GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 25, PAGES 3763-3766, DECEMBER 15, 1996

A surface-trapped intrusion of slope water onto the continental shelf in the mid-Atlantic bight

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Abstract

A high-resolution hydrographic transect across the shelfbreak south of Nantucket Shoals in August, 1995, revealed an unusual surface-trapped intrusion of saline Slope water onto the continental shelf. The intrusion was confined to the upper 25 m of the water column and penetrated 15 km shoreward of the 100-m isobath, the typical position of the shelfbreak front. The maximum salinity within the intrusion was 35.0. Several strong jets were present within the surface layer with maximum velocities between 0.30 and 0.44 m s^{-1} in the alongshelf direction. Satellite thermal imagery confirms the presence of a warm-core ring at the offshore edge of the section and shows a warm feature penetrating shoreward of the 100-m isobath.

Introduction

The shelfbreak front in the Middle Atlantic Bight is the water mass boundary between cool, fresh continental shelf water and warm, saline continental slope water. The front is an important factor in the cross-shelf exchange of heat, fresh water, and carbon between the continental shelf and continental slope. Many studies have shown that shelf water is lost from the shelf to the slope relatively easily through streamers associated with warm-core rings [e.g., *Bisagni*, 1983], frontal eddies [*Houghton et al.*, 1986], and wind-driven transport. However, onshore compensating flows of continental slope, Gulf Stream, or warm-core ring water penetrating onto the continental shelf have been observed less frequently and are not well understood. For example, *Beardsley et al.* [1985] found that warm-core rings did not affect the currents shoreward of the shelfbreak south of Nantucket Shoals based on a one-year mooring array.

Paper number 96GL03427.
0094-8534/96/96GL-03427$05.00

Slope water has typically been observed over the shelf during the summer within the seasonal pycnocline [*Boicourt and Hacker*, 1976; *Gordon and Aikman*, 1981]. These features may appear due to forcing from warm-core rings [*Churchill et al.*, 1986] or Gulf Stream filaments [*Gawarkiewicz et al.*, 1990]. The dynamics of these intrusions are not well-understood, but may result from the mismatch of mixed layer depths between the shelf and slope which creates an onshore-directed baroclinic pressure gradient [*Aikman*, 1984], or from the onshore propagation of internal solitons [*Burrage and Garvine*, 1987]. The onshore velocities of these intrusions may be substantial [as large as 0.2 m/s over 1–2 days, *Flagg et al.*, 1994]; however, they are typically concentrated between a depth of 10–40 m and lie beneath fresh shelf water in the surface layer.

In this note, a detailed hydrographic transect across the shelfbreak south of New England in mid-August, 1995, shows the presence of Slope water penetrating shoreward of the typical position of the shelfbreak front. The intrusion is remarkable in that it is surface-trapped and occupies the entire surface mixed-layer. First we will present a climatological mean summer frontal section to show the typical frontal configuration in summer. Next we will present the section from mid-August 1995 and the associated geostrophic velocity shears. Finally, we will discuss these intrusions.

Climatological Frontal Structure

The shelfbreak front in the Middle Atlantic Bight is a highly variable feature. In order to describe the mean frontal structure, we have produced a climatology of the cross-shelf two-dimensional structure of the front in the vicinity of Nantucket Shoals. This was produced by averaging all historical hydrographic observations from the National Ocean Data Center [*Curry*, 1996] over the outer shelf between 69 and 72°W. The stations were grouped by depth in bins roughly 4–10 km wide in the cross-shelf direction with the highest resolution near the shelfbreak. The stations were averaged over a two-month time interval (August–September) for all the historical observations and over 10 m in the vertical. Details appear in *Linder* [1996].

The resultant salinity and density structure appears in Figures 1a,b. The salinity monotonically increases offshore, with a value of roughly 33 in the mid-shelf region increasing to the slope water value of roughly 35 seaward of the shelfbreak. The bottom outcrop of the 34.5 isohaline is at the 100-m isobath, consistent with previous descriptions of the shelfbreak front [*Wright*, 1976]. Over the slope, the upper 25 m of the water column is fresher than the underlying water with salinities between 34 and 34.5. As Figure 1b shows, the shelf water is less dense than the slope water, with typical near bottom values of 25.6 σ_0 on the shelf side of the front and 26.8 σ_0 on the slope side of the front. The isopycnals are relatively flat in the upper 40 m of the water column. The geostrophic velocity structure shows a strong westward jet with a maximum velocity of 0.28 m s−1 (Figure 1c) at the surface at the 110-m isobath. The jet width (defined by half the maximum jet velocity) is 15 km with a vertical extent of 50 m. We will see considerably different frontal structure in August, 1995.

