters that matched the physical dimensions of eddy features. Phytoplankton production in these blooms averaged about $2\ \mathrm{g\ C\ m}^{-2}\ \mathrm{d}^{-1}$. Primary production in the upwelled waters of the eddy events for the 6-month winter–spring period was estimated at $180\ \mathrm{g\ C\ m}^{-2}\ (6\ \mathrm{months})^{-1}$ of which at least 50% is new production.

The outer shelf eddy decay regions between 30° and 32°N and between Cape Fear and Cape Hatteras should represent areas of enhanced primary production. *Deibel* [1985] found blooms of dinoflagellates and diatoms togther with large doliolid blooms near midshelf at about 32°N during spring. *Ishizaka* [1990*a*] analyzed coastal zone color scanner (CZCS) images from the 30° to 32°N region together with optimally interpolated flow and temperature fields from the Georgia Bight Experiment (GABEX) I data set to show that the outer shelf chlorophyll distributions were produced by the passage of frontal eddies. *Ishizaka* [1990*b*] used these interpolated flow and temperature fields with a coupled physical-biological numerical model, upgraded with the CZCS imagery, to show that horizontal advection is the primary mechanism controlling variability of phytoplankton distributions and that biological processes responding to nutrient input from eddy-induced upwelling controlled the chlorophyll concentrations.

Moored measurements of outer shelf flow and temperature variability from the eddy decay regions span all seasons and indicate that the weekly passage of frontal eddies and meanders dominates shelf edge exchange throughout the year [*Lee et al.*, 1981; *Atkinson et al.*, 1983; *Lee and Atkinson*, 1983; *Lee and Pietrafesa*, 1987]. Therefore we can use the vertically averaged, net nitrate flux calculated by *Lee and Atkinson* [1983] from shelf edge current meter data at 30°N for a 4-month winter–spring period to estimate the total amount of nitrogen (N_T) transported onto the shelf from the NBS in the 30°–32°N eddy decay region over a 1-year period:

$$\mathrm{N}_T = Q_N H L t \qquad (1)$$

where Q_N is the vertical average, net nitrogen flux for the 4-month period and is $-0.91\ \mathrm{mg\ N\ m}^{-2}\ \mathrm{s}^{-1}$, as determined from the $-65\ \mu M\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$ nitrate flux computed by *Lee and Atkinson* [1983]; $H = 75$ m, the depth of the shelf edge; $L =$ 278 km, the approximate along-shelf distance of the Florida-Georgia shelf eddy decay region; and t is the time period over which the nitrogen transport is calculated, in this case, 1 year (3.154×10^7 s). The annual nitrogen input to the Florida-Georgia shelf from the NBS is estimated at $0.6 \times 10^{12}\ \mathrm{g\ N\ yr}^{-1}$ or 0.66×10^6 tons N yr^{-1}. This amounts to about $19\ \mathrm{kg\ N\ s}^{-1}$ over the total 278-km alongshore distance.

Using the approach presented above we estimate the cross-shelf nitrate flux in the outer shelf of the North Carolina eddy decay region from current and temperature records for a 20-month period from July 1983 to August 1985 [*Lee*, 1986]. Nitrate flux time series from current and temperature data at 7, 40, and 70 m depths at the shelf edge (75 m) off Onslow Bay gives a net onshore vertically averaged nitrate flux of $-80\ \mu M\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$. Using (1) above with $Q_N = -1.12\ \mathrm{mg\ N\ m}^{-2}\ \mathrm{s}^{-1}$, $H = 75$ m, $L = 278$ km (the alongshelf distance of the eddy decay region between Cape Fear and Cape Hatteras), and $t = 1$ year or 3.154×10^7 s, the annual nitrogen input to the North Carolina shelf from the NBS is approximately $0.74 \times 10^{12}\ \mathrm{g\ N\ yr}^{-1}$, or 0.8×10^6 tons N yr^{-1}, which is about $25\ \mathrm{kg\ N\ s}^{-1}$ over the total 278-km alongshore distance. The total Gulf Stream input to the SAB outer shelf is therefore $1.3 \times 10^{12}\ \mathrm{g\ N\ yr}^{-1}$ (1.4×10^6 tons N yr^{-1}), found by adding the annual nitrogen inputs to the Florida-Georgia and North Carolina shelves.

