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GULF STREAM FRONTAL EDDY INFLUENCE ON
PRODUCTIVITY OF THE
SOUTHEAST U. S. CONTINENTAL SHELF

by

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Abstract. Weekly period meanders and eddies are persistent features of Gulf Stream frontal dynamics from Miami, FL, to Cape Hatteras, NC. 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 34°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. Annual carbon production on the shelf due to Gulf Stream input is estimated at 7×10^{12} g C year⁻¹ or about 7 million tons carbon per year. Seasonal carbon cycles are estimated for the outer, mid and inner shelf regions from Gulf Stream nutrient input, carbon production, and carbon export.

INTRODUCTION

Previous studies in the South Atlantic Bight (SAB) have shown that interaction between the Gulf Stream and adjacent shelf waters often determines the biological production. Upwelling in frontal eddies and summer bottom intrusions can advect nutrients into the euphotic zone of the upper slope and shelf (Lee, Atkinson and Legeckis, 1981; Lee and Atkinson, 1983; Lee and Pietrafesa, 1987; Atkinson, Lee, Blanton and Paffenhofer,

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; Ishizaka, 1990a,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 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.

Satellite Imagery

Satellite AVHRR thermal imagery (Fig. 1) typically shows that wave-like 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° to 30°N and again between 32° to 34°N. Dissipation appears to occur between 30° to 32°N and again between 34 to 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 800m 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 to 200 km in the downstream direction, while the features remain coupled to the parent offshore meanders, with cross-stream scales of 30 to 50 km (Lee, Atkinson and Legeckis, 1981; Bane and Brooks, 1979; Lee and Atkinson, 1983).

A second amplification region occurs between 32° and 34°N, just downstream of the Charleston bump, a topographic anomaly of the slope

extending seaward into the Gulf Stream (Brooks and Bane, 1978; Pietrafesa, Atkinson and Blanton, 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 to 250 km and periods of 2 to 14 days (Legeckis, 1979; Bane and Brooks, 1979; Brooks and Bane, 1981; Bane, Brooks and Lorenson, 1981; Olson, Brown and Emmerson, 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, Atkinson, Blanton and Yoder, 1983). Immediately downstream of the "bump" the Gulf Stream undergoes 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, FL, where eddies with diameters of 10 to 30 km are embedded in frontal meanders with wavelengths of 75 to 122 km. Northeast of Cape Hatteras, Gulf Stream meanders are no longer restricted by the continental shelf, as along the southeast U.S., and the well-known warm- and cold-core "rings" develop.

Weekly Period Frontal Eddies and Meanders

Meanders were first observed on the Blake Plateau 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 "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, Bumpus and Richardson, 1955) or folded wave patterns (Legeckis, 1979). This is the characteristic SST pattern of an eddy/meander combination seen in satellite thermal imagery of the Gulf Stream (Fig. 1).

Cyclonic, cold-core eddies are observed embedded in the Gulf Stream front in the Florida Straits region (Fig. 2a) along the Florida/Georgia outer shelf (Fig. 3a) and along the North Carolina outer shelf (Fig. 4). 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 1 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 transport nutrients into the euphotic zone for biological uptake (Lee and Atkinson, 1983) (Figs. 2b, 3b and 4).

A schematic representation of a fully developed Gulf Stream frontal eddy/meander field, identifying the various features, is shown in Fig. 5. The approach of a meander crest displaces the front shoreward, toward the outer-shelf. This results in strong northward currents and increased temperatures throughout the water column from the outer shelf and slope (Figs. 2c and 3c). A meander trough moves the front seaward, away from the shelf break, causing decreasing northward current speeds, current reversals and decreasing temperatures. Since meanders and frontal eddies are seldom symmetrical in shape, but rather are elongated and skewed (Figs. 1-4), 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 (Figs. 2b,c and 3b,c).

