Gulf Stream and Western Boundary Undercurrent observations at Cape Hatteras

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Abstract—During July 1967 three volume transport measurements of the Gulf Stream were made off Cape Hatteras, North Carolina. The measurements were made using 'transport floats', free falling instruments which measure the vertically averaged horizontal velocity and depth. The transport values were 58, 67 and 64 $\times$ 10⁶m³/sec; the average transport was 63 $\times$ 10⁶m³/sec. The edge of the Gulf Stream for these determinations was defined as the point at which the transport per unit width of the Stream vanished. The transport refers to values normal to a baseline bearing 135°. The velocity measurements indicated that the Gulf Stream extends to the bottom underneath and offshore of the high speed surface layer. A deep southward flow was found on both sides of the deep northward flow. A single hydrographic section was also made across the Gulf Stream. Absolute velocities of the geostrophic currents were determined by forcing the geostrophic transport to agree with the direct transport measurements. An analysis of the temperature–salinity and dissolved oxygen distributions failed to reveal discontinuities between the deep north and south flows. These properties can be related to water properties in the slope water region and Labrador Basin and thus indicate that the southward flowing water is the Western Boundary Undercurrent.

INTRODUCTION

IT HAS been clear for some time that the Gulf Stream undergoes significant changes in the vicinity of Cape Hatteras. South of Hatteras the Gulf Stream runs close to shore as a true boundary current and seldom meanders far from the edge of the continental shelf. Downstream from Cape Hatteras, the meandering of the Gulf Stream intensifies and its position is rarely constrained by the edge of the shelf.

In recent years a number of observers have presented evidence indicating that beyond Cape Hatteras the Gulf Stream extends to the bottom, even in depths in excess of 4000 m where the water temperature is less than 2·5°C (FUGLISTER, 1963; WARREN and VOLKMANN, 1968; KNAUSS, 1969b; SCHMITZ, ROBINSON and FUGLISTER, 1970).

South of Cape Hatteras the Gulf Stream runs over the Blake Plateau where the water depths are less than 1000 m and the lowest temperature of the Gulf Stream water is about 7°C. Thus the Gulf Stream must in some manner entrain colder and heavier water as it moves off the Blake Plateau at Cape Hatteras and down the continental slope into the deep Western North Atlantic. In this region the depth of the water along the mean path of the Gulf Stream increases from 1000 to 2000 m in 20 km, a slope of 5%, and from 1000 to 3000 m in about 150 km, a slope of less than 1·5%.

Finally, there is the relationship of the deep Western Boundary Undercurrent (WBUC) to the Gulf Stream in the vicinity of Cape Hatteras. The WBUC was first reported by SWALLOW and WORTHINGTON (1961) south of Cape Hatteras along the

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continental slope and seaward of the Gulf Stream. Since then it has been observed by VOLKMANN (1962) north of Cape Hatteras along the continental slope and landward of the Gulf Stream. If the WBUC is a continuous feature and if the Gulf Stream extends to the bottom along its entire course, the Cape Hatteras region takes on special interest since it would appear that here one current would somehow have to pass through the other.

The oceanographer who attempts today to observe complex ocean circulation phenomena such as the Gulf Stream is confronted with a dilemma. Rarely are facilities available to do the job properly. At the one extreme he can move about making a single set of observations over a large area and assume that time variations during the measurement program are sufficiently small that he can treat his observations as having been made simultaneously. The other extreme is to stay in one location and make a long time series. Although such a program can provide a good measure of local variability, it is often difficult to infer much about broader questions of oceanic circulation.

The strategy adopted here was a compromise. To a first approximation it was assumed that the Gulf Stream–WBUC system was steady over the period of observations and that measurements made at different times could be treated as simultaneous. At the same time there was sufficient redundancy in the program so that it was possible to test in part the validity of the assumption. The result is an average picture of the Gulf Stream–WBUC system during this three week period, the details of which are blurred somewhat because the system is not steady. Some estimates of the variability within the Gulf Stream are given. The estimates are useful in providing a measure of confidence in the steady state assumptions. They do not provide very useful statistical data on variability.
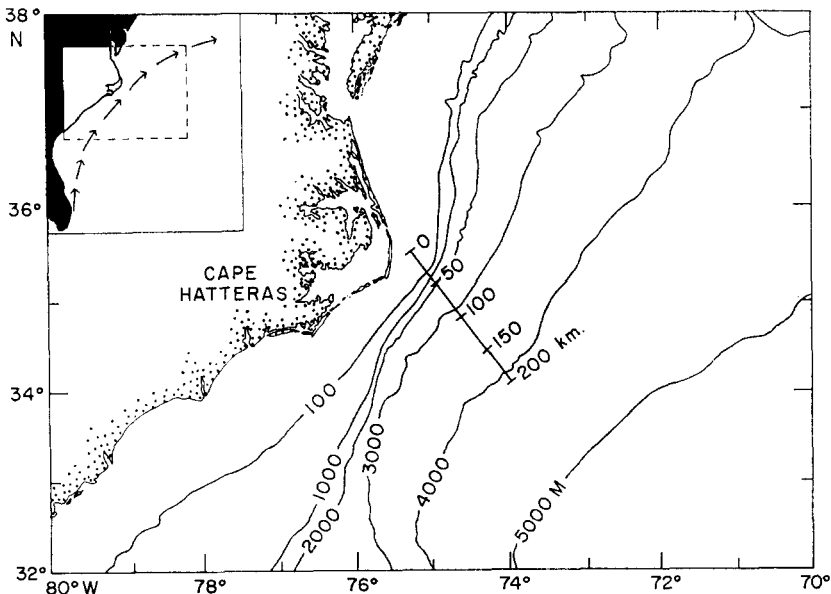

Fig. 1. Location and orientation of the baseline used in making hydrographic and transport measurements at Cape Hatteras, North Carolina.

METHODS

The primary observational material is from R.V. *Trident* Cruise TR-038 for the period 26 June–18 July 1967 and consists of 14 hydrographic stations in a single section 230 km long across the stream made at the beginning of the cruise and 87 transport float observations consisting of three complete and one partial crossing of the Gulf Stream made along the same section (Fig. 1). Several additional crossings of the Gulf Stream were made with expendable bathythermographs. Attempts to observe the Gulf Stream using the GEK (geomagnetic electrokinetograph), neutrally buoyant floats and bottom mounted current meters were unsuccessful. A preliminary attempt to measure the transport and velocity structure of the Gulf Stream in the vicinity of Cape Hatteras was made in 1965 (*Trident* Cruise TR-026). The data for TR-038 and TR-026, as well as a discussion of the methods and error estimates, is available as a technical report (RICHARDSON and KNAUSS, 1970).

Hydrographic data

The hydrographic casts were made using standard Nansen bottles and Richter and Wiese reversing thermometers, calibrated at the Woods Hole Oceanographic Institute. Thermometers were read in a water bath and by two observers. Deep temperatures were measured with -2 to $6°C$ thermometers.

The dissolved oxygen and salinity determinations were carried out on the ship. Salinity measurements were made on a model RS-7B Portable Induction Salinometer made by Beckman Instruments, Inc. Four hundred and eight samples were measured including 21 duplicates from 21 deep cast bottles to evaluate machine precision. Two standard deviations of the duplicates amounted to $\pm 0.007°/\%_0$.

