Mean Flow and Variabilities in the Deep Western Boundary Current

DAVID Y. LAI[1]

Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882

(Manuscript received 17 August 1983, in final form 11 June 1984)

ABSTRACT

The Deep Western Boundary Current (DWBC or Western Boundary Undercurrent) was observed for over 100 days by an L-shaped array of current meters along and across the Blake Escarpment. The measurements show a mean southward flow, which at its core, 10 km east of the break of the escarpment, reaches a maximum of 22 cm s^{-1} at a depth of 2500 m. The mean flow decreases to zero at the break and 6 cm s^{-1} 50 km east of the escarpment. The core of the current decreases to 15 cm s^{-1} near the bottom and to zero at 800 m depth. The mean southward volume transport is estimated to be 24×10^6 m^3 s^{-1} (24 Sv).

Two fluctuations in the southward current with amplitudes of the same order as the mean flow are observed. Below 2000 m these events are consistent with the flow patterns of southward-moving anticyclonic features. The much reduced currents observed might not reflect actual large reductions in the volume transport of the DWBC.

The array measurements, together with a SOFAR float that got caught in the DWBC, document a cyclonic eddy between 1000 and 2000 m during the passage of the two anticyclonic features. There is no clear relationship between this eddy and the two deeper features.

1. Introduction

The existence of a deep southward-flowing current along the western margin of the North Atlantic Basin was proposed by Stommel (1958) to supply the deep ocean interior with a source of cold water from the north to be upwelled through the thermocline. The Deep Western Boundary Current (DWBC hereafter) (Hogg, 1983), or Western Boundary Undercurrent, was observed the first time by Swallow and Worthington (1961). It flows southward under the Gulf Stream near Cape Hatteras (Richardson, 1977), southeastward along the eastern slope of the Blake-Bahama Outer Ridge, turns northwestward along the western slope of the Ridge, and follows the bottom contours westward before turning southward near the Blake Spur (Heezen *et al.*, 1966; Amos *et al.*, 1971; Mills and Rhines, 1979). Some SOFAR float trajectories (Riser *et al.*, 1978) and hydrographic data (Amos *et al.*, 1971) show that the DWBC continues its southward journey along the Blake Escarpment.

An accurate estimate of the DWBC volume transport is important to the study of the heat budget in the ocean. Previous transport estimates vary from 6 (Worthington, 1976) to 40 ($\times 10^6$ m^3 s^{-1} ≡ Sv) (Riser *et al.*, 1978). Richardson (1977) estimated the DWBC transport off Cape Hatteras to be 24×10^6 m^3 s^{-1} from a hydrographic section, using current meter measurements to establish reference levels for the absolute current. A maximum southward velocity of 24 cm s^{-1} was observed as shallow as 700 m. The volume transport observed there is similar to the 22 Sv along the eastern flank of the Blake-Bahama Outer Ridge (Amos *et al.*, 1971) calculated from a hydrographic section, although the levels of no motion they chose were around 2000 m. Along the Blake Escarpment, Riser *et al.* (1978) observed a maximum southward velocity of 50 cm s^{-1} at 2000 m depth which is about at the levels of no motion chosen there by Amos *et al.* (1971). The difference in the levels of no motion accounts for the large difference in the volume transport estimates (40 Sv in the former compared with 10 Sv in the latter).

There have been other direct current measurements in the DWBC. Mills and Rhines (1979) obtained year-long current-meter time series across the Blake-Bahama Outer Ridge. Unfortunately the mooring deployed near the core of the current was lost, presumably dragged downstream by the strong current. Short (two weeks) time-series of near-bottom currents on the lower continental rise of Nova Scotia were obtained by Richardson *et al.* (1981). No volume transport for the DWBC was estimated from either set of observations.

There are variabilities associated with mean currents. For example, the Gulf Stream meanders (Hansen, 1970), spins off eddies (Fuglister and Worthington, 1951) and reabsorbs eddies (Cheney *et al.*, 1976). The volume transport of the Gulf Stream off Cape

---

[1] Present affiliation: Applied Physics Laboratory, University of Washington, Seattle, WA 98105.

Hatteras has a standard deviation which is 15% of the mean (Rossby and Halkin, 1982). For the DWBC the variability may be greater; large fluctuations in the observed current of the same order as the mean flow for a period of several weeks have apparently been observed by others (Mills and Rhines, 1979; Wimbush, personal communication, 1983). Fluctuations in the observed current at a mooring can be due to actual fluctuations in the volume transport of the mean current, the meandering of the current away from the mooring site, or the presence of an eddy in the mean current, in which case the current observed is actually the sum of the mean and eddy circulations. With the above-mentioned fluctuations in the DWBC observed at just one mooring, it is not possible to identify their causes.

This paper describes an experiment in which an L-shaped array of current meters was deployed along and across the Blake Escarpment (Section 2). The array provides current observations at both edges and near the core of the DWBC for three and a half months. Observed mean properties of the current, such as the volume transport, are examined in Section 3. Section 4 describes two large fluctuations in the observed southward flow of the DWBC and their possible causes. The current meter measurements are complemented by data from a SOFAR float that got caught in the current (Riser *et al.,* 1978) during the same period.

2. The data

The Blake Escarpment is a step-like topographic feature about 400 km east of the coast of Florida. It runs in an exceptionally uniform north-south direction, joining the gentle plains of the Blake Plateau and the Blake Basin (Fig. 1). It drops from 1500 m to 5000 m in less than 10 km, with a typical slope of about 0.4. An L-shaped array of current meters, temperature sensors and bottom-pressure gages (Table 1) was deployed on four moorings along and across the Blake Escarpment during June through October, 1975. All the deployed instruments were recovered successfully. Two of the 15 current meters (instru-

