Deep-Sea Research, 1977, Vol. 24, pp. 139 to 159. Pergamon Press. Printed in Great Britain

On the crossover between the Gulf Stream and the Western Boundary Undercurrent*

PHILIP L. RICHARDSON†

(*Received* 20 *April* 1975; *in revised form* 21 *June* 1976; *accepted* 10 *July* 1976)

Abstract—To determine how the Gulf Stream and Western Boundary Undercurrent cross each other near Cape Hatteras, six current meters were moored from May to July 1971 along a line normal to the Gulf Stream axis and 100 m above the ocean floor in depths from 1200 to 4200 m. Peak velocities of the six records (including one of 47 cm s^{-1}) and the mean velocities of four of the deepest records (2800 to 4000 m) were in the southwest quadrant. During the observations the Gulf Stream did not extend to the bottom in this area except in brief current reversals to the northeast. The Western Boundary Undercurrent flowed southwest under the Gulf Stream parallel to the bottom contours. The transport of the undercurrent, estimated using two geostrophic velocity sections and deep current meter observations, was 24×10^6 m^3 s^{-1}.

INTRODUCTION

CAPE HATTERAS marks an important location in the North Atlantic circulation. Here the Gulf Stream flows from the Blake Plateau over the continental slope and rise into the deep North Atlantic. Here the Gulf Stream passes over the deep southward-flowing Western Boundary Undercurrent (WBUC). A fundamental problem exists: How do the two currents cross each other? The simplest explanation is that the WBUC flows obliquely under the stream, as suggested by BARRETT (1965). There is evidence, however, that at times the Gulf Stream extends to the sea floor and splits the WBUC (RICHARDSON and KNAUSS, 1971). The highly variable character of the stream and deep currents suggests that these two sets of short time series were inadequate to describe the mean currents in the crossover region and that a longer time series is needed.

Recently measurements have documented the existence of the WBUC as a continuous current flowing south along the continental slope and rise in depths of 1000 to 4000 m. The origin of the WBUC is in the Norwegian and Labrador seas where the cold deep water of the North Atlantic is formed (WRIGHT and WORTHINGTON, 1970; WRIGHT, 1973). The WBUC has been traced by its distinctive oxygen and salinity content to Cape Hatteras (BARRETT, 1965). Direct current measurements in this current suggest a mean speed of 10 cm s^{-1} (LUYTEN, 1977). There is evidence that the WBUC has been active for at least the last 3×10^5 years (NEEDHAM, HABIB and HEEZEN, 1969).

Also recently two important aspects of the Gulf Stream have been revealed by long time series of current meter measurements. The first is that in the deep water off New England the stream extends to about 2000 m as a coherent unidirectional flow (LUYTEN, 1977). Large velocity fluctuations have been observed under the stream with a speed amplitude of 40 cm s^{-1} and a time scale of 30 days, and the velocities appear to be polarized in the

* Contribution No. 3525 from the Woods Hole Oceanographic Institution.
† Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, U.S.A.

north–south direction (SCHMITZ, ROBINSON and FUGLISTER, 1970). One interpretation of the current measurements is the presence of quasi-stationary bottom intensified eddies (or waves) under the Gulf Stream (LUYTEN, 1977). The recent measurements contrast strongly with earlier short time series using neutrally buoyant floats. The float velocities were combined with geostrophic velocity calculations and implied that the stream penetrated coherently to the sea floor (FUGLISTER, 1963; WARREN and VOLKMANN, 1968).

The second aspect is that along 70°W a large component of the long-term deep mean flow under the stream is in the same direction as the long-term mean surface current (Schmitz, personal communication). Thus there is some evidence that on the average the stream does extend to the sea floor. There has been a suggestion from model studies that the deep mean flow under the stream is driven by the deep fluctuations and therefore the fluctuations are an integral part of the mean (HOLLAND and LIN, 1975).

If on the average the Gulf Stream extends to the bottom along its path, near Cape Hatteras it must encounter the WBUC, which flows to the southwest. To investigate the crossover between the two currents an experiment was conducted using eight deep moored current meters under the stream off Cape Hatteras. Six months of measurements were planned but a high loss rate of meters resulted in 3 months of records.

OBSERVATION PROGRAM

Current meters were placed along a baseline bearing 135° running southeast from Cape Hatteras and normal to the mean axis of the Gulf Stream. They were 100 m above the ocean floor under the Gulf Stream and along the continental slope and rise in depths of 1265 to 4145 m (Table 1). Six records were obtained from 8 May to 23 July 1971. The current meters used have been described by RICHARDSON, STIMSON and WILKINS (1963); they were manufactured by Geodyne Corporation and the data are recorded on photographic film.

Table 1. Current meter locations, depths, and mooring dates. The first letter of the current meter designation is used throughout the text to refer to the individual meters. The number in parentheses is the record number used by the Graduate School of Oceanography, University of Rhode Island, where the data are on file.

Current Meter Designation	Position		Depth (m)	Date (1971)		Record Length (Days)
	Latitude	Longitude		Moored	Recovered	
A (84)	35°05' N	75°02' W	1265	8 May	26 May	17.9
B (93)	34°59' N	74°59' W	2575	30 May	23 July	53.6
C (86)	34°51' N	74°49' W	2810	8 May	26 May	5.4
D (88)	34°32' N	74°30' W	3220	9 May	27 May	17.6
E (94)	34°17' N	74°13' W	3720	31 May	22 July	28.3
F (90)	34°06' N	74°01' W	4145	9 May	31 May	22.0

During May 1971 on R.V. *Trident* the location and direction of the Gulf Stream were determined using expendable bathythermographs (XBT) and GEK. Two hydrographic sections were occupied across the stream. Salinity was measured on a Beckman Salinometer, reactive silicate was determined by the method of FANNING and PILSON (1973), and station positions were determined by satellite navigator. A more complete discussion of the measurements is given by RICHARDSON (1974).

Suspended particles were measured and bottom photographs were also made along the baseline (BETZER, RICHARDSON and ZIMMERMAN, 1974).

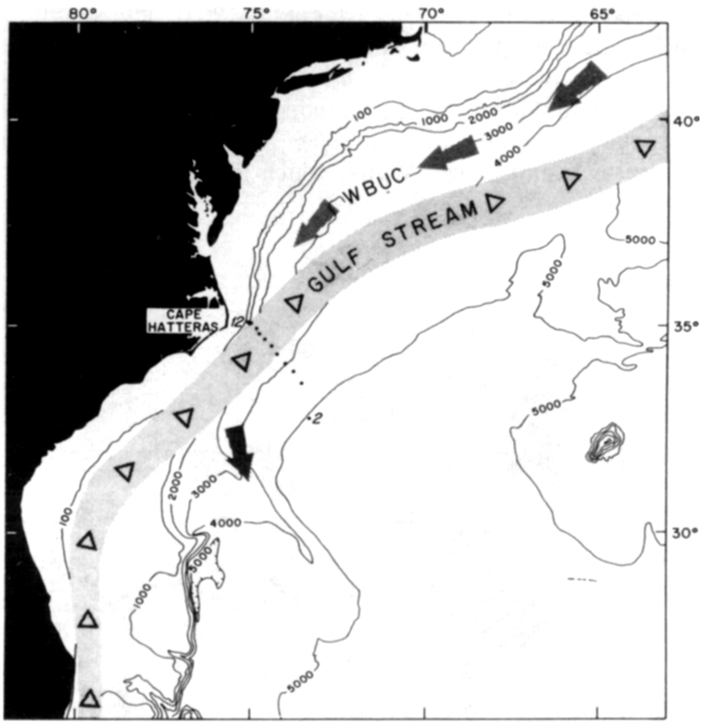

Fig. 1. Gulf Stream and Western Boundary Undercurrent meeting near Cape Hatteras. Hydrographic station locations are indicated by closed circles.

HYDROGRAPHIC SECTIONS

Two hydrographic sections were occupied along the baseline and over the line of current meters. The temperature, salinity, and silicate profiles from the first and most complete section (Figs. 2 to 4) are dominated by large horizontal gradients through the Gulf Stream and a Gulf Stream ring. The ring is apparent on the offshore side of the section by the doming of isopleths. The warm core of the stream, centered between Stas. 7 and 9, is conspicuous by the anomalously cooler water located in the ring.

