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An observation of a deep countercurrent in the Western North Atlantic

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INTRODUCTION

THE DEPTH of the level of no motion under the Gulf Stream has been a matter of interest to oceanographers for many years, and widely-varying estimates of the volume-transport have been arrived at, according to the choice of reference level. DIETRICH (1936) used the oxygen-minimum as a reference surface, at a depth of about 800 metres, but it was pointed out by ROSSBY (1936) that this choice implied the existence of a deep counter-current with a transport more than double that in the upper layers. ISELIN (1936) in his study of the circulation of the western North Atlantic, presented currents calculated relative to the 2000-decibar surface, and from the observations available at that time it appeared that the dynamic topography in the deeper water was relatively weak. DEFANT (1941) chose a surface of no motion sloping downwards from west to east, at a depth of about 1500 m under the Gulf Stream off Cape Hatteras, and calculated southward velocities of the order of 3 to 6 cm/sec at 2000 m depth. The high oxygen content of the deep water in this region was recognized as being consistent with a southward flow (ISELIN, 1936) but the notion of a current increasing in velocity towards the bottom was rejected by many oceanographers as unlikely (SVERDRUP *et al.*, 1942, p. 456).

Three recent developments led to renewed interest in this problem and to the measurements described here. During the last few years the R.V. *Atlantis* of the Woods Hole Oceanographic Institution has made a number of more detailed hydrographic sections across the Gulf Stream, paying particular attention to the deep water, and it has become clear that the steep temperature gradients across the stream, already well known in the upper layers, persist all the way to the bottom (FIG. 1, Cape Romain Sect.). This implies, if the geostrophic equation is valid, a relatively strong narrow flow in the deep water, northward if the reference level is at the bottom, or southward below any mid-water reference level. No satisfactory choice could be made from considerations of continuity from one section to another, nor from the temperature-salinity relationship of the water masses themselves.

At the same time, STOMMEL (1956, 1957) devised a theoretical model of the circulation of the Atlantic Ocean which required, as an essential feature, the existence of a narrow southward current in the deep water at the western boundary.

A suitable instrument for making direct measurements of such a current was recently developed (SWALLOW, 1955, 1957) in the form of a neutrally-buoyant float, and it was arranged that the R.V. *Atlantis* should co-operate with the R.R.S. *Discovery*

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II of the British National Institute of Oceanography in current-measuring and water-sampling, in an attempt to detect the south-going current and to locate the level of no motion.

Parachute drogues (VOLKMANN, KNAUSS and VINE, 1956) were also available for current measurements at all depths, and a new method had been devised by A. S. LAUGHTON for measuring currents very near the bottom using an underwater camera.

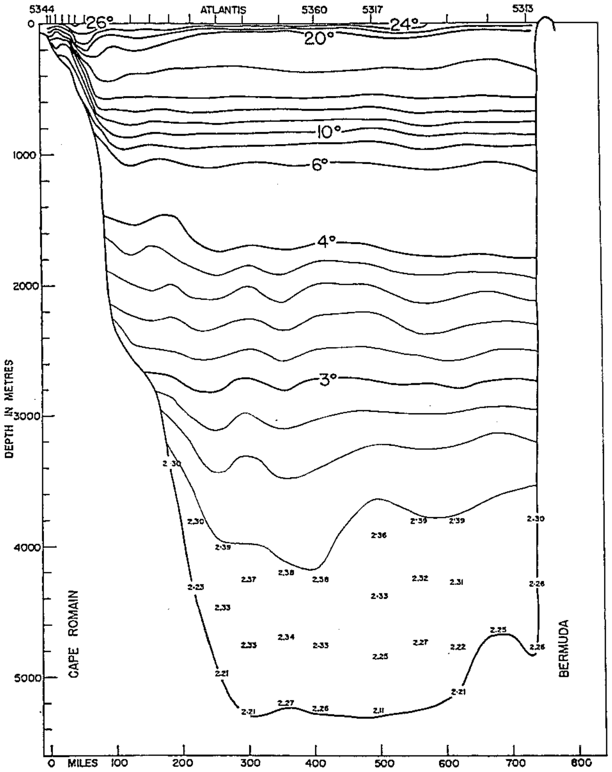

FIG. 1. Temperature Section, Cape Romain to Bermuda, made by *Atlantis* in June 1955.