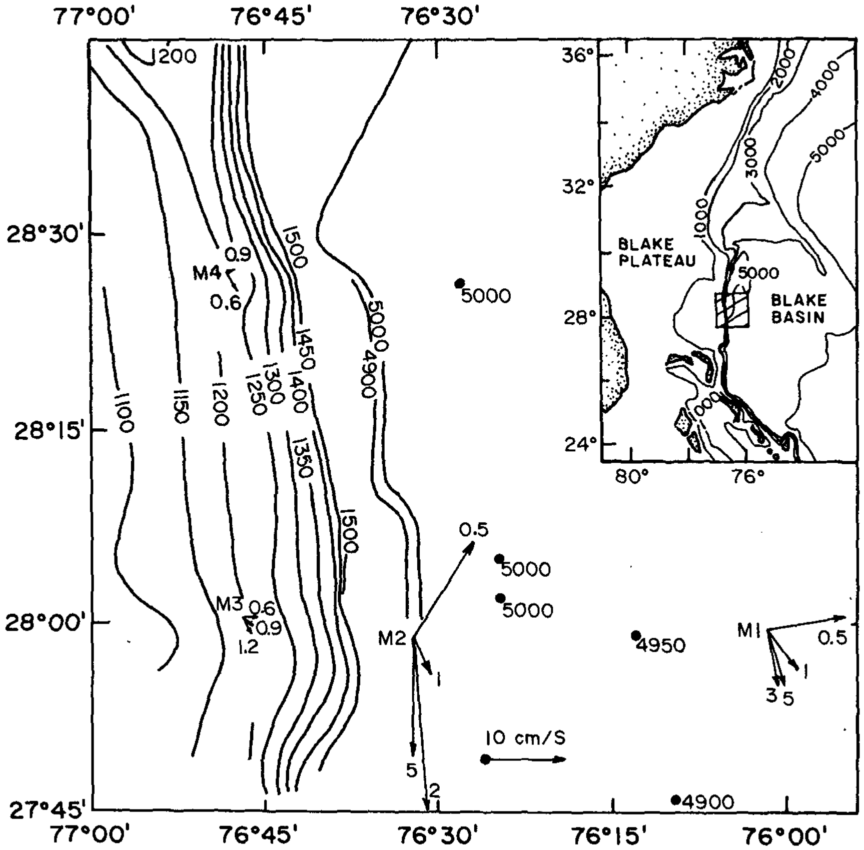

FIG. 1. Bathymetry of the Blake Escarpment. Locations of the four moorings are indicated by M1, M2, etc. The observed mean currents are represented by arrows. The water depths in km at which they are observed are shown next to the arrows. Other depths shown are in meters. Currents at mooring 2 are computed from the mooring-motion model (see text). The inset shows the location of the Blake Escarpment and surrounding topography.

TABLE 1a. Locations and bottom depths of mooring sites.

Mooring	Latitude	Longitude	Depth (m)
1	27°59.7′N	76°01.6′W	4934
2	27°58.9′N	76°32.2′W	4930
3	28°00.5′N	76°46.9′W	1200
4	28°26.9′N	76°48.3′W	1205

ments 24 and 42) failed. Figure 2 shows the time-series of the daily low-passed current observations at each instrument.

Before these measurements can be studied, a problem in the data has to be addressed. Large temperature fluctuations of 15°C were observed by instrument 21 (Fig. 3). Similar (though smaller) fluctuations were recorded by deeper instruments on the same mooring. Previous studies (Amos *et al.,* 1971) and historical temperature data from the National Oceanographic Data Center (NODC hereafter) do not show temperature fluctuations of this magnitude in the region. These findings, together with the strong currents observed, strongly suggest that the recorded temperature fluctuations are mainly due to vertical excursions of the instruments through the water column as the mooring is dragged to tilted positions by the strong current. Investigation of these mooring motions is necessary to obtain a more realistic description of the current.

Chhabra (1973, 1976) developed a model which computes the positions of instruments on a subsurface mooring exposed to drag forces from a horizontal current varying vertically and with time. His model was tested successfully in the weak-current regime of MODE (Chhabra, 1977). Modifications have to be made for it to be applicable in the presence of strong currents. A summary of the model and these modifications is found in the Appendix.

The model shows that the shallower instruments on mooring 2 did undergo huge vertical excursions of up to 1900 m. The mean temperature profile computed from NODC historical data is used to verify the results since there is no pressure sensor on this mooring. The observed temperature-versus-predicted depth diagram for instrument 21 is shown in Fig. 4. The diagram for instrument 22 is similar. There is a lot of scatter in the predicted depth values for the same observed temperature although most of the points at the top of or below the main thermocline lie within one standard deviation from the mean NODC values. The predicted depths are consistently shallower than the NODC mean when the instrument is in the main thermocline, i.e., during the transit between its two extreme positions when there is a large change in the strength of the current. During these times, the top two current meters are above, and the bottom two below, the core of the DWBC which is at 2500 m (see Section 3). Thus the full strength of the current is not observed and consequently the predicted depths are shallower than the actual depths of the instruments as reflected in the observed temperatures. Examples of this can be found on July 15 and August 6 (Figs. 2 and 3).

Fortunately, these shallower predicted depths in the main thermocline represent less than one-fifth of the data. Since we are mainly interested in the southward mean current whose core is below the main thermocline where the predicted depths of the instruments agree reasonably well with the mean temperature profile, the corrected data at mooring 2 give a meaningful description of the current there. Time series of horizontal current for fixed depths at mooring 2, obtained by linearly interpolating velocity measurements at their predicted depths, are shown in Fig. 5.

The same mooring-motion model shows that vertical excursions of instruments on moorings 1, 3 and 4 are small: a maximum of less than 300 m for mooring 1, and 50 m for the others. No correction for mooring motions was applied at these moorings.

3. The mean flow

a. The volume transport

Superimposed on the bathymetry in Fig. 1 are the mean currents for the 107-day mooring deployment.

TABLE 1b. Instrument types and depths. Current meters are identified by two digits. The left one is the mooring number and the right one the instrument number which increases from surface to bottom. Pressure gauges are identified by the letter P and the mooring number.

Instrument	Type	Nominal depth (m)
11	VACM	470
12	VACM	1070
13	VACM	2990
14	VACM	4907
21*	VACM	460
22*	VACM	1070
23*	VACM	2980
24**	Aanderaa	4899
25*	VACM	4904
31	Aanderaa	568
32	Aanderaa	872
33	Aanderaa	1169
41	Aanderaa	573
42	Aanderaa	877
43**	Aanderaa	1174
P3	Vibrotron	1200
P4	Vibrotron	1205

* Instruments on mooring 2 underwent large vertical excursions and their nominal depths should be ignored.