A pronounced salinity minimum and silicate maximum, most noticeable between Stas. 7 to 10, are in the temperature interval 7 to 10°. The minimum salinity is 34.956‰ and the maximum silicate is 21.4 μg atoms l^{-1}; they are both characteristic of Antarctic Intermediate Water (MANN, COOTE and GARNER, 1973; WRIGHT and WORTHINGTON, 1970). ISELIN (1936) traced the spread of water with this salinity minimum from the South Atlantic through the Caribbean and Straits of Florida to Cape Hatteras. It appears that the silicate maximum can be traced in the Gulf Stream at least as far as the Newfoundland Banks where a maximum of 15.7 μg atoms l^{-1} at 8°C has been found (GRANT, 1968).

A second salinity minimum is centered near 1000 m adjacent to the continental slope in the region where the 35.96 and 35.98‰ isohalines spread apart next to the slope (Fig. 3). This minimum suggests the presence of Labrador Basin Water, which is less saline than North American Basin Water from below 4 to about 6° (Wright and WORTHINGTON, 1970) and which has been traced to Cape Hatteras (BARRETT, 1965). The second section (Fig. 5) indicates that the Labrador Basin Water was occupying nearly twice its area on Section 1 and that it penetrated as a relatively thin layer all the way through the stream immediately under the Antarctic Intermediate Water and also extended to the bottom near current meter B.

The broad minimum in silicate with values of 12 µg atoms l^{-1} and centered at 4° is associated with North Atlantic Deep Water, which is composed of various amounts of

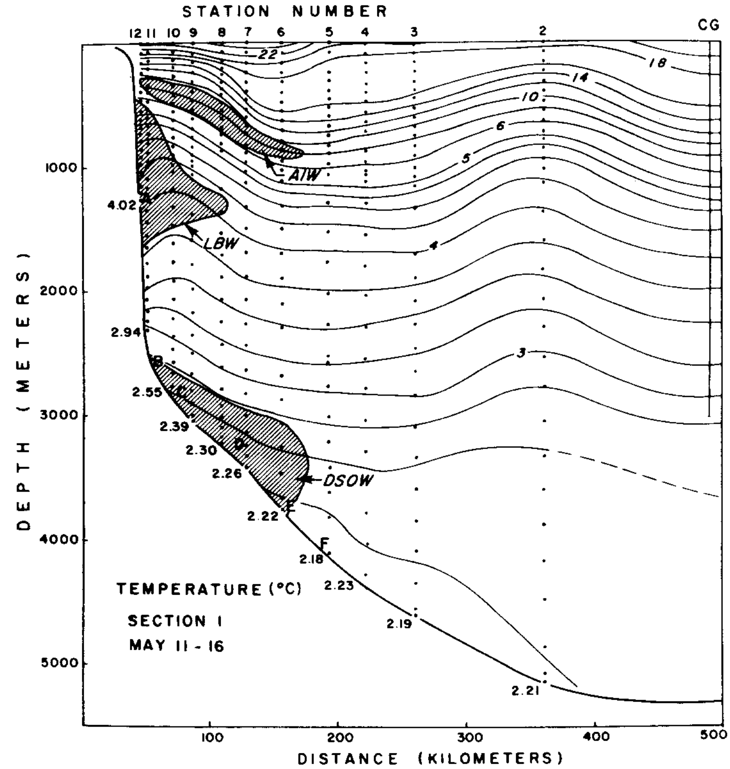

Fig. 2. Temperature Section 1. An STD station taken by the U.S. Coast Guard (CG) on 13 May 1971 offshore of the ring is included. The anomalous regions corresponding to Antarctic Intermediate Water (−0.050‰ in salinity), Labrador Basin Water (−0.010‰ salinity) and Denmark Strait Overflow Water (−3 µg atoms l^{-1} in silicate) are shown by shading. Current meter locations are indicated by letters A through F.

Norwegian Sea, Labrador Sea, and Mediterranean Sea Water—all of which have a low silicate content (MANN, COOTE and GARNER, 1973). A second silicate minimum is found in depths of 2500 to 3000 m on the continental slope side of the section. This deeper minimum consists of silicate values down to 18.6 to 18.8 µg atoms l^{-1} in the potential temperature range 2.45 to 2.65° and marks the top of an anomalously silicate-poor water mass. It is interpreted to be the remnants of the silicate-poor Denmark Strait Overflow Water (DSOW). An atlas by GRANT (1968) clearly shows the southward spread of DSOW through its low silicate and high oxygen content. At a section between Newfoundland and the Azores the silicate minimum associated with the DSOW has increased to about 17 to 18 μg atoms l^{-1} and the presence of the minimum is associated with a dramatic spreading of the 15 to 20 μg atoms l^{-1} contours next to the continental slope at depths between 2500 and 4500 m. METCALF (1969) has given evidence for the southward movement of the silicate-poor water along the western margin of the North Atlantic.

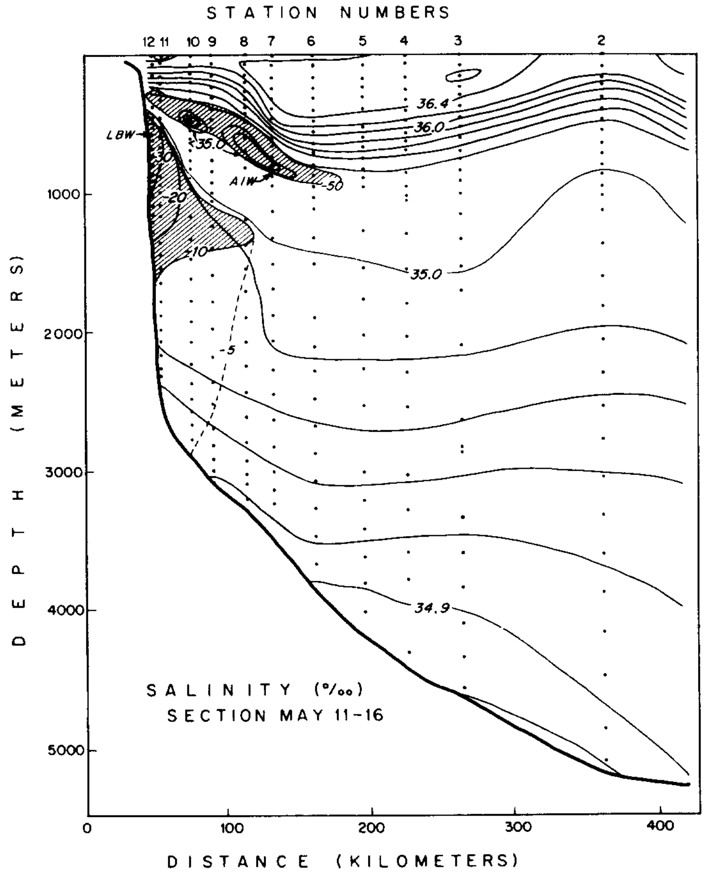

Fig. 3. Salinity section. Shaded areas denote the core of the anomalously fresh (−0.010‰) Labrador Basin Water and (−0.050‰) Antarctic Intermediate Water. The anomaly was computed using the mean θ–S of the western North Atlantic (ISELIN, 1936; WORTHINGTON and METCALF, 1961).

The deep isotherms slope down in an offshore direction to Sta. 2. They indicate a core of cold water that hugs the bottom between 4000 and 5000 m. The deep water is characterized by silicate values increasing toward the bottom, indicating the presence of silicate-rich Antarctic Bottom Water. The northward spread of this high silicate water has been discussed by METCALF (1969) and MANN, COOTE and GARNER (1973).

