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Short title:  SAB SUMMER UPWELLING

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Abstract. Unusually cold sea-water temperatures were observed along much of the U.S. eastern seaboard during the summer of 2003. In this study, hydrographic and atmospheric observations from spring through summer were analyzed to track the evolution of the cold water event and investigate links to various forcing mechanisms of this event in the South Atlantic Bight (SAB). The hydrographic observations included 13 cross-shelf transects over the central region of the SAB, surface temperature time series from several NDBC stations and bottom temperatures from a mid-shelf mooring. Atmospheric data were obtained from NDBC stations. Additional data included water level from NOS stations, river discharge from USGS stations and current volume transport from the Florida Straits. The conditions observed during spring and summer of 2003 were compared with climatological values. Record precipitation and increased river discharge during spring produced strong salinity stratification over the inner- and mid-shelf. Anomalously intense and persistent upwelling-favorable winds were present from May until August. On the mid- and outer-shelf, the resulting upwelling and subsurface shoreward penetration of cold water acted as a feedback mechanism to preserve the stratified conditions through the summer. The characteristics of the upwelled water corresponded to water from the lower part of the Gulf Stream water column. On the shelf, the resulting temperature values under the thermocline were significantly lower than climatological temperatures by 5-7 °C. The coastal water level was also anomalously low during the summer, suggesting a complex interaction between local and remote atmospheric forcing, and open ocean effects.
1. Introduction and Background

The South Atlantic Bight (SAB, Figure 1) extends from Cape Canaveral, Florida, to Cape Hatteras, North Carolina, along the eastern coast of the United States. The oceanography of this region has been studied for several decades [Atkinson et al., 1985; Menzel, 1993] including a number of intensive field studies (GABEX, Lee and Atkinson [1983], GALE, Blanton et al. [1987], FLEX, Werner et al. [1993]). The continental shelf of the SAB historically has been divided into three hydrographic regions [Lee et al., 1991]: inner-, mid- and outer-shelf. The inner-shelf extends from the coast to the 20-m isobath and its circulation is controlled primarily by winds, tides and freshwater inputs. In the mid-shelf region, extending from the 20-m to the 40-m isobath, the influence of river discharge decreases and the circulation is controlled by wind and tides, with sporadic Gulf Stream inputs. The outer-shelf extends from the 40-m isobath to the shelf-break, and its circulation is controlled by fluctuations in the Gulf Stream position and associated frontal eddies and is influenced by winds to a lesser extent. In fact, the Gulf Stream and its instabilities dominate the outer-shelf dynamics on weekly time scales, with the western boundary of the Stream generally appearing around the 100-m isobath [Lee et al., 1981; Lee and Atkinson, 1983].

The upwelling and intrusion of cold, nutrient rich water from the Gulf Stream onto the SAB shelf during the summer has an important impact on hydrography and biological productivity [Paffenholz et al., 1987; Atkinson et al., 1987; Lee et al., 1991]. The upwelling process occurs throughout the SAB with different strengths, generally strongest in the area north of Cape Canaveral [Blanton et al., 1981]. The intensity of the upwelling events is
highly variable interannually. There have been several studies of these events with the earliest focusing on the NE Florida shelf [Green, 1944; Taylor and Stewart, 1959]. Subsequent studies by Blanton [1971], Atkinson et al. [1980] and Hofmann et al. [1981] focused on the northern part of the SAB shelf in the Carolina Capes region. The most intensive summer upwelling study was conducted in 1981 as part of GABEX II [Paffenhöfer et al., 1987; Atkinson et al., 1987; Lee and Pietrafesa, 1987; Hamilton, 1987], which concentrated on the region extending from Cape Canaveral to Savannah. These studies showed that the influx of cold water is largely episodic and that the intrusion events occurred when cold, cyclonic, Gulf Stream frontal eddies were observed along with upwelling favorable wind at a time when the Stream was in a relatively onshore position. The cold water intrusions were found to be associated with the passage of cyclonic frontal eddies, which travel northward (propagation speeds around 40 km day\(^{-1}\)) along the western edge of the Gulf Stream and occurring at intervals of 2-14 days [Bane et al., 1981; Lee et al., 1981; Lee and Atkinson, 1983]. The penetration of these intrusions is enhanced by the change of vorticity following isobaths in regions downstream of capes and shoals [Leming, 1979; Blanton et al., 1981]. Understanding of oceanographic dynamics in the central part of the SAB during upwelling events remains incomplete. The present study is intended to provide further description of the characteristics of this region during upwelling events through analyses of observations from cruises, NDBC stations and the South Atlantic Bight Synoptic Offshore Observation Network (SABSOON) towers [Seim, 2000].

During 2003, a “cold event” on the continental shelf extended from Florida to New Jersey, and its effects have been described in the Mid-Atlantic Bight (MAB) by Sun et al. [2004a].
Additional analyses presented by Schwing and Pickett [2004] used observed wind to calculate a time series of upwelling index (off-shore component of Ekman transport). These studies suggested a teleconnection between global atmospheric systems and the anomalous coastal and shelf conditions during 2003 in the SAB and MAB. In particular, the Bermuda-Azores High was unusually strong and extended much farther to the west than normal during the summer of 2003 [NOAA, 2003], which explained the anomalously strong upwelling favorable winds observed along the U.S. eastern seaboard.

Several informal announcements from the Departments of Natural Resources (DNR) of Georgia and South Carolina, as well as from divers and beach-goers, were the first reports of abnormally low bottom water temperatures in the SAB during July and August of 2003. Some of these reports described bottom temperatures of 19-20 °C off the coast of Georgia and South Carolina around the 30-m isobath, where normal summer temperatures are around 25-26 °C [Blanton et al., 2003]. Similar low temperatures were reported off the coast of Florida. The biological impacts of this anomalously cold water included mortality of reef fish (Florida Fish and Wildlife Research Center) and cold-stunning of loggerhead turtle hatchlings (Loggerheadlines, June-July, 2003, SC DNR). In response to these reports, several cross-shelf transects were conducted by the Skidaway Institute of Oceanography across the continental shelf to measure vertical profiles of temperature and conductivity.

In this study we compiled the available hydrographic and atmospheric observations during spring and summer of 2003, focusing on the central SAB. The objective is to characterize the conditions present in this region and consider what the possible forcing mechanisms were that triggered the event. The main characteristic of the event in the SAB
was a strong and unusually persistent thermocline that extended from the shelf-break to about the 15-m isobath. Temperature under the thermocline in 2003 was significantly lower, by as much as 5-7 °C in some locations. The occurrence of this temperature stratification was apparently influenced by the presence of anomalously strong salinity stratification in late spring associated with larger than average river discharge during the early spring.

2. Data Sources

Because of the unexpected nature of the 2003 event, there was no specific effort to produce a rigorous set of observations to describe the water intrusion until late July, 2003. Hydrographic observations before that time were collected for other purposes, and therefore the availability of data for the summer of 2003 presents significant spatial and temporal gaps.

2.1. Atmospheric data

The available wind observations during 2003 were compiled from the following sources: offshore towers (SABSOON), QuickScat satellite scatterometer, and NDBC buoys. The possibility of having complete records during the entire study period as well as long records from previous years made the NDBC buoy data the most appropriate for this study. Precipitation data were obtained from NOAA’s National Climatic Data Center (www.ncdc.noaa.gov). River discharge information was obtained from U.S. Geological Survey (USGS) stream gauge stations for three rivers: Altamaha, Savannah, and Pee Dee.
2.2. Hydrographic data

Offshore towers instrumented through the SABSOON program [Seim, 2000] constitute a real-time observational network in the center of our region of interest, providing observations of atmospheric conditions (winds, heat fluxes, atmospheric pressure) and oceanic conditions (e.g., temperature, salinity, currents). Unfortunately, during the summer of 2003 the towers were being refurbished by the US Navy and most SABSOON data were not available from mid-June until September. A temporary mooring was deployed at the R2 tower (26-m isobath) to reduce the effect of this data interruption. This mooring recorded current (ADCP), bottom temperature, and bottom salinity from mid-June to the end of July.