It was planned that the *Atlantis* would first find the region of steep temperature gradients in the deep water, and then the *Discovery II* would make current measurements whilst the *Atlantis* occupied more hydrographic stations in the same area. Previous work had shown that, north of Cape Hatteras, the deep temperature gradients lay under the surface stream, and it was thought that surface currents of several knots would make deep current-measuring difficult. STOMMEL suggested that the most favourable area would be off Cape Romain, South Carolina, where

the surface stream flows over the Blake Plateau, and the deep temperature gradients are found farther off-shore at the foot of the continental slope. Farther south, the deep temperature gradients become weaker, and it was decided to work as near as was practicable to the point of departure of the surface stream from the Blake Plateau.

METHODS OF MEASURING CURRENTS

In tracking neutrally-buoyant floats or parachute drogues, the accuracy of the measurement is limited by uncertainties in fixing the ship's position. The area chosen for the present measurements was within the ground-wave coverage of Loran stations 1H6 and 1H7, and good fixes could be obtained from them at most times. For the greater part of the work, the Loran readings were combined with radar fixes on an anchored buoy. This allowed averaging over groups of Loran readings, giving an improvement in accuracy and an estimate of the remaining uncertainty.

The parachute drogues, and their method of use, have been fully described by VOLKMANN, KNAUSS and VINE (1956), and the same technique was used in the present measurements, except that more use was made of radar in fixing the drogues. Although it seemed possible that a fairly strong deep countercurrent, of the order of 10 cm/sec, might be detected by this means, the results with the deep drogues were rendered uncertain by strong variable winds and surface currents, and only the measurements in the upper layers are considered reliable. Surface currents were measured occasionally by releasing fluorescein dye near the anchored buoy, and tracking it for a few hours.

One successful measurement of current near the bottom was made by the photographic method. A deep-sea camera (LAUGHTON, 1957) was mounted on a tripod looking vertically downward, and took a series of 60 photographs while on the bottom for 24 minutes. The orientation and tilt of the tripod were obtained from a combined compass and clinometer in the field of view. Two methods of current registration were used. First, drops of neutrally-buoyant aniline were ejected into the water from a spring-loaded hypodermic syringe. The velocities were higher than expected however, producing a large number of small drops (more than one per picture) so that only the direction and not the speed of the current could be obtained from them. The second method used was to observe the deflection from the vertical of a free-flooding ping-pong ball suspended on a thin thread. This angle could be calculated from the photographs, dimensions of the camera tripod and ball suspension being known. A calibration was made by towing a similar ball suspension in a tank at known velocities and measuring the deflection. Unfortunately, in an attempt to make another current measurement, the entire assembly was lost. The calibration could not therefore be made on the original ball, and one having the mean properties of six different makes was used instead.

The neutrally-buoyant floats, and the equipment used for receiving their sound signals, have already been described (SWALLOW, 1955, 1957). Only a brief account has been given previously of the method of operation, and some further details are given below.

First, the float has to be loaded to make it sink to the required depth. This load is calculated as follows. Each complete float is made neutrally-buoyant in a tank of salt water of known density and temperature. This adjustment is made to within 1 gm in a float weighing 10 kg, or 1 in 10^4. Suppose the density is ρ_0 at temperature T_0. Then the density of the float at depth D meters, where the temperature is T, will be approximately

$$\rho_0\,(1 + kD - \alpha\,(T - T_0))$$

where k is the bulk compressibility of the float, per metre depth change, and α is the coefficient of volume expansion of the float material. For the tubes used, k was $15\ (\pm\ 1) \times 10^{-7}$ per metre, and α was 69×10^{-6} per °C.

If the density of the sea water at the required depth D is ρ (*in situ*) obtained from observations of temperature and salinity, then the extra load needed to make the float sink to that depth is

$$\delta M = M \left(\frac{\rho\ (in\ situ)}{\rho_0\,(1 + kD - \alpha\,(T - T_0))} - 1 \right)$$

where M is the mass of the float.

An allowance has to be made for movement of the rubber sealing rings in the end plugs, under pressure, and for the extra compressibility of the insulation on the transducer winding. Previous experience suggested that the calculated load should be reduced by 6 gms to allow for these effects.

Each float was tested for leaks, and for satisfactory working of its sound transmitter, by lowering it on a wire to more than the required working depth (usually 3000 m). If all was well when the float was recovered, the calculated load would be added and the float dropped over the side at a chosen position. They take three or four hours to sink to the stable depth, and usually no fixes were taken during that period.