** Instrument failed.

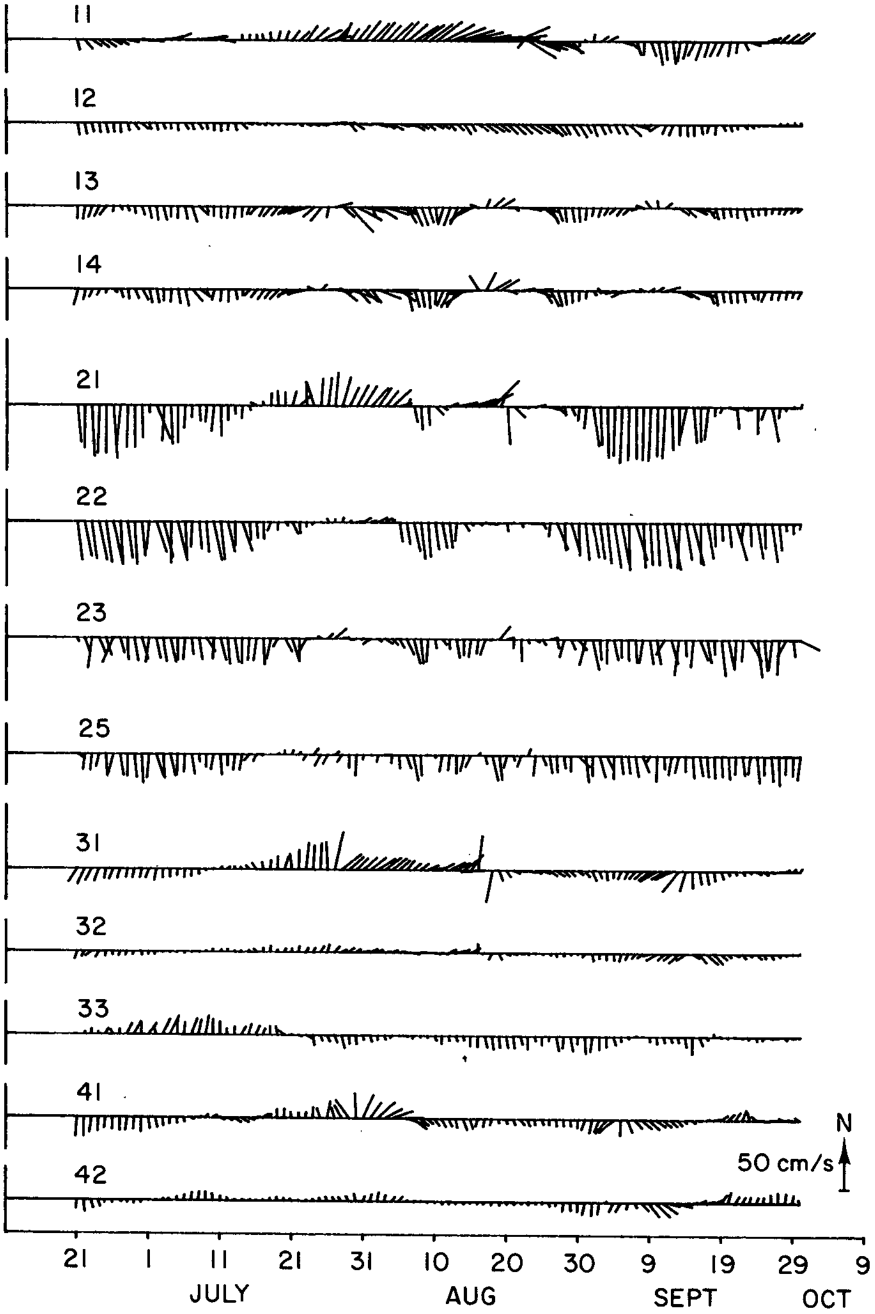

FIG. 2. Three-and-a-half-month current records observed from the array along and across the Blake Escarpment. Each line represents a horizontal current vector scaled according to the arrow in the lower right-hand corner. North is upward.

Except for current meter 11, the mean flows in *u* (east direction) are not well-defined; they are small (1 to 2 cm s^{-1}) and much smaller than the standard deviations (Fig. 2, Tables 2 and 3).

A strong southward mean current, presumably the DWBC, is observed at mooring 2 (Table 3). It reaches a maximum of 22 cm s^{-1} at a depth of 2500 m, decreases rapidly to zero at 800 m and more gradually to 15 cm s^{-1} near the bottom. The DWBC extends to at least 50 km east of the escarpment (at mooring 1) where it has vertically-averaged speed of 6 cm s^{-1} below 1000 m (Table 2). No significant southward

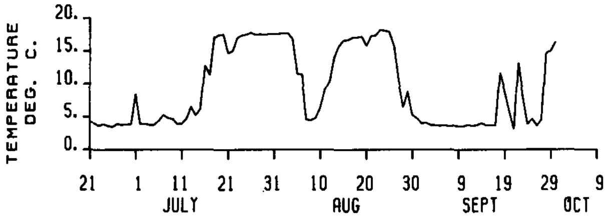

FIG. 3. Time series of temperature measurements recorded by instrument 21, the topmost instrument on mooring 2.

mean flow is detected at moorings 3 and 4 on top of the Blake Escarpment.

A mean northward flow of 10 cm s^{-1} is observed at 500 m. Although the designated depth of instrument 21 is 460 m, it stays within 40 m of this depth level for only one-fifth of the time (Fig. 3, Table 3). Thus, this northward flow is probably not a good representation of the true mean flow at this level. No significant northward mean current is found above the DWBC at mooring 1.

A simple model is used to compute the southward volume transport of the DWBC (Fig. 6). The Blake Escarpment and mooring 1 are taken to be the boundaries of the current. The current is assumed to be zero at the Escarpment and 800 m depth. Current observations at instruments 13 and 14 on mooring 1, and at 2500 m (corresponding to the core of the current) and 5000 m on mooring 2, are used for the transport calculation. Linear velocity profiles are assumed for the current at positions between the locations given above. Although the current meter array is not dense enough to observe the true horizontal profile of the DWBC, the linear horizontal profile assumed in this model is similar to that observed by SOFAR floats along the Blake Escarpment (Riser *et al.,* 1978).

The computed daily transports are shown in Fig. 7. The model shows a mean southward volume transport of 24 Sv, with a standard deviation of 12 Sv. An uncertainty of 1 Sv in the transport comes from the precision of the current meters. If the shallower predicted depths (from the mooring motion model) in the main thermocline at mooring 2 (Fig. 4) were taken into consideration, the DWBC would go to zero at 1000 m instead of 800 m, with the rest of the current observations unchanged. This, in effect, reduces the transport estimate by 1 Sv. The volume transport east of mooring 1 amounts to 2 additional Sv, if the mean current is assumed to reduce to zero eastward linearly. Using a more detailed vertical structure for the DWBC, as shown in Tables 2 and 3, only changes the transport by less than 1 Sv. Thus, when the quantifiable uncertainties in the model are taken into consideration, there is an error of ±3 Sv in the estimated volume transport of the DWBC.