Oxygen values were obtained by the CARPENTER (1965) modified technique of the Winkler method. Smooth curves were drawn through a plot of the dissolved oxygen values at each station to obtain the oxygen distribution across the Gulf Stream. The individual measurements varied from this smooth curve by an average deviation of between 0·1 and 0·2ml/l. Values in excess of 6·6 ml/l. were observed several times in depths greater than 1000 m. FUGLISTER (1963) finds no values higher than 6·6 ml/l. in deep water north of this section, and Barrett (personal communication) notes that he did not find values greater than this in the Cape Hatteras region. The excessively high oxygen values and the deviations from the profiles suggest absolute errors of as much as 1·0 ml/l. and a precision of 0·2 ml/l. The oxygen distribution is considered to be correct in its gross features. The oxygen minimum layer is well defined and each profile is consistent with the adjacent profiles.

Station positions were located by Loran-A. The estimated precision is ± 1 km based on repeated fixes over short periods.

Transport floats

Recently RICHARDSON and SCHMITZ (1965) developed a new method of determining transport which is independent of standard hydrographic measurements. They initiated use of the 'transport float', an instrument that falls freely to a preselected depth, drops a weight and floats to the surface. A very careful measurement of the horizontal distance travelled by the float, the time to travel this distance and the depth reached by it give horizontal transport (per unit width). The transport of the Gulf

Stream can be measured by making a series of individual measurements across the Stream. By dropping floats to different levels, the vertical distribution of velocity and transport per unit width can be calculated.

The transport floats used were a modification of those originally described by Richardson and Schmitz. The floats consisted of an aluminum cylindrical pressure case 7 in. in dia. and 21 in. long; a series of 12 Corning glass floats 10 in. in dia. and 1/4 in. thick, held tightly by two disks 48 in. in dia., were fastened to the pressure case. A Benthos model 2040 lighted glass float was inserted to aid night location. Inside the pressure case was a Geodyne type A-427 radio transmitter and a Benthos model 1170 pressure–time recorder. A rupture disk release mechanism was used to release weights at mid-depth. A device that released weights upon contact was used on the bottom transport floats. Although the rupture disks were designed to fail by tension, failure frequently occurred by shear at the edges of the disk. Thus the depths reached by the intermediate floats varied considerably from the planned depths.

Transport floats were dropped to the bottom and usually to one or two intermediate depths. The shallowest was dropped first, then the deeper ones, thus allowing adequate maneuvering time for pickup.

Loran was used to fix the position of the transport float drops, except for the inshore stations where visual bearings and radar were used. Decca Hi-Fix was used to measure the distances travelled by the transport floats. As a measure of absolute position, the Hi-Fix is only as good as its initial setting, which was from Loran. But as a measure of the relative distance between two points, it is very accurate. The estimated error in Hi-Fix readings is approximately ± 2 m.

Proper operation of the Hi-Fix system as used on TR-038 depends on a continuous transmission path between the slave stations located ashore and the master station aboard ship. The system has no built in 'memory' (or rate correction) in the event a pulse is not received. The lack of memory coupled with high speed servos enables the dial reading to skip several lanes (one lane is approximately 90 m) if the transmission path is interrupted by rain or thunder squalls. Loss of lane count caused many delays, wasted seven transport float drops and essentially limited activity to daylight hours.

Errors in calculating transport per unit width and velocity are of several kinds and include positioning errors with Hi-Fix, errors in relating the position of the float relative to the Hi-Fix antenna aboard *Trident*, errors related to any change in the surface current between the time the float surfaces and the time it is retrieved, and errors related to the uncertainty of the depth which the float reached. An error analysis has been made (see Appendix I of RICHARDSON and KNAUSS, 1970).

The uncertainty in deep velocity measurements is approximately 2–3 cm/sec. This estimate is based on random error addition and is supported by observations on two occasions where repeated drops were made over a short time span and at the same location. On these two occasions the deep velocities agreed within 2 cm/sec. The errors of the velocity averaged over the surface layer are considered to be less than 1% in the high speed core and less than 5% near the edges (where the velocity has decreased to 0·1 of the central values). These estimates combined with errors due to depth measurement of less than 2–5%, give errors of 5% for individual transport measurements.
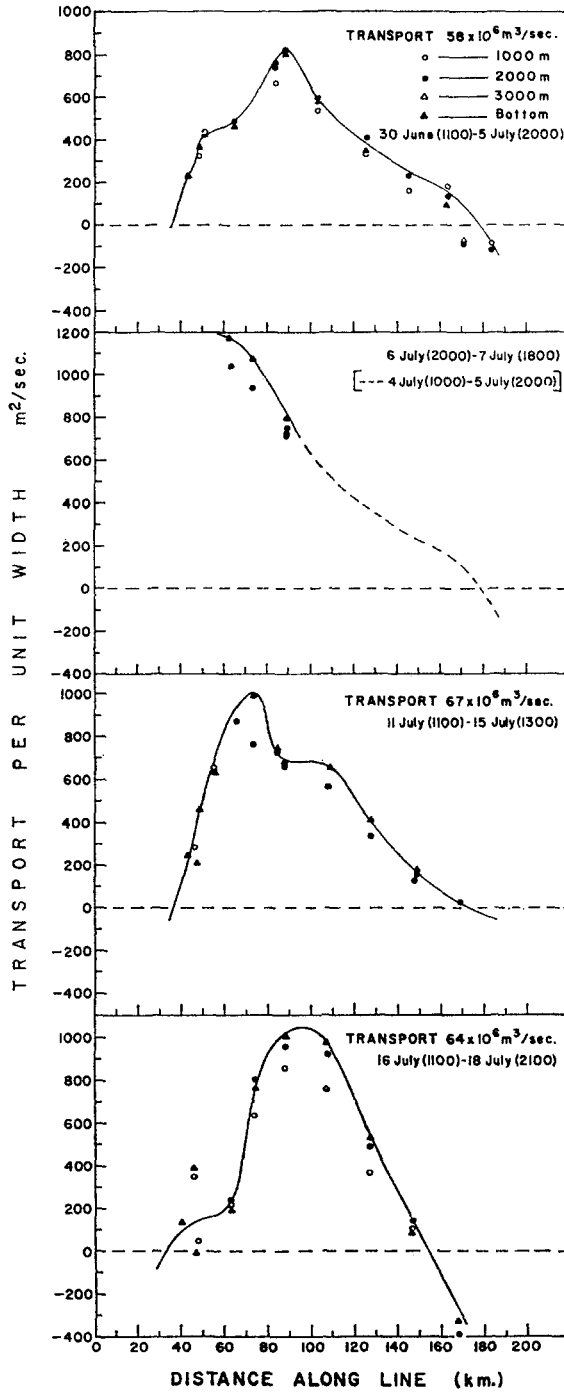
Fig. 2.   Observed transport per unit width across the Gulf Stream for four individual crossings. The total transport is the area under the curve. The depths given indicate the approximate depth range that the floats reached.
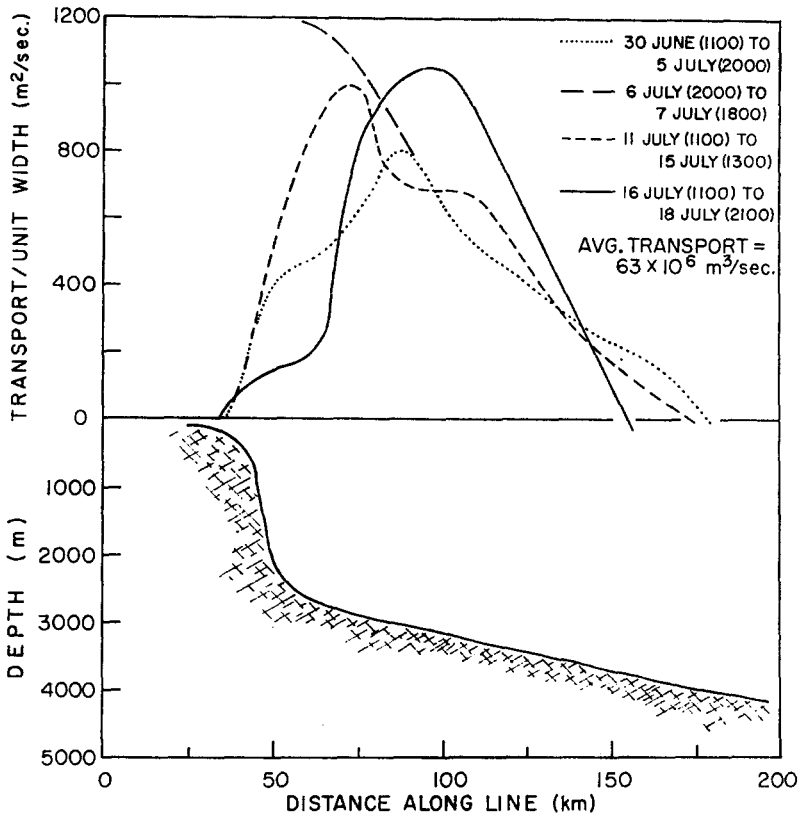
Fig. 3. Superposition of the four transport per unit width crossings with the depth profile along the line shown on the lower part of the figure.