Bearings could be obtained on the acoustic transmitter by stopping the ship head-to-wind and putting two hydrophones over the side, about 30 m apart. As the ship fell away from the wind direction, the path difference between the signals arriving at the two hydrophones was observed as a function of the bearing of the ship's head relative to north. Fig. 2 is a block diagram of the receiving equipment. The path difference was measured as a time delay on an oscilloscope. It was usually in the range 0 to 20 milliseconds and could be estimated with an accuracy of about $\frac{1}{2}$ milli-second. The amplifiers were tuned to 10 kc/s, with a bandwidth of about 500 c/s. In taking a bearing, a series of from six to ten readings of the time difference t was taken, while the ship's head swung through an arc of about 60°. If $t_{\max}$ is the time difference that would be observed with the ship heading directly towards the float, then

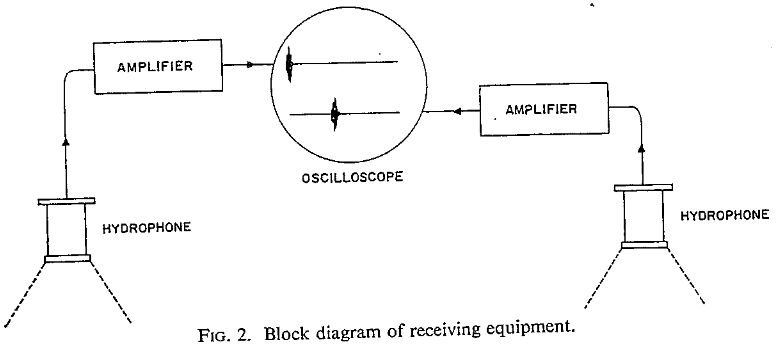

Fig. 2. Block diagram of receiving equipment.

$$t = t_{\max} \cos(\phi - \theta)$$

where ϕ is the heading of the ship, and θ is the bearing of the float, relative to north (Fig. 3). To determine θ and $t_{\max}$ from the series of observations of t and ϕ, rays were plotted at successive values of ϕ, and lines were drawn at right angles to them at distances from the centre proportional to the corresponding values of t. These lines should all pass through a point, at a distance proportional to $t_{\max}$ from the centre and on the ray making an angle θ with north (Fig. 4a).

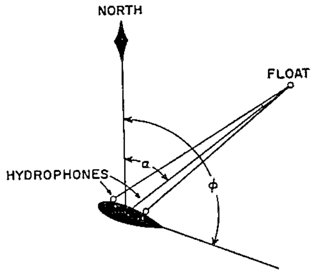

Fig. 3. Taking a bearing on a float.

Three or more bearings were taken in quick succession from different positions, their intersection defining the position of the float in a horizontal plane. It usually took about an hour to complete three bearings, in the R.R.S. *Discovery II*. To determine the ship's position, radar fixes and Loran readings were usually taken before and after each bearing. In most cases, the bearings intersected sufficiently well (Fig. 4b) for the position of the float to be determined relative to the anchored buoy with an error of less than 0·2 km, so that the six Loran fixes could be run together to give a mean Loran position for the float at the mean time of taking the bearings. To simplify the transferring of these fixes, a Loran plotting sheet for the area on a scale of 1 in. to the mile (1 cm to 0·73 km) was made by interpolation from Loran tables (USNHO Pub. 221). A minimum estimate of the uncertainty of the mean position could be obtained from the scatter of the individual Loran readings; this will be discussed below.

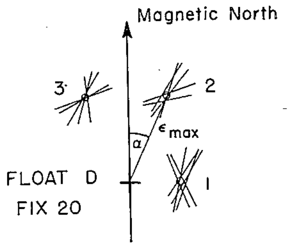

Fig. 4a. Part of laboratory plotting sheet.

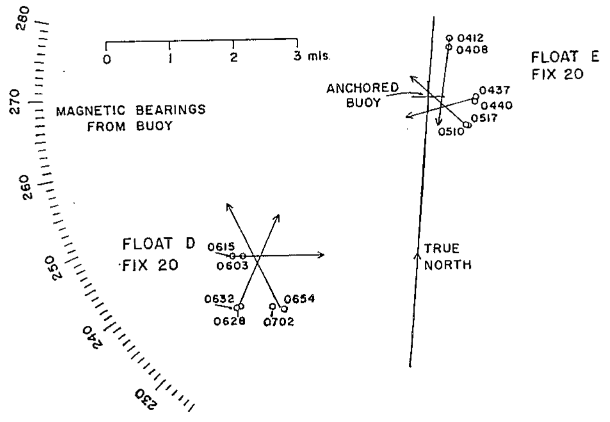

Fig. 4b. Part of a navigational plotting sheet.

