Dynamics of the Cold-Water Event off the Southeast Coast of the United States in the Summer of 2003

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ABSTRACT

The cold-water event along the southeast coast of the United States in the summer of 2003 is studied using satellite data combined with in situ observations. The analysis suggests that the cooling is produced by wind-driven coastal upwelling, which breaks the thermocline barrier in the summer of 2003. The strong and persistent southwesterly winds in the summer of 2003 play an important role of lifting the bottom isotherms up to the surface and away from the coast, generating persistent surface cooling in July–August 2003. Once the thermocline barrier is broken, the stratification in the nearshore region is weakened substantially, allowing further coastal cooling of large magnitudes by episodic southerly wind bursts or passage of coastally trapped waves at periods of a few days. These short-period winds or waves would otherwise have no effects on the surface temperature because of the strong thermocline barrier in summer if not for the low-frequency cooling produced by the persistent southwesterly winds.

1. Introduction

In the summer of 2003, the sea surface temperature (SST) along the entire east coast of the United States from Ocean City, Maryland, to Florida was found to be unusually cold. At the peak of the event, the SST offshore of the east Florida coast, which is usually above 28°C in summer, was in the low 20s (°C). The cold water, together with the weak economy and the rainy summer season, has made the fishery and recreational business along the east coast suffer greatly. This cold-water event was in direct contrast to the hot summer season that was partially blamed for the blackout of electricity in the northeastern area of the United States.

The cold-water event was not predicted, nor has a plausible explanation been given. In this study, the cause of the cold SST anomalies is investigated using the Moderate Resolution Imaging Spectroradiometer (MODIS) and SeaWinds scatterometer measurements, combined with coastal and satellite altimetry sea level data, shelf mooring observations, and ship hydrography measurements. The focus will be on the SST anomalies in the South Atlantic Bight, where mooring measurements in the midshelf and hydrographic data across the shelf are available in the summer of 2003.

This paper is organized into six sections. In the next section, the oceanography of the study region is reviewed. The satellite and in situ measurements used in this study are described in section 3 and the results of the analysis are presented in section 4. A discussion of the dynamics of the coastal cooling is given in section 5. Conclusions are summarized in section 6.

2. Oceanography of the study region

The South Atlantic Bight is defined as the continental shelf area between Cape Hatteras, North Carolina, and West Palm Beach, Florida, with the curved coast of the United States to the west and the warm Gulf Stream to the east flowing northward along the continental slope. A general description of the oceanography of this area is given by Atkinson and Menzel (1985). Climatological averages show that the currents of this area can be classified into circulation over the inner, middle, and outer shelves. The inner-shelf circulation is influenced by river runoff. In summer, when the wind is from the south, the inner-shelf currents flow...
northward (Atkinson et al. 1983). A salinity front is observed between the inner and the middle shelves that acts as a dynamic barrier to river discharge moving further offshore (Blanton 1981). The outer-shelf circulation is dominated by the variations of the Gulf Stream with a strong thermal front separating the middle-shelf waters from the outer-shelf circulation (Lee and Atkinson 1983). Low-frequency currents in the middle shelf (20–40 m) are due primarily to local wind forcing, although Gulf Stream events can penetrate the area occasionally (Atkinson et al. 1983).

Observations have shown that SST over the South Atlantic Bight in summer is dominated by solar heating, with SST greater than 28°C present over the inner shelf of the central and southern South Atlantic Bight in July through August (Atkinson et al. 1983). Upwelling is forced by summer southerlies, inducing SST slightly colder than 28°C over the inner shelf north of 29°N (Atkinson et al. 1983).

The anomalous cold-water event in the summer of 2003 along the mid-Atlantic coast north of the area of interest of this study has been investigated by Sun et al. (2004a). The investigation shows that the SST anomalies measured at a buoy off the coast of Virginia in July of 2003 are induced by a cold-water intrusion from the north during 3–5 July and by a coastal upwelling event induced by a southerly wind burst in 24–25 July 2003. A comment on that study by Schwing and Pickett (2004) suggests that the upwelling in the Middle Atlantic Bight in the entire summer of 2003 is abnormally high, which may be associated with global multidecadal variations of the climate. In a reply to the comment, Sun et al. (2004b) show that the buoy SST is indeed highly correlated with the Southern Oscillation index. While all of these studies are interesting, none of them have focused on the SST anomalies in the South Atlantic Bight.