New Carbon Production

Frontal eddies strongly influence mass exchange on the outer shelf of Florida, Georgia, and North Carolina throughout the year [*Lee et al.*, 1981; *Atkinson et al.*, 1983; *Lee and Atkinson*, 1983; *Lee and Pietrafesa*, 1987]. The outer shelf extends from approximately the 40 m isobath to the shelf edge, which is about the outer third of the SAB shelf in the eddy decay regions, or about 30 km. Therefore the total shelf area that the shelf edge nitrate flux supplies is about 556 km × 30 km or $1.67 \times 10^{10}\ \mathrm{m}^2$. The annual nitrogen input to this outer shelf area is $78\ \mathrm{g\ N\ m}^{-2}\ \mathrm{yr}^{-1}$, found by dividing the annual nitrogen input to the shelf from the NBS (1.3×10^{12} g N year^{-1}) by the shelf area.

Using Redfield's carbon : nitrogen ratio of phytoplankton biomass (5.7, by weight) and the nitrate flux estimate from above yields a potential new carbon production rate on the outer shelf of $445\ \mathrm{g\ C\ m}^{-2}\ \mathrm{yr}^{-1}$, or a total potential annual new production for the outer shelf of 7.4×10^{12} g C. The realized new production rate depends upon the rate at which nitrate is converted into phytoplankton biomass, which must be compared with the residence time of nitrate in the euphotic zone on the shelf. Both of these rates change with season. Biological dynamics may also change along the length of the SAB, but the available biological data are not sufficient to calculate along-shelf variability. Thus along-shelf differences in biological responses are ignored in the estimate derived below.

Previous studies suggest that the outer southeastern shelf has two main seasons with respect to phytoplankton processes: fall-winter-spring (September through May) and summer (May through August) [*Yoder*, 1985]. The seasons are delineated by the fate of upwelled waters. Eddy-induced onshore nitrate flux and resulting carbon production is primarily restricted to the outer shelf region during the fall, winter, and spring, when the shelf is vertically well-mixed and horizontally stratified. However, during summer the shelf becomes vertically stratified, and eddy-induced upwelled waters in the outer shelf can penetrate to middle and even inner shelf regions. These large, subsurface intrusions of nutrient rich waters were first thought to result from wind-induced upwelling [*Green*, 1944; *Taylor and Stewart*, 1959]. More recent results, combining shipboard surveys and moored current meter records, show that the conditions necessary for NBS waters to extend in a subsurface intrusion to the inner shelf are (1) vertical stratification on the shelf, (2) eddy-induced upwelling at the outer shelf, and (3) sustained upwelling favorable (northward) winds [*Atkinson et al.*, 1987; *Lee and Pietrafesa*, 1987; *Lorenzzetti et al.*, 1987]. These conditions are met on several occasions each summer on the Florida-Georgia shelf where intrusions start in the vicinity of Cape Canaveral, extend onshore to the middle and inner shelf, and can be advected northward by the mean flow as far as Savannah, Georgia, where offshore transport occurs [*Atkinson et al.*, 1987].

Nutrients in summer intrusions are utilized in about 2 weeks, leading to a succession of phytoplankton and zooplankton blooms [*Yoder et al.*, 1985; *Paffenhofer et al.*, 1987*b*; *Pomeroy et al.*, 1987]. *Hofmann and Ambler* [1988] used a time dependent biological model to show that the phytoplankton maximum in these summer bottom intrusions occurred about 8 days after the nitrate maximum and was followed about 8 days later by a zooplankton maximum. Hofmann and Ambler found that carbon production in the bottom intrusions was approximately 4 g C m^{-2} d^{-1}, which agrees well with *Yoder*'s [1985] measured values in these summer intrusions and is a factor of 2 greater than the carbon production in the eddy-induced upwelled waters in the outer shelf. *Hofmann* [1988] used a time dependent biological model coupled to flow and temperature fields from optimal interpolation of current meter data [*Ishizaka and Hofmann*, 1988] to show that owing to the longer residence time of summer bottom intrusions (order of 1 month), compared with frontal eddies (about 1–2 weeks), larger zooplankton communities develop in the former.