Although the observed mean southward current at 800 m (or 1000 m) is zero (Table 3), it represents slack current conditions and is based on half the number of data points as in deeper current observations. Thus the choice of zero current for the DWBC at this depth level may be biased.

The currents observed at mooring 2 are higher than those observed at other moorings and they are assumed to be the actual maximum speeds for the DWBC in the volume transport calculation. The actual core of the current may not be at the location of mooring 2, though the presence of the escarpment to the west and the float data of Riser *et al.* (1978) to the east suggest that it is probably within 5 km of this location. Any displacement of the core would imply a larger core velocity, resulting in a larger transport.

b. Discussion

Our volume transport estimate of 24 Sv along the Blake Escarpment is larger than the estimate from

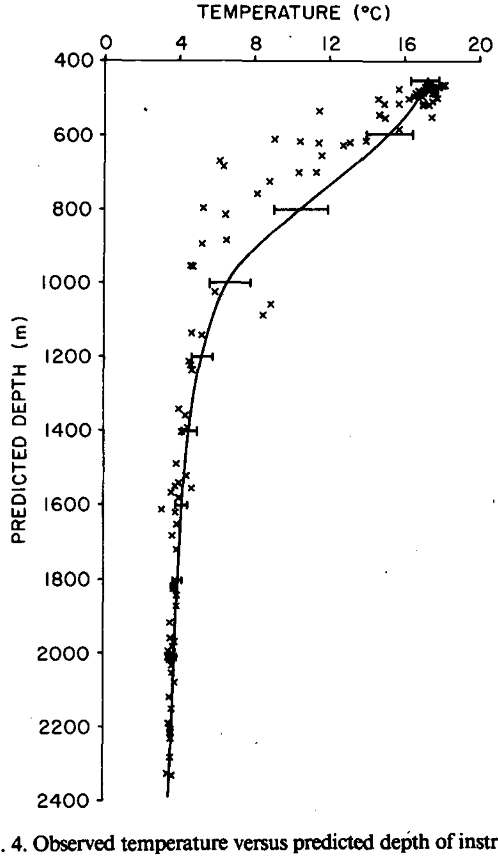

FIG. 4. Observed temperature versus predicted depth of instrument 21. Each point corresponds to an actual daily observed temperature and a depth predicted by the mooring-motion model. Superimposed on it is the mean temperature-depth profile and standard deviations of temperatures at selected depths computed from NODC historical data.

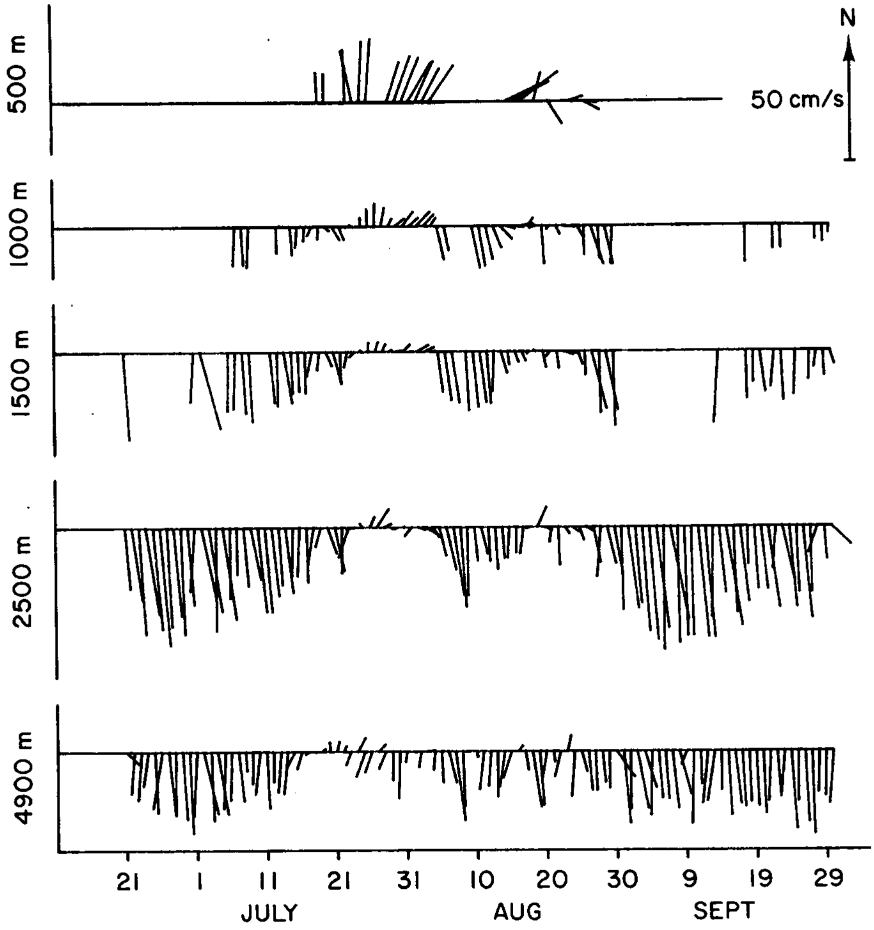

FIG. 5. Time series of computed absolute velocity of current at selected depths on mooring 2. The absolute velocity of current at the predicted depths of the instruments is the sum of the relative velocity (as observed by the current meters) and the computed velocity of the mooring from the mooring-motion model. Absolute velocities at fixed depths are obtained by linear interpolation of the above velocity profiles. Missing points in a series indicate that all the current meters on the mooring were dragged below that particular depth level.

hydrographic data in the same region (Amos *et al.*, 1971). They calculated the volume transport of the DWBC along the Blake Escarpment to be 10 Sv. They showed the DWBC extending from the bottom to a depth of about 2000 m, the level of no motion chosen for their hydrographic section. Direct current measurements along the Blake Escarpment suggest that the DWBC extends to a much shallower depth (Riser *et al.*, 1978; Table 2 and 3). Our measurements suggest that it extends typically to 800 m. If the 15 cm s^{-1} mean southward flow at 2000 m observed in our measurements were added at all levels to the flow of Amos *et al.* (1971), the resulting volume transport of the DWBC would be 28 Sv which is similar to our estimate.