RESULTS

Transport of the Gulf Stream

The total transport value for each crossing of the Gulf Stream was obtained as follows. Transports (per unit width) at each station were plotted against distance across the Stream, and a smooth curve was drawn through the maximum points and the area measured. Figure 2 shows the transport as a function of distance along the base line and Fig. 3 shows the superposition of the individual crossings with the addition of the depth profile to show the relation of the Stream to the continental shelf.

It is important to note that on two of these complete crossings the transport goes negative on the offshore edge, and on the third the data points approach the zero line so closely that there is negligible error in extending the curve to the zero transport position. On the inshore end of the line, while there are no negative values of transport observed, the transport does decrease very rapidly towards the continental shelf. Furthermore, the shallowness of the water inshore of the shallowest measurements suggests a negligible transport in either direction. Again the transport curve was extended down to the zero transport line. Thus the total transport of the Gulf Stream is the area under the curve, and the 'edges' of the Gulf Stream in this case refer to the

points at which the curve intersects the zero transport line. The width of the Gulf Stream on these crossings are 145, 140 and 120 km.

The total transports for the three crossings were 58, 67 and $64 \times 10^6 m^3$/sec, the average value is $63 \times 10^6 m^3$/sec. The variation from the mean is less than the standard deviation of 10% of the mean reported by SCHMITZ and RICHARDSON (1968) from 50–60 transects in the Straits of Florida and is certainly less than the 20–30% uncertainty given by WARREN and VOLKMANN (1968).

The shape of the curves of transport versus distance across the Stream are similar to the velocity profiles across the Stream as indicated by GEK measurements (VON ARX, 1952; WEBSTER, 1961), The maximum transport core is relatively narrow and is located to the left of the midpoint of the northward flow. The left hand edge has a larger transport gradient than the right and the sharp gradient is located close to the continental slope.

The fourth crossing is considered to be the most complete and accurate of the four crossings for the following reasons:
1. the scientific party was well versed in the transport float procedure;
2. the return of floats was best;
3. the coverage to different depths was best;
4. the Hi-Fix was working well;
5. the weather was generally good;
6. the crossing was completed in the shortest time.

On this crossing, the transports from intermediate depths were subtracted from deeper transports and are shown on Fig. 4. The total transport amounts to
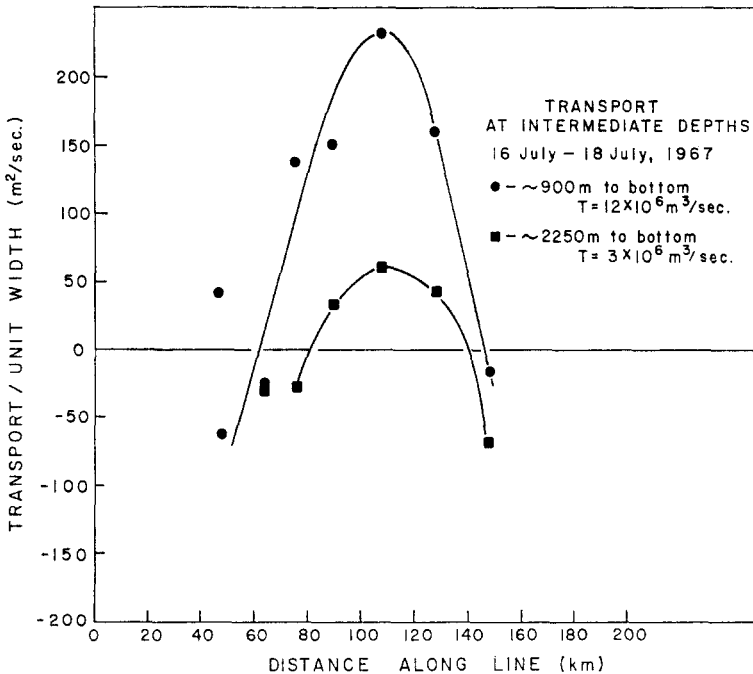

Fig. 4.   Transport at intermediate depths. The depths are averages of the depths reached by the floats at the 1000 and 2000 m range.

$64 \times 10^6 \text{m}^3/\text{sec}$. Fifty-two million m^3/sec or 80% of the total transport is above 900 m. The transport in deep water is correspondingly small. The transport from 900 m to the bottom is $12 \times 10^6 \text{m}^3/\text{sec}$, 20% of the total, and from 2250 m to the bottom is $3 \times 10^6 \text{m}^3/\text{sec}$, 5% of the total.