Theoretical studies of coastal upwelling with oceanic stratification similar to that of the east coast of the United States have been conducted by Romanou and Weatherly (2001) and Austin and Lentz (2002). The former shows that bottom Ekman transports resulting from the interior geostrophic flow can be arrested by the strong stratification of the ocean thermocline so that the bottom boundary layer is detached from the topography, resulting in a shallow upwelling cell in the upper ocean. The latter demonstrates the case of strong wind-driven upwelling that penetrates through the ocean thermocline and lifts subthermocline cold water to the surface. It will be shown that the climatological upwelling over the South Atlantic Bight corresponds to the former case whereas the cooling in the summer of 2003 corresponds to the latter case.

3. The data

The satellite data used in this study include the MODIS SST and ocean color data, the wind data of the QuikSCAT scatterometer, and the merged altimetry data of the Ocean Topography Experiment (TOPEX)/Poseidon, Jason 1, and European Research Satellites. The MODIS SST and ocean color data are archived at the Distributed Active Archive Center (DAAC) and the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) project, respectively, of the Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA). The scatterometer wind data of the SeaWinds instrument onboard QuikSCAT are archived at the Physical Oceanography DAAC of the Jet Propulsion Laboratory of NASA. The merged sea level anomalies and geostrophic currents are produced by the French Archiving, Validation, and Interpolation of Satellite Oceanographic Data (Aviso) project.

The MODIS 11-μm sensor is a heritage of the traditional Advanced Very High Resolution Radiometer (AVHRR) sensor with an accuracy of 0.3 K. The MODIS 4-μm sensor is less sensitive to atmospheric water vapor and has a nominal accuracy of 0.2 K. The MODIS instruments have been put on two satellites, Terra and Aqua, both of which are in sun-synchronous polar orbits. In this study, the 11-μm nighttime SST images of MODIS on Terra (hereinafter MODIS/Terra) are shown. Analyses of other SST products of MODIS show essentially the same large-scale structures. Images of the chlorophyll-a concentration from MODIS on Aqua (hereinafter MODIS/Aqua) will also be shown. Images of chlorophyll-a concentrations observed by MODIS/Terra and the SeaWiFS sensor show essentially the same large-scale structures as in the MODIS/Aqua images and will not be shown.

The merged altimetry data are mapped onto a global grid of 1/3° resolution between 82°S and 82°N and are archived in weekly (7 days) averaged frames by the Aviso project using the method of Ducet et al. (2000). The sea level anomalies (SLA) are relative to a 7-yr mean from January 1993 to December 1999. The altimetry data have had tidal and sea level pressure signals removed. Over the shelf area, however, the data still contain aliases from tides and internal waves (O. Lau- ret 2005, personal communication). Thus, the data over the shelf shallower than 50 m are masked out in the figures. The geostrophic currents are calculated from the absolute dynamic topography (ADT) data. According to the user handbook of this product (Aviso 2006),

\[
\text{ADT} = \text{SLA} + \text{Mean Sea Surface Height} - \text{Geoid}
\]
Therefore, the geostrophic currents include the mean circulation and errors induced by the geoid. However, the total geostrophic currents are in good agreement with the SST and ocean color data, suggesting that the errors introduced by the geoid in the Gulf Stream area are small. The difference of the Gulf Stream between 2002 and 2003 is calculated by subtracting the currents of the two years and, therefore, has the geoid errors removed.

Monthly wind data are averaged from the daily mapped product of the QuikSCAT scatterometer wind speed. The $\frac{1}{4}$-degree resolution is subsetted into $\frac{1}{2}$-degree resolution for a clearer presentation. In addition to the above data, the precipitation data measured by the Tropical Rainfall Measuring Mission (TRMM) are used to study the spatial correlation between the SST anomalies and the precipitation anomalies.