CURRENT METER MEASUREMENTS

The current meter locations and velocities are shown in Fig. 6. The records indicated predominant strong flow to the southwest under the Gulf Stream. The flow in this direction is indicated by the highest instantaneous velocities and by the mean velocities. All the records had their peak instantaneous velocity in the southwest direction (Table 2). The peak speeds (unfiltered) ranged from 16 to 47 cm s^{-1}. The highest speeds of 44 and 47 cm s^{-1} from meters B and C were recorded in depths of 2575 and 2810 m under the mean axis of the Gulf Stream,

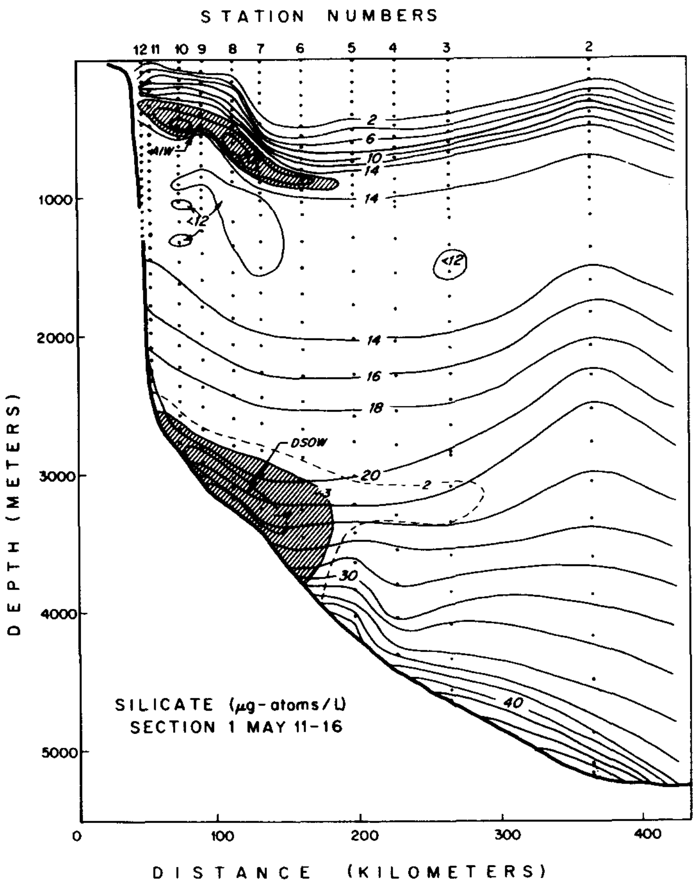

Fig. 4. Silicate section. Shaded area indicates the core of the anomalously low silicate (−3 μg atoms l^{-1}) Denmark Strait Overflow Water and anomalously high silicate Antarctic Intermediate Water (+2 μg atoms l^{-1}). The anomaly was computed from the θ-silicate relation measured on the offshore end of the section.

near the junction of the continental slope and rise.* The high speeds of meters B and C can be seen on Fig. 7, which shows the distribution of speed and direction measurements recorded over 1 min.

The progressive vector diagrams for these records (Fig. 8) can be divided into two different sets (B, C, D, F, and A, E). The mean vectors of meters B, C, D, and F indicate a strong flow to the southwest. Little variation from the mean velocity was recorded by these meters; when

* Meters B and C coincide with the silicate minimum indicative of DSOW.

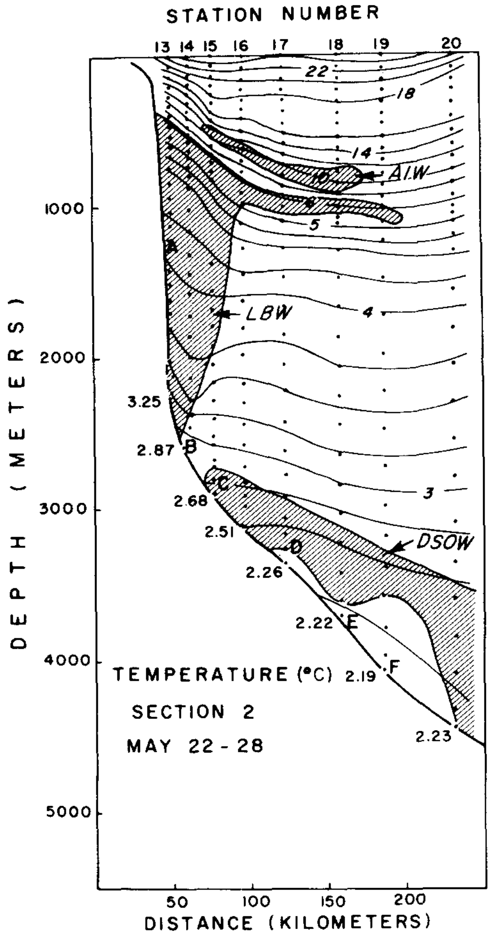

Fig. 5. Temperature Section 2. Limits of water masses are the same as those given in Figs. 2 to 4.

Table 2. Current meter data summary. The accuracy of the depth of the meters is estimated to be ± 50 m except for meter A, which could have an error as large as 100 to 200 m (see text). The speed and direction of the 'highest velocity' observations were recorded over 1 min. The quantities in parentheses are the root mean square fluctuations about the mean speed.

Current Meter	Meter Depth (m)	Record Length (Days)	Highest Velocity		Average Velocity		Average Speed Relative to Axes Rotated 45° Clockwise	
			Speed (cm/sec)	Direction (°T)	Speed (cm/sec)	Direction (°T)	045° Component Speed (cm/sec)	135° Component Speed (cm/sec)
A	1265	17.9	15	257	0.3	026	+ 0.2(± 1.2)	-0.1(±2.2)
B	2575	53.6	47	230	10.9	228	-10.8(±11.0)	-0.6(±3.2)
C	2810	5.4	44	267	12.6	266	- 9.5(± 4.7)	-8.3(±3.5)
D	3220	17.6	23	255	6.8	228	- 6.8(± 3.6)	-0.4(±3.0)
E	3720	28.3	26	250	0.8	169	- 0.4(± 6.6)	+0.6(±7.3)
F	4145	22.0	16	254	9.1	253	- 8.0(± 2.6)	-4.3(±2.2)

viewed together they show a remarkable consistency in motion. Record B does exhibit two brief current reversals of a few days each in which currents flow towards the northeast, but these are small compared to the strong southwestward flow over most of the record. The magnitudes of these average vectors range from 7 to 13 cm s^{-1} and clearly indicate the strong average flow. One of the largest of these magnitudes, 10.9 cm s^{-1}, was calculated from the longest record, 53.6 days.

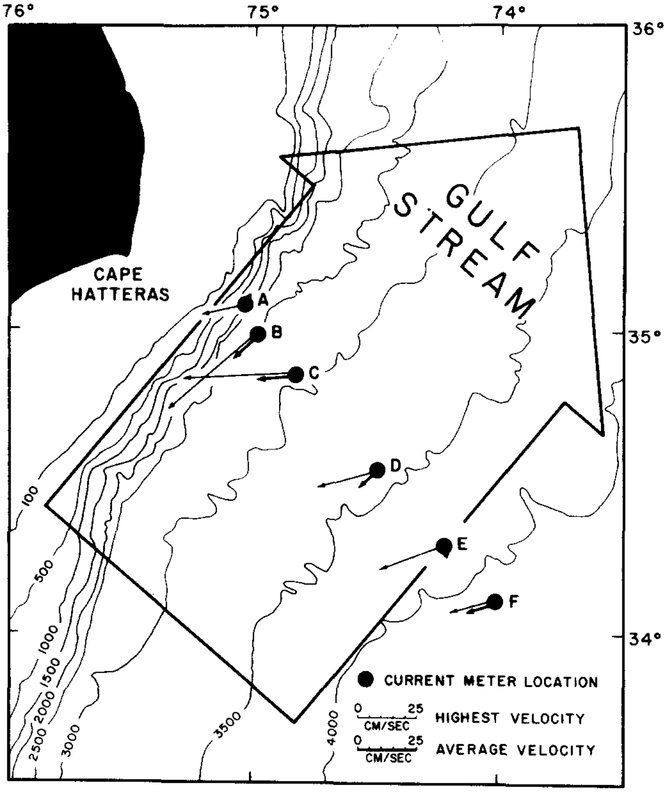

Fig. 6. Current meter locations and velocities. The highest velocity is recorded over a 1-min period and the average velocity is a vector mean over the length of each record. The approximate mean position and direction of the Gulf Stream shown are based on observations in May 1971. Bottom contours are based on the bathymetry given by NEWTON and PILKEY (1969).

In comparison to these four time series the records from meters A and E appear to be distinctly different. They indicate a very low average velocity, less than 1 cm s^{-1}, but such large fluctuations that the calculated 'mean velocity' is not significant when used in the traditional context of 'mean flow'.