It is fortuitous that our estimate of 24 Sv is the same as that observed near Cape Hatteras (Richardson, 1977) where southward currents of 20 cm s^{-1} were observed as shallow as 500 m. However, the shallowing of the DWBC there is not unlike the observation along the Blake Escarpment. Also, our estimate is consistent with an upper bound of 40 Sv determined from SOFAR float data at 2000 m depth in the Blake Escarpment region (Riser *et al.*, 1978).

It is unlikely that all of the 24 Sv in the DWBC observed along the Blake Escarpment came directly from surface sources in the north. Portions of the volume transport there could be due to the entrainment of Sargasso Sea water from the deep Recirculation Gyre (Worthington, 1976). There are existing evidences that suggest such entrainment took place in the DWBC. Jenkins and Rhines (1980) found that the width and thickness of the DWBC along the Blake-Bahama Outer Ridge indicated by tritium con-

TABLE 2. Basic statistics of observed currents at all four moorings. T, u and v represent the temperature, eastward and northward velocity.

Instrument	$\bar{u}$ (cm s^{-1})	$\bar{v}$ (cm s^{-1})	$\overline{u'^2}$ (cm^2 s^{-2})	$\overline{v'^2}$ (cm^2 s^{-2})	$\overline{u'v'}$ (cm^2 s^{-2})	$\overline{u'T'}$ (cm °C s^{-2})	$\overline{v'T'}$ (cm °C s^{-2})
11	10.30	1.45	99.40	96.63	43.82	−3.93	−0.54
12	3.49	−5.06	13.76	12.67	−0.89	−0.87	1.06
13	1.31	−7.10	57.64	31.25	2.44	0.02	−0.18
14	1.91	−6.44	67.90	40.70	8.03	−0.002	0.07
21*	3.13	−12.02	37.21	488.41	61.86	19.70	110.31
22*	2.95	−20.66	9.99	210.25	−16.77	−1.00	14.74
23*	1.35	−14.94	18.75	85.56	6.59	−0.04	0.98
25	0.35	−12.95	7.78	61.15	−1.58	0.02	−0.05
31	1.65	−0.10	42.51	116.64	34.98	−0.51	−2.58
32	1.01	−1.11	12.67	14.21	4.16	0.43	−0.99
33	0.98	−1.38	3.80	62.41	3.88	0.04	−0.24
41	1.80	−2.17	30.80	68.06	5.30	−1.04	−0.90
42	1.24	0.18	10.37	30.25	−1.73	0.72	−0.25

* Upper instruments on mooring 2 underwent large vertical excursions. The values there are dubious.

centrations are different from that observed by current meters. They also observed a 5- to 10-fold reduction of the tritium concentration in the DWBC there compared with concentrations in the north. This reduction cannot be accounted for by the radioactive decay of tritium, considering the short advection time scale of the DWBC. Dilution of the tritium-rich water from the north has to take place in the DWBC. Several instances of such entrainment can be found in the SOFAR float data (Riser *et al.*, 1978).

It is interesting to point out that there is considerable southward current to the east of the Blake Escarpment where the topography is flat (Fig. 1), as observed by floats (Riser *et al.*, 1978) and assumed in this study based on two current meter moorings. Thus the current appears to be dynamically different from the deep southward "topographic jet" (Fofonoff, 1981) which is a result of the conservation of potential vorticity as deep westward flows move up sharply rising topography.

4. Large fluctuations in the mean flow

There are two occasions (mid-July and mid-August) in which the temperature observed at instrument 21 is greater than 16°C for more than a week (Fig. 3).

TABLE 3. Mean velocities and their standard deviations at selected depths at mooring 2. Values are computed from the mooring-motion model. The numbers of daily observations (out of a possible 102) used in computing the averages are shown in the last column. They vary with depth because of the vertical excursions of the instruments. Units are cm s^{-1}; u is eastward and v northward.

Depth (m)	$\bar{u}$	$\bar{v}$	σ_u	σ_v	Number of daily observations
500	8.42	11.48	7.34	9.20	22
800	4.05	0.67	4.33	8.40	49
1000	2.30	−5.04	3.00	7.57	54
1500	1.69	−12.13	2.79	10.20	67
2000	2.17	−18.69	2.80	13.30	87
2500	2.70	−21.62	3.46	14.70	102
3500	1.41	−17.38	3.90	10.60	102
4900	0.44	−15.19	3.13	9.64	102

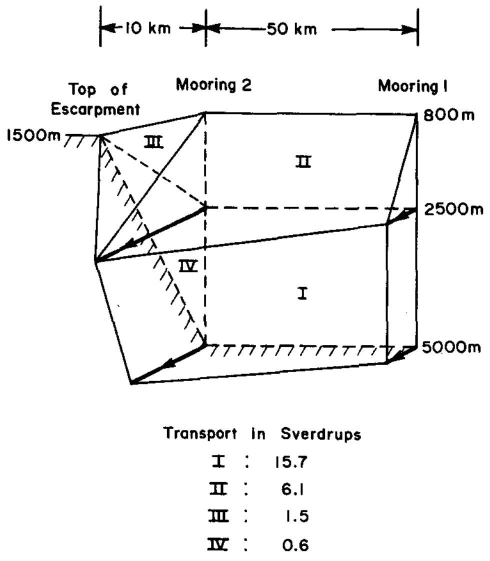

FIG. 6. Schematic diagram of volume transport of the Deep Western Boundary Current (not drawn to scale). The arrows represent the observed velocities. Current goes to zero at 800 m and at the top of the Blake Escarpment. Velocities at other positions are linearly interpolated from the observed values. Estimated mean volume transports in four separate regions are shown.

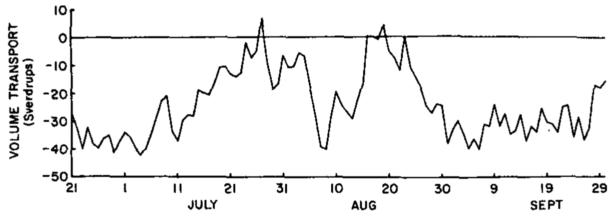

FIG. 7. Time series of southward volume transport of DWBC calculated using model in Fig. 6. Positive is northward.

These temperatures are close to the mean value (from NODC data) at the designated depth of this instrument (470 m). This suggests that during these periods the current slows down enough at the mooring site to prevent significant tilting of the mooring. It is corroborated by the observed velocity data at this mooring (Figs. 2 and 5); the current slows down to zero throughout its entire vertical extent and even turns back to flow northward. Similar slow-downs are found at the edge of the current at mooring 1. During the same periods, there is no detectable velocity increase or decrease at the bottom instruments at moorings 3 and 4.