The in situ data used in this study include those from coastal tide gauge, coastal and shelf moorings at the NOAA buoy stations 41004 and 41008, and two cross-shelf hydrography sections measured by Skidaway Institute of Oceanography during two cruises of 28–30 July and 17–18 August 2003, respectively (Fig. 1). Near-bottom temperature and salinity were also measured in June 2003 at an offshore tower of R2 in about 26-m water (Fig. 1), which provide evidence of bottom upwelling during a period of southwesterly wind.
4. Results

a. Surface observations

The monthly averaged SST image in July 2003 shows a much cooler strip of water along the southeast coast of the United States than in July 2002 (Fig. 2). The SST distribution in July 2002 is close to the climatological distribution (Atkinson et al. 1983), which shows SST close to 28°C along the coast of the South Atlantic Bight. In contrast, the averaged coastal SST in July 2003 is in the low twenties (°C), except near the coast between Charleston, South Carolina, and Fernandina, Florida (Fig. 1), where the SST is slightly higher. The slightly warmer SST along this section of the coast is also observed in the climatological distribution (Fig. 2a), the dynamics of which are not clear at present.

The monthly averaged winds observed by the SeaWinds scatterometer during July 2002 and 2003 are predominantly from the southwest over the shelf. The wind patterns are close to that of the climatological mean of Hellerman and Rosenstein (1983) in July (not shown) except that the winds in 2003 are much stronger and more persistent than in 2002 (see Fig. 9 below). The narrow strip of the cool water along the coast and the dominant southwesterly wind suggest that the cold SST anomalies in the summer of 2003 are induced by coastal upwelling forced by the wind-driven offshore Ekman transport. Classical Ekman theory suggests a surface mass transport at a right angle to the right of the wind stress vector in the Northern Hemisphere resulting from the earth’s rotation (Pond and Pickard 1983). The wind patterns in July 2002 and July 2003 are similar, suggesting that the magnitudes and the persistence of the winds are the main reasons for the SST difference between the two years.

The cold SST anomalies are accompanied by higher
chlorophyll concentration along the east coast of the United States in July 2003 than in July 2002 (Fig. 3). Data from MODIS/Terra and SeaWiFS confirm the difference (not shown). The enhanced chlorophyll concentration near the coast is most likely produced by the nutrient-rich bottom water from the enhanced upwelling and from the enhanced offshore surface Ekman transport. Therefore, the satellite images in Figs. 2 and 3 suggest that the cold coastal water in the summer of 2003 is generated by anomalous coastal upwelling induced by the unusually strong southwesterly wind. The much larger anomalies of chlorophyll concentration along the Middle Atlantic coasts relative to those along the South Atlantic coasts in July 2003 suggest the significant role played by ocean stratification. The large anomalies of chlorophyll concentration in the north can be explained by the weak stratification there that is relatively easier to overcome by the upwelling currents.

b. Sea level variations

The coastal upwelling can be examined using the tide gauge sea level data along the east coast of the United States. The tide gauge data have been adjusted to the atmospheric surface pressure of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis in an inverted hydrostatic balance. The sea level depressions in mid-May, early June, and July through August along the east coast of the United States are clearly indicated by the coastal tide gauge data (Fig. 4). Significant southward-propagating signals are detected in the sea level time series, consistent with the coastally trapped
wave theory (Wang and Mooers 1976; Clarke and Brink 1985; Clarke and Van Gorder 1986; Brink 1991). The waves are trapped to the coast, propagating to the south with the coast on the right-hand side facing the direction of wave propagation. Thus, the sea level in the South Atlantic Bight is determined by both remote and local wind forcing. Negative sea level anomalies indicate upwelling, and positive anomalies downwelling.

The upwelling events in mid-May and early June 2003 appear to be forced primarily by local winds, because the sea level amplitudes at Cape Hatteras during these events are small and the sea level time series in the South Atlantic Bight are in good correlation with the wind stress time series in the top panel. A significant downwelling event in the South Atlantic Bight takes place in late June, which follows a significant sea level buildup in the Middle Atlantic Bight, suggesting that this downwelling event is primarily forced remotely from the north. The upwelling events in July through August 2003 are also forced primarily by local winds.
winds, because the average of the sea level variations at Atlantic City, New Jersey, during this period is nearly zero. The largest upwelling episode in the summer of 2003 is generated in the South Atlantic Bight during 20–23 July, apparently by local upwelling-favorable winds. After the maximum upwelling event, the wind in the South Atlantic Bight is switched to northerly briefly on 24 July. However, the upwelling is maintained in the South Atlantic Bight evidently by the propagation of sea level depression from the north (see the phase line). In early August, the sea level in the Middle Atlantic Bight is small, suggesting that the episodic upwelling events in the South Atlantic Bight during this period are forced primarily by local winds.