A set of cross-shelf hydrographic surveys were conducted from the R/V Savannah in the central part of the SAB during the spring and summer of 2003. Most of the transects were conducted over the mid- and inner-shelf between the coast and the SABSOON towers (Figure 2), while several extended across the entire shelf to the shelf-break. CTD profiles were measured at stations at 8-10 km intervals.

Several NOAA NDBC buoys, CMAN stations, and NOS stations provided near-surface water temperature time series. For some of these stations the 2003 time series can be compared to a long-term average. The NOS stations are usually located in estuaries or rivers, and therefore are not representative of shelf water conditions and thus the analysis below focused on the data from NDBC buoys and CMAN stations.

The available satellite products for the study period included MODIS SST, AVHRR SST and microwave SST from TMI. A more in depth analysis of the satellite SST data during this
period is included in the study by Yuan et al. (personal communication).

2.3. Additional data

Data from the NOS coastal water level stations in the SAB were also analyzed. In this study we concentrate on a subset of stations representative of different portions of the SAB (Figure 1): Virginia Key in southern Florida (1995-2004), Trident Pier in the Cape Canaveral region (1995-2004), Fort Pulaski in the central part of the SAB (1936-2004), Springmaid Pier in the Carolina Capes region (1978-2004), and Cape Hatteras in the northern part of the SAB (1977-2003).

The data on Florida Current transport within the Florida Straits is estimated from submarine cable voltage measurements [Baringer and Larsen, 2001]. During the summer of 2003, there were problems with the calibration of cable derived transport. Postprocessing of these data is still underway, and data for at least part of the period may be unrecoverable (C. Meinen, NOAA/AOML, personal communication). The available transport information includes cable data from the spring and fall as well as in situ cruise transport measurements from several calibration cruises across the Florida Straits. The in situ observations were horizontal transports integrated from dropsonde or lowered acoustic Doppler profiler (LADCP).
3. Results

3.1. Winds

The comparison of 2003 winds with those from previous years for the Gray’s Reef buoy (NDBC 41008) is presented in Figure 3. The wind during the summer of 2003 was predominantly in the along-shelf direction and upwelling favorable between the months of May and August. The variability during the summer months was smaller than during other periods of the year. On average, the across-shelf wind was small during the entire year (Figure 3b).

A statistical comparison of mean wind velocities (t-test) was used to determine if the mean winds for 2003 were significantly stronger than mean winds in previous years. The results for the Gray’s Reef buoy are shown in Table 1. The mean wind for the months of May, June, July, and August of 2003 was significantly greater than the mean wind for those months combining all the previous years data at Gray’s Reef. By contrast, the winds during spring of 2003 were weaker than the long-term average. Similar results were obtained for the rest of the NDBC sites within the SAB (not shown).

Histograms of wind direction measured at the Gray’s Reef buoy in July 2003 (Figure 4) indicated that the wind during the summer of 2003 was more persistent in direction than during previous years, and that this corresponded closely with the upwelling favorable direction. The time percentage of upwelling favorable wind occurrence in summer 2003 was higher than in previous summers. Similar results were observed for every summer month in 2003 for every available buoy in the region (not shown).
3.2. Precipitation and river discharge

Relatively high rainfall during the winter-spring 2002-2003 marked the end of a period of extended drought for much of the southeast and mid-Atlantic regions that lasted from June 2001 to October 2002 (National Climatic Data Center, NCDC). During the spring months the precipitation over much of the region that drains into the SAB was considered “record wettest” (NCDC), and anomalously high rainfall (although of lower absolute magnitude than in spring) persisted during the summer months. The combined spring and summer precipitation levels were “much above average” to “record wettest” for the entire region (Figure 5). The record regional precipitation resulted in elevated river discharge into the SAB coastal region (Figure 6). Using the Altamaha River as a reference, discharge during March and April exceeded the long-term mean (1931-2003) by a factor of two or more. Moreover, from June to September, discharges were 2 to 3 times higher than the long-term summer mean (typically the annual minimum in river discharge). Thus, the higher-than-normal discharge coupled with weak or upwelling-favorable winds during the spring and summer months (Table 1) supplied a higher than average buoyancy source to the inner shelf.

3.3. Water Level

Coastal water level in the SAB is controlled by several forcing mechanisms, including wind stress, tides, atmospheric pressure, steric effects, river input, and Gulf Stream effects. These forces vary at a variety of frequencies from short-term to seasonal and even larger scales. In order to describe the anomalous conditions of 2003, the seasonal effects were removed from the signal and the water level anomaly was considered. The anomaly was then
divided into three different period bands in an attempt to determine the forcing mechanisms affecting the water level at each period band (Figure 7). The 30-day low-pass filtered water level anomaly revealed a lower water level during the summer months of 2003 for most of the stations (Figure 7a). Historical data from the SAB shows a lower water level in July-August when compared with the rest of the year [Taylor and Stewart, 1959; Sturges, 1974; Blaha, 1984]. With the exception of the Virginia Key station (South Florida), the values for July and August of 2003 are 0.1-0.15 m lower than that monthly historical mean. Figure 7b shows the 10-day to 30-day band-pass filtered water level. The signals from all the stations displayed oscillations at the same period (20-25 days). The third panel (Figure 7c) corresponds to the 40-hour to 10-day band-pass filtered water level for the month of July. No consistent pattern is found in these signals.

3.4. Transport data from the Florida Straits

During summer of 2003, the available Florida Current transport estimates from calibration cruises fell outside the one standard deviation envelope from the long-term mean (Figure 8). This long-term mean included cable data from previous studies [Baringer and Larsen, 2001] as well as more recent data (2000-2005). These measurements suggest that the Florida Current transport during the summer of 2003 was significantly lower than the long-term average. However, there was some concern about a possible 10% low bias for transport data estimated with LADCP (C. Meinen, NOAA/AOML, personal communication). If a correction was applied for this bias, the transport estimates for summer of 2003 remained below the long-term mean, but inside the standard deviation envelope. Further analysis of the
transport characteristics will be conducted after the reprocessing of the cable transport data is completed.

3.5. Temperature time series

Time series of near-surface seawater temperature anomalies were constructed from the NDBC buoys and CMAN stations records. The temperature anomaly (2003 data minus long-term time series mean for that date) at each station is presented in Figure 9. Anomalously cool near-surface water was observed at the mid-shelf station off Georgia (41008 buoy) from early July to mid-August. The other nearby station (SABSOON tower R2) was not operational during the summer period. Anomalously cool water was also observed between mid-July and end of August on the outer-shelf off NE Florida (41012 buoy). The station on the outer-shelf off South Carolina (41004 buoy) recorded small negative anomalies (less than 1°C) during short periods, but remained at near-normal values for most of the study period. The NDBC buoy near Cape Canaveral (41009) recorded large negative temperature anomalies during mid-August. The CMAN stations south of Cape Canaveral (Lake Worth, Fowey Rocks, Molasses Reef, Sand Key) remained at near-normal conditions during the entire period, as did the NDBC buoys located in the open ocean (41010, 41002, and 41001). The stations in the northern SAB and southern Mid-Atlantic Bight (MAB, north of Cape Hatteras) recorded large negative temperature anomalies (2-4 °C) during most of the summer.