Reductions in the observed mean current at a mooring can be due to actual reductions in the volume transport of the current, the meandering of the current away from the mooring site, or the presence of an eddy in the mean current in which case the current observed is actually the sum of the mean and eddy circulations.

A SOFAR float (Number 17) (Riser *et al.*, 1978), caught in the DWBC at estimated depths of 1500 to 2000 m, came within 100 km of the moorings during the two fluctuations (Fig. 8). The cycloidal trajectory of the float during this period resembles the path of a float embedded in an eddy which is being advected by a mean current. This hypothesis is investigated next. Both the mean and the trend in the float velocity are subtracted. The means of u and v are 1.5 and -7.7 cm s^{-1} respectively. There is no trend in u and the trend in v is 6.8 cm s^{-1}/100 km, which agrees qualitatively with the cyclonic shear of the southward mean flow from the current meter measurements. When the new positions of the float are computed from the residual velocities, the trajectory resembles a cyclonic eddy. It is oriented in a north–south direction with a major axis of 60 km and minor axis of 40 km. The float goes around the eddy in 40 days with a mean tangential velocity of 5 cm s^{-1}. The eddy appears to be advected southward by the DWBC. It also moves slowly towards the edge of the current until it gets out of the stream (Fig. 8).

The observed velocities at current meter 12 (1000 m depth) agree reasonably well with the circulation pattern of this eddy (Fig. 9). The cyclonic circulation of the eddy is observed at this instrument while the eddy is 80 km south of the center of the eddy (Figs. 9a and b), suggesting that the north–south extent of the eddy is at least twice that indicated by the float trajectory. The eddy exists in the DWBC at depths between 1000 and 2000 m (depths of current meter 12 and the float respectively) and there is no indication that it extends to the surface (Fig. 2).

Another cyclonic eddy with a diameter of 60–80 km is found above the DWBC during 17–24 August (Perkins and Wimbush, 1976; Fig. 2). It only exists above 1000 m and is being advected eastward across the DWBC by the background flow. There is no apparent relationship between this shallower eddy and the deeper one in the DWBC as the latter is being advected southward by the DWBC.

While the circulation pattern between 1000 and 2000 m is consistent with that of the advected cyclonic eddy observed by the SOFAR float, currents below these levels are not. As the eddy passes through the array there are several periods of time during which velocities at current meters 13 and 14 differ substan-

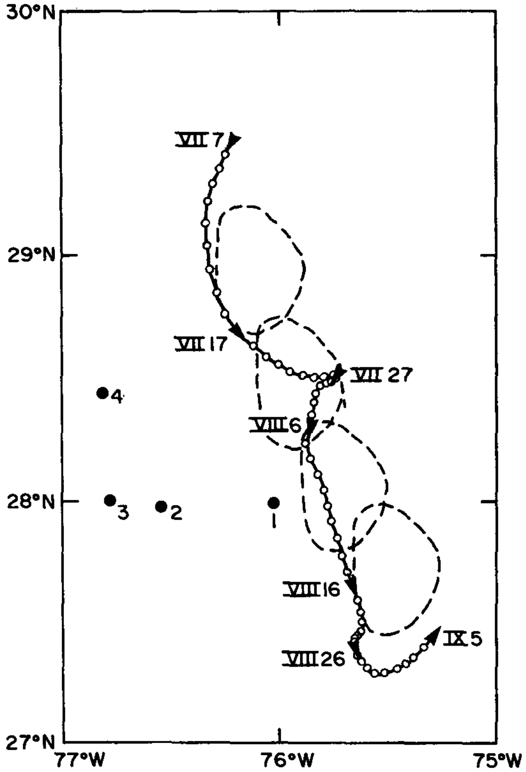

FIG. 8. Overall trajectory of SOFAR float. Superimposed on the trajectory are the positions of the cyclonic eddy every 10 days; the positions of the float are marked by solid arrowheads and the dates next to them. The eddy and its positions are computed by subtracting the mean flow (including the horizontal shear) from the float positions. Locations of the four moorings are indicated by the solid circles.

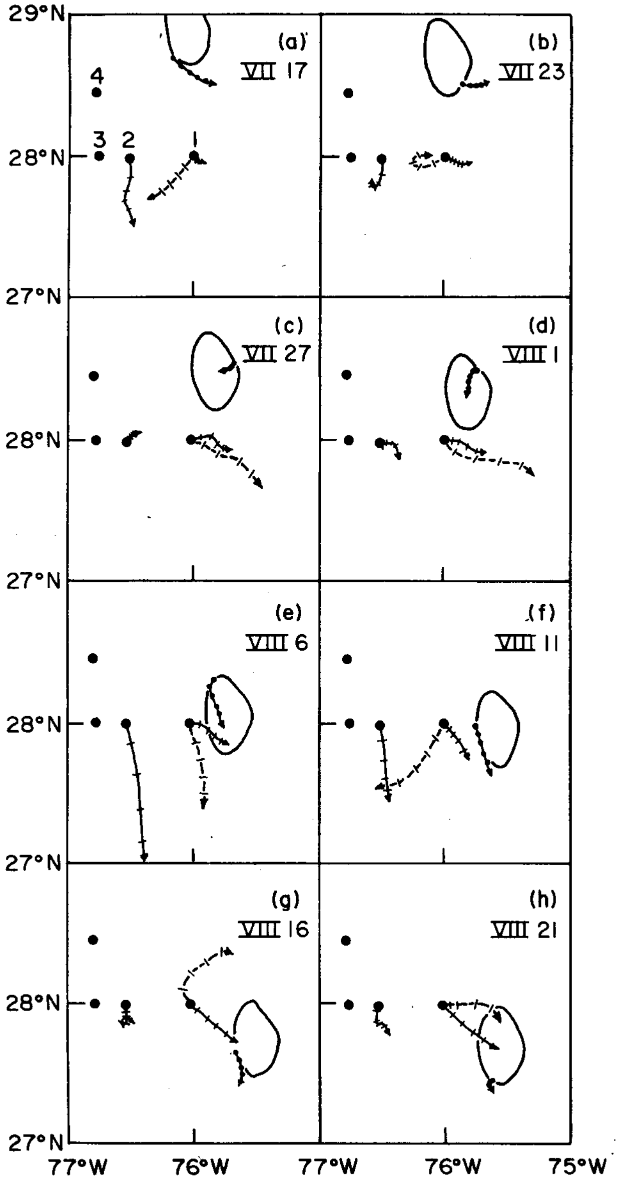

FIG. 9. Comparisons between SOFAR float and current meter observations. Positions of floats and progressive-vector diagrams of currents at 1000 and 3000 m at mooring 1, and 2000 m at mooring 2 are shown in 5-day segments, the former as circles and the latter as tic-marked lines. The lines for currents at 3000 m at mooring 1 are dashed. The positions of the cyclonic eddy are also shown. The beginning date of each segment is indicated by a Roman numeral (month) and a number (day). Positions of the four moorings are marked by solid circles.