Because of the southward propagation of the coastally trapped waves, the response of the South Atlantic Bight circulation to the wind forcing is an integration of the wind stress from the north. The trapped waves thus enhance the oceanic responses in the South Atlantic Bight, as suggested by the increase of sea level amplitudes from Ocean City, Maryland, down south to St. Simon Sound, Georgia. Southward propagation of the sea level anomalies is clearly identified in Fig. 4. The propagation speeds are estimated to be from 2.5 to 6 m s\(^{-1}\). For example, the sea level depression at Virginia Key, Florida, on 28 July can be traced northward to the maximum upwelling event at Atlantic City on 26 July. Considering the distance of about 1200 km between these two cities, the wave propagation speed is estimated to be around 6 m s\(^{-1}\) on average.

A calculation of the cross-shelf modal pressure of the first mode of the coastally trapped wave at the wave-number of 10\(^{-6}\) m\(^{-1}\), based on the topography along the 28–30 July cruise track offshore to about the 1000-m isobath (over 300 km from the coast) and the density profile based on the Levitus and Boyer (1994) temperature and Levitus et al. (1994) salinity, has resulted in a wave speed of 5.8 m s\(^{-1}\) at the frequency of 5.8 \times 10^{-4} s\(^{-1}\). This wave has a period of about 2 days, which corresponds to the propagating signals detected in the tide gauge sea level data mentioned above. The buoyancy frequency of the Levitus data and the cross-shelf modal pressure of this wave are shown in Fig. 5. The calculation, which is based on the theory of Clarke and Van Gorder (1986), has adopted a long-wave approximation of the more general coastally trapped wave theory. For even lower-frequency waves, the propagation speeds and cross-shelf modal pressure of the first-mode coastally trapped wave are essentially the same. The structure of the cross-shelf modal pressure suggests that the leading mode response of the shelf circulation to wind forcing is nearly barotropic and strongly trapped to the coast. The Burger number for the summer of 2003, defined as \(B = (NH/\alpha L)^2\), where \(N = 3 \times 10^{-2} s^{-1}\) (so that \(N^2 = 10^{-3} s^{-2}\); see section 4e) is the buoyancy frequency, \(f = 7 \times 10^{-5} s^{-1}\) the Coriolis parameter, and \(H = 50\) m and \(L = 100 km\) the scales of depth and shelf width, respectively, is calculated to be 0.05. Because the Burger number is much less than 1, the structure of the modal pressure is essentially barotropic. The monotonic offshore decrease of the modal pressure suggests that the bottom Ekman transport of this mode is contiguous from the slope to the coast, which brings the offshore subsurface cold water to the nearshore area. The discussion of the structures of higher-mode waves is omitted here. It is known that the coastal sea level response to wind forcing is dominated by the first-
mode coastally trapped wave (Clarke and Van Gorder 1986).

The fast wave speeds of the first-mode coastally trapped waves suggest that the remote wind effects can be carried from the northern end of the South Atlantic Bight to the Florida coast within 2 days. For episodic wind bursts with large horizontal scales and at periods of a few days or longer, the trapped wave propagation thus superimposes the remote wind effects from the northern area onto the local wind effects in the South Atlantic Bight, resulting in increased sea level fluctuations southward. Along the coast from Georgia to Florida, however, the sea level amplitudes decrease, probably because of the curved coastline and the shrink of the shelf width, which make the southwesterly wind less effective in generating sea level fluctuations over that area.

c. Near-bottom observations

The existence of upwelling currents in the bottom Ekman layer at the time of sea level depressions has been recorded by the near-bottom observations of temperature and salinity at tower R2 during the first half of the month of June 2003 (Fig. 6). The data after 15 June are interrupted because of instrument maintenance. The sea level data in Fig. 4 suggest that a significant upwelling event takes place in early June 2003. The increase of the bottom salinity is clear evidence of the bottom upwelling, which transports the more saline subsurface water from offshore. The near-bottom temperature, on the other hand, does not decrease immediately. Instead, it continues increasing for the first few days of June, which can be interpreted as a result of surface heating and mixing. As the salinity keeps on increasing, on 6 June, the bottom temperature starts to decrease rapidly, suggesting that the upwelling has overcome the heating at the bottom of this location.

