Cold Event in the South Atlantic Bight During Summer of 2003: Anomalous Hydrographic and Atmospheric conditions.

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Abstract. Unusually cool sea-water temperatures were observed along much of the U.S. eastern seaboard during the summer of 2003. Large scale wind patterns were upwelling favorable during this period. In the South Atlantic Bight, the presence of salinity stratification in late spring, due to larger than average river discharge, preconditioned the shelf waters to favor shoreward penetration of upwelled cold water. The resulting thermal stratification had significant effects on the dynamical and biological processes in the shelf. The characteristics of the upwelled water corresponded with water coming from the deeper part of the Gulf Stream. The cold water entered the shelf in the Cape Canaveral region through shelf-break frontal eddies and then it was transported by along-shelf currents into the Georgia Bight region, where it was observed. The water column in the inner-shelf was partially mixed during periods of increased upwelling-favorable wind conditions. In the mid- and outer-shelf the upwelling of cold water acted as a feedback mechanism to preserve the stratified conditions.
1. Introduction and Background

During the summer of 2003 an intense upwelling event took place in the South Atlantic Bight (SAB). The SAB (Figure 1) region extends from Cape Hatteras, North Carolina, to about Cape Canaveral, Florida in the eastern coast of the United States.

The mid and outer-shelf is influenced on weekly time scales by the Gulf Stream and its instabilities, with the western boundary of the stream generally appearing around the 100-m isobath [Lee et al., 1981; Lee and Atkinson, 1983].

One of the most important processes on the SAB shelf is the influx of cold, nutrient rich water from the Gulf Stream during the summer [Paffenhofer et al., 1987; Atkinson et al., 1987; Lee et al., 1991]. This upwelling process occurs throughout the SAB with different strengths, generally being stronger in the area north of Cape Canaveral. The intensity of the upwelling events presents high interannual variability. There have been several studies of these events [Green, 1944; Taylor and Stewart, 1959] but the most intensive study was conducted during the summer of 1981 as part of GABEX II [Paffenhofer et al., 1987; Atkinson et al., 1987; Lee and Pietrafesa, 1987; Hamilton, 1987]. The main results of that study were that the influx of cold water is mainly episodic and that the intrusion events occurred when cold cyclonic frontal eddies were observed together with upwelling favorable wind at a time when the Gulf Stream was in a relative onshore position. They concentrated on the region extending from Cape Canaveral to south of Savannah. In previous studies [Atkinson et al., 1980; Hofmann et al., 1981] the focus was on the northern part of the SAB shelf in the Carolina Capes region. The understanding of the Georgia Bight region during upwelling periods remains incomplete and the availability of observations during the summer of 2003 both from cruises and the SABSOON towers [Seim, 2000] allowed for a better description of the characteristics of this region during upwelling events.

The main characteristic of the summer of 2003 event was a strong thermocline that expanded from the shelf-break to about the 15-m isobath. When the temperature values under the thermocline were compared with climatological temperatures [Blanton et al., 2003] a significant difference is observed (4-6 C). The occurrence of this temperature stratification was influenced by the presence of anomalous salinity stratification in late spring associated with larger than average river discharge during the early spring.

The cold event extended all the way from Florida to New Jersey and its effects have been described in the Mid Atlantic Bight [Sun et al., 2004a]. Additional comments were presented by [Schwing and Pickett, 2004] using the wind observations to calculate a time series of upwelling index (off-shore component of Ekman Transport) following calculations by the Pacific Fisheries Environmental Lab. These studies suggest a teleconnection between global atmospheric systems that set up the conditions for 2003.
2. Data Description

Because of the unexpected nature of the event there was no specific effort to produce a rigorous set of observations to describe the water intrusion until mid-August. The available observations before that time were collected with other purposes. Therefore the availability of data for the summer of 2003 presents significant gaps.

2.1. Winds

The available wind observations during 2003 were compiled from different sources (e.g., SABSOON towers, satellite, NDBC buoys). The possibility of having complete records during the whole study period as well as a long record from previous years makes the NDBC buoy data the most appropriate for this study. The comparison of 2003 wind data with previous years for the Gray’s Reef buoy is presented in Figure 2.

The wind during the summer of 2003 was in the along-shelf direction (upwelling favorable) between the months of May and August. The variability during the summer months was smaller than during other periods of the year, as given by the standard deviation. The across-shelf wind was small during the whole year.