Each of the transport curves (surface to the bottom, 900 m to the bottom and 2250 m to the bottom) goes to zero on either side of the central core. One interpretation is a Gulf Stream that extends to the bottom, bounded on both sides by counterflows. The point of maximum transport slopes down to the right with a slope of 1 in 10. The maximum surface velocity, 2·5 m/sec, determined from tracking floats on the surface, is at 75 km along the baseline and is located over the deep reverse flow. The maximum transport is at 97 km, the maximum from 900 m to the bottom is at 107 km, and from 2250 m to the bottom, 112 km. It is apparent from Fig. 3 that the point of maximum transport shifts approximately 35 km along the baseline over the 19 day
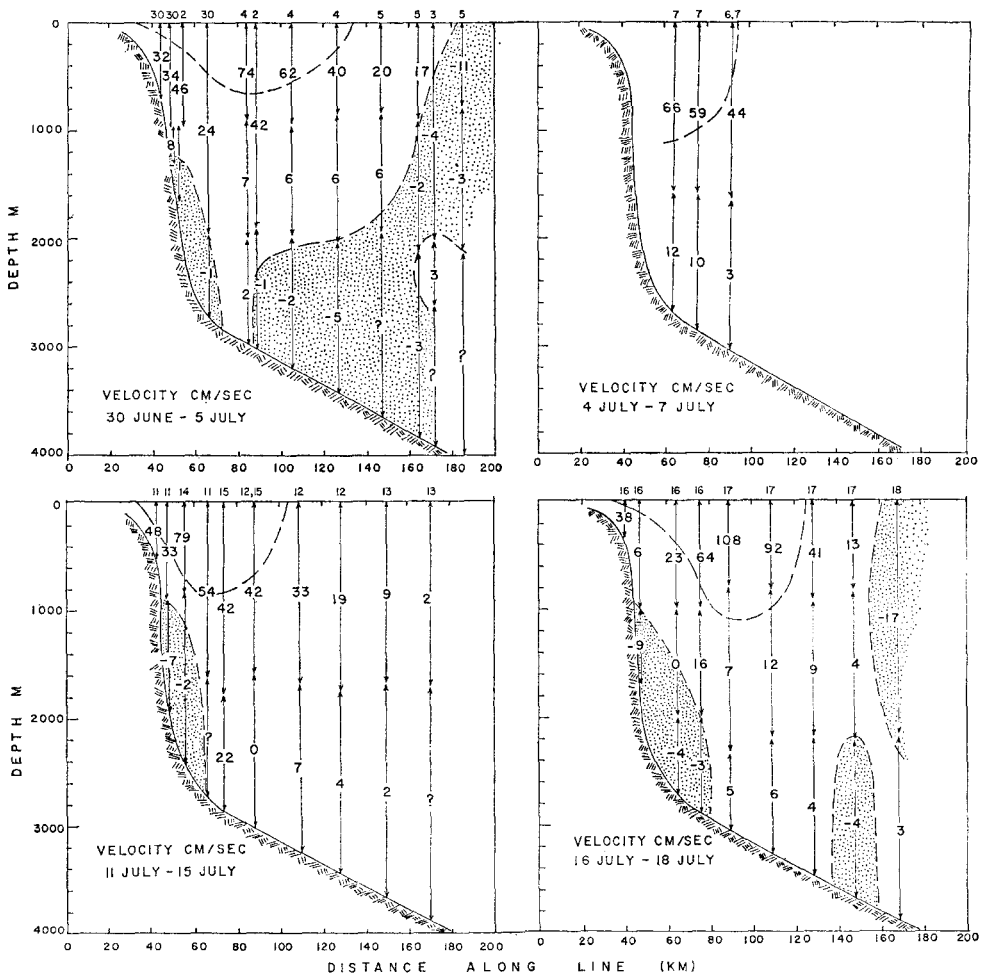

Fig. 5. Average velocities perpendicular to the baseline. The numbers above the section indicate the date of each station. The arrows indicate the depths over which the velocities were averaged. Negative velocities indicate southward flow.

sampling period. There are prominent 'shoulders' on the transport curves. It is difficult to know if they are long-term features or are a result of sampling errors, the effects of tidal and inertial motion, or the lateral shifts in the Stream.

Velocity field

The velocity field of the Gulf Stream can be calculated directly from the transport measurements and also from the hydrographic data by use of the geostrophic equation. The average velocities at intermediate depths were obtained from the transport data as follows. The velocity from 1000 m to 2000 m, for example, was calculated by subtracting the transport to 1000 m from the transport to 2000 m and dividing the result by the necessary depth interval. The average velocities perpendicular to the baseline on the four crossings are indicated on Fig. 5. Average velocities for each level were plotted at the midpoint of each level. The high velocity sections (velocity greater than 50 cm/sec) are outlined by a dashed line and the southward flows are indicated by stippling.

In general, there is a broad surface current which narrows and decreases in speed with depth. The position of maximum velocity slopes down to the right. In the central portion the average velocity between 2000 m and the bottom is in the direction of the Gulf Stream on all crossings. If there is a vertical shear in the bottom 1000 m of the order of 10 cm/sec per 1000 m there could be a countercurrent along the bottom. The hydrographic data suggests shear less than 10 cm/sec per 1000 m. Otherwise it appears that the Gulf Stream extends to the bottom. A reverse flow is located on both sides of the Gulf Stream. On the west, the reverse flow was discovered on all three complete transects. It hugs the slope and appears to have maximum velocity in depths of 1500 to 2000 m. These measurements indicate that this deep reverse flow is under the northward surface flow. On the east the reverse flow was found on two of the three crossings. On the third, velocities were decreasing in an offshore direction indicating that reverse flow may have been located beyond the most offshore measurement. The counterflow apparently extends from the surface to the bottom but is quite variable in extent and magnitude.
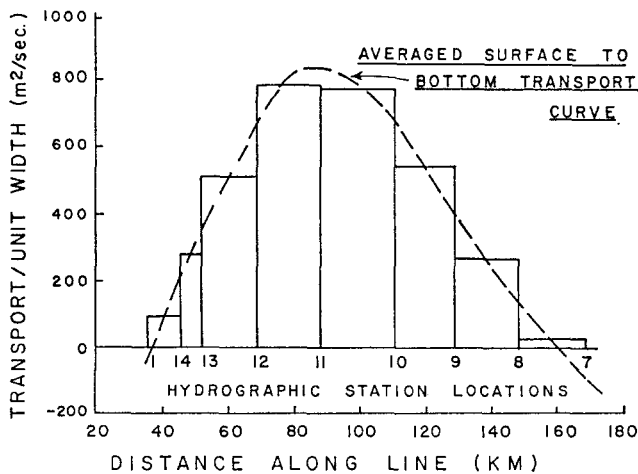

Fig. 6.   The geostrophic transport between hydrographic stations fitted to the curve representing the average measured transport per unit width of the three complete crossings of the Gulf Stream.
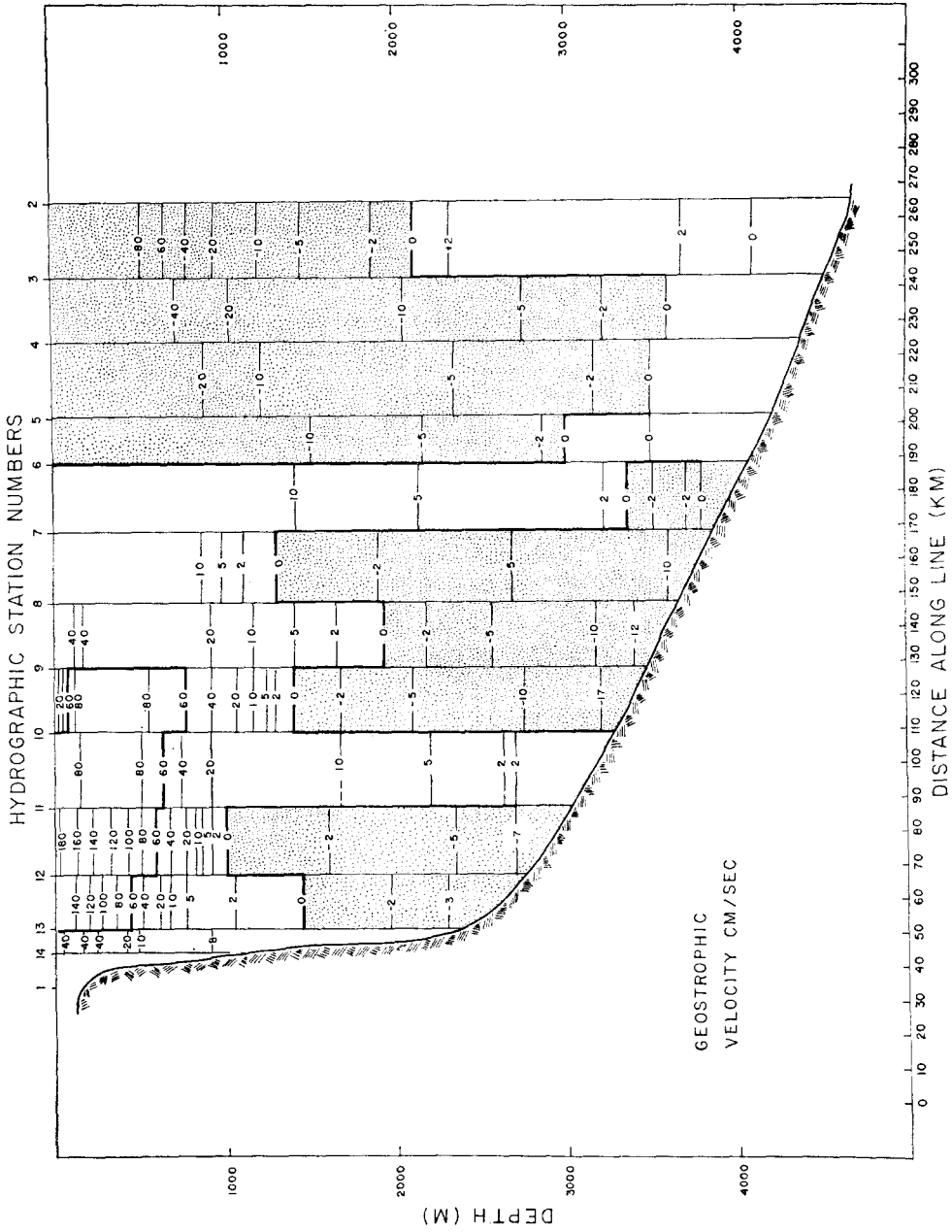
Fig. 7. Geostrophic velocity between hydrographic stations. Stippled areas indicate southward velocities. The velocity was assumed to equal zero at the bottom offshore of hydrographic station 7.