The only bottom temperature time series for the SAB was collected at the R2 location (Figure 10). The data for spring (up to mid-June) was collected by the SABSOON package, while the data for most of summer (mid-June to end of July) was recorded by a temporary
mooring. The bottom temperature data were compared to the mean for the R2 time series (1999-2004), and a significant decrease in temperature below the mean was observed starting in mid-June and persisting through summer. The magnitude of the anomaly in the bottom temperature was around 4 °C, and reached 7 °C by late July.

3.6. General hydrographic characteristics

The general mass field in the central SAB off Georgia was repeatedly observed in the set of hydrographic survey cruises from mid-April to the end of August (Figure 2). The evolution of the temperature structure is presented in Figure 11. The progressive warming of the surface layer of the shelf from spring into summer is evident, along with continuing cooling of the bottom layer in the mid- and outer-shelf starting in mid-June. The early August transect showed the partial breakdown of thermal stratification in the near-shore region. Seaward of the 20-m isobath, there was a strong pycnocline with temperature gradients of approximately 1 °C m$^{-1}$ off Georgia and 2 °C m$^{-1}$ off NE Florida (August 18 transect). These gradients are significantly greater than those reported for previous intrusions off NE Florida [Atkinson et al., 1987].

Figure 12 shows the evolution of the salinity field on the same transects during the spring and summer of 2003. Low salinity waters present during April and May resulted from the peak in river discharge (Figure 6). While the salinity structure during April was mostly unstratified, starting in May a surface low salinity layer overlying more saline near-bottom water was present over the inner and mid-shelf. Due to tidal mixing in the estuarine and near-shore regions of the SAB (the tidal range is 2-2.5m along the Georgia and South Carolina
coasts [Blanton et al., 2004]), freshwater input from the rivers along the SAB coast typically is mixed into a near-shore, low salinity band, often referred to as the “coastal frontal zone” [Blanton, 1981]. When winds are from the north to northeast, as is typical of much of the winter to late spring [Weber and Blanton, 1980], the low salinity water tends to be confined to the coast. When the winds relax or shift to become south-to-southwesterly, the lower salinity coastal waters can spread seaward as a buoyant surface layer [Blanton and Atkinson, 1983]. These latter wind conditions were present during most of the spring of 2003 (Table 1) and facilitated the extension of the surface low salinity cell into the mid-shelf. By July most of the observations on the shelf showed high salinities (around 36 psu), although few observations shallower than the 20-m isobath (inner shelf) were obtained. In late August, an additional low-salinity pulse was observed extending across most of the surface waters of the inner shelf, following higher than average river discharge in the summer (Figure 6).

The cross-shelf density evolution during 2003 is shown in Figure 13. Minimum densities were associated with low salinity waters in spring. Maximum densities were associated with the cold water intrusion in the lower part of the water column starting in late June. In April, the entire water column was at least partially mixed in the vertical. By May, with the development of the surface low-salinity layer, strong stratification was observed. In July, the effect of the persistent upwelling-favorable wind caused the pycnocline to begin shallowing in the near-shore region. The stratification persisted in the mid- and outer-shelf, but the near-shore region was affected by pulses in wind intensity. By mid-August, when the upwelling-favorable wind partially relaxed, the density field over the inner-shelf became more vertically mixed (the normal condition for the coastal zone). In late August the strongest stratification remained
over the mid-shelf, but the stratification over the inner-shelf increased due to the combined thermal and saline effects.

3.7. Comparison with climatological fields

Several aspects of the hydrographic conditions observed during the study period were anomalous when compared with climatological values [Blanton et al., 2003]. The first was the anomalously strong salinity stratification encountered during May. High river input of fresh water generated a surface, low-salinity layer by late spring that extended all the way to the mid-shelf (Figure 14), a structure that is not present in the climatological fields. The salinity in the surface layer was 3-5 psu lower than climatological values, while the bottom layer salinity was consistent with normal conditions.

The second anomalous condition was that by June, the salinity stratification had been replaced by thermal stratification. This was caused by the combined effects of surface heat flux, reduced mixing and the upwelling of cold water from the Gulf Stream (Figure 15). The strongest thermal stratification was observed over the mid-shelf, while the inner-shelf stratification was dominated by the salinity structure.

The final condition that significantly differed from climatological values was the most noticeable: the presence of cold water temperatures during the latter part of the summer. By late August the anomalously cold water extended from the shelf-break to the mid-shelf in the lower part of the water column, and it was affecting the near-shore waters. While the surface water temperature remained at climatological values, the lower part of the water column had temperatures that were up to 8 degrees colder than normal (Figure 16).
Another factor to consider is the change in the direction of the cross-shelf slope of the isopycnals. During 2003, the vertically integrated cross-shelf density gradient (Equation 1) was negative across the entire shelf, while the climatological values are positive for the inner- and mid-shelf and negative only on the outer-shelf [Blanton et al., 2003]:

\[ R_x = \int_{-h}^{0} \frac{\partial \rho}{\partial x} dz \]  

(1)

where \( \rho \) corresponds to water density and \( h \) is the water column depth.

3.8. T-S characteristics

To determine the origin of the cold water on the outer-shelf, a set of T-S diagrams was constructed (Figure 17). The R/V Savannah cruise observations were separated into two groups: observations from the bottom part of the water column over the mid- and outer-shelf (depths > 30 m); and observations from the rest of the shelf (including the entire water column in the inner shelf and the upper part of the water column in the mid- and outer-shelf). The observed T-S distributions were compared with climatological Gulf Stream T-S characteristics (green dots in Figure 17). During May the upper part of the water column was strongly influenced by river discharge (Figure 17a). By June the T-S characteristics of the cold water in the deeper part of the mid- and outer-shelf water column was largely consistent with Gulf Stream T-S characteristics (Figure 17b). By July, the T-S distribution for most of the shelf water column closely resembled that of Gulf Stream water (Figure 17c). The close correspondence between the T-S pattern for the colder water on the shelf and for the Gulf Stream was maintained through August (Figure 17d) and started to disappear in September.
To evaluate the likely source depths of the Gulf Stream water found on the shelf, we calculated the minimum “normalized T-S distance” between the water on the shelf and the Gulf Stream water using the expression:

$$(\text{dist}_{TS})_j = \text{abs} [(T_j - T_{GS}) \alpha + i (S_j - S_{GS}) \beta] \times 1000 \quad (2)$$

where $\alpha$ is the thermal expansion, $\beta$ is the saline contraction, $T_{GS}$ ($S_{GS}$) is the temperature (salinity) of the Gulf Stream and $T_j$ ($S_j$) is the observed temperature (salinity) at point $j$ on the shelf, and $i = \sqrt{-1}$.

This (non-dimensional) minimum “normalized T-S distance” provides the closest distance between the characteristics of a parcel of water on the shelf and the T-S curve for the Gulf Stream waters in a T-S diagram. A comparison between the water characteristics on the shelf during the August 27 cruise and climatological conditions is presented in Figure 18. The first panel (Figure 18a) presents the minimum T-S distance between the cruise data and the mean T-S curve for the entire Gulf Stream water column. Figure 18b corresponds to the same cruise characteristics but compared to the T-S curve of the lower part of the Gulf Stream water column exclusively (depths $> 200$ m). The third and fourth panels (Figure 18c,d) present similar analyses but, instead of the cruise data, uses the shelf climatological T and S values sampled at the cruise positions.