To determine if the mean winds for 2003 were significantly bigger than the ones for previous years we used statistical test to compare the means. The results for the Gray’s Reef buoy are shown in Table 1. This shows that the mean wind for the months of May, June, July, and August of 2003 was significantly bigger than the mean wind for the previous years at Gray’s Reef. By contrast, the winds during spring of 2003 were weaker than average. Similar results were observed in the rest of the network of wind observations for this region (not shown).

To see if the wind during the summer of 2003 was more persistent in direction than during previous years, we look at histograms of wind direction (Figure 3). We can see that for July of 2003 the wind direction corresponded approximately with the upwelling favorable direction. The percentage of upwelling favorable wind in 2003 was higher than in previous years. Similar results are observed for every summer month for every available buoy in the region (not shown).

2.2. 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 region (Figure 4). During the spring months the precipitation on the region that drains on the SAB was considered “record wettest”.

This record precipitation resulted in an increased river discharge on the SAB coastal region (Figure 5). (Do we need the total discharge? I think with the lower figure we can make the points we need). Using the Altamaha River as a reference, discharge during March
and April exceeded the 20-year mean (1975-1994) by a factor of two or more. Moreover, from June to September, discharges were 2 to 3 times higher than the summer mean. Thus, the higher than normal discharge coupled with weak or upwelling-favorable winds (Table 1) supplied a higher than average buoyancy source to the inner shelf.

2.3. Satellite data

The available satellite products for the study period include MODIS SST, AVHRR SST and microwave SST from TMI. The MODIS products have a 4km resolution while the AVHRR has a resolution of 9km. The TMI products have a much coarser spatial resolution but are not affected by most clouds. A more in depth analysis of the satellite SST data during this period is included in the study by Yuan and Li [2005].

2.4. SABSOON tower data

The SABSOON stations constitute a real-time observational network in the center of our region of interest [Seim, 2000]. This network provides observations both of the atmospheric conditions (e.g., winds, heat flux, atmospheric pressure) and the oceanic conditions (e.g., temperature, salinity, currents). Unfortunately, during the period of interest the instrumented towers were being refurbished by the US Navy and data was not available from mid-June until September.

2.5. Cruise data

A set of hydrographic surveys were conducted on board R/V Savannah on the Georgia Bight region during the spring and summer of 2003. Most of the transects were conducted in the mid and inner shelf between the coast and the SABSOON towers (Figure 6), while several extended through the whole shelf up to the shelf-break. Stations were taken at approximately 8-10 km intervals.

2.6. Additional hydrographic data

Data from available NDBC buoys and CMAN stations provided surface temperature time series. The long records available for some of these stations allow the comparison of the 2003 time series with the long-term average.

2.7. Water Level

Data from the NOS coastal water level stations in this region has been analyzed. The complete set of stations covers the whole SAB coastal region. In this study we concentrate in a subset of stations representative of the different regions: Trident Pier (1995-2004) in the Cape Canaveral Region, Fort Pulaski (1936-2004) in the Georgia Bight and Springmaid...
Pier (1978-2004) in the Carolina Capes region. The comparison of the 2003 data with the long-term average revealed a lower water level during the summer months of 2003 (Figure 7).

2.8. Transport data from Florida Straits

The data from the Florida current transport across the Florida Straits using cable voltage [Baringer and Larsen, 2001] presented calibration problems and postprocessing of this data is still underway. The only available transport information was collected during two calibration cruises across the Florida Straits. The two transport estimates fall outside the standard deviation envelop from the 16-year mean (Figure 8). This data suggests that the Florida Current transport during the summer of 2003 was significantly lower than the long-term average.

3. Results

3.1. General hydrographic characteristics

The general mass field trends of this region were observed in the set of hydrographic cruises that extended from mid-April to the end of August (Figure 6). The temperature cycle of the shelf can be seen in Figure 9. This includes the progressive warming of the surface layers of the shelf from spring into summer and a continuing cooling of the bottom layers in the mid- and outer-shelf starting in mid-June. The near-shore region suffered the effect of the increased mixing and therefore it was more affected by the pulses in upwelling-favorable wind intensity. The temperature during early August showed the partial rupture of the thermal stratification in the near-shore region. At depths of 20 m and deeper, there was a strong pycnocline marked by temperature gradients of approximately 1 degC m$^{-1}$ in the Georgia Bight region and 2 degC m$^{-1}$ off Florida. These gradients are significantly greater than those reported for previous intrusions off Florida [Atkinson et al., 1987].

