Space–Time Variability of the Deep Western Boundary Current Oxygen Core*

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ABSTRACT

Twelve historical CTD/oxygen sections between the Grand Banks and Cape Hatteras, occupied over the time period 1981–85, are analyzed to investigate the variability of the Deep Western Boundary Current (DWBC) property core. The sections are transformed into a coordinate system of bottom depth versus height above the bottom, then interpolated onto a regular grid in order to facilitate an inter-sectional comparison. The average sections show a high-oxygen core near 3200-m depth, θ = 2.2°C, which corresponds to a region of upward sloping isotherms against the boundary, inshore of the deep Gulf Stream. As the DWBC progresses toward Cape Hatteras it shoals significantly and becomes less dense as a result of mixing with surrounding fluid along its path. There is, however, much scatter about this general alongstream trend and large density fluctuations are correlated with changes in bottom depth and cross-sectional area of the DWBC core. This variability is most likely the downstream response to changes in the overflow source waters of the DWBC. Some of the DWBC appears to recirculate with the deep Gulf Stream near Cape Hatteras (where the two currents cross each other), forming a weaker offshore oxygen core.

1. Introduction

Although the existence of the North Atlantic Deep Western Boundary Current (DWBC) is now well established, very little is known about its variability, both in terms of water-mass properties and velocity structure. Since this current is the means by which newly formed water replenishes the deep interior ocean, characterizing the variability is an important step toward understanding the consequences of climate change. The deepest component of the DWBC consists of water colder than 3°C (potential temperature), which is formed convectively in the Norwegian–Greenland Sea and enters the North Atlantic through the Denmark Strait and Iceland–Scotland overflows. This deep core is easily identified by its anomalously high concentrations of oxygen, tritium, and chlorofluorocarbons, all indicative of relatively young water.

There is still some uncertainty as to the core speed of the DWBC. Synoptic estimates based on hydrographic data have been as large as 20 cm s^{-1} (e.g., Joyce et al. 1986), while mean estimates from current meters have ranged from 3–4 cm s^{-1} (Pickart and Watts 1990) to 5–10 cm s^{-1} (Luyten 1977; Watts 1991). Tracer-based estimates of the core speed, which represent an alongstream mean over thousands of kilometers, tend to give the smallest estimates—for example, 1–2 cm s^{-1} (Smethie and Trumbore 1984). Mixing, however, may cause these tracer-derived values to underestimate the true core speed (Pickart et al. 1989).

The uncertainty in the core speed is partly due to sampling resolution. Moored arrays may or may not sample the swiftest part of the current. This may be due to insufficient instrument coverage or a current that meanders (e.g., Lee et al. 1990). In addition, it is now well documented that topographic Rossby waves superposed on the DWBC often give rise to swift currents that can even reverse the deep flow. Pickart and Watts (1990), using an array of current meters across the DWBC, separated the DWBC contribution from the topographic wave field. They found the rms variability of the cross-stream–averaged DWBC to be quite small, 1–2 cm s^{-1}. The location of their study, however, was directly under the Gulf Stream, which undoubtedly influenced the results.

The issues of sampling resolution and the topographic wave field make it difficult to accurately describe the DWBC from current measurements alone. A valuable asset to the study of the DWBC is its anomalous water property signal. First, the tracer core of the DWBC clearly reveals the proximity of the current; second, this water-mass signature is not destroyed by the presence of topographic waves. As there have been many (direct and indirect) current measurements of the DWBC in the North Atlantic, so have there been property measurements. In this study we compile some of these historical tracer measurements and investigate the structure and variability of the DWBC from a water-mass viewpoint. This perhaps will enable us to bet-

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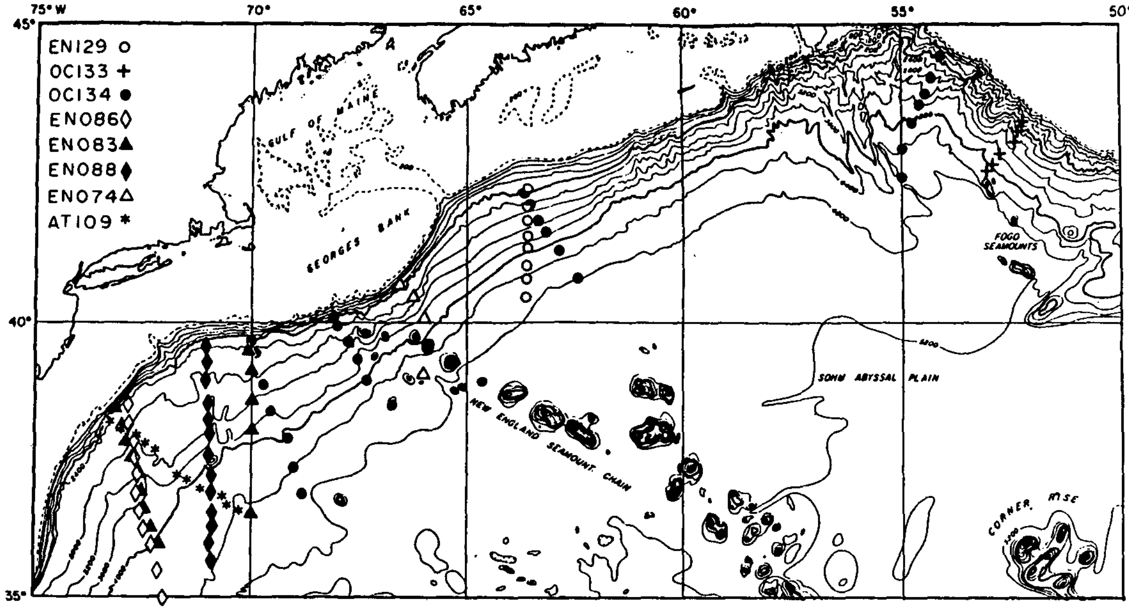

FIG. 1. Station positions comprising the 12 sections used in the study.

ter interpret some of the complex deep current measurements.

We chose to focus in particular on the oxygen core of the DWBC. Twelve historical CTD/oxygen sections across the DWBC are used in the study, ranging in location from the Grand Banks to Cape Hatteras and in time from 1981 to 1985. In section 2 we explain why these particular sections are chosen and how the data are regridded to allow the different sections to be effectively compared to each other. The average DWBC oxygen and potential temperature sections are presented in section 3, followed by an analysis of the observed section-to-section variability of the oxygen core. Interestingly, most of the sections contained a second, distinct oxygen core offshore of the DWBC, which apparently is recirculated water flowing with the deep Gulf Stream. The characteristics and nature of this core are discussed in section 4.

2. Data and methods

Figure 1 shows the locations of the 12 historical CTD sections used in the study. Several criteria were used in assembling this set. First, we required that each section contain high quality data and be finely resolved, and that the oxygen data be from a CTD oxygen probe. This offers significantly greater resolution in the vertical versus water sample oxygen. The accuracy of the CTD oxygen sensor is ±.04 ml l^{-1} (all the profiles were calibrated using bottle oxygen), and based on the consistency between sections, this accuracy is quite sufficient to resolve the DWBC. Another stipulation in choosing the sections was that their location be poleward of the Gulf Stream–DWBC crossover. Recent evidence suggests that, as the DWBC crosses under the Gulf Stream at Cape Hatteras, it undergoes significant changes in structure (e.g., Hogg and Stommel 1985; Pickart and Watts 1990). Sections near the crossover would thus complicate the analysis and, for this study, we wanted to keep the number of degrees of freedom reasonably small. The 12 sections that comprise the set come from eight different cruises over a 5-year period, 1981–85 (Table 1). Note that the farthest east section is at 53°W (just west of the Grand Banks); thus, we do not consider sections close to the source overflows as well.

It is not a simple task to systematically compare deep CTD sections from different locations. The bottom topography varies, and different sections cross the DWBC at different angles. To standardize the analysis and get around these difficulties we first transformed each of the sections into a bottom depth versus height above bottom coordinate system. Hence, the different sections could be plotted on the same grid and quantitatively

TABLE 1. Historical sections used in the study.