When the entire Gulf Stream water column was considered (Figure 18a,c), the T-S distance values for 2003 were similar to climatological values (distance $< 1$). This suggested that most of the shelf water originated as Gulf Stream water during the late part of the summer.
period both in 2003 and in other years, the exception being the near-shore surface layer in August 2003 (T-S distance $\sim 2$, 18a). This was due to the above average river discharge during the summer months of 2003. When the T-S distance between shelf water and the Gulf Stream water from deeper than 200 m was considered (Figure 18b,d), there was a clear differentiation between the upper and the lower part of the shelf water column. The T-S distance between the anomalous cold water of 2003 and the deeper part of the Gulf Stream water column (T-S distance $< 1$), suggests that the origin of the anomalous water was from deeper part of the Gulf Stream water column. Comparing Figures 18a and 18b indicates that the upper layer of the shelf water column (depth $< 10$ m) originated from the upper part of the Gulf Stream water column (depth $< 200$ m) except near-shore.

4. Analysis

4.1. Coastal Water Level

The long-period anomaly in coastal water level (0.1-0.15 m) observed in the majority of stations in the SAB during July and August (Figure 7a) had to be associated with one of the forcing mechanisms controlling water level in the SAB. Possible forcing mechanisms include wind stress, tides, atmospheric pressure, steric effects, river input, and Gulf Stream effects. The fact that the 30-day low-pass values for Virginia Key did not show a comparable anomaly during July and August suggests the forcing mechanism was constrained to the SAB (from Cape Canaveral to Cape Hatteras) and did not affect the southern part of Florida.

When coastal water level was compared with wind forcing, an inverse correlation was
observed between the time series for different stations (not shown). In order to assess whether wind forcing could explain the anomalous water levels observed during 2003, an analytical model was used to isolate the importance of the wind forcing. Csanady [1978] presented a model that predicted the coastal water level setup by the local wind stress. This model was used by Hickey and Pola [1983] to predict the latitudinal change in coastal water level along the West Coast of the U.S. A similar approach was followed by Blaha [1984] for the East Coast. The basic equation for water level at the coast is:

\[
\zeta(y) = \frac{1.12f \tau_s}{\lambda g \rho} \left[ [Ky]^{1/2} - [K(y - Y)]^{1/2} \right] 
\]

where \(y\) is distance alongshore, \(\zeta(y)\) is coastal water level, \(f\) is the Coriolis parameter, \(g\) is the acceleration due to gravity, \(\tau_s\) is the alongshore component of the surface wind stress, \(\lambda\) is the linear bottom friction coefficient such that \(\lambda v\) is bottom stress. \(K = \lambda/(fs)\), where \(s\) is the bottom slope. The wind stress is prescribed for \(0 < y < Y\) and zero elsewhere. The bottom friction coefficient used in these calculations was \(\lambda = 2 \times 10^{-4} \text{ m s}^{-1}\). This corresponds to a bottom drag coefficient of \(C_D = 2 \times 10^{-3}\) assuming a bottom velocity of 0.1 m s\(^{-1}\), which is consistent with climatological bottom tidal velocities on the SAB shelf [Blanton et al., 2003]. Monthly mean wind stress from NDBC stations in the vicinity of the NOS water level stations was used. Predictions using Equation 3 were consistent with the climatological water levels evaluated with a linear finite element 3-D model (Fundy) forced with climatological winds [Blanton et al., 2003].

Figure 19 shows the comparison between observed and predicted water level for summer 2003. Equation 3 showed adequate skill in predicting the water level during May and June.
During July and August it overpredicted the water level by about 0.1-0.2 m, while during September it underpredicted the observations. The underprediction is consistent with the temporal pattern of anomalous water level observed in the 30-day low-pass anomaly data (Figure 7a), suggesting that the anomalous water level in July and August was not caused by the anomalous wind conditions and there was another mechanism that caused the conditions during 2003. Water level can be affected by several mechanisms that were not included in the Csanady analysis: the annual cycle of heating and cooling, river runoff, stratification and variability in adjacent open ocean circulation.

A possible explanation is the effect that the lower temperatures would have on the water level through changes in the steric anomaly. The changes in water level associated with the steric effect were determined to be on the order of 1-3 centimeters (not shown) and therefore did not explain the anomalous conditions present during 2003.

Regarding open ocean effects, Blaha [1984] and Noble and Gelfenbaum [1992] presented evidence that coastal water level in this region is influenced by the transport of the Gulf Stream. The basic argument is that during periods of low transport, there is a reduced cross-stream slope and a consequent higher coastal water level. During the summer of 2003 the only transport measurement collected in the Florida Straits at 27°N (Figure 8) was lower than average, which suggests an anomalously high water level. The cable transport data for the rest of 2003 was higher than average, which would be consistent with the observed coastal water level being lower than average (Figure 7).

It should be noted that the transport estimates from the submarine cable are only for the Florida Current in the northern Florida Straits. The transport of the Gulf Stream increases
from about 30 Sv in the Straits to about 100 Sv in the Cape Hatteras region [Richardson et al., 1969; Leaman et al., 1989]. The variability of Gulf Stream transport due to fluctuations of the Antilles Current [Lee et al., 1990, 1996] and recirculation of the Gulf Stream in the northwest Atlantic [Worthington, 1976] might additionally affect the coastal water level. There were no data to evaluate these potential sources of variability during 2003. The only available simultaneous Antilles and Florida current transports were for the period between April 1986 and January 1992 [Lee et al., 1996]. When monthly coastal water level anomalies during that period were compared with transport observations, a not-so-simple relation was found (not shown), suggesting the necessity to include the transport from both currents in order to evaluate the relationship between coastal water level and Gulf Stream transport in the SAB.

Far-field pressure fields could also affect coastal water level. These far-field conditions could have set a low water level during the entire period of interest. The Bermuda-Azores High controls the large-scale winds and pressure over the North Atlantic. The High during the summer of 2003 was unusually strong and extended much farther to the west than normal [NOAA, 2003; Schwing and Pickett, 2004], possibly altering coastal water level over large spatial scales.

The previous analysis focused on the coastal water level variability in the longer period band (30-day low-pass). The 10-day to 30-day band-pass filtered water level (Figure 7b) revealed oscillations with periods around 20-25 days. This type of oscillation has been previously described along the Oregon Coast by Bane et al. [2005], who suggested that these oscillations are associated with alongshore wind stress fluctuations driven by similar low-frequency variations in the north-south position of the atmospheric jet stream. An
explanation of the mechanism driving these atmospheric intraseasonal oscillations is provided by Ghil et al. [2003]. The oceanic effects of these oscillations are only beginning to be understood. While Bane et al. [2005] reported an association between the coastal surface ocean temperature and these intraseasonal oscillations, in the present study, the oscillations were observed in the water level signal.

The remaining period band (40-hour to 10-day band-pass) was intended to evaluate weather band effects (Figure 7c). The combined signals did not show a consistent pattern. The observed fluctuations correlated with local oscillations in the atmospheric forcing (e.g., passage of frontal systems). The nature of these oscillations was not consistent with coastal-trapped waves as a driving mechanism for the upwelling events of summer 2003; there was no consistent pattern with northern station fluctuations leading southern station fluctuations.