Figure 10 shows the salinity cycle during the spring and summer of 2003 with low salinity waters present during April and May due to the peak in river discharge (Figure 5). While the salinity structure during April was mostly unstratified, starting in May the inner and mid-shelf presented a surface low salinity cell over more saline waters near the bottom. Due to strong 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), freshwater input from the rivers along the SAB coast typically mixed into a near-shore, low salinity band, the “coastal frontal zone”. When winds are from the north to northeast (as is typical of much of the winter to late spring), the low salinity water tends to be confined to the coast. When the winds relax or shift to south-to-southwesterly, the lower salinity coastal waters can spread seaward as a buoyant surface layer [Blanton and Atkinson, 1983]. This conditions were present during most of the spring of 2003 (Table 1) and facilitated the extension of the low salinity cell into the mid-shelf.
By July most of the observations on the shelf presented a high salinity value (around 36 psu), but the near-shore region lacked observations. In late August an additional low-salinity pulse was observed extending most of the surface waters of the inner shelf.

The density evolution during 2003 is shown in Figure 11. The minimum densities were associated with low salinity waters and were present during the whole study period. The maximum densities were associated with the cold water intruded in the shelf that was encountered in the lower part of the water column starting in late June. In April the whole water column was at least partially mixed. By May, with the development of the low-salinity cell, a strong stratification was observed. In July, the effect of the persistent upwelling-favorable wind caused the pycnocline to start shallowing up in the near-shore region. The stratification persisted in the mid- and outer-shelf, but the near-shore region was affected by the pulses in wind intensity. By mid-August, when the upwelling-favorable wind partially relaxed, the pycnocline returned to normal conditions in the inner-shelf. In late August the strongest stratification remained in the mid-shelf but the stratification in the inner-shelf increased due to the combined thermal and saline effects.

3.2. Comparison with climatological fields

Several hydrographic conditions during the study period were anomalous when compared with climatological values [Blanton et al., 2003]. The first condition was the anomalous salinity encountered during May. The excess fresh water on the shelf generated a surface low salinity cell by late spring that extended all the way to the mid-shelf (Figure 12) and that structure 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. Therefore, the main difference was the presence of a strong salinity stratification during the spring months.

The second anomalous condition was that by June, the salinity stratification had transformed into a thermal stratification. This was caused by the combined effect of surface heat flux, reduced mixing and the upwelling of cold water from the Gulf Stream (Figure 13). The strongest thermal stratification was observed in the mid-shelf while the inner-shelf stratification was dominated by the saline structure.

The final condition that significantly differed from climatological values was the more noticeable. That condition was the presence of the cold water temperatures during the last part of the summer. By late August the cold water reached from the shelf-break to the mid-shelf in the lower part of the water column and was affecting the coastal waters. While the surface water remained at climatological values, the lower part of the water column presented temperatures up to 8 degrees colder than normal (Figure 14).
3.3. T-S characteristics

To determine the origin of the cold water on the outer-shelf, a set of T-S diagrams were constructed (Figure 15). The SAV cruise observations were separated into two groups: observations from the bottom part of the water column in the mid- and outer-shelf (depths < 40 m); and observations from the rest of the shelf. When the observed T-S distributions were compared with Gulf Stream T-S characteristics, a clear correspondence was observed. By June the cold water on the shelf clearly shared the same T-S characteristics as the Gulf-Stream water. This correspondence was maintained through August and started to disappear in September. During May the upper part of the water column was strongly influenced by river discharge. By June the lower part of the water column was related to Gulf Stream water while the upper part was still influenced by fresh water. By August most of the water column was closely linked to Gulf Stream water.

To determine the specific location in the vertical of the Gulf Stream water further analysis of the T-S characteristics were developed. We calculated the normalized T-S distance between the water on the shelf and the Gulf Stream water using the expression:

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

where \( \alpha \) is the thermal expansion, \( \beta \) is the saline contraction, \( T_{GS} \) is the temperature of the Gulf Stream and \( T_j \) is the observed temperature at point \( j \) on the shelf.