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, Bleck and Schott, 1988; and 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 (Duing, Mooers and Lee, 1977; Johns and Schott, 1987; Lee and Williams, 1988; Schott, Lee and Zantopp, 1989). Boudra, Bleck and Schott (1988) used an isopycnic coordinate model to show that the growth of Florida Current perturbations was primarily due to baroclinic instability and resulted in meanders with wave properties that matched observations. Fluctuations of volume transport of ± 3 to $\pm 5 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ and changes in the slope of isopycnal surfaces accompany these disturbances on time scales of about one 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, Leaman and Lee, 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, non-linear, 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 Stream converges on the Charleston bump. Oey (1988) shows good agreement between observations and modeled frontal eddy/meander phase speeds ($\sim 40 \text{ cm s}^{-1}$ toward north), wave lengths 100 to 200 km, asymmetric spatial structure, forward-upwelling and backward-downwelling regions, warm filaments, growth rate (3 to 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 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 one 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 one to three months (Bane and Dewar, 1988; Lee, Blanton, Lee and Evans, 1990) with a cold, cyclonic gyre (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 vortices 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 principally controlled 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 in Yoder, 1985, and Yoder, 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 (Yoder et al., 1985; Paffenhofer et al., 1987). For example, during the summer of 1981 primary production averaged $1.9 \text{ g C m}^{-2} \text{ day}^{-1}$ 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. In this manuscript we estimate temporal and spatial variability of nitrate flux to southeastern shelf waters, and its potential effect on productivity, using a large number of current meter records and other data sources collected over a 10-year period. We will show that the preferred areas of frontal eddy decay are also areas of preferred onshore nitrate flux and carbon production.

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 Fig. 6 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), u' and v' are the fluctuating current components in the cross- and along-isobath directions which generally tend to align with the mean frontal orientation. The overbar represents a time average. The fluctuating temperature is given by T' . Arrows represent the sign or direction of the flux, +offshore or against the gradient in the cyclonic front, and -onshore or with the

gradient. The magnitudes and ranges of these fluxes are given in Table 1. There was no attempt to attach magnitudes to the arrows due 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 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 shelfbreak 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

$$[\text{NO}_3] = 53.0 - 2.6T$$

where $[\text{NO}_3] = 0$ for $T > 20^\circ\text{C}$. Given this relationship, nitrate flux ($\overline{u'\text{NO}_3'}$) 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

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 200m isobath from the Straits of Florida to about 32°N lat. where it is displaced offshore due to the offshore turning of the Stream by bottom steering of the flow over the Charleston bump (Fig. 6). North of about 34°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. Cross-front momentum fluxes tend to be positive at Miami and all locations north of 30°N, and variable from 27° to 29°N where the 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° to 32°N and off Onslow Bay.

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 and potential energy 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, 1986; Leaman, Molinari and Vertes, 1986):

$$\overline{u'v'} \frac{\partial \bar{v}}{\partial x} < 0 \text{ implies barotropic instability}$$

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

The direction of energy transfer as computed by these terms is shown in Fig. 7. Negative values imply an energy flux to the perturbations (unstable) and is shown by an onshore arrow. Positive values imply an energy flux to the mean (stable) and is shown by an offshore arrow. 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 (Fig. 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 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 Fig. 7, between 30° to 32°N and from about 34°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 (Fig. 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 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 (Fig. 6). 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 (Fig. 8). 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 Fig. 1. Upwelling in the mature eddy occurs within the northern, or front half, of the feature where the flow is onshore due to the cyclonic circulation of the vortex. This results in an onshore transport of nutrient rich waters onto the shelf, and a negative nitrate flux. 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 to 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, Sherman and Lee, 1987).

DISCUSSION

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 700m, respectively, (Roemmich and Wunsch, 1985). 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 200m of the surface, respectively. Unlike the Mid Atlantic Bight (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.

A shelf edge exchange model for the SAB is shown in Fig. 5. 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., 1990). 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 (75m) for the eddy event shown in Fig. 3 to be onshore at $-115 \mu\text{M m}^{-2}\text{s}^{-1}$, and for the total 4 month record it was onshore at $-65 \mu\text{M m}^{-2}\text{s}^{-1}$. 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 $2 \text{ g C m}^{-2}\text{d}^{-1}$. Primary production in the upwelled waters of the eddy events for the 6 month winter/spring period was estimated at $180 \text{ g C m}^{-2} (6 \text{ months})^{-1}$ 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 together with large doliolid blooms near mid shelf at about 32°N during spring. Ishizaka (1990a) analyzed coastal zone color scanner (CZCS) images from the 30° to 32°N region together with optimally interpolated flow and temperature fields from the GABEX-I data set to show that the outer shelf chlorophyll distributions were produced by the passage of frontal eddies. Ishizaka (1990b) 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, Lee, Blanton and Chandler, 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° to 32°N eddy decay region over a one year period:

$$N_T = Q_N H L t \quad 1)$$

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

Using the above approach 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 five month period from March to August 1984 (Lee, 1986). Nitrate flux time series from current and temperature data at 7, 40 and 70m depths at the shelf edge (75m) off Onslow Bay gives a net onshore

vertically averaged nitrate flux of $-42 \mu\text{M m}^{-2} \text{s}^{-1}$. Using eq. 1) above with $Q_N = -0.59 \text{ mg N m}^{-2} \text{s}^{-1}$, $H = 75\text{m}$, $L = 278\text{km}$, the alongshelf distance of the eddy decay region between Cape Fear and Cape Hatteras and $t = \text{one year or } 3.154 \times 10^7 \text{s}$, the annual nitrogen input to the North Carolina shelf from the NBS is approximately $0.4 \times 10^{12} \text{ g N year}^{-1}$ or $0.44 \times 10^6 \text{ tons N year}^{-1}$, which is 12.7 kg N s^{-1} over the total 278 km alongshore distance.

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 $1.0 \times 10^{12} \text{ g N year}^{-1}$ ($10^6 \text{ tons N year}^{-1}$) or 31.7 kg N s^{-1} over the total 556 km alongshore distance, which is equivalent to $57 \text{ mg N m}^{-1} \text{s}^{-1}$ for the 556 km distance. Surprisingly, this is almost exactly the same as that found for a 900 km alongshore stretch of the MAB of $56 \text{ mg N m}^{-1} \text{s}^{-1}$ from 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 $56 \text{ mg N m}^{-1} \text{s}^{-1}$. 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 for 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 mid and inner shelf regions (Atkinson, Lee, Blanton and Paffenhöfer, 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 1 to 3 month periods 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 to the other outer shelf regions of the SAB.

Carbon Production

Frontal eddies strongly influence mass exchange on the outer shelf of the SAB 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 depth 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 x 30 km or $1.67 \times 10^{10} \text{ m}^2$. The annual nitrogen input to this outer shelf area is $60 \text{ g N m}^{-2} \text{ year}^{-1}$ found by dividing the annual nitrogen input to the shelf from the NBS ($1.0 \times 10^{12} \text{ g N year}^{-1}$) by the shelf area. Using Redfield's carbon:nitrogen ratio of 7:1 for new production gives an annual carbon production rate on the outer shelf of $420 \text{ g C m}^{-2} \text{ year}^{-1}$, or a total annual production of $7 \times 10^{12} \text{ g C}$. Yoder et al. (1983) combined direct measurements of primary production (averaged about $2 \text{ g C m}^{-2} \text{ d}^{-1}$ for eddy events) with the frequency of frontal eddies on the Florida/Georgia outer shelf to estimate an annual carbon production rate of $360 \text{ g C m}^{-2} \text{ year}^{-1}$, which is within 15% of the above moored estimate of carbon production rate using nitrogen transports with carbon:nitrogen ratios. Yoder et al. (1983) reports that 50% or more of the carbon production is "new production", which is less than half the potential for new production from eddy-induced upwelling.

Eddy-induced onshore nitrate flux and resulting carbon production is primarily restricted to the outer shelf region during the winter, spring and fall when the shelf is vertically well-mixed and horizontally stratified. However, during summer months of June, July and August 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; 3) sustained upwelling favorable (northward) winds (Atkinson et al., 1987; Lee and Pietrafesa, 1987; Lorenzetti, Wang and Lee, 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 mid and inner shelf and can be advected northward by the mean flow as far as Savannah, GA, where offshore transport occurs (Atkinson et al., 1987). Nutrients in the intrusions are utilized in about two weeks leading to a succession of phytoplankton and zooplankton blooms (Yoder, Atkinson, Bishop, Blanton, Lee and Pietrafesa, 1985; Paffenhofer, Sherman and Lee, 1987; Pomeroy, Paffenhofer and Yoder, 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 $4 \text{ g C m}^{-2} \text{ d}^{-1}$, which agrees well with Yoder's (1985)

measured values in these summer intrusions and is a factor of two 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, due to the longer residence time of summer bottom intrusions (order of 1 month), compared to frontal eddies (about 1-2 weeks), larger zooplankton communities develop in the former.

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 > 40m) and seasonal atmospheric changes in the mid and inner shelf. The major circulation features are shown

schematically in Fig. 9a,b,c, 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 southwestward due to the offshore shift of the Gulf Stream by the Charleston bump and spin-up of a cold, cyclonic gyre (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, Blanton and Lee, 1990). 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 steering 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, GA, and Charleston, SC, 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 stratified 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 Fig. 9a. The time scale for this cycle is approximately 1 to 2 months for particles that remain in suspension.