Section name	Research vessel	Date	Principle investigator
AT109	RV *Atlantis II*	Jun 1981	D. Roemmich, C. Wunsch
EN074	RV *Endeavor*	Sep 1981	T. Joyce
EN083	RV *Endeavor*	May 1982	T. Joyce
EN083U	RV *Endeavor*	May 1982	T. Joyce
EN086U	RV *Endeavor*	Jun 1982	T. Joyce
EN088U	RV *Endeavor*	Aug 1982	R. Schmitt
OC133	RV *Oceanus*	May 1983	M. McCartney
OC134A	RV *Oceanus*	Jun 1983	N. Hogg
OC134B	RV *Oceanus*	Jun 1983	N. Hogg
OC134C	RV *Oceanus*	Jul 1983	N. Hogg
OC134D	RV *Oceanus*	Jul 1983	N. Hogg
EN129	RV *Endeavor*	Apr 1985	M. McCartney

compared in a meaningful way. The bottom depth axis (analogous to cross stream) ranges from 2000 to 4500 m, and the height above the bottom axis from 0 to 1500 m above the bottom. After the transformation, each section was then regridded using Laplacian–spline interpolation onto a regular grid with 100-m spacing in bottom depth and 25-m spacing in height above bottom (prior to the regridding step the oxygen data at each station were smoothed with a running filter of width = 100 m). Several regridded sections were untransformed and compared to the original sections, which documented that the interpolation was indeed accurate. Thus, at each of the 12 locations we produced a section of oxygen, potential temperature, and σ_3 (potential density referenced to 3000 m), all on the standard grid.

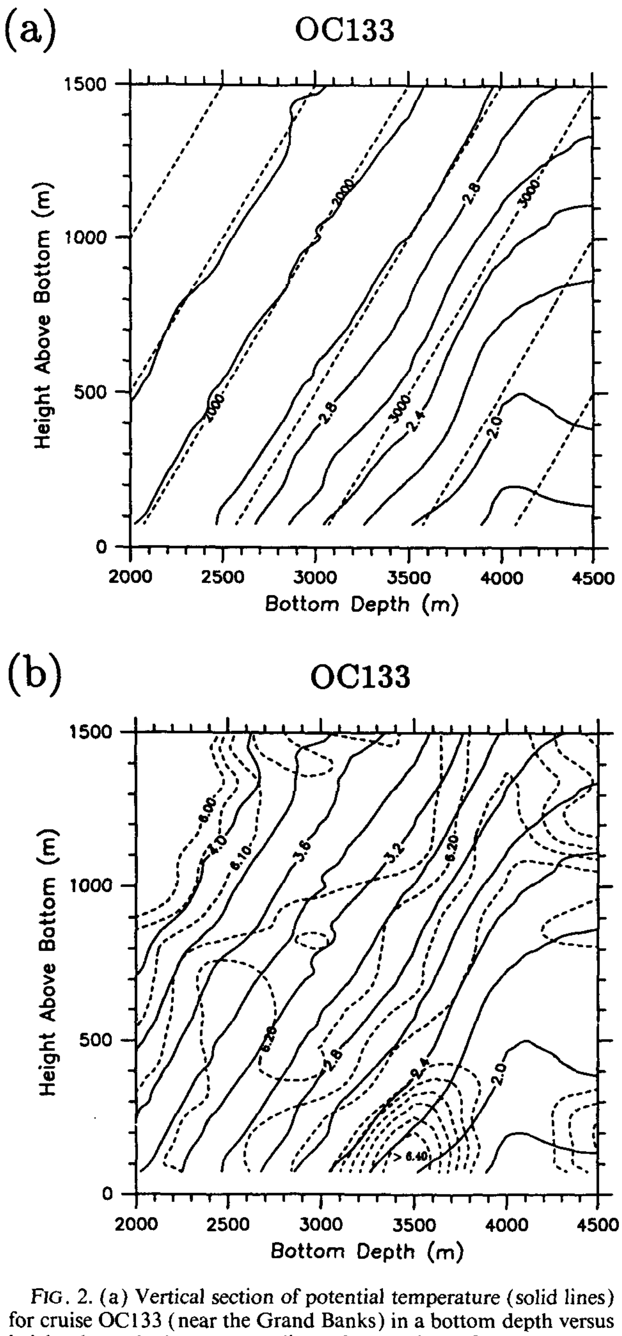

FIG. 2. (a) Vertical section of potential temperature (solid lines) for cruise OC133 (near the Grand Banks) in a bottom depth versus height above the bottom coordinate frame. Lines of constant water depth are indicated by the dashed lines. (b) Vertical section of oxygen (ml l^{-1}) (dashed lines) overlaid on the potential temperature. The oxygen contour levels range from 6.0 to 6.35 by 0.05 increments, then to 6.40 by 0.01 increments.

The reader is probably not accustomed to viewing a vertical section in such a coordinate system, so in Fig. 2 we show the regridded sections for a single cruise. Figure 2a is the section of potential temperature (solid lines) with lines of constant water depth overlaid (dashed lines). Note that the warmest inshore isotherms are flat, that is, parallel to the dashed lines in the upper left-hand portion of the regridded section. The thermal shear of the DWBC is evident as the downward-sloping isotherms near the bottom (below 500 m off the bottom) between 3000 and 3500 m. This region is precisely where the high-oxygen core of the DWBC is found in Fig. 2b. Note that deeper than 4000 m all of the isotherms in Fig. 2a begin to slope downward; this is the edge of the deep Gulf Stream whose shear is present throughout the water column (some of the sections farther west extend across the entire Gulf Stream into the Sargasso Sea). With such a set of sections on an identical grid we were easily able to quantitatively compare them and characterize the various properties of the DWBC.

3. The DWBC core

Using the regridded sections we first computed a mean DWBC section of oxygen and potential temperature. Instead of presenting these averages in the transformed coordinate system, we converted them back into the more familiar x–z coordinate frame using an average bottom profile. The shear of the DWBC is evident against the boundary (shoreward of 140 km) in the temperature section below 2500 m (Fig. 3a). The sharpest gradients occur at roughly 3200-m depth, and it is here that the highest oxygen concentrations are found in the core of the boundary current (Fig. 3b). At roughly 150 km the "north wall" of the deep Gulf Stream is encountered. The thermal shear of the Gulf Stream is present throughout the deep water column. Notice that the outer part of the DWBC oxygen tongue extends into the deep Gulf Stream and penetrates to deeper depths along the isotherms.

a. Alongstream trends

We quantitatively investigated changes in the DWBC oxygen core as follows. In each section we defined the core as the region where oxygen values are greater than 0.985 of the maximum value (for example, if the max-

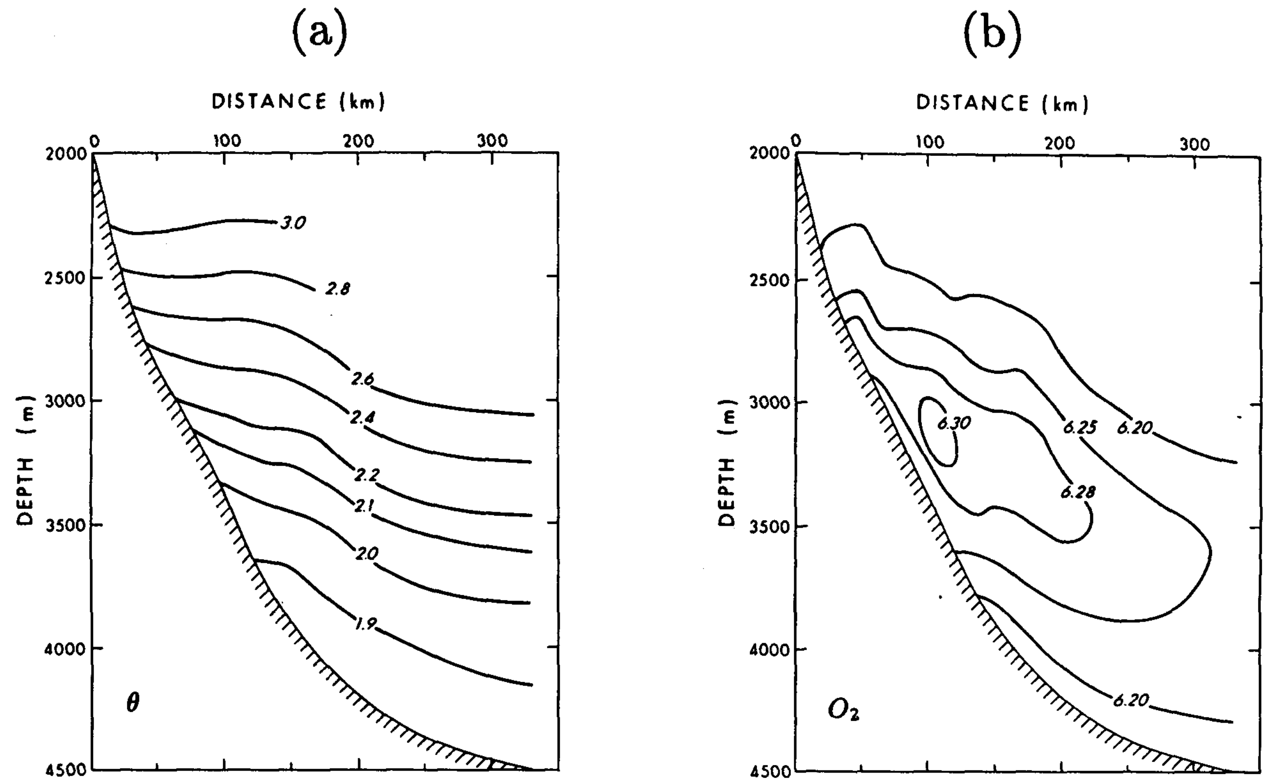

FIG. 3. (a) Average DWBC potential temperature section from the 12 boundary crossings. (b) Average oxygen section.