When the whole Gulf Stream water column was considered, the T-S distance values for 2003 were similar to climatological values (Figure 16). This suggest that most of the water on the shelf was closely related to Gulf Stream water. The upper part of the water column near-shore presented different characteristics. This was due to the continuous river discharge during the summer months of 2003 that was above average. When instead of considering the whole water column of the Gulf Stream to evaluate the distance, we only considered the lower part of the water column (depths greater than 200 m), we identified a clear differentiation between the upper and the lower part of the water column on the shelf observations. The anomalous cold water of 2003 was closely linked to the lower part of the Gulf Stream water column. This suggests that the origin of the anomalous water was that region of the Gulf Stream.

4. Discussion

The effects of the upwelling and the associated cold water intrusion were observed in several characteristics of the continental shelf waters on the SAB.
4.1. Water Level implications

The occurrence of coastal water level fluctuations (Figure 7) contradicts the possibility of coastal trapped waves as a driving mechanism of upwelling events. There is no consistent pattern of fluctuations of northern stations leading fluctuations of southern stations.

When the coastal water level was compared with the wind forcing during summer of 2003 we observed an inverse correlation between the time series for different stations (Figure 17). But when we tried to establish if the wind anomaly could explained the water level anomaly (0.1-0.15 m), we realized that the wind explained the variability in the water level but not the absolute value of the anomaly. Therefore there were additional factors that influenced the coastal water level during this period.

*Noble and Gelfenbaum* [1992] presented evidence that coastal water level was associated with the transport of the Gulf Stream. The basic argument is that during periods of low transport, there is a reduced cross-stream slope and that is associated with higher coastal water level. During 2003 the Gulf Stream transport was lower than average and that would suggest an anomalously high water level. The observed water level was lower than average (Figure 7) which suggest that this mechanism was not a factor during 2003.

The transport measurements were only for the Florida Current at the Florida Straits, but the transport of the Gulf Stream increases from 30 Sv in that region to 100 Sv in the Cape Hatteras region. The variability of Gulf Stream transport due to fluctuations of the Bahamas Current and recirculation of the Gulf Stream on the SAB would additionally affect the coastal water level. There was no data to address the effects of this kind of variability.

Another possible explanation is the effect that the lower temperatures would have on the water level through changes on the steric anomaly. The changes in water level associated with this process were on the order of 1-3 centimeters and therefore do not explain the anomalous conditions present during 2003.

Another possible factor is the effect of the far-field pressure fields on the coastal water level. These far-field conditions could have set a low water level during the whole period of interest. The anomalous conditions of the Bahamas-Azores High [*Schwing and Pickett*, 2004] could have altered the coastal water level at large scales (???).

The long term water level variation (month scales) might have been associated with larger features and Gulf Stream effects. Meanwhile, the short term (1-5 days) variations of the water level corresponded with the 1-5 day variations on the wind (Figure 17). Increased intensity of the upwelling favorable winds corresponded with lower water level.

The persistence of these upwelling favorable conditions allowed the rupture of the stratification on the near-shore region and the detection of the low temperature signal on the surface. This low temperature signal seemed to be more predominant on the southern region (Cape Canaveral to Florida-Georgia border). In the Georgia Bight region this rupture of the stratification on the near-shore region was not as frequent due to the preconditioning by the...
river discharge. A more complete discussion of the time evolution of the event can be found in Yuan and Li [2005].

4.2. Pressure gradients

The along-shelf pressure gradient present in the SAB during summer [Sturges, 1974; Lee and Pietrafesa, 1987; Blanton et al., 2003] drives poleward shelf flow (range 0.01 - 0.05 m s\(^{-1}\)). Variations on this pressure gradient could have modified the shelf-wide flow, but the available observations did not provide enough information to address this possibility.

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 2) is negative across the whole shelf while the climatological values suggest a positive value for the inner- and mid-shelf and a negative value only in the outer-shelf [Blanton et al., 2003].

\[
R_x = \int_{-h}^{0} \frac{\partial \rho}{\partial x} dz
\] (2)

From the few cruises that provided along-shelf hydrographic information, a small along-shelf slope of the isopycnals was observed. The isopycnal surfaces were generally deeper in the northern region at least in the outer-shelf region but the slope presented a high variability. These density gradients (both along- and cross-shelf) controlled the internal structure of the flow on the shelf.

4.3. Region of cold water intrusion

In the literature the point of entrance of the Gulf Stream water into the shelf has been associated with the Cape Canaveral region (1981 study, Atkinson et al. [1987]; Lorenzzetti et al. [1987]). Additional model results focus on the 2003 event support this hypothesis (in prep). The Gulf Stream water entered the shelf predominantly in this region and then was transported into the region in which it was observed during 2003 (Georgia Bight region) (Figure 18). This “remote” origin of the anomalous water is consistent with the climatological summer flow [Blanton et al., 2003] and current observations during 2003.