Ishizaka (1990c) used a coupled physical-biological model, upgraded

with CZCS data, to estimate that 6-9% of the total carbon production in a 20 km x 200 km box centered at 30°N between the 40m and 75m isobaths for a 26 day period in April 1980 (the GABEX-I data set) was exported offshore. This offshore export ranged from 961 - 1331 g C m⁻¹d⁻¹ and is located south of the primary offshore export region shown in Fig. 9a. 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).

Seasonal averaged alongshore flows in the mid 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 x 10⁴ m³ s⁻¹ (Lee, Ho, Kourafalou and Wang, 1984; Lee and Pietrafesa, 1987; Lee et al., 1989). These mean flows were reproduced using one and two layer numerical circulation models to represent winter and summer conditions, respectively (Kourafalou, Wang and Lee, 1984; Lorenzzetti, Wang and Lee, 1988). The model experiments indicate that the northward mean flows over the shelf are largely driven by the Gulf Stream as depicted by a negative alongshore sea level slope at the shelf edge. Thus, carbon production at mid and inner shelf during the summer moves northward on the mean with an offshore component that transports the production into the outer shelf export regions between Savannah and Charleston and near Cape Hatteras. Mean residence time of materials in suspension over the mid 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; Atkinson et

al., 1983). A schematic representation of the mean summer carbon transport cycle through mid and inner shelf waters is shown in Fig. 9b.

During the fall season strong southward winds persist for up to a week duration (Weber and Blanton, 1980; Blanton, Schwing, Weber, Pietrafesa and Hayes, 1985) and drives 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 mid and inner shelf, accounting for a southward volume transport of about $-30 \times 10^4 \text{ m}^3 \text{ s}^{-1}$ (Lee, 1988). During this season carbon production on the mid 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 to 3 months. The carbon cycle for production on the mid or inner shelf in the late summer, followed by export to the outer shelf in fall, is shown schematically in Fig. 9c.

CONCLUSIONS

A regional pattern for baroclinic instability of Gulf Stream frontal perturbations in the SAB is found by comparing frontal patterns displayed in satellite AVHRR thermal imagery with moored current meter estimates of cross-frontal flux of momentum and heat. Unstable areas most often occur near Miami, Cape Canaveral, and between the Charleston bump and Cape Fear. Explosive eddy growth occurs in the regions downstream of the Straits of Florida and the Charleston bump as frontal eddies become fully developed in just a few days. Likewise, stable regions occur in the northern Straits of Florida, between 30° and 32°N , and between Cape Fear and Cape Hatteras. The unstable regions off Miami and Long Bay appear to be related to flow over topographic features, the Miami Terrace and Charleston bump,

respectively; whereas, off Cape Canaveral the instabilities appear to occur due to the change from channelized flow in the Straits of Florida, with fixed lateral boundaries, to a flow bounded only on the shoreward side by a continental shelf that increases rapidly in width in the downstream direction. Frontal perturbations are advected downstream by the Gulf Stream where they are no longer confined by the boundaries of the channel, and rapid growth takes place as the distance from the shelf edge to the front increases. The stable areas occur where the flow converges on the Charleston bump and Cape Hatteras, decreasing the distance between the shelf edge and the front. Stable areas are characterized in satellite imagery as regions of frontal eddy elongation and stranding over the outer shelf as the eddy deforms and shears apart from the Gulf Stream front.

Upwelling in frontal eddies is the primary mechanism for transport of nutrient rich waters from the NBS beneath the Gulf Stream onto the outer shelf. Nitrate flux estimates from current and temperature data show that there are preferred regions along the SAB outer shelf for onshore nitrogen transport that correspond to the stable areas between 30° and 32°N and downstream of Cape Fear, where mature frontal eddies elongate and shear apart, stranding their nutrient load in the outer shelf for use in carbon production. Frontal eddies occur throughout the year at weekly intervals. The net onshore flux of nitrate across the shelf edge in the eddy decay regions off Florida/Georgia and North Carolina is estimated at -65 and -42 $\mu\text{M m}^{-2}\text{s}^{-1}$ from current and temperature records, respectively. The annual nitrogen input to the SAB outer shelf from eddy-induced upwelling is estimated at 1.0×10^{12} g N year⁻¹ or about 32 kg N s⁻¹. This input is spread over the two eddy decay regions with a total alongshore distance of about 556 km, resulting in 57 mg N m⁻¹s⁻¹, which is the same as the

nitrogen input estimated for a 900 km length of the MAB outer shelf (Csanady, 1990).