imum value were 6.30 ml l^{-1} then the core is the region where concentrations are greater than 6.20 ml l^{-1}). Then we simply integrated various properties within the core for each section. The different core properties we considered were 1) average oxygen concentration, 2) bottom depth, 3) height above bottom, 4) cross-sectional area, 5) potential temperature, and 6) potential density (σ_3). Note that "bottom depth" refers to the depth of the topography below the core (the core need not be situated on the bottom) and "height above bottom" signifies how far off the bottom it is. Thus, bottom depth and height above bottom together specify

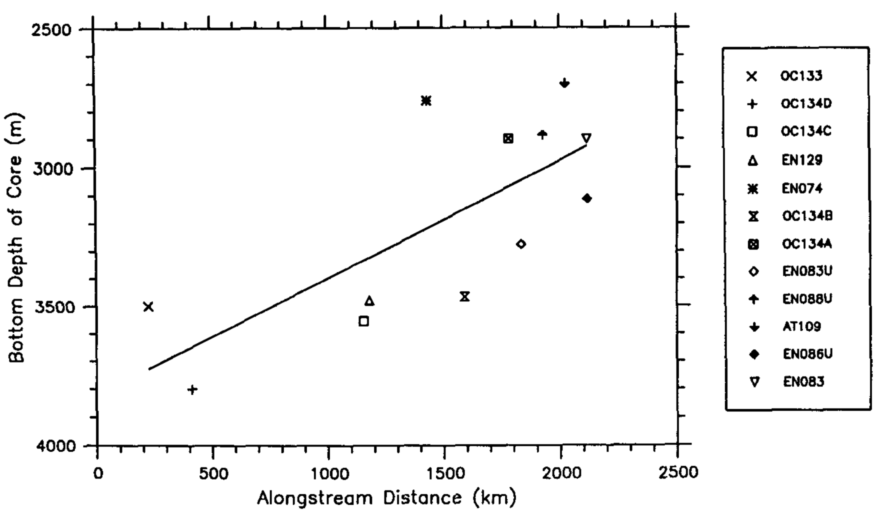

FIG. 4. Bottom depth of the DWBC core for each section versus alongstream distance. The different sections are identified according to the key on the right. The solid line is the least-squares fit.

TABLE 2. Characteristics of the DWBC core (see text for definition of core). Column 1 lists the mean core quantities from the average sections of Fig. 3; column 2 lists the means obtained by summing the core values from each section. Columns 3, 4, and 5 list the alongstream linear fit parameters. The 90% confidence level is $r = 0.50$.

Core property	Mean (average section)	Mean (individual sections)	Correlation coefficient (r)	y intercept	Slope
Bottom depth (m)	3436	3194 ± 349	.74	3824 ± 195	−.424 ± .122
Height off bottom (m)	350	146 ± 67	.01	145 ± 56	.000897 ± .034
Water depth (m)	3086	3048 ± 315	.82	3679 ± 150	−.425 ± .093
Concentration (ml l^{-1})	6.27	6.31 ± .080	.47	6.40 ± .058	−.0000614 ± .0000366
Area (m^2)	5.85×10^5	$2.84 \times 10^5 \pm 1.19 \times 10^5$	.51	$4.31 \times 10^5 \pm 8.56 \times 10^4$	−99.3 ± 53.3
Temperature (°C)	2.18	2.28 ± .17	.65	2.00 ± .11	.000187 ± .0000690
Density (kg m^{-3})	41.519	41.508 ± .022	.54	41.500 ± .0184	−.0000227 ± .0000115

the water depth of the core. Figure 4 shows the bottom depth of the DWBC core as a function of alongstream location of the section, where 0 km corresponds to slightly west of the Grand Banks, and 2200 km is just north of the Gulf Stream crossover at Cape Hatteras. Keep in mind that the 12 sections were taken over a 5-year period, so this picture is not synoptic. Note the distinct alongstream trend showing that the core of the DWBC progresses into shallower topography as it moves equatorward (the solid line is the least-squares fit). Also note the pronounced scatter about this trend, which we address in the next section.

Similar plots can be made for the other core characteristics as well. As a measure of whether a particular core quantity has a significant alongstream trend, we computed the correlation coefficient (r) of the least-squares fit to the 12 points (Table 2). A value of $r = 1$ means a perfect trend with no scatter, and $r = 0$ means all scatter with no trend at all. Five of the core properties showed significant trends at the 90% confidence level ($r = 0.5$) (Fig. 5). The exceptions were average concentration (just below 90% confidence) and height off the bottom. Thus, as the DWBC progresses from the Grand Banks to Cape Hatteras—a distance of approximately 2000 km—it shoals, becomes warmer, less dense, smaller in cross-sectional area, and to a lesser extent, its oxygen concentration decreases.

These changes in the DWBC core are presumably due in part to mixing with the surrounding fluid along the path of the current. This mixing must include a significant amount of cross-isopycnal mixing, as evidenced by the systematic change in density. It is not immediately obvious, however, why vertical mixing should reduce the density of the DWBC core since the core itself is surrounded by water of both higher and lower density. A possible reason may be due to the presence of the sloping bottom. A sloping western boundary (versus a vertical sidewall) means that less of the core perimeter is in contact with the denser, deeper water (Fig. 6). Thus, even though the intensity of the vertical mixing may not change with depth, there is more "area of contact" with lighter water that results in a net density loss. Note that this effect is stronger for weaker bottom slopes, and near the Grand Banks

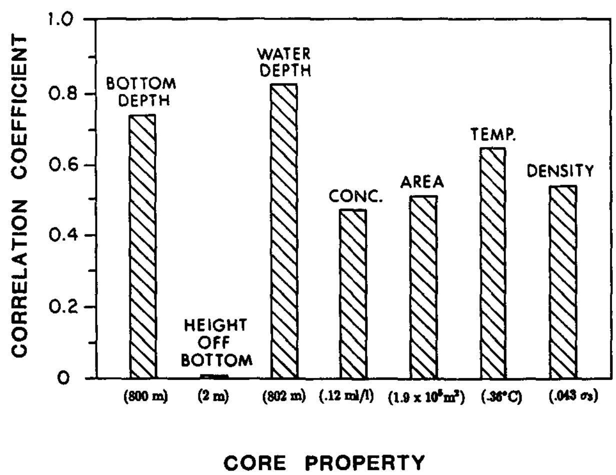

FIG. 5. Correlation coefficient for the different DWBC core properties, signifying the alongstream trend. Included in parentheses is the change in each property from the Grand Banks to Cape Hatteras, according to the linear trend.

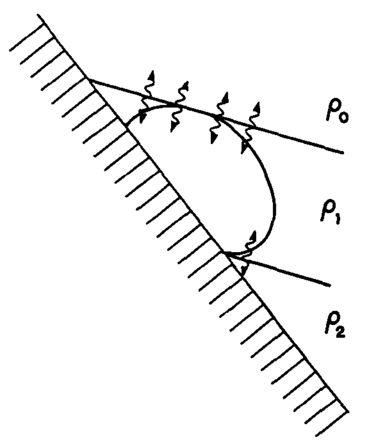

FIG. 6. Schematic showing how a sloping bottom causes the DWBC core to have more contact with the above-lying lighter water.