Previous studies show that all upwelled nitrate is utilized when intruded waters remain on the shelf for 2 weeks or more [*Yoder et al.*, 1983, 1985]. Thus we assume that all upwelled nitrate is utilized during the summer season. To estimate the proportion of upwelled nitrate utilized during the fall-winter-spring season, we compared nitrate flux to the outer shelf averaged over several upwelling events (0.20 g NO^3 −N m^{-2} d^{-1} [*Lee and Atkinson*, 1983]) with average phytoplankton nitrate uptake rates on the outer shelf measured during the same sequence of events (0.09 g NO^3 −N m^{-2} d^{-1} from *Yoder et al.* [1983]). This comparison suggests that approximately 45% of upwelled nitrate is utilized during the fall-winter-spring season events.

Dividing the annual NO^3 −N flux to the outer shelf (78 g NO^3 −N m^{-2} yr^{-1}) proportionately between the summer and the fall-winter-spring seasons and using our estimates of nitrate uptake efficiency for the two seasons yields an annual new production rate for the outer shelf of 260 g C m^{-2} yr^{-1} (after converting from N to C units with the Redfield ratio of 5.7). Outer shelf primary production was previously estimated to be 360 g.C m^{-2} yr^{-1} [*Yoder*, 1985], suggesting that new production averages 72% of the total primary production. Using our annual outer shelf new production estimate of 260 g C m^{-2} yr^{-1} and the outer shelf area of 1.67×10^{10} m^2 implies an annual new production for the entire outer shelf of the SAB of 4.3×10^{12} g C.

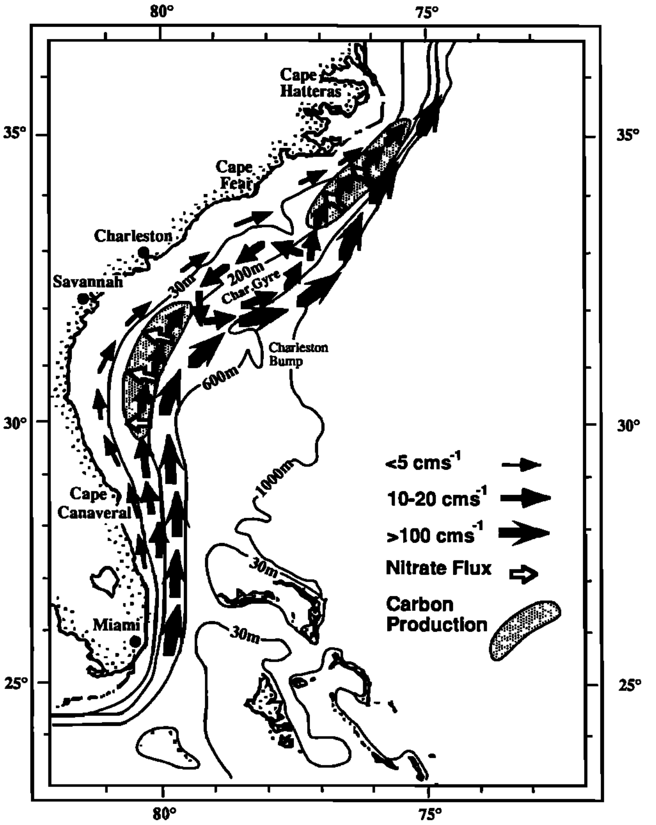

Fig. 8*a*. Characterization of mean circulation, onshore nitrate flux, and sites of potential Gulf Stream–induced new carbon production in the SAB during winter and spring conditions.