The individual pictures of the crossings differ from one another in details but appear to have certain gross features in common. The Gulf Stream extends to the bottom under the high speed core. The average speeds over the deepest 1000 m are approximately 5 cm/sec. There are deep reverse flows to the right and left of the Gulf Stream. The average speeds over 1000 m in the counterflow are approximately 5 cm/sec south.

As a comparison to the velocity picture obtained from transport measurements, geostrophic calculations were made in the usual manner to obtain the geostrophic velocity field (Fig. 7). The geostrophic transport was also calculated. Absolute velocities were obtained by making the geostrophic transport between each pair of hydrographic stations fit an average transport curve obtained by averaging the three direct transport curves as shown in Fig. 6. It was assumed that the velocity remained unchanged below the deepest calculated velocity. Geostrophic profiles offshore of any direct transport measurement (greater than 170 km along the section) were assumed to have zero velocity at the bottom.

To obtain the contoured section of geostrophic velocities (Fig. 8) the velocities averaged over station intervals were plotted along the line and then a smooth velocity curve was superimposed on them. The positions of isotachs were plotted on a vertical
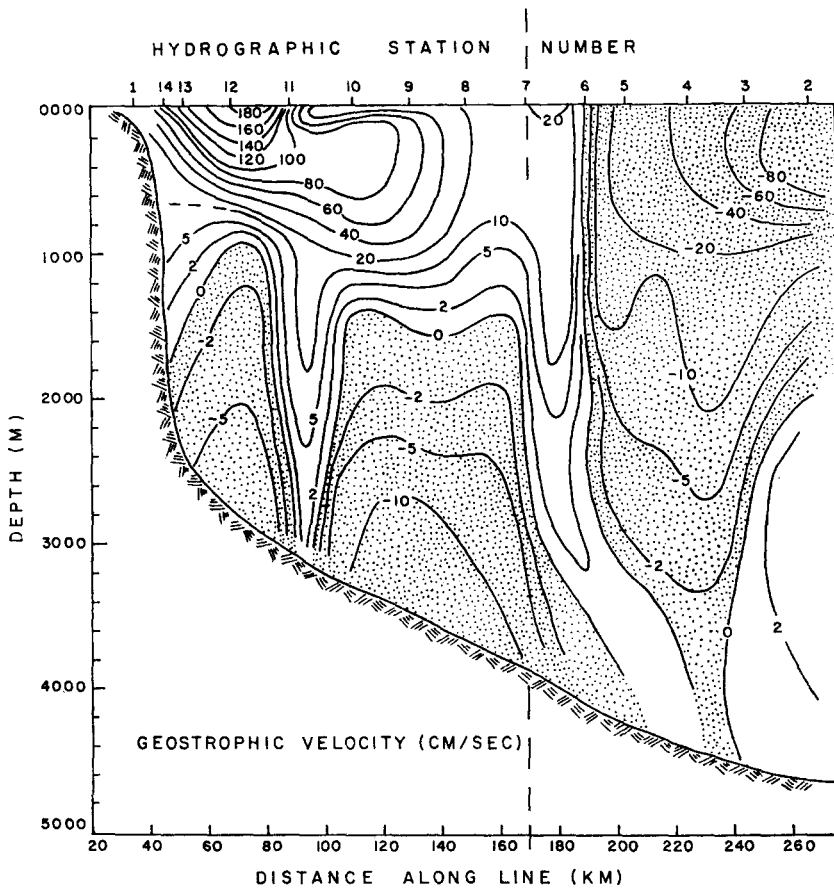

Fig. 8.   Contoured geostrophic velocity.

section and contoured. Basic levels used in this method were 100 m; 200 m; 200 m intervals to 1000 m; and 500 m intervals to 4500 m. This method of contouring was used by WARREN and VOLKMANN (1968) and is considered by them as the most valid method of presenting such computations.

The most striking feature of the contoured geostrophic velocity section is how closely it resembles the velocity field of the first and fourth direct transport crossings. The Gulf Stream becomes narrower with depth but does extend to the bottom in 3000 m. On both sides of the northward flowing water there is a counterflow. The reverse current on the left hugs the continental escarpment in depths of 1000 to 3000 m and lies below the maximum surface current. The surface of zero velocity is a complex shape resembling a sine wave.

We have no explanation for the apparent large reversal of the flow beyond the limit of the transport section. Whether the absolute flow is as depicted is difficult to say since we have no direct transport measurements offshore of a distance of 170 km along the baseline. We do know from the hydrographic data that the vertical shear is large. A possible explanation is that the section extended into an eddy of the Gulf Stream.

A solution to the problem of resolving the different time scales of hydrographic and direct transport measurements appears to be very difficult since the hydrographic stations were taken before the three direct transport crossings were begun. And it has been noted from the transport curves that the Gulf Stream changes location rapidly with respect to these time scales. Therefore it is difficult to know in what detail Fig. 7 describes real features in the ocean. The gross features are probably correct. A justification for the method of obtaining the absolute velocity used here is that when the geostrophic transports between stations were matched with individual direct transport crossings, the general features remained essentially the same. When the geostrophic transport is matched to the individual direct transport crossings, three slightly different pictures result. The results from two (the second and third) of the three complete crossings show the Gulf Stream extending to the bottom and also two (the first and third) show reverse flows on either side of the northward flowing water. When the second crossing was used, the reverse flow hugging the slope was not apparent. Figure 3 indicates that the Gulf Stream at the time of the second crossing had shifted inshore of the other crossings. It is suggested that this shift is the reason the northward flow has replaced the deep reverse flow in this case. When the first crossing was used the positive flow extends almost (within 150 m) to the bottom between the reverse flows. While there are minor differences, the individually matched geostrophic sections do agree with the basic features of the averaged geostrophic velocity section.