4.2. Energetics during the cold water intrusion

Stratification of shelf waters results from the interaction between buoyant forces caused by heating and runoff, and mixing forces such as wind stress at the surface, current stress at the bottom, and cooling. Changes in stratification occur at short time scales as well as at tidal and seasonal scales. A comprehensive analysis of the processes affecting stratification in the SAB was included in Atkinson and Blanton [1986]. The characterization of the spatial and temporal variability of these processes presents significant challenges and remains poorly understood. Future work will address the complete work balance and its variability in the SAB. In the present analysis, the stratification effects on the potential energy levels of the
The potential energy (PE) content of the water column can be estimated following the formulation included in Simpson and Bowers [1981] and Atkinson and Blanton [1986]. The equation for PE can be written:

$$PE = \frac{1}{h} \int_{-h}^{0} (\bar{\rho} - \rho) g z dz; \quad \bar{\rho} = \frac{1}{h} \int_{-h}^{0} \rho dz;$$

(4)

where $\rho$ is density, $\bar{\rho}$ is the vertically-averaged density, $g$ is the acceleration due to gravity and $h$ is the water column depth. Transition from a stratified state to an unstratified state requires an energy input into the water column equal to the PE provided by the stratification. The PE is evaluated per unit volume in order to compare profiles from different sections of the shelf.

To evaluate the possible breakdown of stratification during specific periods, the potential energy estimated from the cruise transects during 2003 was considered (Figure 20). In general, the potential energy across the continental shelf increased from a minimum during spring, to a peak during the summer and then decreased to practically zero during autumn. A clear separation of the potential energy content of the water column was observed between the inner-shelf and the mid- and outer-shelf. To better illustrate this separation, the mean potential energy for each region of the shelf was calculated for several cruises and compared with the climatological values for the same positions (Table 2). Some of the variability observed in the climatological values in Table 2 is due to the sampling of the fields at different locations on the shelf.

In the inner-shelf region the potential energy was small (less than 40 J m$^{-3}$) for most of the study period. In early spring the water column was well mixed and therefore the
PE content was small. During early May the surface low salinity cell developed as winds were weak and there was a continuous input of fresh water into the shelf. In 2003, the elevated river discharge and the anomalous cold water near-shore favored a maintenance of the stratification in the inner-shelf, with partial mixing associated with pulses in the upwelling favorable winds. By late August, the decrease wind intensity and additional pulses of river water onto the shelf produced a maximum in PE (50 J m$^{-3}$). By the next cruise in early October, downwelling-favorable winds and the passage of storms had already destroyed the stratification.

On the mid-shelf PE levels (range [45 J m$^{-3}$, 100 J m$^{-3}$]) were significantly higher than in the inner shelf for the period between May and August. The PE peaks occurred in early May (93 J m$^{-3}$, associated with the salinity stratification), late July (90 J m$^{-3}$, associated with the anomalously cold water) and end of August (105 J m$^{-3}$, continuing cold water presence). The complete breakdown of the stratification occurred during September with the change-over from upwelling- to downwelling-favorable winds which quickly destroyed the stratification, first at the coast, then working its way seaward, resulting in a well mixed water column in October.

Potential energy on the outer-shelf was greater than in the inner- or mid-shelf. The PE values in the outer-shelf (usually > 100 J m$^{-3}$) were up to four times higher than climatology during 2003. The presence of the intruded cold water contributed to the maintenance of high levels of stratification during the entire period for which observations were available. Data regarding the breakdown of the stratification during fall was not available.
5. Discussion

In the previous sections the available data were presented and analyzed to determine the basic conditions during 2003 in the central SAB. These conditions were anomalous with respect to at least four parameters: 1) wind intensity and persistence, 2) precipitation and river discharge, 3) coastal water level, and 4) presence of cold water over the shelf. There were several other conditions for which the available data did not allow the determination of the conditions during spring and summer of 2003 (e.g., Florida Current transport, Antilles Current effect, Gulf Stream position and meander/frontal eddy activity). The cold water event of 2003 was produced by a complex interaction between local and remote forcing mechanisms both in the atmosphere and in the ocean. No single mechanism seems to explain the full set of anomalous observations.

The SAB shelf was modified during winter and spring 2003 to conditions that differed from previous years. The first anomalous condition that helped to trigger the cold event was the record precipitation during spring of 2003 in the region that drains into the SAB shelf (Figure 5), that resulted in elevated river discharge during from March to May (Figure 6). The combination of high fresh water input and relatively low wind intensity during April followed by upwelling favorable winds during May, produced a low-salinity layer in the upper part of the water column that extended from the near-shore region to the mid-shelf (Figure 14). The presence of this low-salinity layer resulted in an anomalously strong salinity stratification during May. The effectiveness of the upwelling-favorable winds was increased by a feedback mechanism caused by the strong stratification (described in next section).
The Bermuda-Azores High was unusually strong during the summer of 2003, and it extended much farther to the west than normal [NOAA, 2003; Schwing and Pickett, 2004], producing anomalous upwelling favorable wind conditions in both intensity (Figure 3) and persistence (Figure 4) from June until the end of August. The anomalous wind conditions increased the persistence and strength of the upwelling process over the entire shelf. The salinity stratification present during May evolved into a thermal stratification during June (Figure 15) due to increased heat flux input, reduced mixing caused by the stratification, and initial inputs of anomalously cold water originating from the Gulf Stream. T-S characteristics indicate the intruded cold water came from the deeper parts (depth > 200 m) of the Gulf Stream water column (Figure 18). The intrusion of cold water onto the shelf was probably associated with the passage of cyclonic frontal eddies from the Gulf Stream.

River discharge was anomalously high for the entire summer period as well, providing a stronger than normal supply of buoyancy to the inner-shelf until the end of August (Figure 12). There were significant differences in the hydrographic characteristics across the entire shelf. While pulses in the upwelling-favorable winds appeared to be sufficient to partially mixed the inner shelf water column, the mid- and outer-shelf showed significantly stronger stratification than climatological conditions (Figure 20). The occurrence of sporadic partial mixing in the inner-shelf resulted in the detection of anomalously cold near-surface water at several stations over the central SAB during July and August (Figure 9).

The coastal water level was also anomalously low during the summer period (Figure 7a). Predictions estimated with a Csanady arrested topographic wave model showed that the water level signal could not be explained as a response to the anomalous wind alone (Figure 19).
Open ocean effects on coastal water level might have contributed to the anomalous coastal signal. Florida Current transport measurements at the Florida Straits suggested low current transport during the study period (Figure 8), which would not explain the observed water level. The effects of additional contributions to the Gulf Stream transport, for instance from the Antilles Current, need to be considered. Additionally, the water level signal showed intraseasonal oscillations with periods around 20-25 days (Figure 7b), which might be associated with similar period wind stress fluctuations that are caused by variations in the north-south position of the atmospheric jet stream. Meanwhile, the short term (40 hours-10 days) variations of the water level (Figure 7c) corresponded with similar period oscillations of the wind. The nature of the oscillations was not consistent with the propagation of coastal-trapped waves along the SAB shelf.

The cold water event and its associated stratification ended with the transition from upwelling- to downwelling-favorable winds conditions starting in September (Figure 3). The breakdown of the stratification likely occurred first in the near-shore region and propagated offshore as the mixing energy provided by the wind increased. This resulted in a well-mixed water column by October.

Most of the analysis presented above focused on the central part of the SAB, but the observations in the Florida region (Figure 9) suggest that, due to the smaller riverine input in this area, the same wind intensity could have produced more frequent breakdowns of the stratification over the inner-shelf, resulting in cooler surface water temperatures. In the mid- and outer-shelf of the Florida region (18 Aug. transect, Figure 11), stronger stratification was observed due to the combined effect of the proximity of the possible main source of cold water
(Cape Canaveral region, Blanton et al. [1981]), the weaker river discharge, and greater heat flux into the ocean than in the central part of the SAB.

A significant limitation for the present analysis is uncertainty associated with open ocean and western boundary current effects. The effects of Gulf Stream transport and dynamics, the contributions of the Antilles Current to total Gulf Stream transport, and the dynamics of frontal eddies and associated cold water intrusions are poorly observed and explained for 2003. Additionally, estimates of the contributions of heat flux, wind, and tidal mixing to the changes in potential energy in the different regions of the shelf contained high levels of uncertainty. Model simulations are planned to evaluate the roles of various mechanisms described in this study in controlling the strength and persistence of the cold water event in summer 2003.