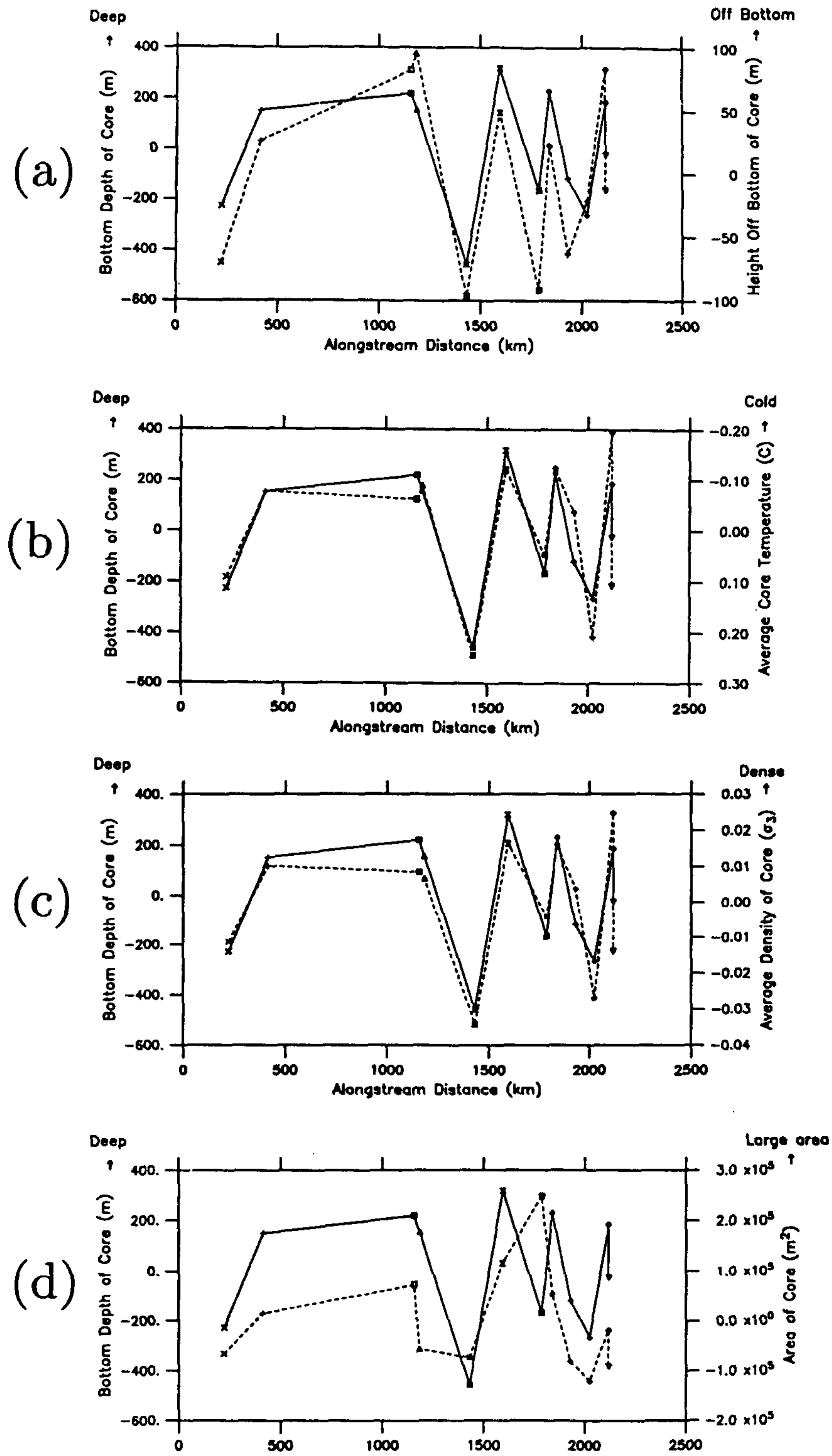

FIG. 7. Comparison of the different DWBC core properties with the linear alongstream trend removed. (a) Bottom depth (solid line) compared with height above the bottom (dashed line). Note the difference in scales; changes in bottom depth are much more pronounced than changes in height off the bottom (implying large changes in water depth). (b) Bottom depth compared with average potential temperature (dashed line). (c) Bottom depth compared with average potential density (dashed line). (d) Bottom depth compared with cross-sectional area (dashed line).

the DWBC is quite deep, where the bottom slope is weak. It is also worth noting that isotherms sloping upward toward the boundary (as they do in the DWBC) will strengthen this effect.

b. Variability

As mentioned, Fig. 4 shows that there are substantial variations in the bottom depth of the DWBC core outside of the general alongstream shoaling. To investigate this variability we first removed the alongstream trend from each of the core properties and then compared the resulting variations. These comparisons are shown in Figs. 7a–d from which emerge a strikingly clear picture of the DWBC variability. First, Fig. 7a reveals that when the core is found at a deeper bottom depth it is always farther off the bottom. Figures 7b, c show that it is also colder and more dense when at deeper-bottom depths. Finally, Fig. 7d shows that the core also tends to broaden as it deepens (though this correlation is not as strong). These comparisons thus reveal a dominant type of DWBC variability that can be thought of as an up- and downslope translation of the current. This "meandering" appears to be very different, however, than that which is commonplace in other boundary currents such as the Gulf Stream; it appears to be caused by changes in the source waters of the current. Presumably a very cold winter produces a colder (denser) overflow water that, when advected downstream, penetrates farther down the continental slope. It still remains to be determined how this change in the current is established dynamically and if there are any basinwide consequences regarding water-mass ventilation.

This view of the up- and downslope translations as a downstream response to changes in source conditions is further supported when the DWBC core temperatures are plotted versus time (Fig. 8). One sees that in 1981 the DWBC was particularly warm at these latitudes (0.5°C warmer than in 1985). The two data points in 1981 correspond to two different sections more than 500 km apart, and in Fig. 4 it is seen that indeed these sections (AT109 and EN074) contain the DWBC at its shallowest observed bottom depths. One also sees in Fig. 8 that there is substantial variability of the DWBC within a given year; however, it should be remembered that Fig. 8 represents a mixture in space, and close inspection of the individual sections sheds some light on this variation.

For instance, in 1982 three of the four sections show a colder, deeper DWBC than the year before. The ex-

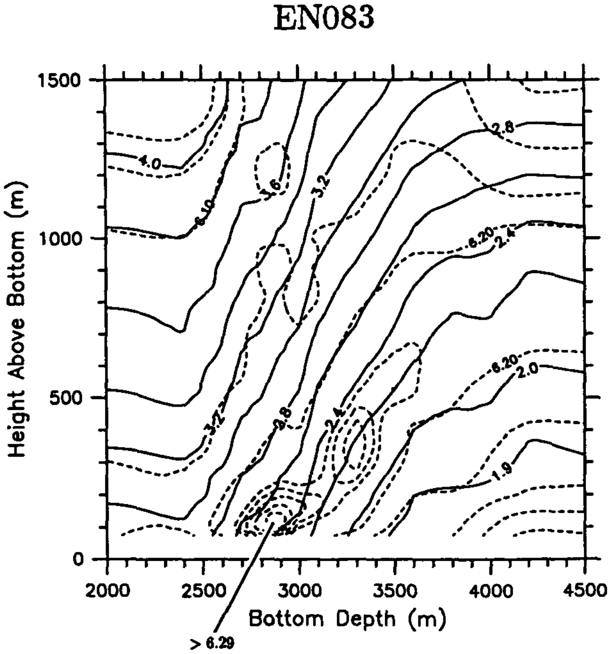

FIG. 9. Vertical section of oxygen for cruise EN083 overlaid on potential temperature. The oxygen contour levels range from 6.0 to 6.25 by 0.05 increments, then to 6.30 by 0.01 increments.

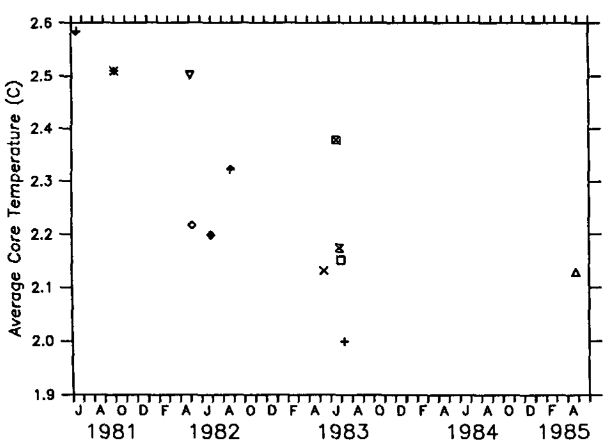

FIG. 8. Potential temperature of the DWBC core for the set of sections, plotted versus time.

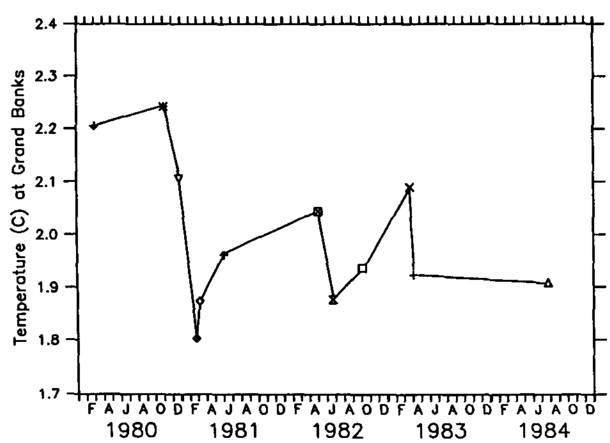

FIG. 10. Inferred time series of DWBC core temperatures at the Grand Banks, constructed from Fig. 8 (see text for explanation).