Counterflow

The counterflow on both sides of the Gulf Stream was observed in both the direct transport velocity sections and the geostrophic velocity section. The deep reverse flow on the left was observed on all transport float transects and is apparent on the geostrophic velocity section. It appears to be centered on the junction of the continental slope and upper rise and extends from approximately 1000 to 3000 m with the highest recorded velocities adjacent to the steep slope. This is in agreement with the findings of BARRETT (1965) and ROWE and MENZIES (1968).

The reverse flow on the left is separated from the countercurrent on the right by

the northward flowing Gulf Stream. The counterflow on the right was observed on two of the transects and is also apparent on the geostrophic velocity section. All indications suggest that the counterflow is highly variable in width and transport.

Since the transport float is an averaging device, the measured southward velocities and transports may be smaller than really exist. Smaller velocities and transports are possible because the average velocity may include some northward flow. The use of average values plus the variability of the Gulf Stream and the small number of measurements in the countercurrent on each crossing suggest a large uncertainty in size and transport values for the counterflow. The transport float measurements indicate the width of the left countercurrent to be approximately 30 km and the transport is estimated at $1 \times 10^6 m^3$/sec. Geostrophic calculations indicate the transport to be approximately $2 \times 10^6 m^3$/sec with a width of 40 km. The counterflow on the right is variable in extent. There are two bands of southward flow indicated on the geostrophic velocity section to the right of the Gulf Stream. The southward flow adjacent to the Gulf Stream is 80 km wide and has an estimated transport of $10 \times 10^6 m^3$/sec. The offshore southward flow, which extends to the surface and which is based on an assumed zero velocity level at the bottom, amounts to around $40 \times 10^6 m^3$/sec. These data are summarized below in Table 1.

Table 1. Summary of countercurrent data.

	Width		Transport	
	Direct	*Geostrophic*	*Direct*	*Geostrophic*
Left counter-current	30 km	40 km	$1 \times 10^6 m^3$/sec	$2 \times 10^6 m^3$/sec
Right counter-current	*Variable*	80 km	*Variable*	$10 \times 10^6 m^3$/sec

The transport of the countercurrent appears to be strongly dependent on the offshore limits one chooses for it. ROWE and MENZIES (1968), from bottom photographs, found the width of the Western Boundary Undercurrent off North Carolina to be over 300 km extending from 1100 to 5100 m. They also found streaks of relatively high velocity which are separated by zones of little or no motion. The problem of establishing its edge, its variability, and its apparent streakiness suggest that the above estimates of the countercurrent transport are very approximate.

In order to differentiate the deep Gulf Stream from the Western Boundary Undercurrent, the water properties were examined. BARRETT (1965) showed that variations from the salinity–potential temperature curve of the North Atlantic given by WORTHINGTON and METCALF (1961) can be used to trace Labrador Basin Water. He showed that negative salinity anomalies in the range of potential temperatures 3·51 to 4·00°C indicate that there is a large body of relatively fresh water in the Labrador Basin and that it extends southwest along the North American coast. Barrett reports that salinity anomalies of $-0.01°/\text{\textperthousand}$ to $-0.03°/\text{\textperthousand}$ have been observed in the slope water region and that negative salinity anomalies have been observed consistantly somewhat to the south of Cape Hatteras. Anomaly values of $-0.03°/\text{\textperthousand}$ were observed near the continental slope on the *Trident* cruise, and these values changed to zero in the offshore direction.

The area of these anomalies can be seen on Fig. 9 as the lower salinity minimum. Two layers of salinity minimum can be seen at intermediate depths near the steep slope. At the 4·4°C level (Fig. 10) a salinity minimum of 34·950–34·955°/$_{oo}$ is found at stations 12, 13 and 14. Around 3·6 to 4·0°C there is a salinity minimum of 34·955°/$_{oo}$. This deeper minimum is characteristic of Arctic Intermediate Water (SVERDRUP, JOHNSON and FLEMING, 1942) and Labrador Sea Water (LEE and ELLETT, 1967). This deeper salinity minimum is reviewed by WARREN and VOLKMANN 1968.

Salinity anomalies do not indicate northern water in the deeper regions since the values are similar to the standard Western Atlantic values. BARRETT (1965) suggested that dissolved oxygen values serve as indicators of the southward spreading water in the Arctic Intermediate Water Region, characterized by the previously mentioned low salinity values, and also in the 2·5°C potential temperature level. Labrador Basin and deep slope water are significantly higher in dissolved oxygen than equivalent areas in the central Atlantic. High oxygen values south of Cape Hatteras off Charleston, South Carolina of 6·17 to 6·51 ml/l. were observed by FECHER (1970) in depths of 1400 to 3000 m adjacent to the continental slope. ROWE and MENZIES (1968) found oxygen values above 6·0 ml/l. off North Carolina from depths of 1100 m on the steep slope down to the abyssal plain near 5100 m. BARRETT (1965) found values of oxygen
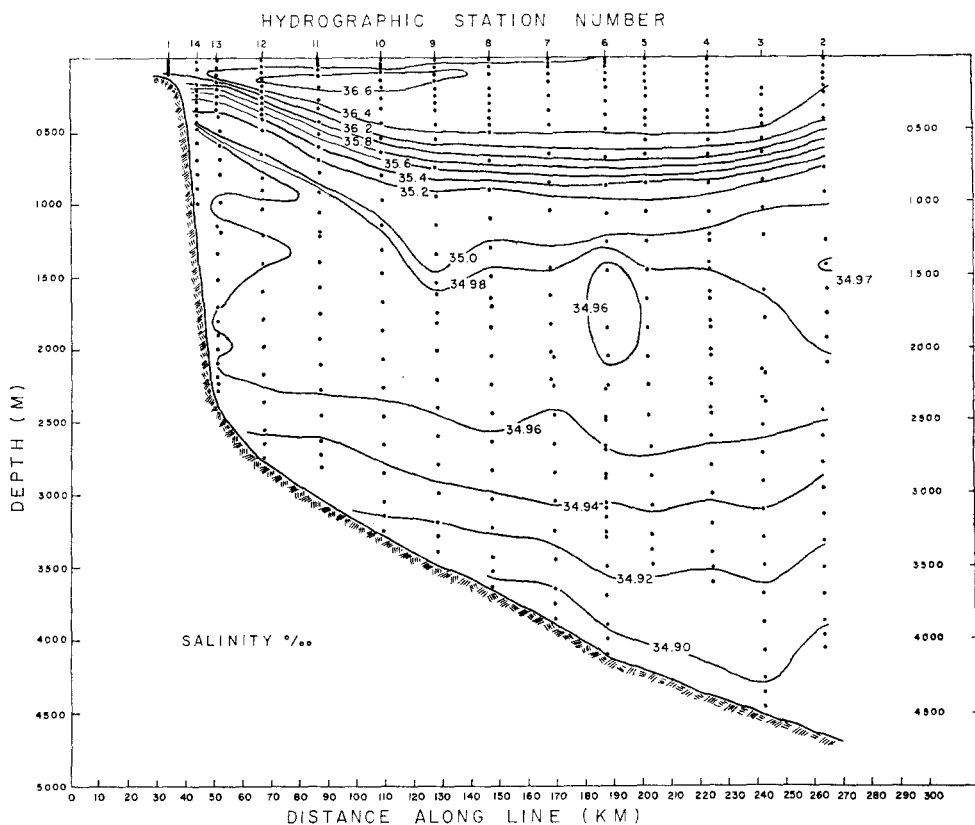