A possible explanation for this difference for record A is the bathymetry. An attempt was made to place the meter on the slope near a depth of 1500 m. The mooring was dropped as the ship drifted in the Gulf Stream into progressively deeper water. A few minutes after the release the echo sounder measured an irregular bottom profile with a decrease in the depth. The depth profiles can be interpreted as several channels running down the slope, and it is

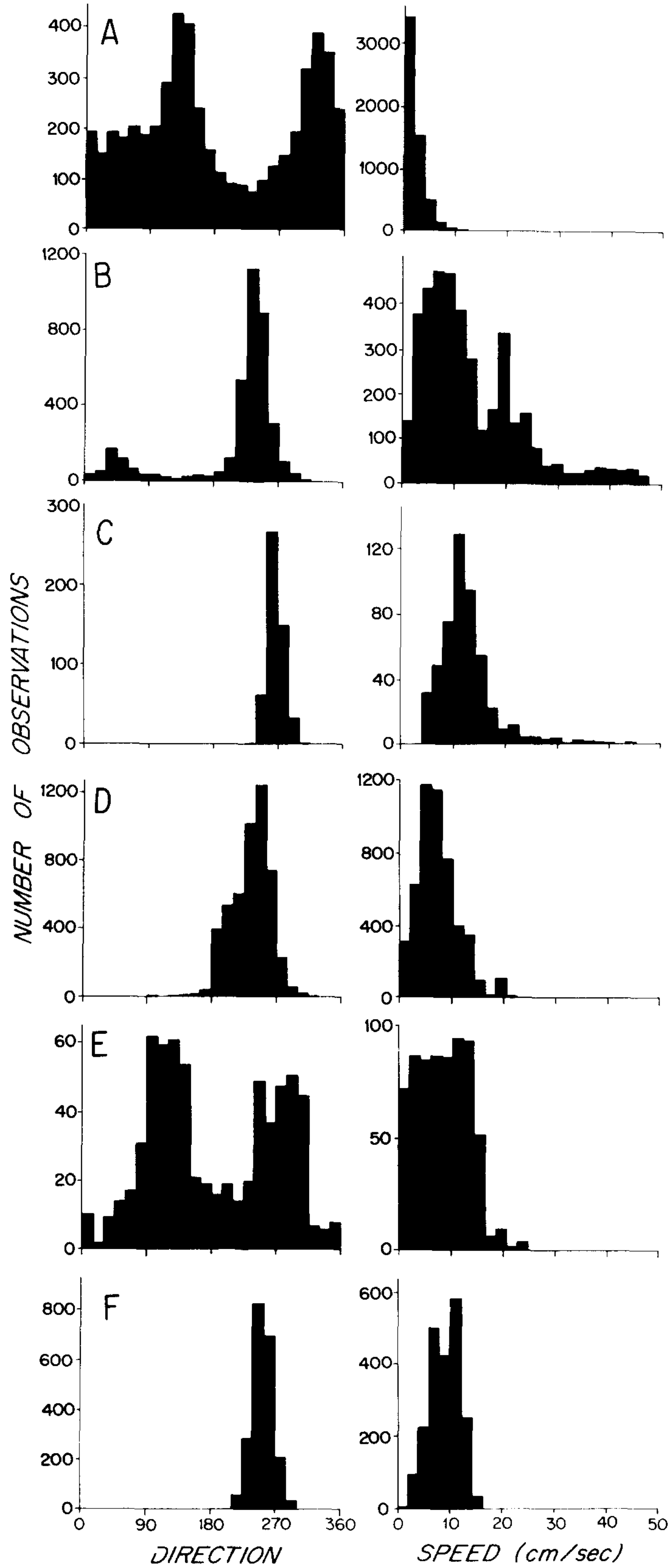

Fig. 7. Distribution of speed and direction recorded by each current meter. Values represent 1-min averages.

suggested that meter A may have been in or near such a channel. This explanation would account for the low speed and predominant northwest and southwest flow (Fig. 8), which is normal to the regional bottom contours and may represent flow up and down a deep sea channel. The few high instantaneous speeds toward the southwest of 15 cm s^{-1} and the average vector toward the northeast suggest, however, that the meter was at certain times

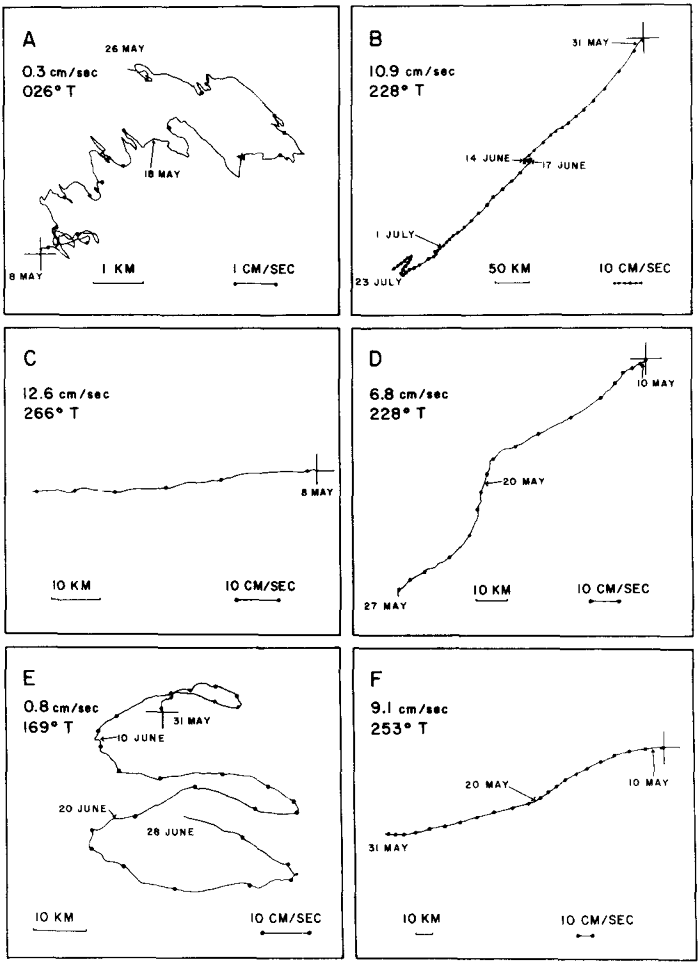

Fig. 8. Progressive vector diagrams. Each dot denotes 1 day. The spacing between dots indicates the average speed over 1 day. A reference value of speed and displacement is given for each diagram. The magnitude and direction of the mean vector is shown in the upper left corner of each diagram.

recording flow in the direction of the WBUC and the Gulf Stream. Another possible explanation is that meter A was near the boundary between the Gulf Stream and WBUC. This would account for the low average velocity but it leaves open the question of the up- and down-slope motion. Perhaps both explanations are partially correct.

There was no irregular bottom topography as seen near meter A at the locations of the other five meters. Moorings were located according to the bathymetric charts of NEWTON and PILKEY (1969) and RONA, SCHNEIDER and HEEZEN (1967) to keep the meters away from channels. As no bathymetric surveys were undertaken at the mooring sites, it is possible that a locally irregular bottom affected the flow past meter E. A puzzling aspect of record E is its low average velocity, because records D and F, taken within 24 miles on opposite sides of it, recorded strong southwest flow. Record E was made after D and F, however, so the difference could be one of either time or location. Other interpretations of the anomalous quality of

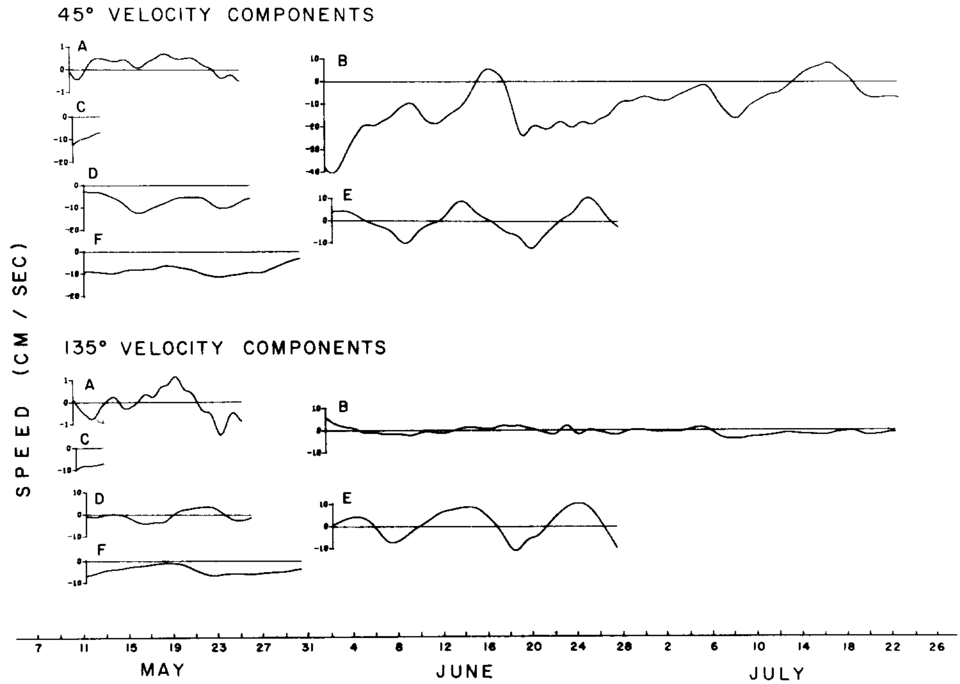

Fig. 9. Velocity components. The axes have been rotated 45° clockwise to align them with the mean direction of the Gulf Stream and deep southwestward flow. The curves represent values low-pass filtered by a running 72-h Gaussian weighted mean. The frequency response of the filter is about 1% for frequencies of 1 xycle day^{-1} (HOLLOWAY, 1958).

record E are that the WBUC is divided into high and low average velocity regions, or that the variability at periods of 10 days, typical of other locations on the rise (LUYTEN, 1977), was dominant.