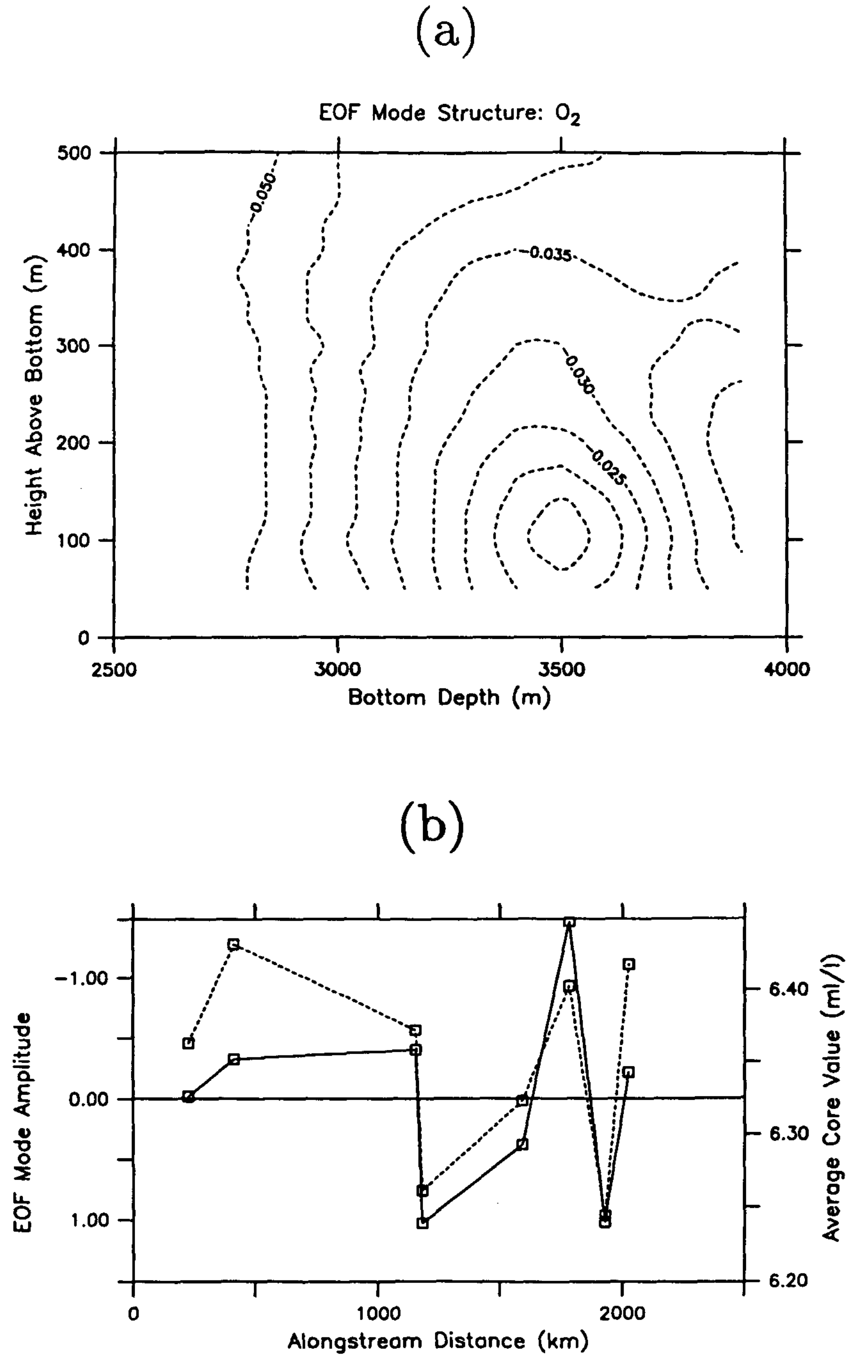

FIG. 11. (a) Vertical structure of EOF mode 1 for the oxygen sections, accounting for 59% of the total variance. (b) Amplitude of the mode plotted versus alongstream distance (solid line), compared with the DWBC core concentration (dashed line).

ception to this is EN083, which has a DWBC temperature similar to 1981, though it was occupied only several days apart from EN083U (which has a temperature indicative of the other 1982 sections). It should be noted, however, that EN083 was approximately 300 km farther downstream, so one might conjecture that the change in the boundary current from warm to cold had not yet occurred at this downstream location. The EN083 oxygen section (Fig. 9) shows that this is probably the case. A distinct (weaker) oxygen core is evident at a temperature of 2.2°C, that is, the same temperature as the core farther upstream. Thus, this section appears

(c)

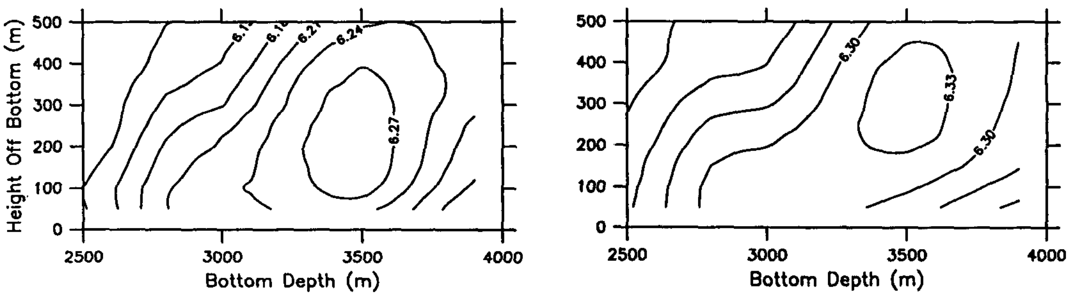

FIG. 11. (*Continued*) (c) Mode 1 added back into the mean with a large positive mode amplitude (left panel) and large negative mode amplitude (right panel).

to have captured the DWBC in a state of transition from warm to cold; this situation might even be considered as two boundary currents: a shallower, warmer one that is weakening in time and a deeper, colder one that is becoming stronger. Presumably at some later time the warmer oxygen core would have disappeared, and in fact the EN086U section was occupied at nearly the same location two months later and shows only the deeper core. In 1983 the same type of scenario exists in that OC134A is warmer than the other sections from that year. Again OC134A is the farthest downstream section and contains a plume of oxygen extending from the warm core into deeper depths and colder temperatures.

In Fig. 10 we have attempted in crude fashion to remove the spatial variation inherent in Fig. 8 (which makes that figure difficult to interpret). First we applied an advective offset to each of the sections to align them at a single location using a mean DWBC speed of 5 cm s^{-1}. Thus, the time axis of Fig. 10 corresponds to the time when the DWBC rounded the Grand Banks (50°W). Next, we attempted to remove the effect of mixing along the path of the current by subtracting out the linear spatial trend calculated earlier. The resulting points in Fig. 10 should thus be thought of as a crude time series of DWBC temperatures at the Grand Banks. As before it is seen that in the first year of sampling, the DWBC was warmer than in the subsequent four years. Note that changes in the boundary current seem to happen on very short time scales (on the order of several months), and that there are significant variations within a given year as well. It is more difficult to imagine that variations in the source waters cause these short-term fluctuations of the DWBC, and recent evidence suggests that the northern overflows have no seasonal signal (Saunders 1990). In light of the role of vertical mixing in influencing the density of the core, it may be that such changes result from variations in the intensity of the local mixing (possibly due to the energetic topographic Rossby waves along the slope). Further work is necessary to sort this out.

In order to better visualize the character of the cross-slope translations of the DWBC, we did an empirical orthogonal function (EOF) analysis on the set of oxygen sections (for reasons explained below we could use only 8 of the sections for this calculation). The EOF technique consists of computing the eigenfunctions and eigenvalues of the oxygen variance matrix, thereby extracting the dominant observed variability. It turns out, however, that most of the variance is due to changes in the concentration of the oxygen core from section to section. Figure 11a shows the eigenfunction, or vertical structure, of the first EOF mode consisting of a single core at 3500-m bottom depth. The amplitude of this mode correlates nicely with the average core concentration (Fig. 11b), and when it is added back into the mean, the core remains near 3500-m bottom depth but changes strength (Fig. 11c).

To isolate the cross-slope translations it was necessary to remove the variance caused by changes in the core concentration, so prior to calculating the EOFs the sections were normalized (core value = 1). The vertical structure of the first mode for the normalized sections appears in Fig. 12a, and in contrast to the nonnormalized case this mode has two cores: a positive core at shallow depths and negative core at deeper depths. This is the signature of the translations, and the mode amplitude correlates with bottom depth of the DWBC core (Fig. 12b). The character of the translations is clearly revealed when this mode is added back into the mean (Fig. 12c). When the core moves upslope it resides on the bottom and is much smaller in area—exactly what was revealed earlier in the property plots of Fig. 7.