Carbon Export

Eventually, most of the carbon produced on the SAB shelf from upwelling of NBS waters will be returned to the deep sea (Gulf Stream), where some fraction will decompose and again become part of the NBS, part will be deposited in the sediments on the slope and Blake Plateau, and part will be transported northward for deposition on the MAB slope. Export of carbon from the shelf depends on many factors determined by the controlling physical, chemical, and biological processes that regulate the fate of biogenic particles. Biological and chemical processes control the form and size of biogenic particles, which can then influence the time scale for carbon export from the shelf through deposition, decomposition, and resuspension. Tides, storms, and weekly period Gulf Stream frontal eddies can produce transient pulses of carbon removal, but large-scale circulation features on time scales of months to seasons have the greatest influence on flushing the shelf carbon production.

The primary circulation features in the SAB are due to the Gulf Stream in the outer shelf (depths > 40 m) and seasonal atmospheric changes in the middle and inner shelf. The major circulation features are shown schematically in Figure 8, with the preferred regions for onshore nitrate flux and carbon production. Gulf Stream entrainment results in strong northward alongshore flow over all of the SAB outer shelf except Long Bay, where the mean alongshore flow is

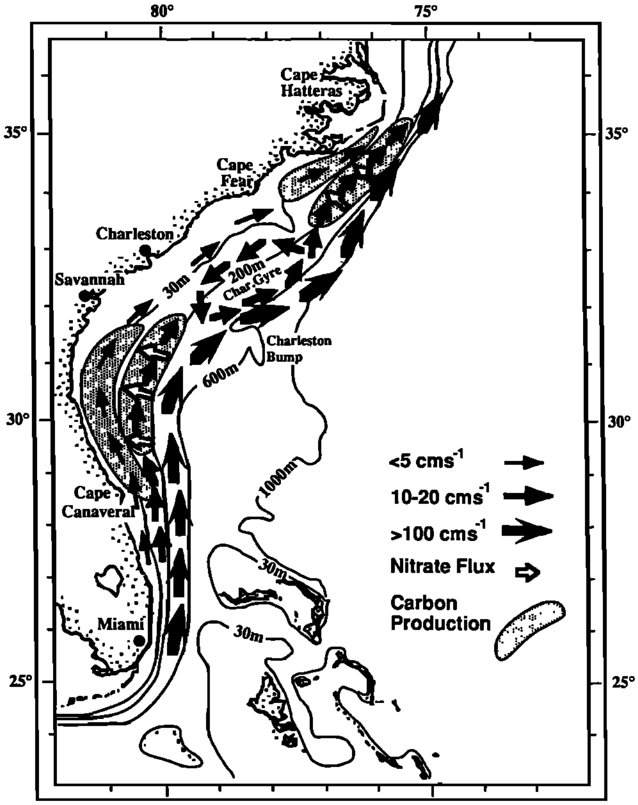

Fig. 8*b*. Characterization of mean circulation, onshore nitrate flux, and sites of potential Gulf Stream–induced new carbon production in the SAB during summer conditions.

southwestward owing to the offshore shift of the Gulf Stream by the Charleston bump and spin-up of a cold, cyclonic gyre (the Charleston gyre) between the Gulf Stream and the shelf [*Lee et al.*, 1989]. The Long Bay outer shelf is located on the westward side of this gyre, where the flow is toward the southwest. Current meter data indicate that the gyre persists about 65% of the time [*Lee*, 1986; *Bane and Dewar*, 1988; *Lee et al.*, 1989; *Lee et al.*, 1991]. When the gyre is not present, the Gulf Stream front can be close to the outer shelf and the mean alongshore flow is northeastward, similar to the other regions of the SAB.

The offshore steerage of the Gulf Stream by the Charleston bump and the formation of the Charleston gyre results in convergence of alongshore flow in the outer shelf between Savannah, Georgia, and Charleston, South Carolina, and a region of apparent offshore export of carbon. Since new carbon production in eddy-induced upwelling occurs primarily in the stable eddy decay regions (30°–32°N and Cape Fear to Cape Hatteras) and remains mostly in the outer shelf, except during the summer stratitied season, then carbon export from the outer shelf should occur primarily in the offshore flow regions between Savannah and Charleston and in Raleigh Bay near Cape Hatteras. The cycle of onshore nitrogen flux, carbon production, and offshore export in these two regions is shown schematically in Figure 8*a*. The time scale for this cycle is approximately 1–2 months for particles that remain in suspension.