Eddy-induced upwelling is primarily restricted to the outer shelf during winter, spring and fall seasons when the shelf is horizontally stratified. The outer shelf area for the eddy decay regions is estimated at 30 km x 556 km or $1.67 \times 10^{10} \text{ m}^2$, with an annual nitrogen input to the area of $60 \text{ g N m}^{-2} \text{ year}^{-1}$. Using Redfield's carbon: nitrogen ratio of 7:1 gives an annual carbon production rate on the outer shelf of $420 \text{ g C m}^{-2} \text{ year}^{-1}$, or a total annual production of $7.0 \times 10^{12} \text{ g C}$ for the outer shelf area. The annual production rate is equivalent to that found by Yoder et al., (1983) by combining primary production estimates of $2 \text{ g C m}^{-2} \text{ d}^{-1}$ with frequency of frontal eddies.

The export of carbon from the SAB shelf depends strongly on shelf circulation features with time scales of one month or longer. New production in the outer shelf is advected in a northerly alongshore direction by Gulf Stream entrainment all along the SAB, excluding the Long Bay region. Mean flows in the outer shelf off Long Bay are in a southerly alongshore direction due to the offshore shift of the Gulf Stream downstream of the Charleston bump and the spin-up of the cyclonic Charleston gyre over the slope. This results in a convergence of alongshore flow between Savannah, GA, and Charleston SC, and a region of net offshore export. Offshore export on the North Carolina outer shelf should occur in the northern section where the flow converges toward Cape Hatteras. The time scale for removal of suspended material from the outer shelf is one to two months.

Circulation features in the mid and inner shelf regions are determined primarily by a combination of Gulf Stream influence and seasonal wind

patterns. During the winter, spring and fall the mean flow is northward over the SAB shelf with an offshore curvature toward the net export regions in the outer shelf between Savannah and Charleston and near Cape Hatteras. Modeling studies show that this pattern can be produced by a negative alongshore pressure gradient at the shelf edge of Gulf Stream origin (Kourafalou et al., 1984; Lorenzetti et al., 1988). Southward alongshore winds prevail during the fall and mean flows are toward the south with offshore export of the late summer production to the outer shelf in the vicinity of Cape Canaveral and Cape Fear. The circulation time scale for removal of suspended particles from the mid and inner shelf is on the order of 3 months, regardless of season.

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, 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, the understanding 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/ecosystems models.

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Figure Captions

Fig. 1. Satellite AVHRR thermal image of the Gulf Stream in the SAB for 0019 UT on April 23, 1980 (prepared by O. Brown and R. Evans of RSMAS, U. Miami).

Fig. 2a. Composite map of surface temperature for 20 to 23 Feb. 1973. Ship track designated by dots; temperature sections by letter (A)-(E); current meter moorings by blackened circles; arrows indicate observed current direction (Fig. 15 of Lee and Mayer, 1977).

Fig. 2b. Temperature sections through frontal eddy shown in Fig. 2a, arrows indicate XBT stations (Fig. 17 of Lee and Mayer, 1977).

Fig. 2c. Time series of hourly current and wind vectors during the passage of the frontal eddy shown in Fig. 2a (Fig. 16 of Lee and Mayer, 1977).

Fig. 3a. Ship measured surface temperature on April 25 (0847) to April 26 (2152) with daily averaged current vectors for April 26 (Fig. 21 of Lee and Atkinson, 1983).

Fig. 3b. Temperature, salinity, density and nitrate sections across the frontal eddy of Fig. 3a, Iselin section #23 (Fig. 22 of Lee and Atkinson, 1983).

Fig. 3c. Time series of 40 hr low pass wind vectors and 40 hr to 2 weeks band pass filtered currents during passage of frontal eddy of Fig. 3a (Fig. 23 of Lee and Atkinson, 1983).

Fig. 4. An extensive, oblique view of the thermal structure of meanders off Cape Fear and Onslow Bay, Feb. 11, 1979 constructed from XBT sections (Fig. 11a of Bane et al., 1981).

Fig. 5. Schematic of Gulf Stream frontal eddies and meanders together with shelf flow regimes on the SAB.