The turbulent fluxes \(<u'v'>\) for the early period of the event (June 2003) evaluated from SABSOON tower data showed that the main mechanism for advective heat flux on the mid shelf was associated with pulses on the along-shelf flow. The flux was predominantly in the along-shelf poleward direction. This is consistent with the possibility of “remote origin” of the cold water. The cross-shelf heat flux was driven by pulses with a 3-5 day period, which is consistent with the passage of Gulf Stream frontal eddies along the shelf-break. (Harvey, should we include in here some reference to the work done by Catherine about the May 2003 stuff??)
4.4. Energetics during the intrusion

To evaluate the possible rupture of the stratified conditions during some events during the summer of 2003, we evaluated the relative importance of the stratification versus the work done by the wind to mix the water column.

The following equations used in this section are based on a 1-dimensional mixing model. The purpose is to evaluate if there was enough wind energy to mix the highly stratified water found during most of the summer. Consider a two-layer system with an upper layer of $\rho_1$ and thickness $h_1$ and $\rho_2$ in the lower layer. The equation for potential energy (PE) can be written:

$$PE = \frac{1}{2} (\rho_2 - \rho_1) gh_1^2$$ (3)

where $g = 9.81 \text{ m s}^{-2}$. To 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. Assuming this energy is supplied only by the wind (i.e., no mixing energy provided by the tides or other processes) at a rate

$$W = \rho_w u^3 = \rho_w \left[ \left( \frac{\rho_a}{\rho_w} \right) c_d \right]^{3/2} U_a^3$$ (4)

where $\rho_a$ is the air density, $U_a$ is the horizontal wind speed, and $c_d = 0.002$. In Figure 19 we present the energy input rate from Equation 4 together with its time accumulation given by the time integral:

$$E = \sum_{0}^{t} W \delta t$$ (5)

where $\delta t$ is the time interval between wind observations. As an example, the amount of wind energy required to completely mix the water column in the central part of the study region was approximately 2500 J m$^{-2}$ (Equation 3). This compares with 1000 to 1500 J m$^{-2}$ required to mix the intrusion of 1981 [Atkinson et al., 1987]. In other words, comparing the two intrusions, the 2003 intrusion required more than twice the mixing energy to destroy the vertical stratification. The cumulative work provided by the wind (the red line in Figure 19) was remarkably steady, as indicated by the uniform slope upward to the right. We can calculate an elapsed time required before the wind could provide enough energy to overcome the stratification, using the cumulative energy at a specific date as the initial condition. The limitation of this estimate is that the work done by the wind not only contributes to overcome the potential energy from stratification, but it provides kinetic energy to the system. Therefore these values provide an lower bound estimate of the time needed to mix the water column.

Figure 19

In order to evaluate the possible rupture of the stratification during certain periods, we looked at the potential energy for each observation in the transects collected during 2003 (Figure 20). In general, the potential energy in the whole continental shelf increased from a minimum during spring, to reach a peak during the summer and then be reduced to practically zero during the fall consistently with the breakdown of stratification. A clear separation on
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 we calculated the mean potential energy per region for several cruises (Table 2).

The estimate of the time needed for the work done by the wind to provide enough energy to overcome stratification is given in Figure 21 and its separation by region is presented in Table 3. This estimate of the potential rupture of the stratification takes into account the specific conditions of the wind during the period prior to the collection of the hydrographic data. The passage of atmospheric systems over this region is usually on scales of 3-5 days, so this is the scale of time that is taken as the upper limit for breaking down stratification. (Is this a good limit for this estimate??). During the summer of 2003 the winds are more persistent in direction and intensity than in previous years so it might have been possible for the wind to have cumulative effects over longer time scales than 5 days. In any case, the cumulative work provided by the wind was enough to break down stratification in the inner-shelf for most of the study period. In the mid- and outer-shelf an elapsed time of 1-2 months was required before the work done by the wind could break the observed stratification.