Fig. 9. Vertical section of salinity across the Gulf Stream (26 June to 30 June).
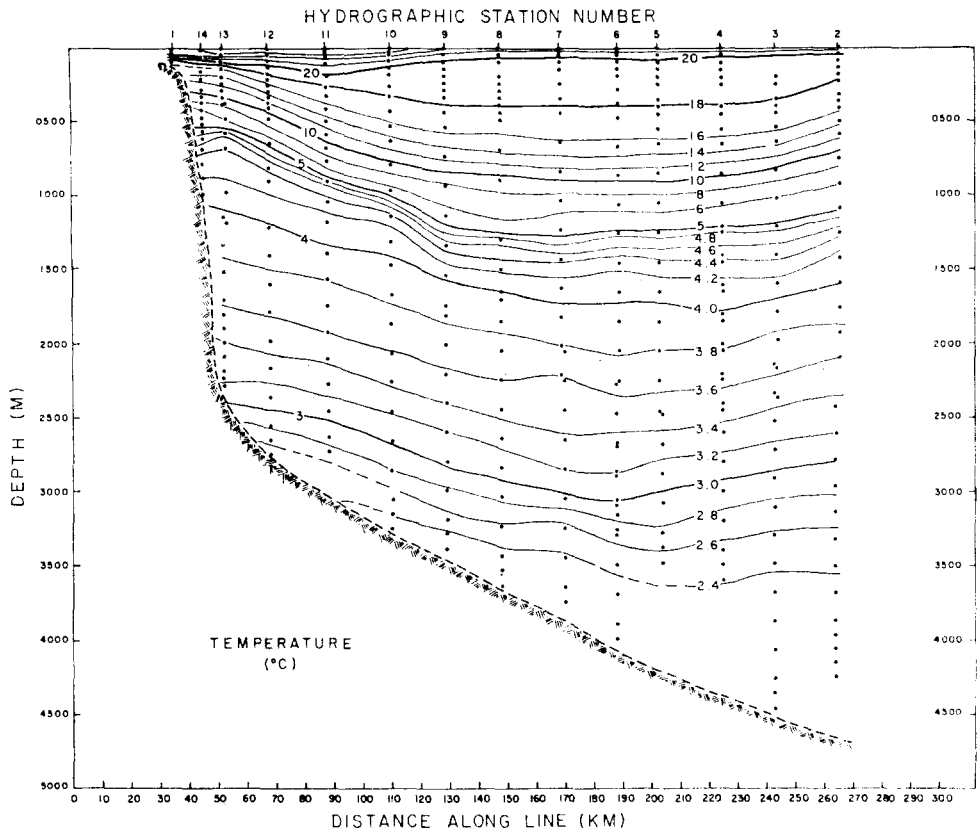
Fig. 10.   Vertical section of temperature across the Gulf Stream (26 June to 30 June).

of 6·10 ml/l. in the 2·5°C range off Puerto Rico. Lower values of dissolved oxygen than these are found in the Sargasso Sea offshore of these areas. Oxygen values on the *Trident* cruise are shown in Fig. 11. It can be seen that high oxygen values are found adjacent to the continental slope in potential temperature regions of 2·5 and 3·51 to 4·00°C. The oxygen values decrease from left to right across the section with no obvious discontinuities.

Both the high oxygen values and the large salinity anomalies do not come from the Sargasso Sea nor do they originate in the Gulf Stream waters. They can be related to southward spreading Labrador Basin and slope water. In these sections the water adjacent to the continental slope has a large salinity anomaly and a high oxygen content but these decrease in an offshore direction. There are no obvious discontinuities to mark the north and southward flows. This lack of significant differences in salinity and oxygen values in the north and south deep flows makes differentiation of the deep Gulf Stream and Western Boundary Undercurrent impossible in this area even though the characteristics of the Western Boundary Undercurrent are apparent here across the section. The continuous nature of the properties across the section and the location of the Western Boundary Undercurrent in relation to the Gulf
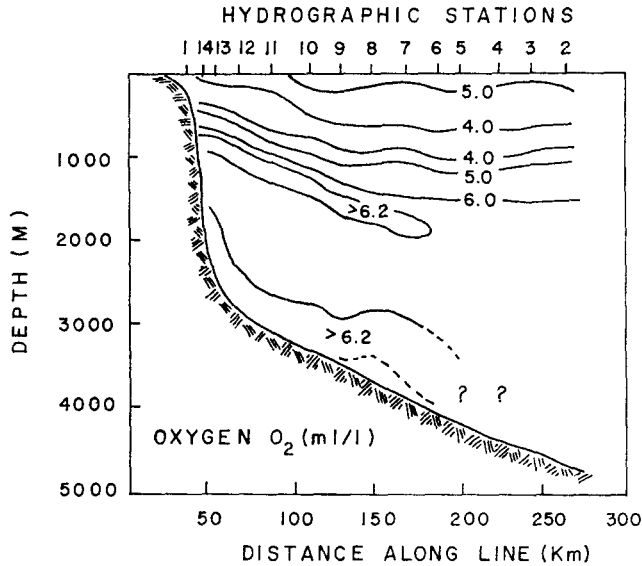
HYDROGRAPHIC STATIONS

Fig. 11.   Vertical section of oxygen in ml/l. across the Gulf Stream (26 June to 30 June).

Stream—to the left of the Gulf Stream off New England, to the right off South Carolina—suggest that one can include the southward flow on the right as part of the southward transport of the Western Boundary Undercurrent at this location. We observed southward flow on the right on two transport sections and southward flow is inferred from the hydrographic section. The salinity and dissolved oxygen values of the southward moving water observed to the south of this section can be related to the properties of the southward moving Labrador Sea water. This distribution of properties is consistent with the idea that the southward flow on the right is part of the Western Boundary Undercurrent.

Variation in position and direction of the Gulf Stream

The position and direction of the maximum transport varied over the four sections. There is a curious correlation between the position and the direction of transport as can be seen in Fig. 12. This relationship is of unknown significance.

The location of maximum transport was picked from the curves of unit transport (Fig. 2). The location of surface velocity was picked from curves of surface velocity determined by tracking transport floats on the surface. Direction was determined by using the transport values in the central part of the Stream (over 300 m^2/sec) determined from surface-to-bottom floats. To find the direction of the Gulf Stream, the transport perpendicular to the baseline was divided by the transport parallel to the baseline giving the tangent of the transport to the line. The direction of flow is greater than that reported by RICHARDSON and KNAUSS (1970) due to the discovery of a 5° systematic error.

The data are summarized in Table 2 below.

Table 2. Summary of results of the four transport float crossings.