The Cartesian velocity components as a function of time are shown on Fig. 9. The records suggest that the largest fluctuations have a period of from 1 to 2 weeks although the longest record, B, appears to have fluctuations commensurate with its length. The average speeds to the southwest (Table 2) range from 7 to 11 cm s^{-1} for records B, C, D, and F but the root mean square fluctuations about the mean are nearly as large, suggesting little statistical significance to the mean velocities.

Record B was separated into its different scales of motion (Fig. 10). The average flow in the southwest direction is 10.8 cm s^{-1} and in the southeast direction 0.6 cm s^{-1}. The lowest frequency seen is given by the linear trend, representing fluctuations on the order of months. The intermediate frequencies are dominated by fluctuations with a time scale of a few weeks.

The root mean square amplitude of the fluctuations about the linear trend for the filtered record is 8 cm s^{-1}. The higher frequency part of the record has a root mean square amplitude of 3 cm s^{-1}. Ninety-two per cent of the fluctuation kinetic energy is associated with frequencies of less than 1 cycle day^{-1} and 92% of the energy is in the 45° components.

An interesting aspect of curve (a) in Fig. 10 is that the shape suggests that pulses of water

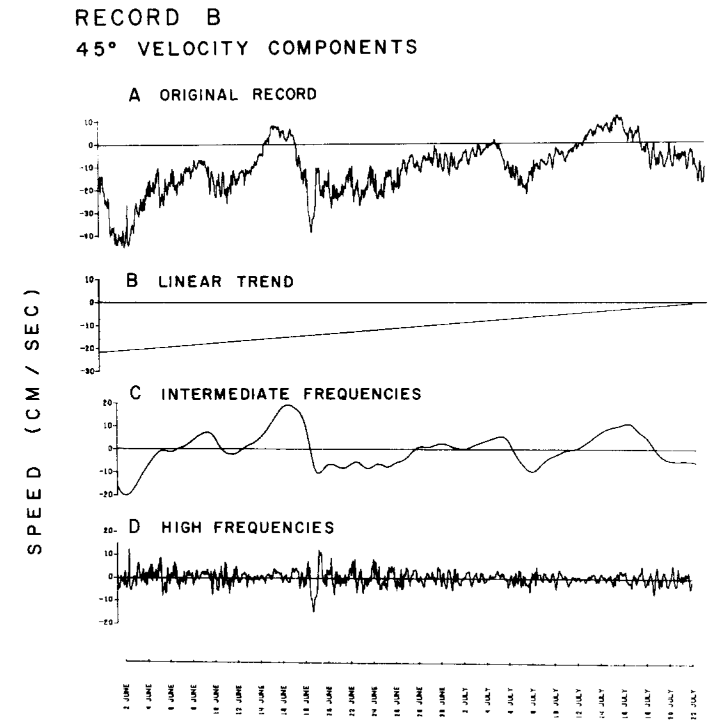

Fig. 10. Velocity components (45°) of Record B. A. Original record. B. Linear trend. The curve is the least squares best fit linear trend through the data. C. Intermediate frequencies. The curve represents the record after it was Gaussian filtered and the linear trend was subtracted from it. D. High frequencies. The curve represents the signal filtered from the original record and is composed chiefly of frequencies greater than about 0.4 cycles day^{-1}, the 50% response frequency of the filter.

periodically flow towards the southwest under the stream. The pulses are characterized by a quick increase of southwesterly speed followed by a slower decrease of speed. The unfiltered signal of record C displays a similar picture of the deep currents. One of these pulses occurred on June 18 and was accompanied by a large peak in the southwesterly speeds. Fluctuations with a period of about 2 days can be seen on curve (c) following this pulse for nearly 2 weeks.

GEOSTROPHIC VELOCITY SECTION

The hydrographic data were used to calculate vertical profiles of velocity using the geostrophic relation. The contoured velocity section is shown in Fig. 11 and the transport in Fig. 12.

The current meter data were used to determine the bottom velocities of the geostrophic profiles. There were too few data to determine accurately the cross-stream variation of bottom velocity; therefore the 45° average bottom velocity during each section was used. The average velocities of 8.9 and 9.2 cm s^{-1} towards the southwest for Sections 1 and 2 were obtained as follows: a 72-h Gaussian mean of 45° velocity components was calculated for each record centered at the time the nearest hydrographic station was occupied. On each

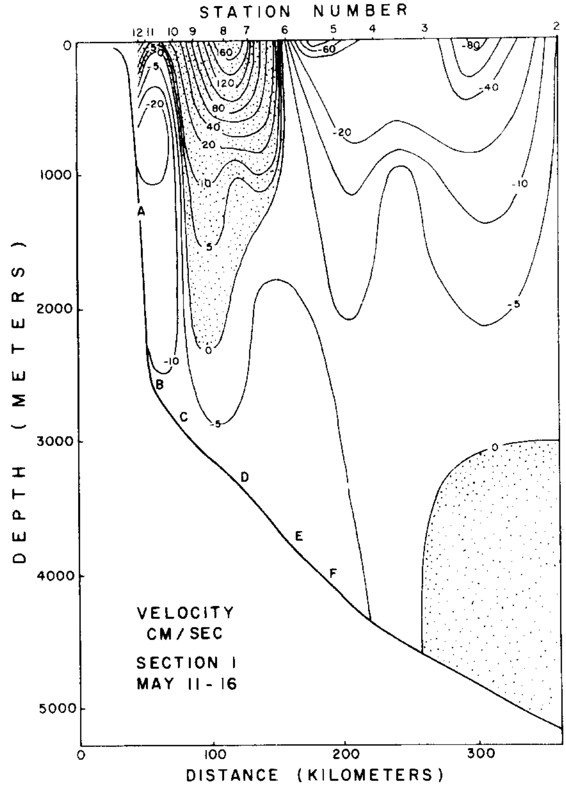

Fig. 11. Contoured velocity section. Stippled areas represent northeastward velocities.

section the individual 45° mean velocity components were averaged and applied to the geostrophic velocity profiles. The values are given in Table 3.* The value from record C is the average of the entire 5.4-day record. This record was short, discontinuous, and may or may not include the time the stations were occupied, therefore the average is considered the best estimate of the velocity. The value of 9.5 cm s^{-1} seems reasonable, however, in that a second meter, B, was placed within 20 km of C and recorded an average speed of 10.8 cm s^{-1} toward 225° over a 53.6-day period. The low velocities from A were not used to calculate the average for each section as there is some question whether this meter was in a channel. Because strong currents next to the slope and near meter A are indicated by the geostrophic velocity profiles

* When the median time of each section was used to calculate the velocities (meters D and F) the average velocities for each section agreed within 1 cm s^{-1} with those obtained by the above technique.

it would appear that meter A was indeed recording anomalously low velocities and should not be included. (If the values from A *are* included, the means for each section, based on the four records, are decreased by about 2 cm s^{-1}.) Record E remains a problem: although it was made after the hydrostations were completed and therefore was not used to calculate the average bottom velocity across the section, it did indicate a low average velocity (0.8 cm s^{-1}). Record E does not agree with records D and F made earlier but near E; the disagreement casts some doubt on the validity of using records D and F to calculate the bottom velocity. Offshore of the direct velocity measurements (Sta. 4 on Section 1) the velocity profiles were arbitrarily assumed to have zero velocity at the bottom.

Table 3. Velocity normal to the hydrographic sections. The values represent a 72-h Gaussian weighted average of the 45° velocity components except for C, which represents an average over its entire 5.4-day record; a plus indicates flow towards 45°. The values in parentheses indicate the range of the average velocity components during each section. Meter C was not recording during Section 2 so the value measured during Section 1 was used to calculate the average for Section 2.