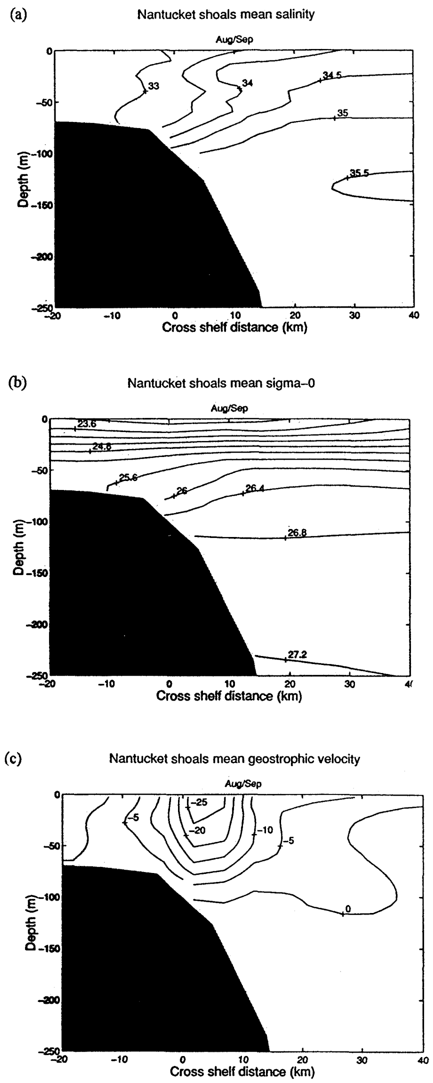

Figure 1. Cross-shelf frontal structure south of Nantucket Shoals based on a climatology of historical hydrographic data. (a) Salinity using PSS (practical salinity scale). The contour interval is 0.5. (b) Density in σ_0. The contour interval is 0.4 σ_0. (c) Climatological mean velocity using seasonally-averaged bottom velocities and the climatological density field. Contours are in intervals of 5 cm s^{-1}, and negative values are to the west (out of the paper). The x-axis origin is at the 100-m isobath.

Cross-shelf Section from August, 1995

On August 10, 1995, the R/V *Endeavor* performed a hydrographic section across the shelfbreak south of Nantucket Island. This line extended due north from 39° 50'N to 40° 27'N along 70°15'W. The section was occupied from 1 pm to midnight UT. The CTD was used in tow-yo mode, continuously undulating beneath the ship while the ship steamed north at 3–4 knots. The average horizontal resolution is 1.2 km.

The salinity and density fields appear in Figures 2a,b and show a marked contrast to the climatological fields. The most dramatic difference is in the surface layer where a surface-trapped intrusion with salinities greater than 34 extends 15 km shoreward of the 100-m isobath, the mean position of the bottom outcrop of the shelfbreak front. The shoreward boundary of this intrusion in Figure 2a is at the 85-m isobath ($x = -18$ km), where there is a sharp surface layer front in the upper 25 m of the water column in which salinity drops from 34.5 to 32.6 over 3.6 km. The most saline portion of the intrusion is between $x = 5$ km and $x = 25$ km in Figure 2a, and is greater than 35.0. The intrusion is divided near $x = 0$ km at the 100-m isobath by a narrow (3 km) patch of shelf water with a salinity of 33, so that there are several sharp fronts within the surface mixed-layer. Beneath this intrusion, the normal summer sub-thermocline "cold pool" water is present with salinities in the range of 33–34.

The saline intrusion affects the density field within the surface layer (Figure 2b). The density within the most saline region of the intrusion (>35) is between 24.0 and 24.4 σ_0, surrounded by water in the surface layer less than 24.0 σ_0. At the shoreward edge of the intrusion, the density contrast between the intrusion and the shelf water in the surface mixed layer is greater than 0.4 σ_0 between $x = -20$ km and $x = -15$ km in Figure 2b. The isopycnals beneath the seasonal pycnocline are similar in structure to the climatology.