4. Recirculation

In each of the 12 sections comprising the historical dataset there is a well-defined DWBC oxygen core relatively close to the bottom, whose variability has been discussed in the previous section. However, it turns out that in 10 of the 12 sections there is a second (usu-

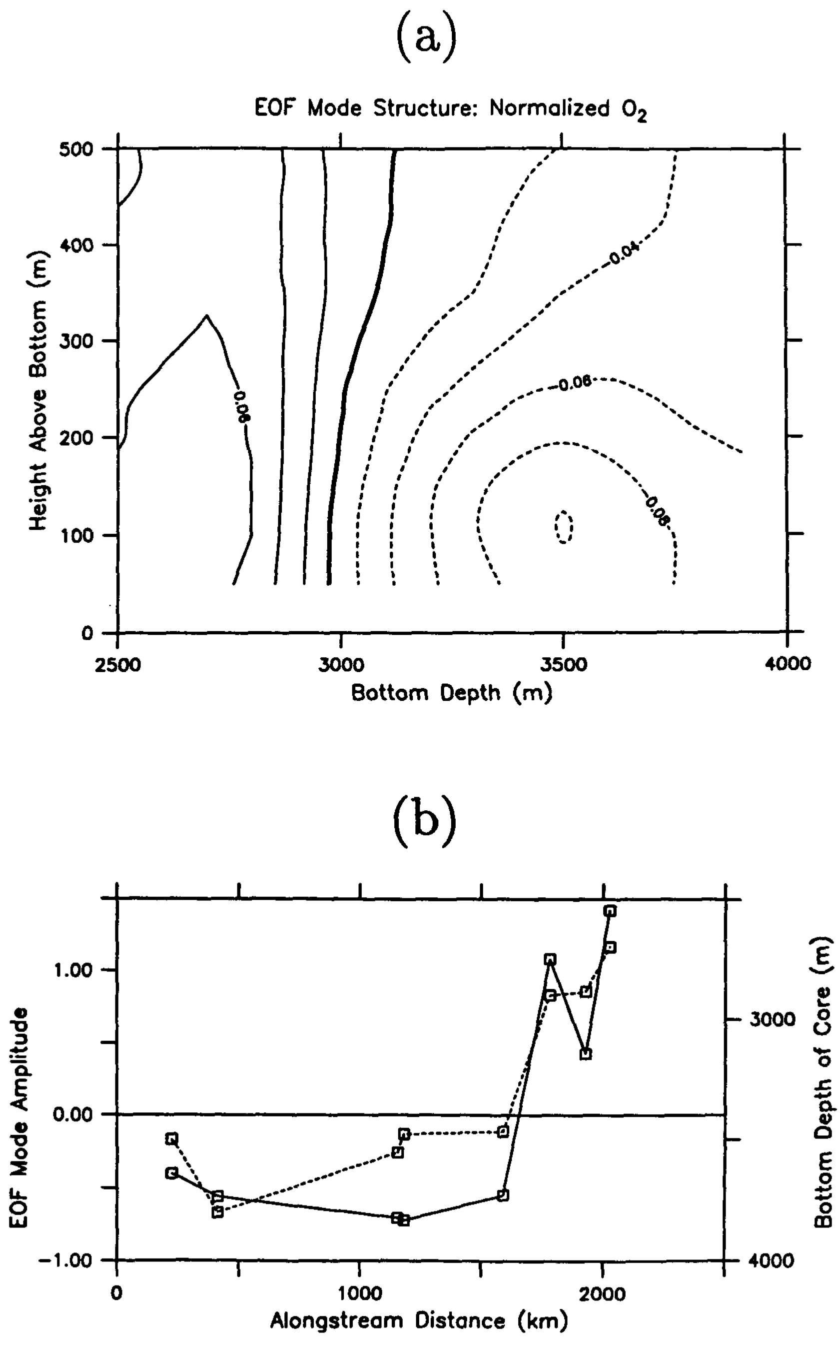

FIG. 12. (a) Vertical structure of EOF mode 1 for the normalized oxygen sections, accounting for 65% of the total variance. (b) Mode amplitude versus alongstream distance (solid line) compared to bottom depth of the DWBC core (dashed line).

ally less pronounced) oxygen core that is located at a deeper bottom depth and farther off the bottom (Fig. 13). This observation was somewhat surprising, and in this section we discuss the features and probable cause of this core. The onshore limit of the deep core was usually 4000-m bottom depth, which is why this depth was used as the seaward cutoff for the above EOF analysis of the shallower DWBC core (the exceptions had to be excluded from the EOF analysis). Coincidentally, the two oxygen sections shown previously in Figs. 2b and 9 are the only two sections without a detectable deep core.

As before, we integrated the properties within the deep core and carefully compared the sections. It turns

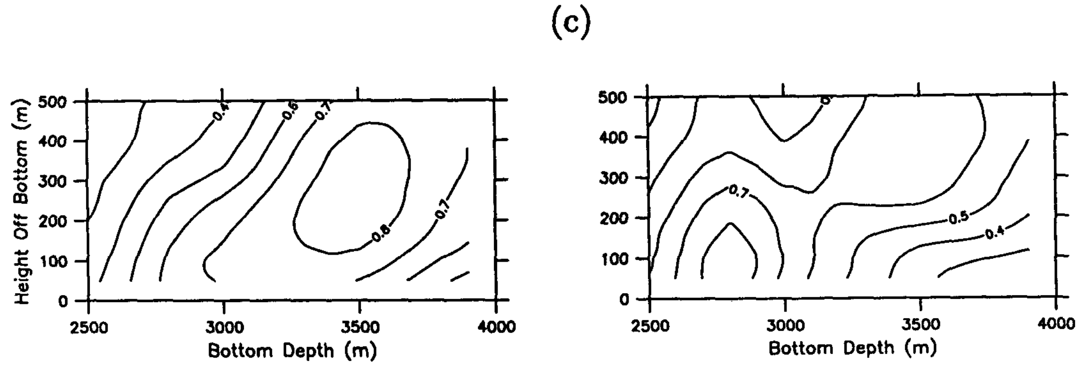

FIG. 12. (*Continued*) (c) Mode 1 added back into the mean with a large negative mode amplitude (left panel) and large positive mode amplitude (right panel).

out that the features of this core are quite different than those of the DWBC core. Figure 14 shows the alongstream trends of the offshore core compared to those of the DWBC core (overlaid from Fig. 5). One sees that from the Grand Banks to Cape Hatteras the offshore core shoals and decreases in oxygen concentration in similar fashion to the DWBC core. However, unlike the DWBC core, this core does have a noticeable trend in height off the bottom (farther off the bottom near Cape Hatteras), and its trend in cross-sectional area is opposite from that of the DWBC (i.e., larger area toward Cape Hatteras). In addition, the offshore core has no significant trend in temperature or density, in sharp contrast to the DWBC core.

With this information we have made the following interpretation of the offshore core (further evidence presented below supports this view as well). We surmise that as the DWBC crosses the Gulf Stream at Cape Hatteras some of it recirculates with the deep Gulf Stream forming the offshore oxygen core. This concept is not new; McCartney et al. (1980) hypothesized such a recirculation based on anomalous silicate measurements in the Gulf Stream. McCartney and Bennett (1992) actually claim that most of the DWBC recirculates with the Gulf Stream based on an observed discontinuity in silicate in western boundary waters north and south of the crossover. Our interpretation is not so extreme; we believe that a small portion of the high oxygen DWBC water is entrained into the onshore edge of the deep Gulf Stream.

To understand the trends in Fig. 14 remember that the water comprising the offshore core is presumably moving to the northeast. As the core progresses downstream (northeast) it flows into deeper topography and also gets closer to the bottom. The net result is that its water depth increases significantly (Fig. 14). However, its density does not change. This means that the isotherms containing the core must deepen significantly, which is consistent with the notion of the core mixing laterally along isopycnals as it advects downstream and

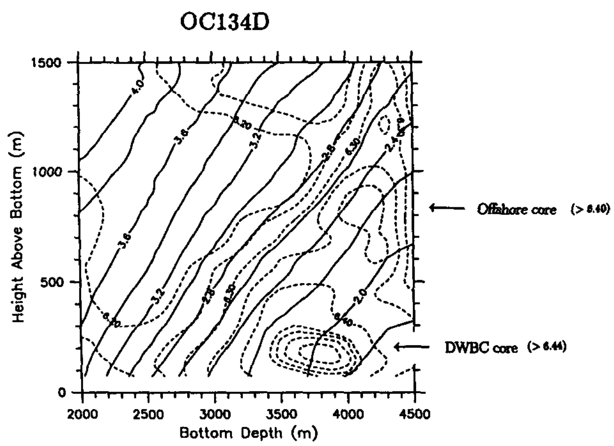

FIG. 13. Vertical section of oxygen from cruise OC134D showing the strong DWBC oxygen core and weaker offshore core. The oxygen contour levels range from 6.2 to 6.4 by 0.05 increments, then to 6.45 by 0.01 increments.