Crossing	Transport ($\times$ 10⁶m³/s)	Location of maximum transport (km)	Location of maximum surface velocity (km)	Direction of flow (deg. true)
1	58	87	52	50
2	—	63	—	39
3	67	73	54	43
4	64	97	74	62

When the angle is largest, on the fourth crossing, the location of maximum transport is farthest offshore, and when the angle is smallest, on the second crossing, the maximum transport is closest inshore. The four direct transport transects took place apparently as the maximum current moved inshore from a point 87 km along the line to a minimum distance of 63 km and then offshore again to 97 km. The BT sections show a comparable sideways shifting of the temperature field. The location of maximum transport moved at an average rate of four km per day with a maximum rate of 6 km per day between crossings three and four. The average direction change was 2° per day with a maximum of 5° per day between crossings three and four.
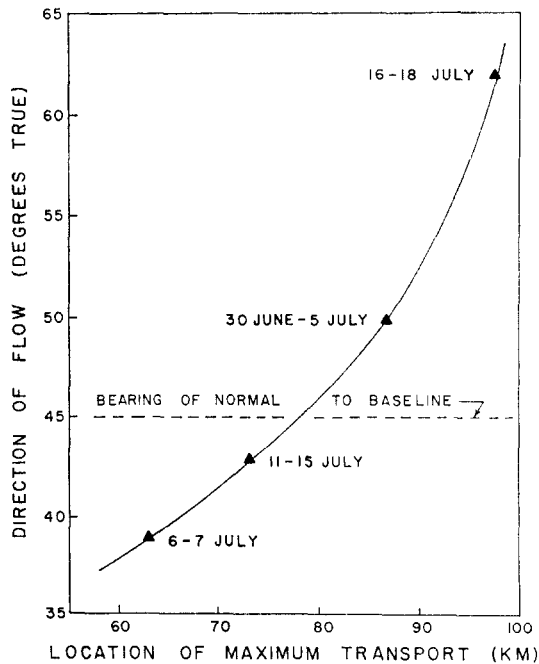

Fig. 12. The relationship between the direction of flow and the position of maximum transport.

These data suggest that large shifts of the central portion of the Gulf Stream (20 km) occur over periods of 5 days. It is clear that the measurements of transport of the Gulf Stream should be made over a period that is small compared to the significant shifts of the Gulf Stream.

Cross-stream flow

To determine whether there was any net cross-stream flow under the Stream, the following procedure was used. In the central portion of the Stream, the average direction of the surface transport was calculated from the surface-to-1000 m nominal depth. This amounted to 80% of the transport and for this determination it was considered to be the true direction of the Gulf Stream. The velocity of the deep layer, 1000 m to the bottom, was calculated in relation to this and the flow under the surface stream calculated. Only crossings one and four were used as only they had several surface-to-1000 m measurements available in the center of the Stream. The data are summarized in Table 3 below.

Table 3. Cross-stream velocity data.

	Direction of surface flow (0–1000 m) (°T)	Direction of deep flow (1000 m–bottom) (°T)	Cross-stream transport (offshore) (m²/sec)	Cross-stream velocity in deep water (cm/sec)
Crossing 1	43	99	49	2
Crossing 4	55	74	64	3

The transport per unit width, normal to the direction of the stream, is approximately 50–60 m²/sec. The direction of the flow is offshore. The agreement between crossings 1 and 4 appears to be better than one could reasonably hope for. The standard deviation of the individual cross-stream transport values is approximately the same size as the average cross-stream transport value. The cross-stream transport amounts to an average cross-stream velocity of 2–3 cm/sec from 1000 m to the bottom. This velocity is of the same order as the velocity in the direction of the Gulf Stream at depth.

While it is obvious that the Gulf Stream is not a stationary system, it can be seen from Fig. 12 that the first transect was made as the Gulf Stream was moving inshore and the fourth transect made as it was moving offshore again. Thus it is suggested that the deep cross-stream flow is not dependent on the offshore movement of the maximum current.

DISCUSSION AND CONCLUSION

Although the detailed structure of the Gulf Stream varied during the 23 days of the investigation, it was possible to obtain a coherent picture of the mean flow. The transport was $63 \times 10^6 \mathrm{m}^3/\mathrm{sec}$ averaged over three crossings. The value is consistent with other estimates of the transport of the Gulf Stream in this region (KNAUSS, 1969a). The edges of the Gulf Stream for these determinations were defined as the points at which the unit width transport in a downstream direction vanished. Transport floats showed the average width of the Gulf Stream was 135 km. Its width was reduced at 3000 m where it reached the bottom. There was a counter transport on each side of the Gulf Stream.

The high velocity region of the Gulf Stream slopes seaward with depth. Measured from the landward edge of the Gulf Stream, the maximum surface velocity is at about 20 km, the maximum transport per unit width at 45 km, and the maximum deep velocity at about 70 km. Data from transport floats also showed that 80% of transport was above 900 m and that there was a deep countercurrent on both sides of the central core.

It is possible to compare transport measured directly with transport calculated by means of the geostrophic relation from the series of hydrographic stations made at the beginning of the program. When the transport is made to agree by a force fit, a consistent velocity picture results, including a Gulf Stream that extends to the bottom, flanked by deep countercurrents. The geostrophic calculations also indicated a large surface counterflow seaward of the region of transport float observations.

During the 23 day period, the location of the maximum transport per unit width shifted, first landward and then seaward, over a range of 35 km. This shift was accompanied by a shift in the direction of flow.

The relationship between the Gulf Stream and the WBUC in this region continues to be a puzzling one. The observational information can be summarized as follows: (a) all attempts at measuring the near bottom velocity of the Gulf Stream indicate that the Gulf Stream goes to the bottom. To the best of our knowledge there is no contrary evidence. Furthermore, the observed meander pattern of the Gulf Stream can be explained at least in part by assuming the Gulf Stream extends to the bottom. (b) There is good evidence for a continuous WBUC along the continental slope and rise from at least southeast of Cape Cod to 200 km south of Cape Hatteras. The evidence is based on direct measurement of the current by SWALLOW and WORTHINGTON (1961), VOLKMANN (1962), BARRETT (1965) and ZIMMERMAN and HOLLISTER (1970); water mass analysis by BARRETT (1965); bottom photography by SCHNEIDER, FOX, HOLLISTER, NEEDHAM and HEEZEN (1967) and ROWE and MENZIES (1968); and the distribution of the bottom sediments reported by HEEZEN, HOLLISTER and RUDDIMAN (1966). NEEDHAM, HABIB and HEEZEN (1969) were able to trace the southward transport of sediment from southeastern Canada to the Blake–Bahama outer ridge and suggest that the WBUC has been active for at least the last 300,000 years. (c) No one has succeeded in separating the deep Gulf Stream from the WBUC on the basis of water characteristics. There appears to be a continuous gradation in temperature, salinity and oxygen as one passes from the WBUC landward of the Gulf Stream, through the Gulf Stream, and into the continuation of the WBUC off the Blake Plateau. The Gulf Stream and the WBUC are identifiable only by their velocity fields.

(d) There is marginal evidence for a cross-stream component to the flow of the deep Gulf Stream compared to its surface direction. This can be seen by a comparison of the results reported by Barrett (1965) and Webster (1965) where the neutrally buoyant floats in the deep Gulf Stream had a cross-stream seaward component of about 1 cm/sec compared to the average surface velocity direction as recorded by the GEK. The transport float data reported here shows a cross-stream seaward flow of 2–3 cm/sec of the water below 1000 m compared with the water in the top 1000 m. It should be emphasized that in both cases the indicated cross-stream component is scarcely above measurement error.

In 1966 one of us proposed a simple flow pattern that has the water of the WBUC passing through the Gulf Stream (Knauss, 1969b). There was no intent then, nor is there now, to suggest that such a simple non-turbulent picture could prevail. However, until there is more detailed information about what must be a very complex flow pattern, the simple picture in that paper seems to fit the observational data as well as any.

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