Fig. 6. 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 Figs. 1 and 2 of Hood and Bane, 1983), term estimates and data sources given in Table 1.

Fig. 7. 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 Figs. 1 and 2 of Hood and Bane, 1983).

Fig. 8. Nitrate flux across the Gulf Stream cyclonic front together with the mean and standard deviation of frontal positions (frontal positions from Figs. 1 and 2 of Hood and Bane, 1983), term estimates and data sources given in Table 1.

Fig. 9a. Characterization of mean circulation, onshore nitrate flux and Gulf Stream-induced carbon production in the SAB during winter and spring conditions.

Fig. 9b. Characterization of mean circulation, onshore nitrate flux and Gulf Stream-induced carbon production in the SAB during summer conditions.

Fig. 9c. Characterization of mean circulation, onshore nitrate flux and Gulf Stream-induced carbon production in the SAB during fall conditions.

Table 1 - Cross-stream flux of momentum and heat and energy transfer within the Gulf Stream cyclonic frontal zone

Location	$\overline{u'v'}$ $\text{cm}^2 \text{s}^{-2}$	$\overline{u'T'}$ $\text{cm s}^{-1} ^\circ\text{C}$	$\overline{u'v'} \frac{\partial \bar{v}}{\partial x}$ $\times 10^{-4} \text{cm}^2 \text{s}^{-3}$	$g \overline{u'\rho'} \frac{\partial \bar{\rho}}{\partial x} \left \frac{\partial \bar{\rho}}{\partial z} \right ^{-1}$ $\times 10^{-4} \text{cm}^2 \text{s}^{-3}$	Stability	Time Period	Data Type & Source
			KE' $\longleftrightarrow$ KE	PE' $\longleftrightarrow$ PE			
26°N	50 to 100	-2 to -10	50 →	50 ←	Unstable	Summer 1974	Dropsonde (Brooks & Niiler, 1977)
27°N	10 to 70	1 to 8	20 to 40 →	5 to 15 →	Stable	82-84	Current meters, STACS (Molinari et al. 1985)
	8 to 20	.2 to .6	4 to 12 →	2 to 4 →	Stable	12/83-8/84	EOF 12 day mode (Johns & Schott, 1987)
	3 to 9	.2 to .8	2 to 4 →	2 to 4 →	Stable	12/83-6/84	EOF 5 day mode (Johns & Schott, 1987)
	-200 to +120	-2 to +6	±60 → ←	±30 → ←	Mixed	4/82-7/84	PEGASUS STACS Leaman et al, 1987)
	200 to 400	20 to 50	→	→	Stable	3/84-8/84	Current meter, FACTS-I (LEE et al. 1986)
	-200	-.4 to +7	←	→ ←	Unstable	10/84-3/85	Current meter, FACTS-II (Lee et al. 1986)
	-300 to -100	-1.4 to +3.5	←	→ ←	Unstable	3/85-6/85	Current meter, FACTS-III (Lee et al. 1986)
27° 30'N	-175 to -90		←		Unstable	3/84-8/84	Current meter, FACTS-I (Lee et al. 1986)
28°N	30 to 100		→		Stable	3/84-8/84	Current meter, FACTS-I (Lee et al. 1986)
	-50 to +30	-1.1 to -.3	→ ←	←	Unstable	10/84-3/85	Current meter, FACTS-II (Lee et al. 1986)