Current Meter	Section One (cm/sèc)		Section Two (cm/sec)	
A	(+0.6)	(+0.7 to - 0.2)	(0.0)	(0.0 to - 0.7)
C	-9.5	(-6.9 to -12.4)	-9.5	
D	-7.7	(-2.7 to -12.5)	-8.2	(-5.9 to -10.5)
F	-9.6	(-8.0 to - 9.9)	-9.8	(-7.0 to -11.4)
Average (excluding A)	-8.9		-9.2	

As the sea floor slopes across the section it was necessary to extrapolate the geostrophic velocity profiles between station pairs to the depth of the current meters (100 m above the bottom). On the average the profiles were calculated within 200 m of this depth. Because the near-bottom velocity shear was generally small the corrections to the profiles were also small and generally less than 1 cm s^{-1}.

There was considerable movement of the stream while Section 1 was occupied. As the stations were made toward shore the axis of the stream moved offshore about 50 km and its direction changed 30°. This caused the stream to appear narrower and more intense than it really was. As the observations did completely transect the stream the transport should be less affected. The curvature of the stream path (radius about 50 km at Section 1) implies that the estimated velocities are somewhat in error because of omission of the centripetal acceleration.

On account of the several possible sources of errors it is difficult to know in what detail these figures describe real features. The coarse features are probably correct, especially those in which the two sections agree. The Gulf Stream is bounded by strong southward flow underneath and on both sides, and the southward flow appears to consist of three major subdivisions—the WBUC, the ring, and the countercurrent.

The Gulf Stream itself appears narrow and is confined primarily between Stas. 6 and 10, a distance of 85 km. It reaches coherently to within about 800 m of the bottom.

The WBUC is interpreted to consist of the southward flow adjacent to the continental slope that extends offshore under the stream. It is partially split by the stream. Its inshore part lies against the steep slope and consists of a jet-like feature that has a maximum southward flow of 24 cm s^{-1}* near 700 m and extends from near surface to about 2500 m. It can be seen between Stas. 10 and 12, above current meter B.† This flow is associated with the isotherms that dip down toward the continental slope between 1000 and 2000 m (Fig. 2). The jet also appears on Section 2 (not shown) extending from 800 to 2800 m with a maximum in the southward flow of 19 cm s^{-1} near 1600 m.

A point of interest about the jet is that it coincides with water mass properties characteristic of water originating to the north—the Labrador Sea Water indicated by the salinity minimum and the remnants of the Denmark Strait Overflow Water indicated by the silicate minimum. Another point is that the jet appears to extend down towards the bottom where meters B and C were located, because these recorded the highest southwards speeds, 47 and 44 cm s^{-1}. Unfortunately, neither meter was recording while the hydrographic sections were being occupied. A possible explanation for these pulsations of high southward speeds is that the jet periodically passed by the current meters. If so, the flow in the jet may occasionally be significantly larger than shown on the geostrophic velocity sections. The jet does not appear to extend offshore as far as meter D on the hydrographic sections, and D did not show such large speed fluctuations as meters B and C.

The appearance of the jet-like structure in the southward flow on the geostrophic velocity profiles for both sections suggests that it was a real phenomenon during these measurements. RICHARDSON and KNAUSS (1971), using free falling transport floats, also found strong flow to the southwest near the same depth and place. Other evidence for the high speed region and the jet was given by BARRETT (1965).

The jet is seen on the temperature sections as isotherms dipping down toward shore. A similar structure has been observed in other studies both north of Hatteras to the left of the stream and south of Hatteras to its right (FUGLISTER, 1960, 1963; AMOS, GORDON and SCHNEIDER, 1971). The jet may be, therefore, a semipermanent feature that is associated with the WBUC and extends along a large part of the western basin of the North Atlantic Ocean.

The WBUC extends offshore near the bottom to at least Sta. 5, where current meter F recorded strong southward flow. The deep horizontal temperature gradients all the way across the section imply deep velocity gradients and may indicate that the WBUC extends all the way to Sta. 2.

Offshore of the stream and concentrated at the surface are two intense southward flows. These are associated with the ring and the Gulf Stream countercurrent, which coincides with the right edge of the stream's warm core. The isotherms in the ring (Fig. 2) slope under the countercurrent, implying that the high speed flow between Stas. 5 and 6 is comprised of both the countercurrent and the ring and that the two currents cannot be separated into distinct entities. The movement and decay of the ring has been described by CHENEY and RICHARDSON (1976).

VOLUME TRANSPORT

The volume transport of the different currents was estimated from the geostrophic velocity sections (Fig. 11), and, for comparison, by assuming zero velocity at the bottom (Table 4). The transport of the Gulf Stream for the two sections was 49 and 47 × 10^6 m^3 s^{-1}. As the stream was bounded by southward flow its limits were clearly apparent. The most striking

* Approximately half of this value was obtained by using the average bottom velocity calculated from current meter data.

† Current meter B was not moored during the two hydrographic sections.

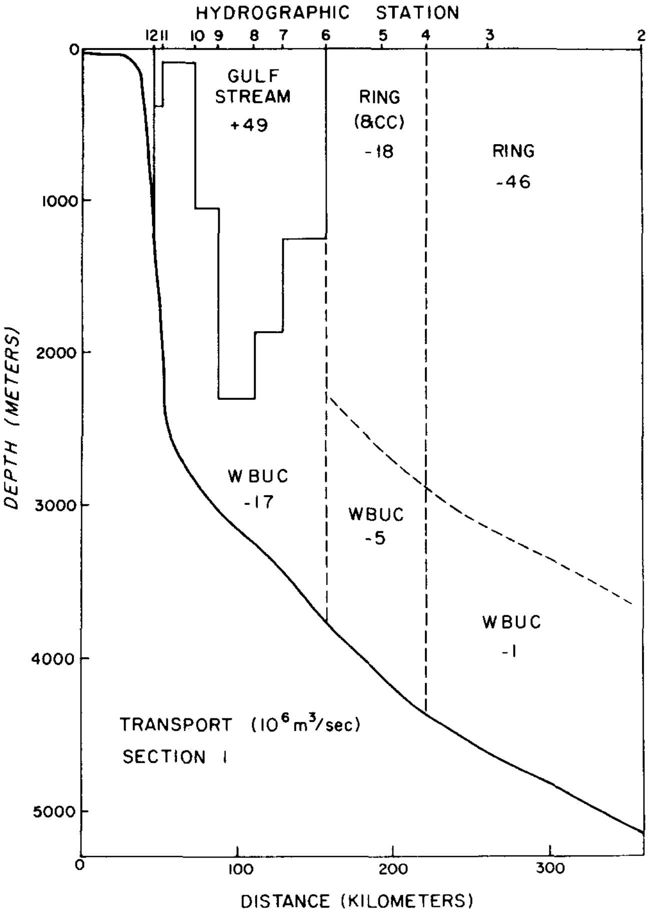

Fig. 12. Transport section.

Table 4. Summary of volume transport calculations. The units are $10^6\,m^3\,s^{-1}$. A plus sign indicates transport toward 45°. Section 2 did not extend to the center of the ring. Figure 12 shows the areas used for the transport estimates. The value in parentheses is the uncertainty in transport implied by a $2\,cm\,s^{-1}$ uncertainty in velocity summed over each current as indicated on Fig. 12. The velocity at the bottom was assumed to be zero between Stas. 2 and 4.

	Section 1		Section 2	
Velocity at Bottom	V = 0	V = -8.9	V = 0	V = -9.2
Gulf Stream	+62	+49 (±3)	+59	+47 (±3)
WBUC				
1) Southwestward flow left of right edge of Gulf Stream	- 3	-17	- 1	-16
2) Deep southwestward flow to the right of Gulf Stream	+ 2	- 6	+ 2	- 8
	- 1	-23 (±5)	0	-24 (±5)
Ring (and countercurrent)				
1) Flow between Stations 4-6	- 6	-18		
2) Flow between Stations 2-4	-46	-46		
	-52	-64		

result is the large southwestward transport associated with the WBUC, the left half of the ring, and the countercurrent, which amounts to $87 \times 10^6 \, m^3 \, s^{-1}$. The ring transport, however, is recirculated to the northeastward of the offshore side of Sta. 2. The net transport through the section exclusive of the ring is toward the northeast and equal to about $26 \times 10^6 \, m^3 \, s^{-1}$.

One of the difficulties in determining the transport values for the three southwestward currents is that their limits are not clear. The WBUC (Fig. 12) was taken to be the flow bounded by the continental slope and extending offshore near the bottom with its upper limit given by the Gulf Stream and by the surface 1500 m above the sea floor offshore of the stream, as this surface approximates its upper boundary near the stream. The transport of the WBUC based on the above limits is 23×10^6 and $24 \times 10^6 \, m^3 \, s^{-1}$ for the two sections.