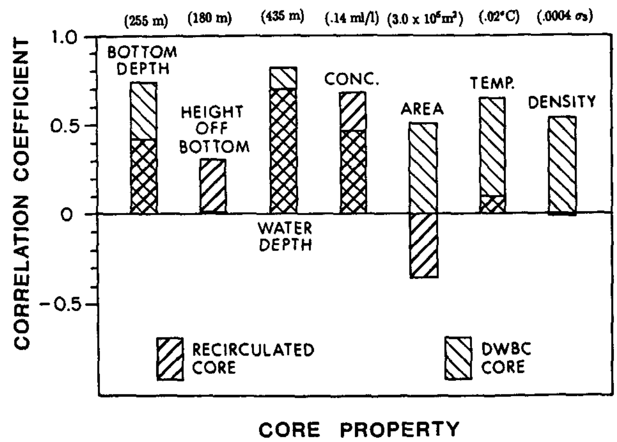

FIG. 14. Correlation coefficients (signifying the alongstream trends) for the offshore oxygen core compared with those for the DWBC core (from Fig. 5). The magnitude of the change in the offshore core is shown in parentheses for each property.

penetrating the Gulf Stream (whose isotherms slope sharply downward offshore). The core moves into deeper bottom depths because, as the Gulf Stream flows to the northeast, it moves into deeper topography. Note that this is a very different scenario than for the DWBC core, which was subject to significant cross-isopycnal mixing and became shallower downstream as a result of a density loss. This contrast is consistent with the mechanism described earlier (Fig. 6) in which the presence of the sloping bottom enhanced the effect of cross-isopycnal mixing. The recirculated core is well off the bottom, so the core has more contact with the denser underlying water and consequently cross-isopycnal mixing has little net effect (and along-isopycnal mixing predominates). Finally, recall that the trend in cross-sectional area of the recirculated core is opposite that of the DWBC core; the downstream direction is opposite, so as before the area of the core decreases away from its source.

The alongstream trend of the remaining core property, average concentration, is harder to interpret. One would expect the recirculated core to decrease in concentration away from its source (this being the DWBC at Cape Hatteras); however, the core concentration increases toward the Grand Banks. The explanation here is most likely that the recirculated core continues to receive oxygen from the DWBC via lateral mixing; keep in mind that the Gulf Stream remains fairly close to the DWBC east of the crossover and the DWBC has a stronger oxygen concentration nearer the Grand Banks. This explanation is further supported by the fact that the detrended oxygen concentration of the DWBC core is highly correlated with that of the recirculated core ($r = 0.72$); thus, when the DWBC core is higher in oxygen, so too is the recirculated core (and vice versa). Oxygen concentration is the only such property that is correlated between the two cores; all the other core characteristics show no similarities whatsoever, which further supports the above argument that the offshore core is a separate entity (aside from oxygen input from the DWBC).

Mean sections revisited

Although the recirculated core is weaker than the DWBC core (and absent in two of the sections) it is nonetheless apparent in the mean. Figure 15a displays

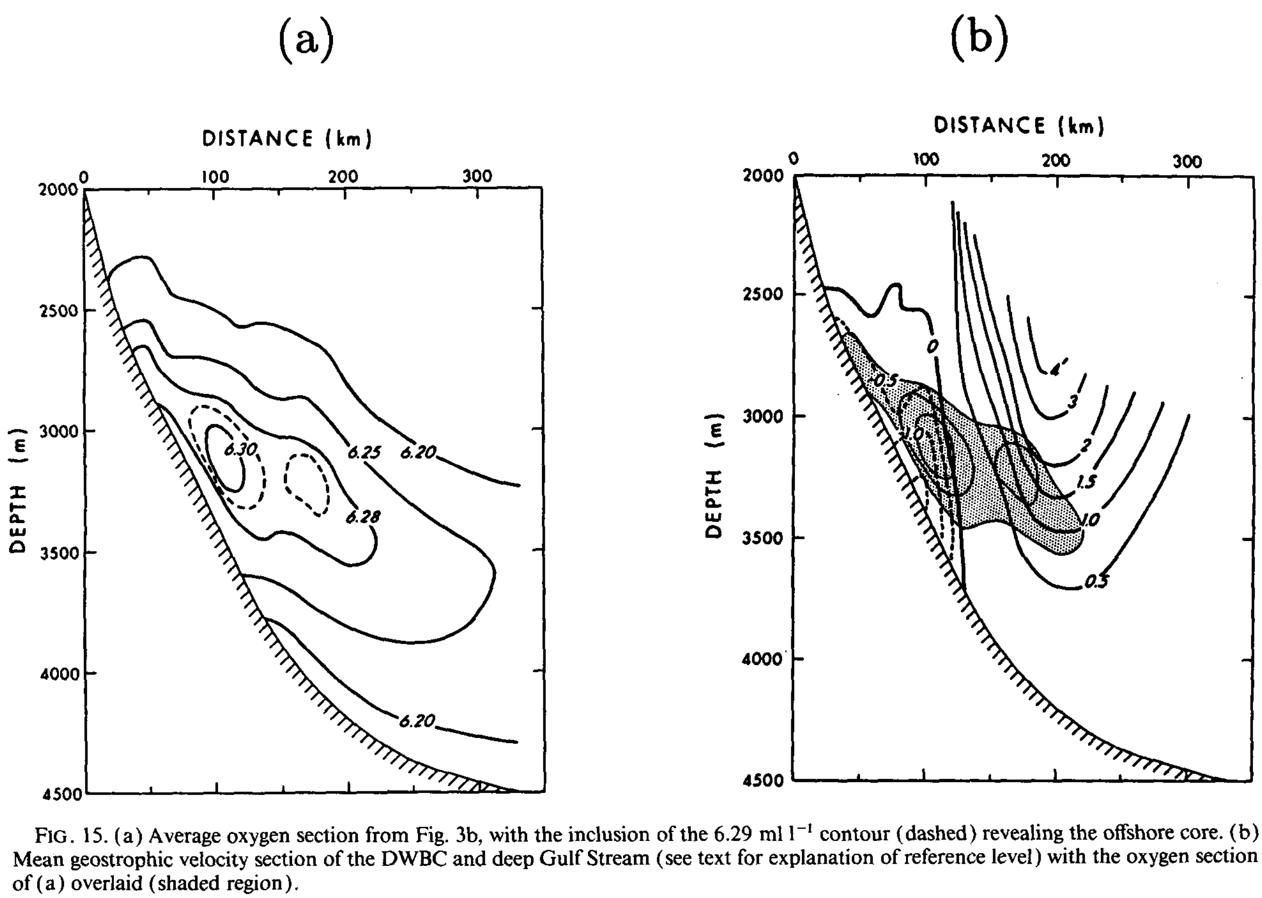

FIG. 15. (a) Average oxygen section from Fig. 3b, with the inclusion of the 6.29 ml l^{-1} contour (dashed) revealing the offshore core. (b) Mean geostrophic velocity section of the DWBC and deep Gulf Stream (see text for explanation of reference level) with the oxygen section of (a) overlaid (shaded region).

the mean oxygen section from Fig. 3b, except that now the 6.29 contour has been included, which reveals the offshore core. Admittedly the offshore concentration increase of 0.01 ml l^{-1} is less than the accuracy of the CTD, but this is the average over 12 sections so the signal is smeared out. In the individual sections the offshore core is much more pronounced (Fig. 13). In addition to the mean temperature section of Fig. 3a we also computed the mean section of potential density σ_3 (not shown, but identical in character to the temperature section) from which geostrophic velocities can be calculated. This is useful in its own right, as well as for comparison with the mean oxygen section.

We computed the geostrophic velocity by integrating the thermal wind equation,

$$\frac{du}{dz} = -\left(\frac{g}{f_0\rho_0}\right)\frac{d\sigma_3}{dx}, \qquad (1)$$

where the Coriolis parameter f_0 is the average over all the sections ($=9.2 \times 10^{-5}$ s^{-1}), and ρ_0 is the basic-state density ($=1.04$ gm cm^{-3}). It is not immediately obvious where one should put the reference level for the DWBC. Worthington (1976) chose the 3.5°C isotherm as a level of no motion, which is the core of the Labrador Sea Water. This is a reasonable choice based on the property distributions, which show that the water deeper than this has been ventilated most recently. It was not possible, however, for us to choose 3.5°C as a reference isotherm because our data only extends to 1500 m off the bottom along the continental slope (the average section was computed in the transformed grid); thus, our sections do not sample the Labrador Sea Water across the entire width of the DWBC. The warmest isotherm that is present over the DWBC is 2.8°C (Fig. 3a), which we have thus chosen as the reference level.