Table 1. Continued

Location	$\overline{u'v'}$ $\text{cm}^2 \text{s}^{-2}$	$\overline{u'T'}$ $\text{cm s}^{-1} \text{ } ^\circ\text{C}$	$\overline{u'v'} \frac{\partial \bar{v}}{\partial x}$	$g \overline{u'\rho'} \frac{\partial \bar{\rho}}{\partial x} \left \frac{\partial \bar{\rho}}{\partial z} \right ^{-1}$	Stability	Time Period	Data Type & Source
			$\times 10^{-4} \text{cm}^2 \text{s}^{-3}$	$\times 10^{-4} \text{cm}^2 \text{s}^{-3}$			
			KE' $\rightleftharpoons$ KE	PE' $\rightleftharpoons$ PE			
19°N	-20 to +130		$\rightarrow$	$\leftarrow$	Mixed	3/84-8/84	Current meter, FACTS-I (Lee et al. 1986)
	-50 to +2-	-2.5 to -.7	$\rightarrow$	$\leftarrow$	Unstable	10/84-3/85	Current meter, FACTS-II (Lee et al. 1986)
	-90 to +45	-8 to +.8	$\rightarrow$		Unstable	3/85-6/85	Current meter, FACTS-III (Lee et al. 1986)
30°N	30 to 50		$\rightarrow$		Stable	3/84-8/84	Current meter, FACTS-I (Lee et al. 1986)
	50 to 100	-1.1 to -.6	$\rightarrow$	$\leftarrow$	Unstable	10/84-3/85	Current meter, FACTS-II (Lee et al. 1986)
	20 to 200	2 to 6	50 $\rightarrow$	60 $\rightarrow$	Stable	2/80-6/80	Current meter, GABEX-I (Lee & Atkinson, 1983)
	30 to 260	1 to 8	12 $\rightarrow$	10 $\rightarrow$	Stable	6/81-10/81	Current meter GABEX-II (Lee & Pietrafesa, 1987)
31°30'	200 to 800	22 to 20	20 to 200 $\rightarrow$	10 to 20 $\rightarrow$	Stable	2/83-7/84	Current meter, Blake Plateau (Lee, 1986)
32°30'	50 to 400	-10 to 20	20 to 30 $\rightarrow$	-7 to -2 $\leftarrow$	Unstable	2/83-2/84	Current meter, Blake Plateau (Lee, 1986)
33°30'	100 to 400	5 to 20	30 to 100 $\rightarrow$	10 to 50 $\rightarrow$	Stable	2/83-2/84	Current meter, Blake Plateau (Lee, 1986)

Fig. 1. Satellite AVHRR thermal image of the Gulf Stream in the SAB for 0019 UT on April 23, 1980 (prepared by O. Brown and R. Evans of RSMAS, U. Miami).

Fig. 2a. Composite map of surface temperature for 20 to 23 Feb. 1973. Ship track designated by dots; temperature sections by letter (A)-(E); current meter moorings by blackened circles; arrows indicate observed current direction (Fig. 15 of Lee and Mayer, 1977).

Fig. 2c. Time series of hourly current and wind vectors during the passage of the frontal eddy shown in Fig. 2a (Fig. 16 of Lee and Mayer, 1977).

Fig. 2b. Temperature sections through frontal eddy shown in Fig. 2a, arrows indicate XBT stations (Fig. 17 of Lee and Mayer, 1977).

Fig. 3a. Ship measured surface temperature on April 25 (0847) to April 26 (2152) with daily averaged current vectors for April 26 (Fig. 21 of Lee and Atkinson, 1983).

Fig. 3c. Time series of 40 hr low pass wind vectors and 40 hr to 2 weeks band pass filtered currents during passage of frontal eddy of Fig. 3a (Fig. 23 of Lee and Atkinson, 1983).

Fig. 3b. Temperature, salinity, density and nitrate sections across the frontal eddy of Fig. 3a, Iselin section #23 (Fig. 22 of Lee and Atkinson, 1983).

Fig. 4. An extensive, oblique view of the thermal structure of meanders off Cape Fear and Onslow Bay, Feb. 11, 1979 constructed from XBT sections (Fig. 11a of Bane et al., 1981).

Fig. 5. Schematic of Gulf Stream frontal eddies and meanders together with shelf flow regimes on the SAB.

Fig. 6. 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 Figs. 1 and 2 of Hood and Bane, 1983), term estimates and data sources given in Table 1.

Fig. 7. Estimates of energy transfer terms $\overline{u'v'} \partial \bar{v} / \partial x$ (negative or onshore for barotropic instability), $\overline{u'\rho'} \partial \rho / \partial x | \partial \rho / \partial z |^{-1}$ (negative or onshore for baroclinic instability), term estimates and data sources given in Table 1, (frontal positions from Figs. 1 and 2 of Hood and Bane, 1983).

Fig. 8. Nitrate flux across the Gulf Stream cyclonic front together with the mean and standard deviation of frontal positions (frontal positions from Figs. 1 and 2 of Hood and Bane, 1983), term estimates and data sources given in Table 1.

Fig. 9a. Characterization of mean circulation, onshore nitrate flux and Gulf Stream-induced carbon production in the SAB during winter and spring conditions.

Fig. 9b. Characterization of mean circulation, onshore nitrate flux and Gulf Stream-induced carbon production in the SAB during summer conditions.

Fig. 9c. Characterization of mean circulation, onshore nitrate flux and Gulf Stream-induced carbon production in the SAB during fall conditions.