The calculated transport values strongly depend on the near-bottom velocity distribution and the limits chosen for the currents. A consideration of the range and typical fluctuations of the current meter records (Table 1, Fig. 6) suggests that the precision of the method of calculating the average bottom velocity from current meter data is approximately $2 \, cm \, s^{-1}$; an error of this size implies a corresponding error in transport of $3 \times 10^6 \, m^3 \, s^{-1}$ for the Gulf Stream and $5 \times 10^6 \, m^3 \, s^{-1}$ for the WBUC.

The problem of determining the accuracy of this method, or how well it reproduces the real *in situ* velocity distribution, is considerably more difficult to assess. One error that can be estimated, however, is that associated with extrapolating the average bottom velocity inshore where no reliable current meter measurements were made. To do this the transport was recalculated using a bottom velocity of zero inshore of the meters. The differences from the previously computed transport magnitudes for the two sections were $+1 \times 10^6$ and $+6 \times 10^6 \, m^3 \, s^{-1}$ for the Gulf Stream and -7×10^6 and $-9 \times 10^6 \, m^3 \, s^{-1}$ for the WBUC. The error associated with assuming zero bottom velocity between Stas. 2 and 4 is difficult to estimate because there were no current meter observations in this area. If the bottom velocity were assumed to be $9 \, cm \, s^{-1}$ to the southwest (instead of zero) then the southwestward transport of the undercurrent within 1500 m of the bottom would increase by about $20 \times 10^6 \, m^3 \, s^{-1}$.

There is some evidence that the WBUC extends to the offshore limits of the section. ROWE and MENZIES (1968) inferred from bottom photographs that the WBUC off North Carolina was over 300 km wide extending from 1100 to 5100 m in depth. SCHNEIDER, FOX, HOLLISTER, NEEDHAM and HEEZEN (1967) presented evidence from bottom photographs that both north and south of the Cape Hatteras area there is a 'swift bottom current' flowing southwest parallel to the bottom contours between 3500 and 5000 m. AMOS, GORDON and SCHNEIDER (1971) found the WBUC flowing along the eastern flank of the Blake–Bahama Outer Ridge out to a depth of about 5200 m. If the WBUC does exist at depths of 5000 m, the water would consist largely of Antarctic Bottom Water and this flow should not be thought of as a net transport to the south.

The published values of transport estimates of the WBUC are listed in Table 5. The values were measured during an 11-year period, over seven different months and over a distance of 1000 km. The range is large, from 2 to $50 \times 10^6 \, m^3 \, s^{-1}$, although, curiously, the mean, $16 \times 10^6 \, m^3 \, s^{-1}$, is remarkably close to the transport of the WBUC ($18 \times 10^6 \, m^3 \, s^{-1}$) estimated by a numerical calculation of the North Atlantic circulation using the observed density field (HOLLAND and HIRSCHMAN, 1972). The mean also agrees well with estimates of the volume transport of newly formed deep water, $14 \times 10^6 \, m^3 \, s^{-1}$, that originates in the Norwegian and Labrador seas (WRIGHT, 1973).

Most of the transport estimates are based on the technique of combining geostrophic velocity profiles with absolute velocities measured with neutrally buoyant floats. The transport critically depends on the assumption that a few, brief, direct velocity measurements can be combined with geostrophic sections to reflect the mean currents. The recent deep current meter measurements near the Gulf Stream in addition to the neutrally buoyant float velocities indicate large variability in space and time and suggest that the assumption may not be valid in the WBUC. Although the velocity measurements consistently show a

Table 5. Volume transport estimates of the Western Boundary Undercurrent. The value in parenthesis is the r.m.s. deviation of the individual transports about the mean.

Measured by	Transport ($10^6 m^3/sec$)	Latitude	Date
Swallow & Worthington (1961)	7	33	Mar 1957
Volkmann (1962)	50	38	Jul 1959
	17	38	Jul 1960
Barrett (1965)	4	35	Oct 1962
	12	35	Oct 1962
Worthington & Kawai (1972)	2	35	Nov 1966
Richardson & Knauss (1971)	12	35	Jul 1967
Amos, Gordon & Schneider (1971)	22	31	May 1968
Average	16 (14)		

southwestward flow, the variability makes an accurate estimate of its transport problematic. It seems that a better measurement of WBUC transport is needed and that it must consist of long (several months minimum) and densely spaced direct current measurements.

Reports of previous transport estimates are reviewed here in an attempt to describe their limitations and assess their accuracy. All used hydrographic measurements and computed the geostrophic velocity field. The first four combined the geostrophic velocity field with neutrally buoyant float measurements, the fifth used velocity measured with free falling instruments (transport floats) and the sixth used no absolute velocity measurements.

(1) SWALLOW and WORTHINGTON (1961)

Six individual transport estimates were obtained. They agree within narrow limits implying a high precision. However, only two neutrally buoyant floats were used for each estimate and virtually all floats were tracked over a short time (1 to 3 days) and in a narrow region, 15 to 20 km wide, in which the water depth was 3000 to 3300 m. Because of the narrow width of the region of float tracking the transport estimates could seriously underestimate the real transport of the WBUC.

(2) VOLKMANN (1962)

The float velocities were determined from short records (1 to 2 days) that did not overlap in time with the hydrographic measurements. The largest estimate ($50 \times 10^6 m^3 s^{-1}$) was based on three float observations, but they were made 150 km apart. The vertical velocity distribution measured by two of these floats conflicted dramatically with the geostrophic velocity profile. Float observations at 1945 ± 595 m and 3200 ± 980 m at the same location indicated westward flow decreasing with depth by 6 cm s^{-1}, while the geostrophic velocity distribution indicated a flow increasing to the west with depth by about 5 cm s^{-1} in these depths. This conflict could be due to many possible sources of error and suggests a large error in the transport estimate. For example, an uncertainty of ± 5 cm s^{-1} in the velocity measurements would result in a transport uncertainty of about $\pm 25 \times 10^6$ m^3 s^{-1}. Although six floats were tracked during the 1960 observations (17×10^6 m^3 s^{-1}), only one float was in the westward flow associated with the WBUC, indicating the possibility of large error.

(3) BARRETT (1965)

The lower estimate (4×10^6 m^3 s^{-1}) was based on two floats only 10 km apart and tracked for 2 to 3 days. There could have been significant additional flow in the WBUC offshore of the float locations and the value could be an underestimate. The higher value (12×10^6 m^3 s^{-1}) was based on three float velocities, but the measurements extended only over a brief time (32 h) and narrow width (38 km).

(4) WORTHINGTON and KAWAI (1972)

Four floats were tracked within a region 50 km wide over bottom depths of 3100 to 3800 m; only two floats moved southwestward. They were not tracked simultaneously with the hydrographic observations. There could have been a relatively large area of southwest transport inshore of these measurements and thus the 2×10^6 m^3 s^{-1} could underestimate the real transport.

(5) RICHARDSON and KNAUSS (1971)

Transport float measurements were not simultaneous with hydrographic measurements. The transport floats alone suggested a transport of 1×10^6 to 4×10^6 m^3 s^{-1} over three repeated sections, but these values are scarcely above measurement error. They are also probably an underestimate as some of the measurements could have included northeastward flow which would reduce the apparent southwestward transport.

(6) AMOS, GORDON and SCHNEIDER (1971)

The transport, computed from salinity–temperature–depth (STD) casts and by two methods of selecting the zero velocity level (DEFANT, 1961; STOMMEL, 1956) was 19×10^6 and 40×10^6 m^3 s^{-1}; the authors chose the smaller value because it was in better agreement with the historical water budget for the area. These transport values are 'net southerly flows'; 22×10^6 m^3 s^{-1} is the transport of the WBUC. The transport estimate obviously has a large uncertainty associated with it. For example, an uncertainty of 1000 m in the depth of the zero velocity level would result in a transport uncertainty of 40% estimated from the typical velocity shear in the WBUC.

The temperature and velocity data suggest that one must consider the ring and countercurrent together when discussing their transport, as there appears to be no good way to separate the two currents. The limits are assumed to be the Gulf Stream on the left and the WBUC below (1500 m above the sea floor). The transport of the ring, based on the velocity section (Fig. 9), is about 64×10^6 m^3 s^{-1}. To obtain this estimate a correction was made to the geostrophic calculation for the centripetal acceleration due to the counter-clockwise flow of the ring: it reduced the magnitude of the ring transport by 5×10^6 m^3 s^{-1}.