Ishizaka [1990*c*] used a coupled physical-biological model, upgraded with CZCS data, to estimate that 6–9% of the total carbon production in a 20 km × 200 km box centered at 30°N between the 40-m and 75-m isobaths for a 26-day period in April 1980 (the GABEX-I data set) was exported offshore. This offshore export ranged from 961 to 1331 g C m^{-1} d^{-1} and is located south of the primary offshore export region shown in Figure 8*a*. The low offshore carbon export in this region indicates that either significant trapping occurred on the outer shelf or the major export was downstream, which would transport the production into the proposed offshore export region. The latter seems more likely, given the strong downstream flows in this area [*Lee and Atkinson*, 1983] and indeed was verified by E. Hofmann (personal communication, 1991). Offshore export between Savannah and Charleston was also indicated by *McClain et al.* [1988] from analysis of surface pigment patterns present in coastal zone color scanner data.

Seasonal averaged alongshore flows in the middle, and inner shelf are northward during the winter, spring, and summer periods at about 1–5 cm s^{-1} and support mean northward volume transports of about 10–20 × 10^4 m^3 s^{-1} [*Lee et al.*, 1984, 1989; *Lee and Pietrafesa*, 1987]. These mean flows were reproduced using one- and two-layer numerical circulation models to represent winter and summer conditions, respectively [*Kourafalou et al.*, 1984; *Lorenzzetti et al.*, 1988]. The model experiments indicate that the northward mean flows over the shelf are largely driven by the Gulf Stream as is depicted by a negative alongshore sea level slope at the shelf edge. Thus carbon production on the middle and inner shelf during the summer moves northward on the mean with an offshore component that transports the production into the outer shelf export

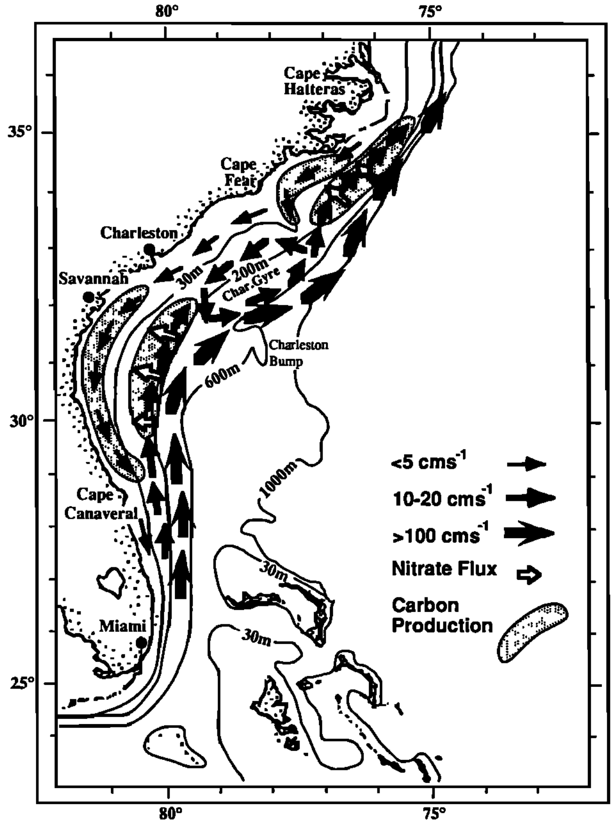

Fig. 8*c*. Characterization of mean circulation, onshore nitrate flux, and sites of potential Gulf Stream–induced new carbon production in the SAB during fall conditions.

regions between Savannah and Charleston and near Cape Hatteras. Mean residence time of materials in suspension over the middle and inner shelf are estimated at about 3 months from both alongshore flow considerations [*Lee et al.*, 1984] and salt balance methods [*Atkinson et al.*, 1978; 1983]. A schematic representation of the mean summer carbon transport cycle through mid and inner shelf waters is shown in Figure 8*b*.