As discussed previously the strong thermal shear throughout the deep water column offshore of the DWBC is the deep Gulf Stream (this is clearly evident when inspecting the individual full-depth sections). Recent moored measurements have revealed that

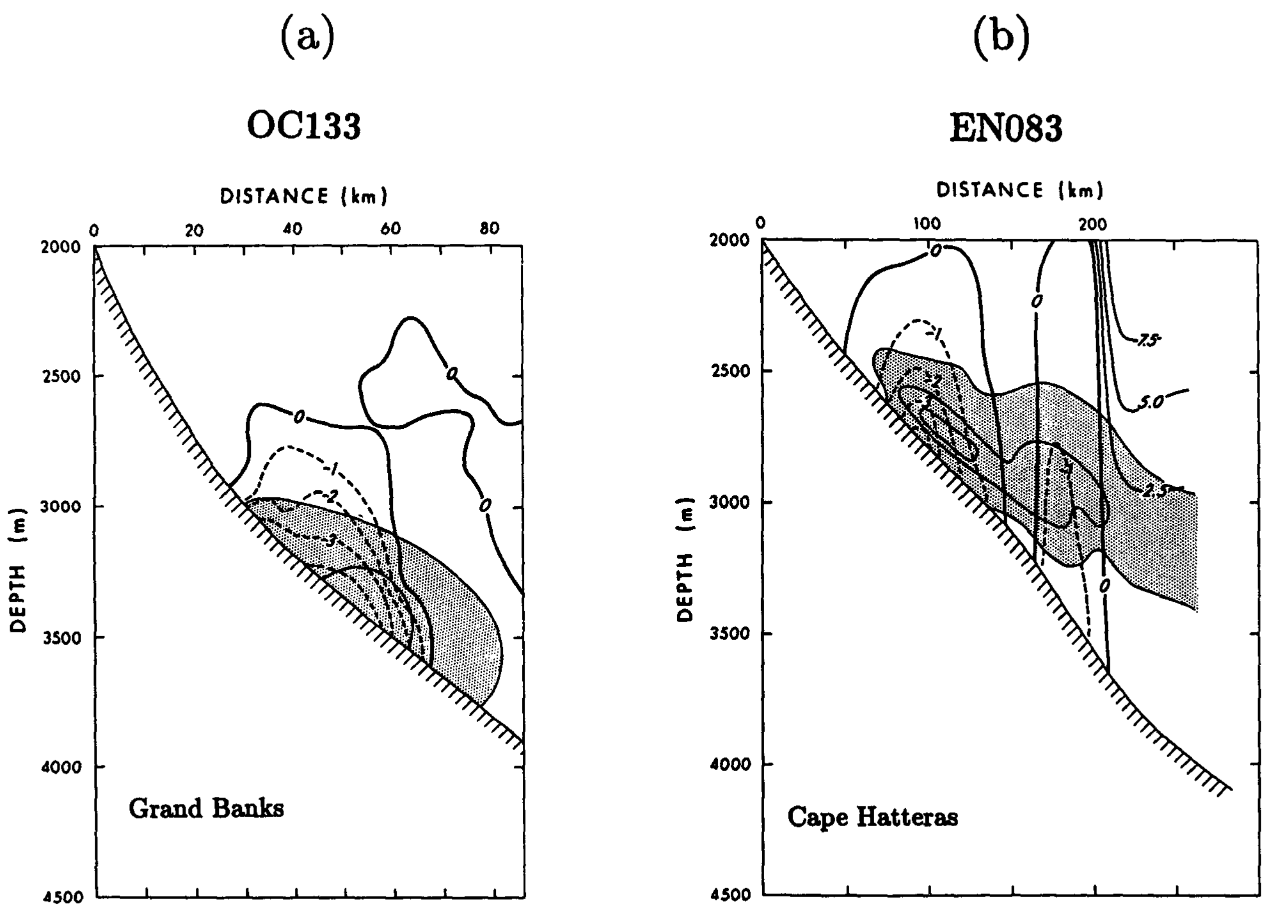

FIG. 16. Comparison of geostrophic velocity at the eastern- and westernmost sections, with oxygen overlaid (shaded region). (a) Section OC133 near the Grand Banks. The 6.35 and 6.40 ml l^{-1} oxygen contours are shown. (b) Section EN083 near Cape Hatteras (6.20, 6.25, and 6.28 ml l^{-1} contours shown).

downstream of Cape Hatteras the Gulf Stream's eastward flow extends to the bottom (Hall 1986; Welsh et al. 1989). Thus, a reference level of 2.8°C (~2500 m) for this offshore region is clearly inappropriate. Consequently, we have chosen the bottom as a reference level in the Gulf Stream. The only question then is where exactly does the transition from the DWBC to the deep Gulf Stream occur in Fig. 3a. Visually it is somewhere close to the deep north wall near 150 km; however, we used the following more precise criterion. If the 2.8°C isotherm is used solely as the reference level then the bottom-most equatorward DWBC flow increases as one moves downslope, eventually reaches a maximum, and then begins to decrease. A bit farther downslope, however, the bottom flow again increases quite sharply; it is clear that this is where the strong Gulf Stream shear is encountered, and, accordingly, this is where we changed to the bottom reference level (approximately 125 km).

The resulting mean geostrophic velocity section is shown in Fig. 15b. The core of the DWBC is at 3400 m and is 1.5 cm s^{-1} westward. Its corresponding transport is 0.5 Sv (Sv ≡ 10^6 m^3 s^{-1}). These values are of course much smaller than most direct current meter measurements that give typical core speeds of 4–8 cm s^{-1} (Watts 1991) and transports of 5–10 Sv (Hogg 1983; Pierce 1986). There are two reasons for this. The first is that our reference level is too deep (i.e., a warmer isotherm is more appropriate). The second reason is that because of the significant cross-slope excursions of both the DWBC and deep Gulf Stream in this region, part of the Gulf Stream flow is averaged into the DWBC. The value of computing the velocity section of Fig. 15b is in determining the structure of the currents. Overlaid on the mean velocity section is the mean oxygen section (shaded region). One clearly sees that the outer oxygen core is situated within the onshore part of the deep Gulf Stream (the transport of the entire deep Gulf Stream in the section is 2.5 Sv). Although our study area extends from Cape Hatteras to the Grand Banks, most of the sections are closer to Cape Hatteras (Fig. 1). Thus, our mean section is geographically weighted toward the region of the Gulf Stream crossover where the recirculated core is presumably best defined.

One also notices in Fig. 15b that the oxygen core is situated about 200 m above the velocity core, which itself is on the bottom. This displacement off the bottom is present in many of the historical DWBC oxygen sections. It may be due in part to boundary mixing effects or increased consumption near the sediments or both. It is curious that when the DWBC oxygen core is found farther downslope it is farther off the bottom. It may be that when this happens the DWBC water begins to override a denser in situ water mass (possibly Antarctic bottom water). In any case this observation requires further investigation. Note, however, that the alongslope location of the oxygen core does roughly coincide with the DWBC velocity core. This is important, for it implies that the cross-slope translation of the oxygen core revealed in these sections corresponds as well to movement of the DWBC velocity core (and is not, for example, an artifact of diffusion). To further document this we computed the geostrophic velocity for the eastern- and westernmost sections, which comparatively show the alongstream shoaling of the oxygen core. We used the same scheme for the reference level except that near Cape Hatteras the 3.2°C isotherm was used for the level of no motion in the DWBC. The two geostrophic velocity sections are shown in Figs. 16a,b, with oxygen overlaid. In both sections it is seen that the property and velocity cores approximately coincide in alongslope location, illustrating that the current itself shoals toward Cape Hatteras.

5. Summary

By quantitatively comparing a set of historical DWBC property sections we have revealed that the boundary current translates up and down the continental slope, apparently in response to changes in the source waters of the current. When the DWBC is found downslope it is colder and more dense, farther off the bottom, and larger in cross-sectional area. The boundary current also undergoes general alongstream changes as it flows from the Grand Banks to Cape Hatteras (a distance of roughly 2000 km). The DWBC decreases in oxygen concentration by 0.12 ml l^{-1}, shoals by approximately 800 m, warms by nearly 0.4°C, and becomes less dense and smaller in the cross-sectional area. These changes are due to mixing with the surrounding fluid along its path. As the DWBC crosses the Gulf Stream at Cape Hatteras a portion of it recirculates with the deep Gulf Stream, forming a weak oxygen core farther offshore. This core is not subject to the same variability as the DWBC, but as the offshore core progresses to the northeast it mixes laterally and penetrates to greater depths along the isotherms of the Gulf Stream.

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