SUMMARY AND CONCLUSIONS

A program to investigate the crossover between the Gulf Stream and WBUC was conducted during May, June, and July 1971 off Cape Hatteras, North Carolina. Deep moored current meter, hydrographic station, XBT, GEK, and ship drift observations were made along a baseline normal to the Gulf Stream axis. Strong southwestward velocities were recorded under the stream. One current meter 100 m above the bottom at a depth of 2575 m recorded instantaneous velocities as high as 47 cm s^{-1} and a mean velocity of 10.8 cm s^{-1} to the southwest over 54 days. The southwestward flow extended from the continental slope out under the stream to a depth of at least 4100 m. Its transport was estimated to be 24 $\times 10^6 m^3 s^{-1}$. A maximum in the southwestward flow with speeds up to 24 cm s^{-1} was observed on both hydrographic sections; it coincided with water with properties traceable to the Labrador and Norwegian seas.

The data indicate that the Gulf Stream did not extend to the sea floor at this location and time. The WBUC flowed swiftly to the southwest under the Gulf Stream in agreement with the suggestion of BARRETT (1965). The current meter records indicate large velocity fluctuations; these may be reflected in the measurements of RICHARDSON and KNAUSS (1971), who found that the velocity under the stream between 2000 m and the bottom was in the same direction as the stream. If the picture of the crossover is also valid farther to the south, where the Gulf Stream leaves the Blake Plateau, then water as shallow as 1000 m could pass southwest under the stream and into the western Sargasso Sea.

Acknowledgements—The study was undertaken while the author was at the University of Rhode Island with funds provided by Office of Naval Research contract N00014-68-A-0215-0003 and by the State of Rhode Island and Providence Plantations. The manuscript was written at the Woods Hole Oceanographic Institution with funds from Office of Naval Research Contract N00014-74-C-0262 (NR 083-004). Data were obtained on two cruises, one on the R.V. *Trident* (TR-98) and one on R.V. *Eastward* (July 1971). Funding for the *Eastward* cruise was provided by the National Science Foundation Grant Number GA 27725 to the Duke University Marine Laboratory. Many people aided this study. L. V. WORTHINGTON generously loaned several current meters and release mechanisms. WILLIAM KRAMER assisted in the programming and current meter analysis. JOHN KNAUSS, WILTON STURGES, and BRUCE WARREN were particularly helpful in the preparation of this paper.

REFERENCES

AMOS A. F., A. L. GORDON and E. E. SCHNEIDER (1971) Water masses and circulation patterns on the region of the Blake–Bahama Outer Ridge. *Deep-Sea Research*, **18**, 145–166.

BARRETT J. R., JR. (1965) Subsurface currents off Cape Hatteras. *Deep-Sea Research*, **12**, 173–184.

BETZER P. R., P. L. RICHARDSON and H. B. ZIMMERMAN (1974) Bottom currents, nepheloid layers and sedimentary features under the Gulf Stream near Cape Hatteras. *Marine Geology*, **16**, 21–29.

CHENEY R. E. and P. L. RICHARDSON (1976) Observed decay of a cyclonic Gulf Stream ring. *Deep-Sea Research*, **23**, 143–155.

DEFANT A. (1961) *Physical oceanography*, Pergamon Press, Vol. 1, 729 pp.

FANNING K. A. and M. E. Q. PILSON (1973) On the spectrophotometric determination of dissolved silica in natural waters. *Analytical Chemistry*, **45**, 136–140.

FUGLISTER F. C. (1960) Atlantic Ocean atlas, temperature and salinity profiles and data from the International Geophysical Year of 1957–1958. *Woods Hole Oceanographic Institution Atlas Series*, **1**, 1–209.

FUGLISTER F. C. (1963) Gulf Stream '60. In *Progress in oceanography*, Pergamon Press, Vol. 1, 265–383.

GRANT A. B. (1968) Atlas of oceanographic sections—Report AOL No. 68-5. Atlantic Oceanographic Laboratory, Bedford Institute, Dartmouth, Nova Scotia, Canada. (Unpublished manuscript.)

HOLLAND W. R. and A. D. HIRSCHMAN (1972) A numerical calculation of the circulation in the North Atlantic Ocean. *Journal of Physical Oceanography*, **2**, 336–354.

HOLLAND W. R. and L. B. LIN (1975) On the generation of mesoscale eddies and their contribution to the oceanic general circulation. I. A preliminary numerical experiment. *Journal of Physical Oceanography*, **5**, 642–657.

HOLLOWAY J. L. (1958) Smoothing and filtering of time series and space fields. *Advances in Geophysics*, **4**, 351–389.

ISELIN C. O'D. (1936) A study of the circulation of the western North Atlantic. *Papers in Physical Oceanography and Meteorology*, **4**(4): 101 pp.

LUYTEN J. R. (1977) Scales of motion in the deep Gulf Stream and across the continental rise. *Journal of Marine Research*. In press.

MANN C. R., A. R. COOTE and D. M. GARNER (1973) The meridional distribution of silicate in the western Atlantic Ocean. *Deep-Sea Research*, **20**, 791–801.

METCALF W. G. (1969) Dissolved silicate in the deep North Atlantic. *Deep-Sea Research*, Supplement, **16**, 139–145.

NEEDHAM H. D., D. HABIB and B. C. HEEZEN (1969) Upper Carboniferous palynomorphs as a tracer of red sediment dispersal patterns in the northwest Atlantic. *Journal of Geology*, **77**, 113–120.

NEWTON J. G. and O. H. PILKEY (1969) Topography of the continental margin off the Carolinas. *Southeastern Geology*, **10**, 87–92.

RICHARDSON P. L. (1974) Current measurements under the Gulf Stream near Cape Hatteras, North Carolina. Ref. No. 74-3, Graduate School of Oceanography, University of Rhode Island. (Unpublished manuscript.)

RICHARDSON P. L. and J. A. KNAUSS (1971) Gulf Stream and western boundary undercurrent observations at Cape Hatteras. *Deep-Sea Research*, **18**, 1089–1109.

RICHARDSON W. S., P. B. STIMSON and C. H. WILKINS (1963) Current measurements from moored buoys. *Deep-Sea Research*, **10**, 369–388.

RONA P. A., E. D. SCHNEIDER and B. C. HEEZEN (1967) Bathymetry of the continental rise off Cape Hatteras. *Deep-Sea Research*, **14**, 625–634.

ROWE G. T. and R. J. MENZIES (1968) Deep bottom currents off the coast of North Carolina. *Deep-Sea Research*, **15**, 711–719.

SCHMITZ W. J., JR., A. R. ROBINSON and F. C. FUGLISTER (1970) Bottom velocity observations directly under the Gulf Stream. *Science*, **170**, 1192–1194.

SCHNEIDER E. D., P. J. FOX, C. D. HOLLISTER, H. D. NEEDHAM and B. C. HEEZEN (1967) Further evidence of a contour current in the western North Atlantic. *Earth and Planetary Science Letters*, **2**, 351–359.

STOMMEL H. (1956) On the determination of the depth of no meridional motion. *Deep-Sea Research*, **3**, 273–278.

SWALLOW J. C. and L. V. WORTHINGTON (1961) An observation of a deep countercurrent in the western North Atlantic. *Deep-Sea Research*, **8**, 1–19.

VOLKMANN G. H. (1962) Deep current observations in the western North Atlantic. *Deep-Sea Research*, **9**, 493–500.

WARREN, B. A. and G. H. VOLKMANN (1968) A measurement of volume transport of the Gulf Stream south of New England. *Journal of Marine Research*, **26**, 110–126.

WORTHINGTON L. V. and H. KAWAI (1972) Comparison between deep sections across the Kuroshio and the Florida current and Gulf Stream. In: *Kuroshio: its physical aspects*, K. YOSHIDA and H. STOMMEL, editors, University of Washington Press, pp. 371–385.

WORTHINGTON L. V. and M. G. METCALF (1961) The relationship between potential temperature and salinity in deep Atlantic water. *Rapports et procès-verbaux des réunions. Conseil permanent internationale pour l'exploration de la mer*, **149**, 122–128.

WRIGHT W. R. (1973) Northern sources of energy for the deep Atlantic. *Deep-Sea Research*, **19**, 865–878.

WRIGHT W. R. and L. V. WORTHINGTON (1970) The water masses of the North Atlantic Ocean: a volumetric census of temperature and salinity. *American Geological Society Serial Atlas of Marine Environment*, Folio No. 19.