During the fall season, strong southward winds persist for up to a week [*Weber and Blanton*, 1980; *Blanton et al.*, 1985] and drive a southward mean flow over the shelf [*Atkinson et al.*, 1983]. The mean southward alongshore flow is about -5 to -8 cm s^{-1} on the Florida-Georgia middle and inner shelf, accounting for a southward volume transport of about -30×10^4 m^3 s^{-1} [*Lee*, 1988]. During this season, carbon production on the middle and inner shelf is transported southward toward Cape Canaveral, where offshore export to the outer shelf can occur. The time scale for this process is also about 2–3 months. The carbon cycle for production on the middle or inner shelf in the late summer, followed by export to the outer shelf in fall, is shown schematically in Figure 8*c*.

CONCLUSIONS

Combining the annual nitrogen input to the Florida-Georgia outer shelf with that estimated for the North Carolina shelf gives a total Gulf Stream input to the SAB outer shelf of about 1.3×10^{12} g N yr^{-1} (1.4×10^6 tons N yr^{-1}) or 44 kg N s^{-1} over the total 556-km alongshore distance, which is equivalent to 80 mg N m^{-1} s^{-1} for the 556-km distance. Calculations indicate that approximately 70% of this nitrate is incorporated into phytoplankton biomass, yielding an annual new production for the entire outer shelf of the SAB of 4.3×10^{12} g C. Surprisingly, our nitrate flux estimate is approximately 40% greater than that found for a 900-km alongshore stretch of the MAB of 56 mg N m^{-1} s^{-1} for *Csanady* [1990] using a totally different approach. Csanady estimated 3.6 kg-at s^{-1} for the total nitrate transport to the shelf over this distance, which is 50.4 kg N s^{-1} or 56 mg N m^{-1} s^{-1}. Both estimates are probably uncertain to about a factor of 2; however, the MAB estimate may represent an upper bound because it was computed for summer conditions when isopycnals connect offshore and shelf waters and high nitrate concentrations were assumed for the slope-sea input, whereas the SAB estimate may be an underestimate because only frontal eddy exchange is considered and this is primarily restricted to the outer shelf and neglects summer conditions when nutrient rich subsurface intrusions can extend into middle and inner shelf regions [*Atkinson et al.*, 1987; *Lee and Pietrafesa*, 1987]. The SAB estimate also does not include the shelf region off Long Bay, where the Gulf Stream can be displaced offshore for periods of 1–3 months and does not directly influence the shelf. During these periods a cold, cyclonic gyre can form between the stream and the shelf, with onshore transport in the northern part of the gyre [*Lee et al.*, 1989]. However, the NBS is located further offshore and deeper in the water column than occurs for the case of direct frontal eddy exchange, so that onshore nitrate transport and shelf carbon production is reduced compared with the other outer shelf regions of the SAB.

In the SAB the rich NBS waters of the subtropical Atlantic are in direct contact with the shelf waters, and rapid exchange takes place via baroclinic instability of the Gulf Stream front. The result is an active recycling of nutrients from the NBS waters to carbon production on the shelf and return to the Gulf Stream for decomposition in the water column and reentry into the NBS or deposition on the continental slope and abyssal plain. Studies of the region to date have discovered preferred regions for nutrient flux onto the shelf and carbon production and removal to the oceanic conveyor belt (Gulf Stream) and have identified the key physical and biological processes involved. These studies provide a reasonable qualitative description of one of the more challenging problems facing marine science, understanding the ocean margin exchange and its impact on production and recycling of biogenic particles. Future studies are needed to quantify the exchange rates and particle transformations through the combination of interdisciplinary process studies that follow intrusion events through their life cycles on the shelf, using time series measurements of important physical, biological, chemical, and geological parameters and improved hydrodynamic-ecosystem models.

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