In the inner-shelf region the potential energy was small (less than 300 J m\(^{-2}\)) for most of the study period. In early spring the water column was well mixed and therefore the energy content was small. During May the development of the low salinity cell occurred due to the small intensity of the winds and the continuous input of fresh water into the shelf. This produced an increase in the potential energy, that peaked during early June. This peak was caused by a positive feedback mechanism, where the upwelling winds advected low-density (low salinity) water from the near-shore region over the top of the pycnocline, also causing the potential energy to increase. Then by July the start of the strong upwelling favorable conditions and a minimum on the river input partially mixed the water column on the inner shelf. Until mid-August the conditions remained favorable to partial mixing of the water column associated with pulses in the upwelling favorable winds. By late August the potential energy reached a maximum consistently with the decreased in upwelling favorable winds intensity and additionally with a pulse of river input into the shelf. By the next observation in early October the downwelling favorable conditions and the passage of storms had already ruptured the stratification.

In the mid- and outer-shelf the results indicate that there was insufficient wind energy to break up the 2-layer system of the intrusion because the strong vertical stratification prevented vertical mixing via wind from penetrating the pycnocline. Instead, the persistent upwelling favorable winds provided a positive feedback whereby high density Gulf Stream water flooding landward along the bottom further enhanced stratification, thus requiring more mixing energy to penetrate the pycnocline and allowing the intruding water to spread ever farther northward. The obvious event required to shut this process down would be the change-over from upwelling- to downwelling-favorable winds which would quickly destroy the stratification, first at the coast, then working its way seaward. This complete rupture of the
stratification due to the winds happened in the inner- and mid-shelf regions during September 2003, resulting on a well mixed water column in October (Table 2).

Most of the previous analysis was focus on the Georgia Bight region, but the observations in the Florida region suggest that due to the smaller riverine input in this area, the same wind intensity produced more frequent rupture of the stratification in the inner-shelf. This produced a cooler temperature in the surface waters. These cool water temperatures on the surface can be observed in the satellite observations (Yuan and Li [2005]). In the mid- and outer-shelf of the Florida region stronger stratification was observed due to the combined effect of the proximity of the main source of cold water (Cape Canaveral region), the smaller river discharge, and greater heat flux into the ocean than in the Georgia Bight region.

5. Conclusions

The main conclusions of this study are: 1) Anomalous upwelling favorable winds (both in intensity and persistence) were a principal driver of this event; 2) Increased river discharge and weaker winds during spring preconditioned the shelf through increased stratification; 3) The cold water upwelled onto the shelf came from the lower part of the water column of the Gulf Stream; 4) The coastal water level suggests a complex interaction between local and remote atmospheric forcing and the Gulf Stream; 5) Even though the specific cold water episodes are related to the wind intensity, the low water temperatures are associated with the persistency of the upwelling, the Gulf Stream frontal eddy activity and the stratification on the shelf; 6) The work done by the wind was enough to break down the stratification in the inner shelf during periods of intense winds.

During a normal year the upwelling is still present and the upwelled water may reach the surface in the inner-shelf. The normal conditions upwelled waters that are persistently warmer than the waters during 2003. The normal stratification is not as strong and therefore the upper and lower parts of the water column are better mixed.

The extend of the anomalous conditions during this period was not only restricted to the SAB. Effects have been described all the way from the west Florida shelf up to Georges Bank. It has been proposed [Schwing and Pickett, 2004; Sun et al., 2004b] that the atmospheric anomalous conditions affected the whole North Atlantic and were related to the record warm summer on 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 implications of this event to other conditions, such as biological conditions remain to be addressed (Jim, somebody was working on this, right?). The presence of upwelled cold water on the shelf has been associated with increased productivity on the shelf [Yoder et al., 1985; Paffenhofer and Lee, 1987; Lee et al., 1991]. Therefore considering the volume and extend of the 2003 intrusion, the resulting alterations on biological conditions might have
been significant.

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Figure Captions

Figure 1. South Atlantic Bight region. The black dots correspond to SABSOON tower locations. The red dots are NOS water level stations used in this study. The green dot corresponds to the NDBC buoy at Gray’s Reef. The blue line represents one of the hydrographic cruises done on board the R/V Savannah during the summer of 2003. The red line corresponds to the location of the submarine cable in the Straits of Florida.

Figure 2. 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 3. Histograms of wind direction for 2003 and the previous years for the month of July for Buoy 41008 (Gray’s Reef). The red line represents the upwelling favorable direction.

Figure 4. Precipitation during spring 2003 provided by NCDC (www.ncdc.noaa.gov).

Figure 5. River discharge to the SAB from the beginning of 2003, based on data from the Altamaha, Savannah, and Pee Dee Rivers. The total discharge was estimated as twice the sum of the three rivers, as done by (??).