tially from those at 12. With the eddy north of the mooring, implying eastward flows at mooring 1 (as observed at meter 12), westward flows are observed at meters 13 and 14 instead (Figs. 9a and b). As the eddy moves to the east and south of the array, implying southward and westward flows at mooring 1, different flows are observed (Figs. 9f, g and h). Similar disagreements are found at mooring 2 although currents there tend to be aligned in a north–south direction. The implication is that the cyclonic eddy described in the previous paragraph does not extend to below 2000 m and other events are associated with the reductions in the observed current at deeper depths.

When the mean currents at the current meters 13 and 14 and at mooring 2 are subtracted, the circulation patterns suggest the presence of two distinct anticyclonic eddy-like features: one during 17 July through

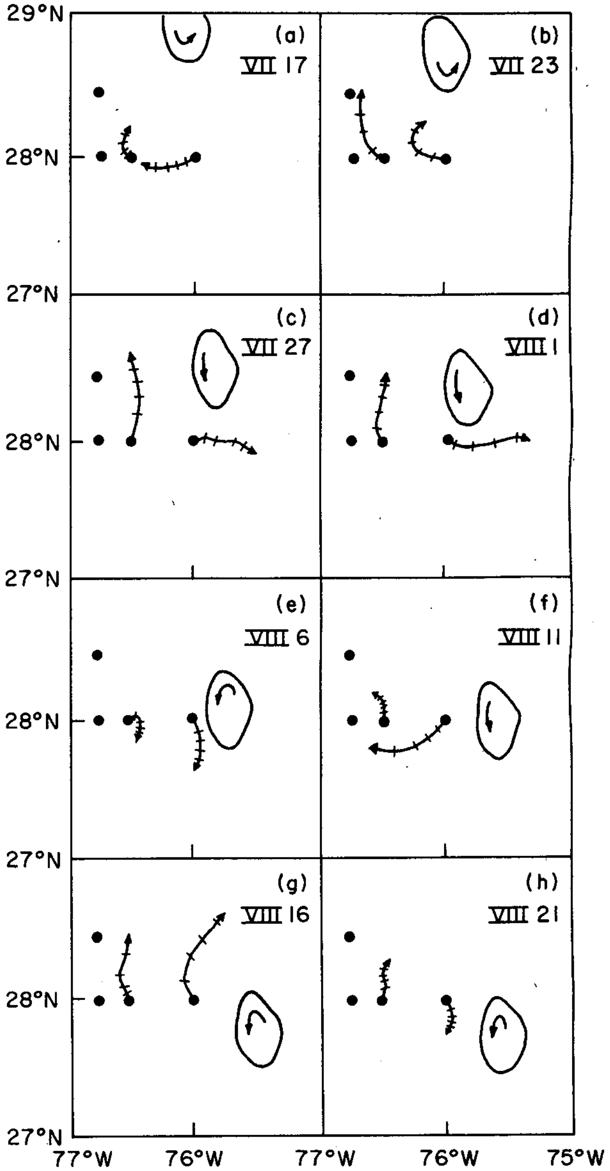

FIG. 10. Progressive-vector diagrams of current (after the means are subtracted) at 3000 m at both moorings 1 and 2. Positions of the cyclonic eddy above 2000 m are shown for comparison. The arrow inside the eddy serves as a reminder of the eddy circulation.

5 August, and the other 11–25 August (Fig. 10). During both events, the velocity is westward, turns northward and then eastward. The clockwise rotation of the velocity vectors at the two moorings fits in with the circulation of the southward-moving anticyclonic features. The observed circulation patterns suggest that the east–west dimensions of these features are larger than the purported width of 60 km for the DWBC. On account of the limited horizontal coverage, possible closed circulations of these features cannot be observed and therefore it is not certain that they are actually anticyclonic eddies. It is possible that these features are associated with meanders of the mean current. Thus the apparent large reductions in the volume transport of the DWBC along the Blake Escarpment (Fig. 7) could be an artifact due to the limited horizontal coverage of the array there.

There is no clear relationship between the cyclonic eddy found between 1000 to 2000 m and the two deeper anticyclonic features other than that they are present in the DWBC during the same time periods. A similar deep anticyclonic feature is observed during 7–17 September at mooring 1 but not at mooring 2 (Fig. 2).

It is not known when and where the eddy (or eddies) observed in this study was entrained into the DWBC. However their presence in the DWBC is consistent with the possible entrainment of the surrounding water into the DWBC, as discussed in Section 3.

5. Summary

The DWBC flows southward along the Blake Escarpment, with its core 10 km east of the break of the escarpment. The mean southward velocity at the core is 22 cm s^{-1} at 2500 m, and it decreases to 15 cm s^{-1} near the botttom and zero at 800 m depth. The width of the current is about 60 km and the mean volume transport is estimated to be 24 Sv.

There are two large fluctuations in the observed deep current which are apparently associated with two southward moving anticyclonic features. During the same period the array measurements, together with a SOFAR float, also document the passage of a cyclonic eddy in the shallower portion of the DWBC. There is no clear relationship between this cyclonic eddy and the other two deeper anticyclonic features.

Acknowledgments. SOFAR float data were kindly supplied by Dr. T. Rossby at the University of Rhode Island. I thank Dr. C. N. Chhabra at the Draper Laboratory for making the original mooring motion program available to me and helping me to use it, Dr. H. Perkins at NORDA for carrying out the experiment, Ms. Renee O'Gara for processing the SOFAR data and two anonymous reviewers for their comments which helped to improve the manuscript. This work would not be possible without the continued support and encouragement of Dr. M. Wimbush.

This research was supported by the National Science Foundation under Grant OCE 76-84617 and the Office of Naval Research Contract N00014-76-C-0026 through the Graduate School of Oceanography, University of Rhode Island. Partial support was provided by University of Rhode Island graduate research assistantships. Portions of the manuscript were prepared while I was at the Applied Physics Laboratory, University of Washington, supported by the Naval Ocean Research and Development Activity Contract N00014-82-C-0083 and Office of Naval Research Contract N00014-84-C-0111.