The large density gradients in the surface layer lead to large vertical velocity shears above the seasonal pycnocline. Figure 2c shows the geostrophic velocities computed relative to zero flow at the bottom using a smoothed (over 5 km) density field. The purely density-driven flow computed here differs drastically from the climatological density-driven velocity field. Rather than having a well-defined vertically coherent jet slightly seaward of the 100-m isobath, the largest velocities in this

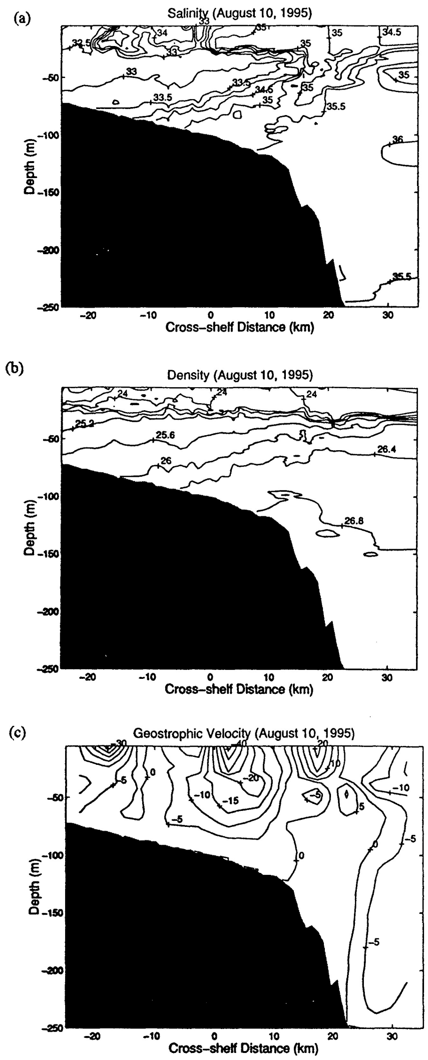

Figure 2. Cross-shelf frontal structure south of Nantucket Shoals on August 10, 1995. (a) Salinity. The contour interval is 0.5. (b) Density in σ_0. The contour interval is 0.4 σ_0. (c) The geostrophic velocity relative to no flow at the bottom. Contours are in intervals of 5 cm s^{-1}, and negative values are to the west (out of the paper). The x-axis origin is at the 100-m isobath.

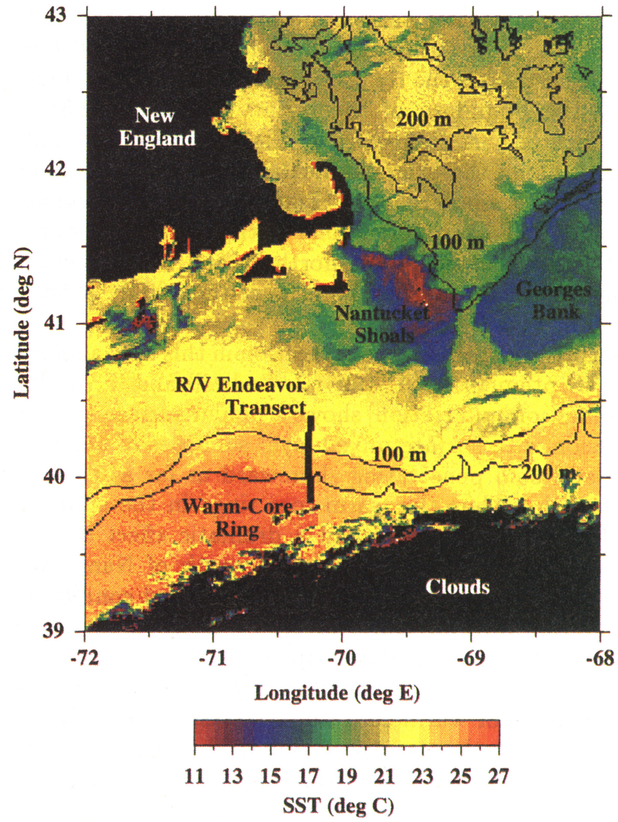

Figure 3. Gray-scale sea surface temperature image derived from data collected by the NOAA-14 satellite, 1758 UT, August 11, 1995. Also shown are the locations of the August 10, 1995 R/V *Endeavor* transect (heavy line), Nantucket Shoals, Georges Bank and the 100-m and 200-m isobaths.