d. Covariation of SST with the sea level

To correlate the SST anomalies with the upwelling currents and to investigate the dynamics of the unusual cooling in the summer of 2003, the time series of coastal SST measured by NOAA buoy 41008 (Fig. 1) and the tide gauge sea level at Charleston in 2001, 2002, and 2003 are shown in Fig. 7. The upper panel shows that the SST time series of 2001, 2002, and 2003 agree very well with each other during the month of June, notwithstanding the differences in May of the 3 yr. The upwelling variations indicated by the sea level fluctuations have little impact on the SST variations in June, suggesting that seasonal heating dominates the SST variations in June. Notice that in early June 2003, the upwelling at the bottom of tower R2 is evident by the increase of near-bottom salinity and the decrease of near-bottom temperature (Fig. 6). However, the surface temperature is still increasing, suggesting that surface heating dominates the SST variations in June.
From late June to late August 2003, the SST at buoy 41008 shows a persistent cooling event that is in agreement with the depression of the sea level at Charleston. The sea level during this persistent cooling event is forced primarily by local wind, as argued in section 4b, based on the coastal tide gauge observations. The covariance between the sea level and the SST suggests that the significant cooling during July–August of 2003 is induced by wind-driven coastal upwelling. On top of the low-frequency cooling event, three episodes of strong cooling take place in mid-July, late July, and early August, each lasting for a few days and each generating a minimum SST value lower than the previous event. The cooling during 13–16 July is coincident with relaxation of the wind (Fig. 4) and sea level (Fig. 7), and lags an upwelling event that peaked on 11 July. The satellite image on 18 July suggests that the decrease of SST at buoy 41008 is due to offshore movement of the pycnocline fronts during the growth stage of the upwelling event (Fig. 8). The offshore movement explains the time lag between the sea level depression and the offshore cooling.

Figure 8 also indicates that the Gulf Stream front stays afar from the coast and the mooring sites at the time of the upwelling. This suggests that the episode of the upwelling is not induced by the encroachment of the Gulf Stream against the shelf. The effects of the Gulf Stream variations to the upwelling of 2003 will be discussed further in section 5.

The upwelling episode in late July is evidently induced by a wind-forced upwelling event, which is followed by the passage of coastally trapped waves originating from the Middle Atlantic Bight (Fig. 4). The wind-forced event produces the lowest sea level in the South Atlantic Bight in the summer of 2003. The passage of the trapped waves helps maintain the depressed sea level, even under a weak northerly wind condition on 24 July. The time lag of 1–2 days between the minima of SST and sea level during this episode is again present and is attributed to the offshore movement of the pycnocline.

The lowest coastal SST at buoy 41008 in the summer of 2003 is observed on 12–13 August, immediately after a weak upwelling event that peaked on 9 August as indicated by the sea level data. From Fig. 4, it is clear that this upwelling event is produced by local wind stress associated with a southwesterly wind burst. The time lag of ~2 days is once more present and is due to the offshore movement of the pycnocline, which is sharper than that in July (see Fig. 11). The sharper pycnocline explains the weak sea level depression but stronger coastal cooling during this event than in late July. The data show that, during this episode, the SST at buoy 41008 decreases from >27° to <24°C, a temperature close to the near-bottom temperature of ~24°C at tower R2 (Fig. 6). This suggests that the upwelling has penetrated through the upper part of the thermocline to reach the bottom of the midshelf ocean during this episode.