5.1. Feedback between stratification and upwelling strength

The Ekman response to upwelling-favorable wind in the upper part of the water column was enhanced by stratification and increased offshore transport wind. The relationship between increased stratification, reduced Ekman depth and increased off-shore transport has been described in previous studies [Niiler and Krauss, 1977; Ralph and Niiler, 1999]. They suggested an inverse relationship between the Brunt-Väisälä frequency \( (N) \) and Ekman depth \( [D_E \propto U_\ast/(f \, N)^{1/2}] \).

During spring 2003 in the mid-shelf, enhancement of the stratification caused a positive feedback, where the upwelling winds advected low-density (low salinity) water from the near-shore region over the top of the pycnocline, and this increased both the stratification and
the potential energy of the water column. The increased stratification reduced the vertical wind mixing and the surface Ekman depth, therefore enhancing the Ekman response in the upper part of the water column, and increasing the offshore transport due to the wind.

Persistent upwelling favorable winds provided another positive feedback mechanism during the summer, whereby Gulf Stream water intruding shoreward along the bottom enhanced thermal stratification, thus requiring more mixing energy to penetrate the pycnocline. This increased the off-shore Ekman transport in the upper layer and enhanced the entire upwelling process, allowing the intruding cold bottom water to progress on-shore and spread ever farther northward from June until the end of August.

5.2. Region of cold water intrusion

In earlier studies, the point of entrance of Gulf Stream water onto the SAB shelf has been associated with the Cape Canaveral region [Blanton et al., 1981; Atkinson et al., 1987; Lorenzzetti et al., 1987]. These studies considered the change of vorticity along isobaths near Cape Canaveral as an explanation for enhanced upwelling in this region. Subsequently, the upwelled water was transported along-shelf into the central part of the SAB. Figure 9 shows the anomalously cold water being observed in 2003 at the buoys where divergence of isobaths occurs and not being present in regions where isobaths converge. However an extensive survey like the one during summer 1981, which included collection of data in the Cape Canaveral region, was not available for 2003. The available surface temperature data and the fact that the cold water was observed in the central SAB over time scales similar to those documented in previous studies suggested a similar origin. The described “remote” (NE Florida) origin of the
anomalous water observed directly in the central SAB was consistent with the climatological summer flow [Blanton et al., 2003] and current observations during 2003 (not shown).

5.3. Teleconnections

The presence of anomalously cold near-shore water was observed in both the South Atlantic and Mid Atlantic Bights during the summer of 2003. Effects have been described from the West Florida shelf up to Georges Bank. Schwing and Pickett [2004] proposed that anomalous atmospheric conditions affected the entire North Atlantic during these period and were related to the record warm summer in western Europe as well as to the anomalous conditions of the east coast of the U.S. A complete analysis of the global atmospheric and oceanic teleconnections during this period remains to be achieved.

The conditions in the MAB during the summer of 2003 have been described in several studies [Sun et al., 2004a; Schwing and Pickett, 2004; Sun et al., 2004b]. They presented evidence that the cold water in that region was caused by anomalous wind conditions. Sun et al. [2004a] suggested that the source of cold water in that region was the cool water pool that develops over the shelf during winter. The conditions in the SAB were related to those on the MAB, however there were several factors that differed between the two regions. The first factor was that normal summer wind conditions on the SAB are usually upwelling-favorable, while in the MAB these conditions are not persistent through the summer. In 2003 persistent upwelling-favorable winds were present in both regions, but those conditions were more anomalous in the MAB than in the SAB. The second factor was the origin of the cold water upwelled onto the shelf. While in the MAB the origin was apparently associated with the cool
water pool, in the SAB the source of anomalous water was the deep part of the Gulf Stream water column. The third factor was the effect of the Stream and therefore it was related to the water sources. In the SAB the Gulf Stream controlled the dynamics of the initial intrusion of cold water onto the shelf, while in the MAB the role of the Stream was not as significant or at least it has not been described. The fourth factor was the role of stratification on the shelf. While in the SAB the stratification enhanced the upwelling event, in the MAB this role has not been determined.

5.4. Biological Impacts

Enhanced primary and secondary production on the SAB shelf in summer results from the input of nutrients in the subsurface intrusions of cold water [Yoder et al., 1985; Paffenhofer and Lee, 1987; Lee et al., 1991]. Given the extent of the 2003 summer intrusion, the impact on shelf primary production was likely to have been considerable. However, since the 2003 cruises were largely opportunistic and emphasized hydrographic surveys, the available biological data is limited. Chlorophyll fluorescence profiles (CTD system) and analyses of filtered samples for chlorophyll concentrations showed well developed subsurface phytoplankton blooms on the mid-to-outer shelf off Georgia in July and August. Chlorophyll concentrations in the warm surface mixed layer in this shelf region ranged from 0.2 — 0.3 $mg \, m^{-3}$ in July and 0.3 — 0.8 $mg \, m^{-3}$ in August, while concentrations in the colder bottom layer ranged from 1 — 4 $mg \, m^{-3}$ in July and 3 — 6 $mg \, m^{-3}$ in August. The subsurface blooms in July included colonial prymnesiophyte, *Phaeocystis globifera* (J. Long, personal communication) and in August a bloom of a large, single-cell diatom
(Coscinodiscus spp.) was encountered in several stations. Other biological impacts of the anomalously cold water in the SAB were noted above, including mortality of reef fish off NE Florida (Florida Fish and Wildlife Research Center) and cold-shock of loggerhead turtle hatchlings (Loggerheadlines, June-July, 2003, SC DNR).

6. Conclusions

During the summer of 2003 an intense upwelling season was observed in the SAB. Observed temperatures were up to 8 °C colder than normal in some areas of the mid-to-outer shelf, and its repercussions were felt even in near-shore areas. The cold water upwelled onto the shelf came from the lower part of the water column of the Gulf Stream (depth $> 200$ m). The driving mechanisms of the cold water intrusion event were: 1) the occurrence of anomalously intense and persistent upwelling-favorable winds during the entire study period associated with an intensification and a westward displacement of the Bermuda-Azores High; 2) the record precipitation and increased river discharge associated with weaker winds during spring that produced strong salinity stratification; 3) the development of a strong thermal stratification during early summer; 4) the contribution of the passage of cyclonic frontal eddies from the Gulf Stream, both locally and remotely associated with the Cape Canaveral region. Both the salinity stratification during late spring in the inner- and mid-shelf, and the thermal stratification during summer in the mid- and outer-shelf enhanced the effect of the upwelling-favorable winds. The enhancement was produced by feedback mechanisms associated with a reduction of Ekman depth and an increase of the off-shore transport in the upper layer.
Additionally, during the same period, anomalous values were observed for coastal water level. The analysis of the water level suggested a complex interaction between local and remote atmospheric forcing, and open ocean effects. The contributions of the several open ocean effects, for instance transport contributions from the Florida and Antilles Currents, remain poorly understood. The detection of intraseasonal oscillations in coastal water level suggested a connection with atmospheric forcing associated with jet stream position.

Model simulations to address some of the observational limitations of the present study are underway. The emphasis of these simulations is to determine the relative importance of the different forcing mechanisms, especially those for which some observational data were available, as well as the dynamical implications of the 2003 event.