Figure 6. Cruise tracks of R/V Savannah during spring and summer of 2003 in the Georgia Bight region.

Figure 7. Coastal water level difference during the summer months of 2003 for three NOS stations.

Figure 8. Florida Current transport across the Florida Straits adapted from [Baringer and Larsen, 2001]. The 16-year average transport is presented with its corresponding standard deviation. The two transport estimates available for 2003 are represented with black dots.

Figure 9. Temperature sections across the SAB shelf during several cruises (Figure 6). The contour intervals are 0.5 degC. The cross-shelf distance corresponds to Km seaward of the 25m isobath.

Figure 10. Salinity sections across the SAB shelf during several cruises (Figure 6). The contour intervals are 0.5 psu.

Figure 11. Density sections across the SAB shelf during several cruises (Figure 6). The contour intervals are 0.5 Kg m$^{-3}$.

Figure 12. Salinity transect across the shelf and its comparison with climatology during May.
Figure 13. Temperature transect across the shelf during June and its comparison with climatology.

Figure 14. Temperature transect across the shelf during late August and its comparison with climatology.

Figure 15. Monthly T-S diagrams for observations collected by SAV cruises. 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 curves and the dashed black line represents one standard deviation envelope.

Figure 16. T-S distance from observations to Gulf Stream evaluated using equation 1.

Figure 17. Correlation between 40-hour low-pass water level anomaly (2003 minus 70-year mean) at Fort Pulasky in meters and upwelling favorable wind anomaly (2003 minus 70-year mean) from NDBC buoy 41008 (Gray’s Reef)

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Figure 20. Potential energy (J m$^{-2}$) for several cruises.

Figure 21. Time (days) needed for the wind to provide enough energy to overcome stratification for different cruises.
# Tables

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**Table 1.** Along-shelf mean wind comparison between the year 2003 and the previous years of observations for Buoy 41008 (Gray’s Reef).

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<th>Date</th>
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**Table 2.** Potential Energy (J m$^{-2}$) per shelf region for different cruises.
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Table 3. Time (days) needed for the wind to provide enough energy to overcome stratification per shelf region for different cruises.
Figures

Figure 1. South Atlantic Bight region. The black dots correspond to SABSOON tower locations. The red dots are NOS water level stations used in this study. The green dot corresponds to the NDBC buoy at Gray’s Reef. The blue line represents one of the hydrographic cruises done on board the R/V Savannah during the summer of 2003. The red line corresponds to the location of the submarine cable in the Straits of Florida.
Figure 2. 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 3. Histograms of wind direction for 2003 and the previous years for the month of July for Buoy 41008 (Gray’s Reef). The red line represents the upwelling favorable direction.
Figure 4. Precipitation during spring 2003 provided by NCDC (www.ncdc.noaa.gov).
Figure 5. River discharge to the SAB from the beginning of 2003, based on data from the Altamaha, Savannah, and Pee Dee Rivers. The total discharge was estimated as twice the sum of the three rivers, as done by (??).
Figure 6. Cruise tracks of R/V Savannah during spring and summer of 2003 in the Georgia Bight region.
Figure 7. Coastal water level difference during the summer months of 2003 for three NOS stations.
Figure 8. Florida Current transport across the Florida Straits adapted from [Baringer and Larsen, 2001]. The 16-year average transport is presented with its corresponding standard deviation. The two transport estimates available for 2003 are represented with black dots.
Figure 9. Temperature sections across the SAB shelf during several cruises (Figure 6). The contour intervals are 0.5 degC. The cross-shelf distance corresponds to Km seaward of the 25m isobath.
Figure 10. Salinity sections across the SAB shelf during several cruises (Figure 6). The contour intervals are 0.5 psu.
Figure 11. Density sections across the SAB shelf during several cruises (Figure 6). The contour intervals are 0.5 Kg m$^{-3}$. 
Figure 12. Salinity transect across the shelf and its comparison with climatology during May.
Figure 13. Temperature transect across the shelf during June and its comparison with climatology.
Figure 14. Temperature transect across the shelf during late August and its comparison with climatology.
Figure 15. Monthly T-S diagrams for observations collected by SAV cruises. 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 curves and the dashed black line represents one standard deviation envelope.
Figure 16. T-S distance from observations to Gulf Stream evaluated using equation 1.
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