When current-measurements were in progress, the deck officer on watch, assisted by one member of the scientific party, took the radar and Loran readings and kept a plot of the ship's movements relative to the anchored buoy on a 1 in. to the mile plotting sheet. At the same time, two others in the laboratory below took the oscilloscope readings and plotted them against ship's head to obtain bearings on the float, putting out hydrophones and recovering them as required. As each bearing was obtained, it was transferred to the navigational plotting sheet, and a suitable position was then chosen for taking the next bearing. Fig. 4a is an example of the laboratory plot for obtaining bearings, and Fig. 4b is part of a navigational plotting sheet.

Some of the floats moved quickly out of radar range of an anchored buoy and, instead of anchoring more buoys, tracking was continued using Loran only, the ship's positions being plotted directly on the large scale Loran plotting sheet.

The depth at which a float has stabilized itself can be estimated, each time a bearing is taken, from the observed value of $t_{\max}$ and the horizontal distance between the float and the ship. Fig. 5 is a vertical section showing the ship heading directly towards the float, when a time difference $t_{\max}$ will be observed. If l is the distance between the hydrophones, and the velocity of sound in the surface layer of water is V_0, then l/V_0 is the maximum time difference that would be observed if the float were at the surface, and when it is submerged the ratio $V_0\, t_{\max}/l$ is the cosine of the angle between the horizontal and the rays arriving at the ship. Assuming that, below a relatively thin surface layer, sounds travel from the depth of the float with a uniform velocity V_m, the angle δ between the sound rays and the horizontal, over most of their path, will be given by

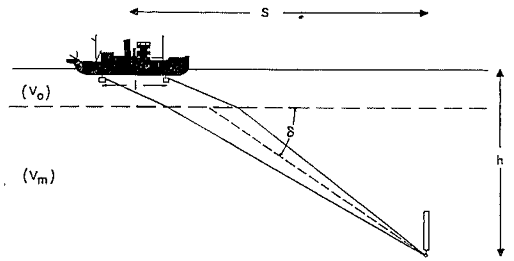

Fig. 5. Estimating the depth of a float.

$$\delta = \text{arc cos}\left(\frac{V_0\, t_{\max}}{l} \times \frac{V_m}{V_0}\right), \quad \text{or} \quad \text{arc cos}\left(\frac{V_m\, t_{\max}}{l}\right)$$

The horizontal range, s, is obtained from the radar plot of the ship's position as each bearing is taken (Fig. 4b) and the depth h is given by

$$h = s \tan \delta$$

The mean velocity V_m can be obtained from the vertical profile of temperature and salinity, using suitable tables (e.g. Matthews, 1939). A value of the depth can thus be calculated for each bearing. The individual estimates show considerable scatter, but the mean value is usually within one or two hundred metres of the expected depth. Part of the scatter arises from uncertainties in the relative positions of the ship as determined by radar, and movements of the float and anchored buoy during a group of bearings. When Loran only was used, the uncertainties of relative positions were often too great for useful depth calculations to be made.

As a check on the validity of the assumption that a mean sound velocity may be used, the ray paths were calculated in detail in a few cases. The error introduced in the calculated depth by using the mean velocity was only a few tenths of one per cent and may be neglected.

To obtain the currents from the sequence of Loran fixes on the drifting floats, the positions were plotted on 1 in. to the mile scale. The north-south and east-west components were then plotted separately against time. Straight lines were then fitted by least squares to these displacement-time curves; in some cases where a change in the current seems to have occurred, the sequence was divided into two parts and separate lines fitted. The components of current derived from the slopes of these lines were then recombined to give the resultant velocities and directions of the mean currents.

ACCURACY OF NAVIGATION

Estimates of the r.m.s. error of a single Loran observation on the *Discovery II* were made from the scatter in the readings taken at each fix on a float. During the first part of the cruise, 82 pairs of Loran readings were taken during 20 fixes on a single float, and the r.m.s. error of a single Loran reading was 3·8 μs on 1H6 and 3·9 μs on 1H7. Some readings were missed because of poor reception, particularly on 1H7 at night. In the second part, 441 pairs of readings were taken during 73 fixes on floats; and the r.m.s. error of a single reading was 1·9 μs on 1H6 and 1·8 μs on 1H7. The decrease in scatter was due partly to improvements in the antenna system for the Loran receiver, and partly to increased operating experience. These correspond approximately to an r.m.s. error in position, for a single Loran reading, of 1·1 km in the first part and 0·6 km in the second part.