The detection of cold water signals extending from the NE Florida shelf to Georges Bank suggested a connectivity between forcing mechanisms at large scales. The characteristics of the observed anomalously cold water as well as the processes acting in the different regions might have been significantly different, but the resulting cool water temperatures anomalies were similar. The source of the intruded cold water has been described as the main difference between the processes observed in the SAB and in the MAB.

The impacts of the 2003 event ranged from economical (reduced tourist income due to the presence of cold water at the beach) to biological (fish mortality and turtle hatchlings cold-stunning). A complete set of implications remains an unlikely goal since most of the information for this period was not collected systematically. The importance of a more comprehensive long-term monitoring system of the coastal ocean is evident from this study. The lack of consistent, sustained observations for most of the shelf makes the interpretation of
events like the one during 2003 only partially successful. Coastal ocean observing systems like SABSOON \citep{Seim2000} and SEACOOS are therefore invaluable.

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This manuscript was prepared with AGU’s \LaTeX{} macros v5, with the extension package ‘AGU+’ by P. W. Daly, version 1.6b from 1999/08/19.
Figure Captions

Figure 1. Study region. The South Atlantic Bight extends from Cape Canaveral, Florida to Cape Hatteras, North Carolina. The black dashed line represents approximate locations of the hydrographic cruises done on board the R/V Savannah during the summer of 2003. The solid gray line corresponds to the location of the submarine cable in the Straits of Florida. The black dot corresponds to the R2 SABSOON tower location and the diamond to the NDBC buoy (41008) at Gray’s Reef National Marine Sanctuary (GR). The squares show NOS water level stations used in this study (VK, Virginia Key; TP, Trident Point; FP, Fort Pulasky; SP, Springmaid Pier; CH, Cape Hatteras). The 20, 40, 60, 200, 600, 1000, and 3000-m isobaths are shown.

Figure 2. Cruise tracks of R/V Savannah during spring and summer of 2003 in the central part of the SAB (black dotted line). The position of the Gray’s Reef Buoy (NDBC 41008) and R2 tower (noted when data were available) is given by the gray circles.

Figure 3. Monthly means of wind observations for all available years from NDBC buoy 41008 (Gray’s Reef). The solid lines represent the monthly means and the vertical bars correspond to the standard deviation for 2003.

Figure 4. Histograms of wind direction for 2003 and the previous years for the month of July for Buoy 41008 (Gray’s Reef). The thick dashed line represents the upwelling favorable direction.

Figure 5. Precipitation rankings during the spring-summer of 2003 period adapted from precipitation reports compiled by the NOAA National Climatic Data Center (www.ncdc.noaa.gov). A value of 109 corresponds to “record wettest” values recorded during this period.

Figure 6. River discharge to the SAB during 2003, based on data from the Altamaha, Savannah, and Pee Dee Rivers. The long-term mean for the Altamaha river is given by the dashed line.
**Figure 7.** Coastal water level anomaly during the summer months of 2003 for five NOS stations. The data is filtered at three different period bands: (a) 30-day low-pass filtered, (b) 10-day to 30-day band-pass filtered, and (c) 40-hour to 10-day band-pass filtered. Panels a) and b) include data from May until October, while panel c) only includes data for July 2003.

**Figure 8.** Florida Current transport across the Florida Straits. The latest data (2000-2005) has been added to the 16-year time series in Baringer and Larsen [2001] (1982-1998) to provide the long-term mean (thin solid line). The corresponding standard deviation envelope is given by the thin dashed line. The calibrated cable data for 2003 (when available) is represented by the thick solid line. In situ transport measurements from calibration cruises is given by solid dots (dropsonde) and solid stars (LADCP). Additionally, transport measurements from LADCP corrected for the possible 10% low bias is represented with open diamonds.

**Figure 9.** Near-surface temperature anomaly (°C) for NDBC stations during summer of 2003. The temperature anomaly is defined as the 2003 value minus long-term time series mean for that date. The data has been 40-hour low-pass filtered. The dark blue part of the curves correspond to anomalous values of more than -1 °C. The cyan part of the curves represent anomalous values between -1 and -2 °C, while the red part of the curves correspond to anomalous values below -2 °C. The black horizontal lines correspond to zero anomaly. The time series have been represented according to latitude. The station names (from south to north) are: Sand Key, Fl (sanf1); Molasses Reef, Fl (mlrf1); Fowey Rocks, Fl (fwyf1); Lake Worth, Fl (lkwf1); Canaveral Buoy (41009); Canaveral East Buoy (41010); St. Augustine Buoy (41012); Gray’s Reef Buoy (41008); Navy Tower R2; Edisto Buoy (41004); South Hatteras Buoy (41002); Hatteras Buoy (41001); Diamond Shoals Buoy (41025); Virginia Beach Buoy (44014); and Chesapeake Light, Va (CHLV2).
Figure 10. Bottom temperature (°C) at the R2 tower location for the summer of 2003 versus the mean for 1999-2004 time series (black dashed line). The solid black curve corresponds to data collected at the R2 SABSOON tower and the solid gray curve corresponds to data from the replacement mooring at the same location. The temperature data has been 40-hour low-pass filtered.

Figure 11. Temperature (°C) sections across the SAB shelf off Georgia (see Figure 2 for cruise tracks). The contour intervals are 1 °C. The x-axis corresponds to cross-shelf distance in kilometers seaward of the 25-m isobath.

Figure 12. Salinity sections across the SAB shelf (see Figure 2 for cruise tracks). The contour intervals are 1 psu. The x-axis corresponds to cross-shelf distance in kilometers seaward of the 25-m isobath.

Figure 13. Density sections across the SAB shelf (see Figure 2 for cruise tracks). The contour intervals are 1 Kg m$^{-3}$. The x-axis corresponds to cross-shelf distance in kilometers seaward of the 25-m isobath.

Figure 14. Salinity transect across the shelf during 7 May (top) and climatological May salinity field from Blanton et al. [2003] (bottom).

Figure 15. Temperature transect across the shelf during 25 June (top) and climatological June temperature field from Blanton et al. [2003] (bottom).

Figure 16. Temperature transect across the shelf during 27 August (top) and climatological August temperature field from Blanton et al. [2003] (bottom).

Figure 17. Monthly (May-August) T-S diagrams for observations collected over the shelf. The blue dots correspond to observations from the bottom part of the water column in the mid- and outer-shelf, red dots correspond to observations from the rest of the shelf and green dots represent long-term observations from the Gulf Stream from climatological means [Blanton et al., 2003]. The solid thick black line corresponds to mean T-S curve for Gulf Stream data and the dashed black line represents one standard deviation envelope.
Figure 18. Normalized minimum T-S distance between T-S characteristics on the shelf and the T-S curve for the Gulf Stream waters evaluated using equation 2. (a) T-S distance between observations from the August 27 cruise and the T-S curve from the entire Gulf Stream water column. (b) As in a) but between the cruise observations and T-S curve of the lower part of the Gulf Stream water column (depths > 200 m). (c) As in a) but using climatological values sampled at the cruise positions. (d) As in c) but for the lower part of the Gulf Stream water column.

Figure 19. Observed (gray dashed) and predicted (black) coastal water level as a function of latitude for selected stations in the SAB. Predictions are made with the Csanady [1978] model, using monthly mean wind stress from NDBC stations near the NOS water level stations. The model results are calculated in relation to observed water level at the southernmost station at Virginia Key. The station names are Virginia Key (vk), Trident Point (tp), Fort Pulaski (fp), Springmaid Pier (sp), and Cape Hatteras (ch).

Figure 20. Potential energy (PE, J m⁻³) per unit volume for several cruises using equation 4. This PE is the amount of work required to breakdown stratification and produce complete mixing of the water column.
### Table 1.