section are surface-trapped and coincide with the surface mixed-layer fronts. The maximum surface velocity is 0.44 m s^{-1} and is located slightly seaward of the 100-m isobath ($x = 5$ km) offshore of the point at which the narrow band of shelf water abuts the more saline portion of the intrusion. At the shoreward edge of the intrusion, $x = -17$ km, the westward flow is also strong (0.30 m s^{-1}) with much greater vertical velocity shear in the upper 20 m of the water column. Beneath the pycnocline, the maximum velocity is 0.22 m s^{-1} to the west. This maxima ($x = 10$ km) is displaced roughly 5 km seaward of the maximum surface velocity near the 100-m isobath. Thus a complicated velocity structure exists with splitting of the westward flowing jet at the seasonal pycnocline due to the presence of the overlying intrusion of saline water near the 100-m isobath.

Discussion

These observations are direct evidence of the penetration of slope and ring water onto the continental shelf shoreward of the 100-m isobath during August 1995. This is in contrast with prior observations in this region [*Beardsley et al.*, 1985; *Houghton et al.*, 1988] which did not find the influence of warm-core rings or slope water intrusions penetrating onto the continental shelf. The vertical structure of the intrusion was different from the pycnocline salinity intrusions previously reported in the literature because the intrusion extended throughout the depth of the surface layer. The intrusion resulted in sharp surface layer fronts in which large geostrophic velocity shears were present above the seasonal pycnocline.

Examination of satellite-derived sea surface temperature (SST) from approximately 1800 UT, August 11, 1995 confirms the presence of a warm-core ring located offshore of the 200-m isobath at the southern end of the R/V *Endeavor* section (Figure 3). This ring has an alongshelf scale of approximately 90 km. The imagery also confirms the presence of a thermal front, located south of Nantucket Shoals and shoreward of the 100-m isobath, with an alongshelf scale of roughly 60 km. This front crosses the R/V *Endeavor* section twice: first, along the boundary of the region of colder (22.5°C) SST located just shoreward of the 100-m isobath and, second, along the extreme northern end of the section where SST is again reduced (Figure 3). The two regions of colder SST likely correspond to the surface low salinity tongues located at the northern end of the section as well as in the narrow band near the 100-m isobath ($x = 0$ in Figure 2a).

Surprisingly, an additional section in this area a month later [September 9–11, 1995; J. Ledwell and T. Duda, personal communication] shows a similar surface-trapped intrusion with surface mixed-layer salinities of between 35.2 and 35.5 penetrating shoreward as far as the 80-m isobath. Thus the warm-core rings in the summer of 1995 appear to have had a dramatic effect on the surface layer over the outer shelf south of Nantucket Shoals over an extended period of time, and conditions during this time obviously favored cross-shelf exchange between the outer shelf and upper slope.

The most obvious explanation for these intrusions is the presence of warm-core rings. Given the correspondence between the structure along the hydrographic section and the surface thermal imagery, it appears likely that the surface-trapped intrusion was related to the warm-core ring in some manner. Adding to the complexity is the possibility that wind-driven Ekman transport may have contributed to the formation of the intrusion. Strong northeasterly winds ranging from 10 to 15 m s^{-1} preceded both the August 10 and September 9–11 sections, and so it is possible that the wind forcing either strengthened or actually forced the intrusion.

Finally, an examination of other transects across the shelfbreak in this region [*Lyne and Csanady*, 1984; *Wright*, 1982] show similar surface intrusions with salinities of 35.0 or greater shoreward of the 100-m isobath. These occurred in 3 out of 20 sections from the time-period of July through September, when the seasonal pycnocline is present. Thus, these surface intrusions are infrequent but have appeared in the historical record.

Acknowledgments. The authors gratefully acknowledge the support of Jeff Simmen (ONR OA) and Steve Ramp (ONR PO) through the SWARM and PRIMER programs respectively (contracts N00014-95-1-0051 and N00014-95-1-0575). We also thank Marshall Orr, John Apel, and Bob Hendricks and the crew of the R/V *Endeavor* for assisting in the collection of the data. Satellite data is provided by J. J. Bisagni, NOAA/NMFS, Narragansett, Rhode Island, through funding supplied by the US-GLOBEC Northwest Atlantic Georges Bank Program and the Gulf of Maine Regional Marine Research Program.

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(Received April 30, 1996; revised August 22, 1996; accepted October 18, 1996.)