In comparison with the sea level data of 2003, the sea level data in 2001 and 2002 suggest that upwelling events in these 2 yr are short lived (middle and bottom panels of Fig. 7). The SST time series show little effects of the upwelling events in 2001 and 2002. Notice that the amplitudes of sea level fluctuations at time scales of a few days in these 3 yr are comparable. For example, the sea level drop in late June of 2002 is larger than in 2003. However, the SST of 2002 shows little effect of this upwelling event. The upwelling in the summer of 2003 is much more persistent, which may explain the extraordinary surface cooling in July through August 2003. The persistent southwesterly wind has been forcing continuously on the South Atlantic Bight since late May until late August 2003 (Fig. 4). The study of McCreary and Rhines (1991) has suggested a buoyancy “shut down” time scale, at which the cross-slope advection alters the force balance within the bottom boundary layer so that the cross-slope transport decreases as $\left(\frac{\nu}{\tau}\right)^{1/2}$, where

$$\tau = \frac{1}{S^2 f \cos \alpha} \left(\frac{1}{1 + \frac{1}{S}}\right).$$

Here $S = (N \sin \alpha / \cos \alpha)^2$, where $f$ is the Coriolis frequency, $\alpha$ the slope angle, $N$ the buoyancy frequency, and $\sigma$ the Prandtl number. Within the shutdown time scale, the upwelling does not exert significant impact on the surface temperature. Taking $N^2 = 10^{-3}$ s$^{-2}$ according to the cross-shelf hydrography (see Fig. 10 below), $f = 10^{-4}$ s$^{-1}$, $\tan \alpha = 0.33 \times 10^{-3}$, and, assuming the Prandtl number is large, the shutdown time scale is estimated to be $10^6$ s = 11 days. When the Prandtl number is not large, this time scale can be even longer. According to the tide gauge sea level data, most of the upwelling events in 2001 and 2002 are around or shorter than this time scale, which explains their insignificance to the SST evolution.

The stronger and more persistent southwesterly winds in the summer of 2003 than that in 2002 can be demonstrated by a comparison of the integrated wind stress vectors of the two years at buoy station 41004 (Fig. 9). The surface wind stress is converted from the wind speed data using the bulk formula with a drag coefficient of $1.4 \times 10^{-3}$ (Pond and Pickard 1983). The net displacement of the integrated vectors of 2003 is
much larger than that of 2002, which clearly demonstrates that the southwesterly wind in the summer of 2003 is stronger and more persistent than that of 2002. Because the spatial structures of the winds of the two years are similar, as seen in Fig. 2, the unusual cooling in the summer of 2003 is believed to be due to the unusual strength and persistence of the winds. Indeed, the cumulative offshore Ekman transports of June–August, calculated based on the surface wind stress, are (0.8, 0.2, 3.8) × 10^6 m^2, respectively, for (2001, 2002, 2003). Assuming a surface Ekman layer thickness of 10 m (see Fig. 10), these correspond to cumulative offshore movement of the pycnocline front of 80, 20, and 380 km, respectively, by just the wind-driven surface Ekman transport. The significantly larger cumulative offshore Ekman transport in the summer of 2003 ac-

Fig. 8. Snapshot of SST at 0255 UTC 18 Jul 2003. Black areas indicate cloud covers. The dash line across the basin is where two swaths are stitched together.
centuates the importance of the wind-driven coastal upwelling in the anomalous cold-water event in the South Atlantic Bight.

e. Cross-shelf hydrography

Two cross-shelf hydrographic sections were run by the Research Vessel (R/V) Savannah during the summer of 2003. An SBE 25 CTD was used to record the vertical structure of water temperature. The first cruise was conducted during 28–30 July and the second was conducted during 17–18 August.

Figure 10 shows the temperature distribution in the first hydrographic section. At this time, a peak cooling event is just over and the SST has been restored somewhat as suggested by the SST time series measured by NOAA buoy 41008 (Fig. 7). However, the significant lifting of the temperature contours in the nearshore region in contrast to the leveled contours in the midshelf is still evident in the data. For example, the temperature contours of 24° through 27°C have all been lifted up to less than 10 m below the surface near the coast. According to Fig. 7, the minimum SST during the cold-water episode of 22–23 July is less than 24°C. This means that the temperature contours are even more uplifted during that event. The structure of the thermocline in Fig. 10 suggests strongly that the surface cooling in the nearshore region seen in Fig. 2b is due to coastal upwelling.

The hydrography data in Fig. 10 also show domed temperature contours offshore over the outer shelf (>40-m depth). As stated in section 2, the outer shelf of the South Atlantic Bight is frequented by Gulf Stream eddies and filaments. The lifted temperature contours offshore are consistent with a cold cross-shelf filament that is entrained by the Gulf Stream as illustrated by the satellite image of SST in Fig. 2b. The leveled temperature contours over the middle shelf suggest that the nearshore event is not induced directly by the offshore feature.