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<td></td>
</tr>
<tr>
<td>07-Aug-2003</td>
<td>N/A</td>
<td>89.91 (32.12)</td>
<td>134.5 (49.59)</td>
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<td></td>
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<tr>
<td>17-Aug-2003</td>
<td>8.00 (9.99)</td>
<td>75.04 (22.71)</td>
<td>157.7 (63.74)</td>
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<tr>
<td>18-Aug-2003</td>
<td>17.96 (10.50)</td>
<td>87.26 (30.88)</td>
<td>127.3 (50.70)</td>
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<td></td>
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<tr>
<td>27-Aug-2003</td>
<td>50.13 (4.79)</td>
<td>104.8 (29.40)</td>
<td>142.3 (50.27)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>07-Oct-2003</td>
<td>1.35 (2.11)</td>
<td>-5.39 (9.54)</td>
<td>N/A</td>
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**Table 2.** Potential Energy per unit volume (J m$^{-3}$) for 2003 (climatology) divided by shelf region for different cruises. The climatological values correspond to the positions for the CTD casts from the cruises.
Figure 1. Study region. The South Atlantic Bight extends from Cape Canaveral, Florida to Cape Hatteras, North Carolina. The black dashed line represents approximate locations of the hydrographic cruises done on board the R/V Savannah during the summer of 2003. The solid gray line corresponds to the location of the submarine cable in the Straits of Florida. The black dot corresponds to the R2 SABSOON tower location and the diamond to the NDBC buoy (41008) at Gray’s Reef National Marine Sanctuary (GR). The squares show NOS water level stations used in this study (VK, Virginia Key; TP, Trident Point; FP, Fort Pulasky; SP, Springmaid Pier; CH, Cape Hatteras). The 20, 40, 60, 200, 600, 1000, and 3000-m isobaths are shown.
Figure 2. Cruise tracks of R/V Savannah during spring and summer of 2003 in the central part of the SAB (black dotted line). The position of the Gray’s Reef Buoy (NDBC 41008) and R2 tower (noted when data were available) is given by the gray circles.
Figure 3. Monthly means of wind observations for all available years from NDBC buoy 41008 (Gray’s Reef). The solid lines represent the monthly means and the vertical bars correspond to the standard deviation for 2003.
Figure 4. Histograms of wind direction for 2003 and the previous years for the month of July for Buoy 41008 (Gray’s Reef). The thick dashed line represents the upwelling favorable direction.
Figure 5. Precipitation rankings during the spring-summer of 2003 period adapted from precipitation reports compiled by the NOAA National Climatic Data Center (www.ncdc.noaa.gov). A value of 109 corresponds to “record wettest” values recorded during this period.
Figure 6. River discharge to the SAB during 2003, based on data from the Altamaha, Savannah, and Pee Dee Rivers. The long-term mean for the Altamaha river is given by the dashed line.
Figure 7. Coastal water level anomaly during the summer months of 2003 for five NOS stations. The data is filtered at three different period bands: (a) 30-day low-pass filtered, (b) 10-day to 30-day band-pass filtered, and (c) 40-hour to 10-day band-pass filtered. Panels a) and b) include data from May until October, while panel c) only includes data for July 2003.
Figure 8. Florida Current transport across the Florida Straits. The latest data (2000-2005) has been added to the 16-year time series in Baringer and Larsen [2001] (1982-1998) to provide the long-term mean (thin solid line). The corresponding standard deviation envelope is given by the thin dashed line. The calibrated cable data for 2003 (when available) is represented by the thick solid line. In situ transport measurements from calibration cruises is given by solid dots (dropsonde) and solid stars (LADCP). Additionally, transport measurements from LADCP corrected for the possible 10% low bias is represented with open diamonds.
Figure 9. Near-surface temperature anomaly (°C) for NDBC stations during summer of 2003. The temperature anomaly is defined as the 2003 value minus long-term time series mean for that date. The data has been 40-hour low-pass filtered. The dark blue part of the curves correspond to anomalous values of more than -1 °C. The cyan part of the curves represent anomalous values between -1 and -2 °C, while the red part of the curves correspond to anomalous values below -2 °C. The black horizontal lines correspond to zero anomaly. The time series have been represented according to latitude. The station names (from south to north) are: Sand Key, Fl (sanf1); Molasses Reef, Fl (mlrf1); Fowey Rocks, Fl (fwyf1); Lake Worth, Fl (lkwf1); Canaveral Buoy (41009); Canaveral East Buoy (41010); St. Augustine Buoy (41012); Gray’s Reef Buoy (41008); Navy Tower R2; Edisto Buoy (41004); South Hatteras Buoy (41002); Hatteras Buoy (41001); Diamond Shoals Buoy (41025); Virginia Beach Buoy (44014); and Chesapeake Light, Va (CHLV2).
Figure 10. Bottom temperature (°C) at the R2 tower location for the summer of 2003 versus the mean for 1999-2004 time series (black dashed line). The solid black curve corresponds to data collected at the R2 SABSOON tower and the solid gray curve corresponds to data from the replacement mooring at the same location. The temperature data has been 40-hour low-pass filtered.
Figure 11. Temperature (°C) sections across the SAB shelf off Georgia (see Figure 2 for cruise tracks). The contour intervals are 1 °C. The x-axis corresponds to cross-shelf distance in kilometers seaward of the 25-m isobath.
Figure 12. Salinity sections across the SAB shelf (see Figure 2 for cruise tracks). The contour intervals are 1 psu. The x-axis corresponds to cross-shelf distance in kilometers seaward of the 25-m isobath.
Figure 13. Density sections across the SAB shelf (see Figure 2 for cruise tracks). The contour intervals are 1 Kg m$^{-3}$. The x-axis corresponds to cross-shelf distance in kilometers seaward of the 25-m isobath.
Figure 14. Salinity transect across the shelf during 7 May (top) and climatological May salinity field from Blanton et al. [2003] (bottom).
Figure 15. Temperature transect across the shelf during 25 June (top) and climatological June temperature field from Blanton et al. [2003] (bottom).
Figure 16. Temperature transect across the shelf during 27 August (top) and climatological August temperature field from Blanton et al. [2003] (bottom).
Figure 17. Monthly (May-August) T-S diagrams for observations collected over the shelf. The blue dots correspond to observations from the bottom part of the water column in the mid- and outer-shelf, red dots correspond to observations from the rest of the shelf and green dots represent long-term observations from the Gulf Stream from climatological means [Blanton et al., 2003]. The solid thick black line corresponds to mean T-S curve for Gulf Stream data and the dashed black line represents one standard deviation envelope.
Figure 18. Normalized minimum T-S distance between T-S characteristics on the shelf and the T-S curve for the Gulf Stream waters evaluated using equation 2. (a) T-S distance between observations from the August 27 cruise and the T-S curve from the entire Gulf Stream water column. (b) As in a) but between the cruise observations and T-S curve of the lower part of the Gulf Stream water column (depths > 200 m). (c) As in a) but using climatological values sampled at the cruise positions. (d) As in c) but for the lower part of the Gulf Stream water column.
Figure 19. Observed (gray dashed) and predicted (black) coastal water level as a function of latitude for selected stations in the SAB. Predictions are made with the Csanady [1978] model, using monthly mean wind stress from NDBC stations near the NOS water level stations. The model results are calculated in relation to observed water level at the southernmost station at Virginia Key. The station names are Virginia Key (vk), Trident Point (tp), Fort Pulaski (fp), Springmaid Pier (sp), and Cape Hatteras (ch).
**Figure 20.** Potential energy (PE, $J/m^3$) per unit volume for several cruises using equation 4.

This PE is the amount of work required to breakdown stratification and produce complete mixing of the water column.