APPENDIX

Summary of Mooring Motion Model

Chhabra (1973, 1976) developed a model to predict the current-induced motions of a moored system. Specifications of the mooring lines and the instruments on the mooring, such as their lengths, weights in air and in water, drag coefficients, etc. are supplied as inputs. Inputs also include velocities observed by the current meters and their nominal depths from which a linearly interpolated current profile in the vertical is calculated. Other current profiles can be chosen if so desired.

The mooring line is divided into segments. Input parameters are used to calculate the various forces, such as gravitational and shear forces, acting on each instrument and mooring line segment. Integration of the equations of motion along these segments from the top of the mooring to the bottom gives dynamic equilibrium positions of the mooring system at discrete times; acceleration of the system is computed from the previous two points in time (Chhabra, 1977). Velocity of the mooring is then calculated from the predicted positions of the instruments and line segments. The absolute velocity of the current is the sum of the relative velocity (as observed by the current meters) and the computed velocity of the mooring. Hence the model produces a time series of the absolute velocity profile of the horizontal current.

Chhabra's model has been tested successfully in MODE, a weak current regime (<10 cm s^{-1}) (Chhabra, 1977). Modifications must be made for the model to be applicable in regions with strong currents such as along the Blake Escarpment.

In the presence of strong currents, instruments undergo large vertical excursions. Their actual depths are very different from their designated depths. Input velocity profiles calculated from the designated depths of the current meters differ substantially from the actual profiles. With erroneous input profiles, the model will give erroneous predicted positions. This problem is remedied by allowing for several iterations at each point in time. At each iteration, the velocity profile obtained from the predicted depths of the current meters in the previous iteration is used. The result converges rapidly (in less than 10 iterations at each time) to the final solution.

Vertical excursions of instruments are due to the tilting of the mooring line as a result of horizontal displacements of instruments and lines away from the vertical. Although floats are deployed just above the current meters, large tilting of the mooring line can cause substantial tilts of the current meters, and hence the rotors, with the vertical. This leads to an underestimate of the horizontal current. A response function relating the observed to the actual currents at different angles of tilt for vector-averaging current meters is used to correct this (Kalvaitis, 1974).

With these modifications, the model gives reasonable results (see Section 2) for the study of the mean flow along the Blake Escarpment. The major weakness of the model is due to the sparse spacing of the current meters. There are only four meters along the 4.5 km length of mooring 2. The spacing is not adequate to resolve the actual profile of the mean flow, thus giving rise to erroneous predicted depths.

REFERENCES

Amos, A. F., A. L. Gordon and E. D. Schneider, 1971: Water masses and circulation patterns in the region of the Blake-Bahama Outer Ridge. *Deep-Sea Res.*, **18**, 145–165.

Cheney, R. E., W. H. Gemmill, M. K. Shank, P. L. Richardson and D. Webb, 1976: Tracking a Gulf Stream ring with SOFAR floats. *J. Phys. Oceanogr.*, **6**, 741–749.

Chhabra, N. K., 1973: *Mooring Mechanics—A Comprehensive Computer Study.* Vol. 1, C. S. Draper Laboratory Rep R-775, 130 pp.

——, 1976: *Mooring Mechanics—A Comprehensive Computer Study.* Vol. 2, C. S. Draper Laboratory Rep R-1066, 277 pp.

——, 1977: Correction of vector-averaging current meter records from the MODE-1 central mooring for the effects of low-frequency mooring line motion. *Deep-Sea Res.*, **24**, 279–287.

Fofonoff, N. P., 1981: The Gulf Stream system. *Evolution of Physical Oceanography,* B. A. Warren and C. Wunsch, Eds., MIT Press, 112–139.

Fuglister, F. C., and L. V. Worthington, 1951: Some results of a multiple ship survey of the Gulf Stream. *Tellus,* **3,** 1–14.

Hansen, D. V., 1970: Gulf Stream meanders between Cape Hatteras and the Grand Banks. *Deep-Sea Res.*, **17,** 495–511.

Heezen, B. C., C. D. Hollister and W. F. Ruddiman, 1966: Shaping of the continental rise by deep geostrophic contour currents. *Science,* **152,** 502–508.

Hogg, N. G., 1983. A note on the deep circulation of the western North Atlantic: Its nature and causes. *Deep-Sea Res.*, **30,** 945–961.

Jenkins, W. J., and P. B. Rhines, 1980: Tritium in the deep North Atlantic Ocean. *Nature,* **286(577b),** 877–880.

Kalvaitis, A. N., 1974: Effects of vertical motion on vector-averaging (Savonius rotor) and electromagnetic type current meters. NOAA Tech. Memo. NOAA-TM-NOS-NOIC-3, 121 pp.

Mills, C. A., and P. Rhines, 1979: The deep western boundary current at the Blake-Bahama Outer Ridge: Current meter and temperature observations, 1977–78. Woods Hole Oceanographic Institution Tech. Rep. No. 79–85, 77 pp.

Perkins, H., and M. Wimbush, 1976: A cyclonic mini-eddy near the Blake Escarpment. *Geophys. Res. Letters,* **3,** 625–628.

Richardson, M. J., M. Wimbush and L. Mayer, 1981: Exceptionally strong near-bottom flows on the continental rise of Nova Scotia. *Science,* **213,** 887–888.

Richardson, P. L., 1977: On the crossover between the Gulf Stream and the Western Boundary Undercurrent. *Deep-Sea Res.*, **24,** 139–159.

Riser, S. C., H. Freeland and H. T. Rossby, 1978: Mesoscale motions near the deep western boundary of the North Atlantic. *Deep-Sea Res.*, **25,** 1179–1191.

Rossby, H. T., and D. Halkin, 1982: The Pegasus Program east of Cape Hatteras. *Proc. Workshop on Gulf Stream Structure and Variability,* Off. Nav. Res. (U.S.), 302–308.

Stommel, H. M., 1958: The abyssal circulation. *Deep-Sea Res.*, **5,** 80–82.

Swallow, J. C., and L. V. Worthington, 1961: An observation of a deep counter-current in the western North Atlantic. *Deep-Sea Res.*, **8,** 1–19.

Worthington, L. V., 1976: On the North Atlantic circulation. *Johns Hopkins Oceanographic Studies,* No. 6, Johns Hopkins University Press, 110 pp.