Figure 11 shows that the temperature distribution in a cross-shelf section from Doboy Sound to the shelf break from the 17–18 August cruise (Fig. 1). The maximum surface coastal cooling of 5–15 August was just over at the time of the cruise (Fig. 7). However, vestiges of the thermocline structure during that upwelling epi-

![Fig. 9. Comparison of time-integrated wind stress vectors of the summers (May–August) of 2002 (dash) and 2003 (solid) at buoy 41004.](image)

![Fig. 10. Cross-shelf temperature distribution in a hydrographic section measured during the 28–30 Jul 2003 cruise.](image)

![Fig. 11. Cross-shelf temperature distribution in a hydrographic section measured during the 17–18 Aug 2003 cruise.](image)
sode can still be identified in the data. In comparison with Fig. 10, the pycnocline in Fig. 11 is much shallower and sharper, which facilitates surface cooling through upwelling and mixing.

5. Discussion

The theoretical study of Romanou and Weatherly (2001) has shown that upwelling in the bottom boundary layer can be arrested by the stratification of the thermocline so that mass divergence is generated at the top of the bottom boundary layer, inducing detachment of the boundary layer from the ocean bottom. The SST image in Fig. 2a suggests that the surface heating dwarfed the SST cooling that was induced by the upwelling forced by the winds and the Gulf Stream in the summer of 2002 so that the SST in the area is uniform and warm. Because ocean currents tend to follow isopycnic surfaces, the warm SST suggests that the vertical upwelling cell is thin over the South Atlantic Bight in a typical summer.

In comparison, the large negative SST anomalies in Fig. 2b suggest that the upwelling of the summer 2003 has penetrated through the upper portion of the thermocline and has lifted much colder water from the deep ocean. The structures of this kind of upwelling have been studied by Austin and Lentz (2002). Their results show outcropped pycnocline and offshore movement of the pycnocline front, consistent with the satellite and coastal mooring observations presented above. The weak stratification in the nearshore region left over by the offshore movement of the pycnocline front facilitates further upwelling of the deep water, resulting in further cooling of the surface SST. Here, the persistence of the southwesterlies in the summer of 2003 plays a key role in breaking the thermocline barrier because the winds have lasted longer than the buoyancy shutdown time scale of the bottom Ekman layer. The low-frequency cooling weakens the nearshore stratification and sets up the stage for winds and coastally trapped waves to generate episodic cooling at periods
of a few days. These short-period events would have no effects on the surface temperature if not for the weakened coastal stratification generated by the strong and persistent southwesterly winds in the summer of 2003. The strong and persistent southwesterly winds in July 2003 also make an intrusion of cold water from the north unlikely, because the midshelf circulation is strongly correlated with the wind forcing (Atkinson et al. 1983). The chlorophyll concentration in Fig. 3 shows strong northeastward entrainment by the Gulf Stream at Cape Hatteras from the coast (Fig. 3). The coastal SST at Cape Hatteras is higher than at the east Florida coasts in July 2003 (Fig. 2b). These facts suggest that the cold water in the South Atlantic Bight could not have been advected from the north. As a comparison, the offshore cooling during 3–5 July 2003 in the Middle Atlantic Bight has been associated with an intrusion of cold water from the north (Sun et al. 2004a). However, the intrusion is weak and appears to be confined within the Middle Atlantic Bight.

In the summer of 2003, enhanced rainfall has been observed over the entire east coast of the United States. Figure 12 shows the monthly averaged anomalies of the TRMM precipitation in July 2003 relative to a monthly climatology of 1998–2003. A large area of positive precipitation anomalies occupies the east coast of the United States. The spatial structures of the precipitation anomalies are significantly different from those of the SST anomalies. Underneath the large area of positive precipitation anomalies, the SST is mostly warm except within a very narrow band along the coast (Fig. 2b). Over the large offshore area, the positive precipitation anomalies are much stronger than along the coast, yet the SST is warmer offshore. Inside the Chesapeake Bay and the estuaries within the barrier islands at Cape Hatteras, the SST is much warmer than over the continental shelf. The estuaries and the nearshore waters are influenced the most by the rain and river runoff. The warm SST in the estuaries suggests that the enhanced rainfall and runoff in the summer of 2003 have resulted in a shallow surface layer that is more easily heated by the sun. Obviously, the surface coastal cooling in Fig. 2b is not induced by the excessive river runoff or precipitation.

In the study of upwelling currents off of the east Australia coast, Roughan and Middleton (2002) have suggested that the variations of the western boundary currents can produce significant upwelling currents over the continental shelf. They have identified three mechanisms that generate upwelling currents over the

Fig. 13. Monthly mean sea level anomalies and total geostrophic currents of the merged altimetry data in July 2002 and 2003, and the difference between the two years.
shelf: the encroachment of the western boundary current over the shelf, the separation of the western boundary current from the coast, and the frontal processes of the western boundary current over the shelf. The frontal processes can only produce upwelling in the vicinity of the Gulf Stream front. This is not in agreement with the satellite SST images, which show SST anomalies away from the Gulf Stream front. The separation from the coast usually produces upwelling currents associated with eddies or mesoscale activity in the vicinity or downstream of the separating point. This is again not in agreement with the SST anomalies in the satellite images.

To investigate the encroachment effects of the Gulf Stream, the sea level anomalies and the total geostrophic currents in 2002 and 2003 and their difference are presented in Fig. 13. Evidently, the Gulf Stream is of about the same strength and path in July of the two years, except that it is slightly weaker in 2003 than in 2002. The weakened Gulf Stream in July 2003 suggests that the low-frequency cooling in July–August 2003 is not induced by the variations of the Gulf Stream entrainment. It is worth mentioning that the mean currents entrained by the Gulf Stream over the shelf in summer is likely important for the climatological balance between the surface heating and the summer upwelling, on top of which the anomalous upwelling in the summer of 2003 produces the pronounced cooling near the coast. The study of the Gulf Stream entrainment over the shelf in the climatological circulation and its contribution to the climatological heat balance in summer is beyond the scope of this study.

The periods of the Gulf Stream variations are usually much longer than a few days (Lee and Atkinson 1983). The weekly merged altimetry data show either small or negative sea level anomalies along the shelf break, suggesting that the Gulf Stream in July–August 2003 encroaches either slightly or offshore (Fig. 14). Given the significant distance between the Gulf Stream front and the coast (Fig. 8), the significant episodic coastal cooling in the summer of 2003 could not have been induced by the Gulf Stream variations.

6. Conclusions

Dynamics of the anomalous cold-water event off of the southeast coast of the United States in the summer
of 2003 are investigated using satellite observations of SST, wind, sea level, precipitation, and ocean color, combined with in situ coastal and shelf mooring data and cross-shelf hydrography from ship-based observations. The structures of SST, wind, sea level, ocean color, and hydrography suggest that the anomalous cooling is induced by wind-driven coastal upwelling. The cold SST anomalies in the summer of 2003 are generated because the buoyancy barrier resulting from surface heating in summer, which is usually strong enough to restrict the upwelling in shallow water in July, is broken by the strong and persistent upwelling induced by the anomalously strong and persistent southwesterly winds in the summer of 2003. The southwesterlies last longer than the buoyancy shutdown time scale, which is estimated to be longer than 11 days using the stratification of the summer of 2003. The strength of the southwesterly wind is also important because it overcomes the surface heating to lift the 24°C isotherm up to the surface and offshore to the middle shelf during the strongest cold episode. Coastally trapped waves propagating southward along the east coast of the United States play an important role of enhancing the upwelling in the South Atlantic Bight. The fast speeds of the trapped wave propagation superpose the wind forcing to the north of the South Atlantic Bight onto the local wind effects within 1–2 days. Once the buoyancy barrier is broken, the stratification in the nearshore region is weakened substantially, facilitating further cooling of SST by southerly wind bursts or propagation of coastally trapped waves at periods of a few days. These winds and trapped waves would otherwise have no impact on the surface temperature because of their short periods in comparison with the buoyancy shutdown time scale.

The Gulf Stream in the summer of 2003 is found to be close to the climatological state. The cold-water event along the southeast coast of the United States in the summer of 2003 is found to not be induced directly by the variations of the Gulf Stream or atmospheric precipitation.

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