Systematic Loran errors due to fluctuations in propagation paths and lack of synchronism in transmitted pulses were unlikely to exceed 1 μs (Pierce *et al.*, 1948) since we were within the normal ground-wave area for these stations. Systematic differences between receivers, of 1 or 2 microseconds, were found on a few occasions when simultaneous fixes were taken from the two ships and their relative positions were measured at the same time by radar. The *Atlantis* Loran positions were adjusted to make them consistent with those of the *Discovery II*, but the existence of these differences suggests that the instrumental contribution to the error of absolute position may be about 0·6 km.

A single Loran fix on the *Discovery II* would then have an r.m.s. error of approximately 1·3 km in the first part of the cruise, and 0·9 km in the second part.

Fixes on floats, being based on from 4 to 8 pairs of Loran readings, should be self-consistent to within about 0.6 km in the first part, and 0.3 km in the second part, assuming that the instrumental Loran errors are fixed. The observed residuals from fitted straight lines are slightly greater, 0·7 km for the first float (B) and 0·6 km for the remainder. The residuals were analyzed for periodicities, but nothing significant was found.

On board the *Atlantis*, Loran fixes were taken at the beginning and end of each hydrographic station, on a receiver on the bridge, and a fix was taken on another receiver in the laboratory when the deep cast was put down. The accuracy of fixes could not be estimated from the scatter of these readings, since the drift due to surface current and wind was insufficiently well known, and sometimes the ship was manoeuvered to reduce the hydrographic wire angle. It is assumed that the r.m.s. error of a station position is approximately 0·9 km, and the error relative to the float positions is approximately 0·6 km.

DIRECT CURRENT MEASUREMENTS

Durring the first part of the cruise, from March 4th to 11th, work was confined to a small area near 32° 29′N, 75° 21′W. The weather was poor, and both ships were hove-to for two of the eight days. Seven parachute drogues were laid, but some were never seen again and only three were tracked for a day or more. Three neutrally-buoyant floats were used but only one gave a useful measurement. The first one laid was abandoned after one fix, after the *Discovery II* had collided with the anchored buoy and spent one night lying-to, with the buoy and its floats wrapped round the screw. A new buoy was anchored 6 km west of the previous position and another float (B) was released near it, loaded for 2000 m depth (Table 2). This float was tracked for two days, and then the weather turned bad. When work was resumed two days later, a third float was launched, loaded for 700 m, since it seemed likely that float B's batteries would have run down. The new float could not be found at first fix, but the old one was heard giving a weak signal, and tracking was continued for another day, when the *Discovery II* had to leave the area in order to refuel at Charleston, S.C.

In the second part of the cruise an area 75 km to the north-west, closer to the surface Gulf Stream, was chosen, and current measurements were continued from March 17th to April 2nd. Six parachute drogues were laid, four of which were followed for periods up to 3½ days. Eight neutrally-buoyant floats were used, seven of which moved in directions between south and south-west at depths exceeding 2500 m. The first one laid, D, moved slowly south-west for three days, when a shallower one, E, was laid. Both floats were followed for another two days, the deeper one continuing south-west and the shallower one moving first north, then curving westwards. Both were abandoned on March 22nd and two more floats, F and G, were launched next day, loaded for 2500 m. They were 7 km apart in an east-west direction, and both moved slightly west of south at about one-sixth of a knot. Float G was the slower, and converged towards float F. Deeper measurements were started on March

26th, when floats H and I were launched, loaded for 2800 m. Again they were laid 7 km apart, and about 6 km north of the starting point for floats F and G. Both moved quickly south, H making about ⅓ knot and I about ¼ knot. Again, the slower eastern track converged towards the other. These two floats went quickly out of radar range of the anchored buoy, and tracking continued using Loran only. They were abandoned on March 29th, by which time float H had travelled 41 km, and had caught up with another float previously abandoned (probably F). In the afternoon of March 29th the bottom current was measured using the photographic method, near the beginning of the track of float I. The direction of flow was very close to south.

Two more floats (J and K) were launched early next day, loaded for 2800 m. One of them was intended to be in the track of the previous fast-moving float H, and the other was 7 km to the west. Another bottom-current measurement was attempted in the afternoon, but the camera and tripod were lost due to the wire parting when only 150 m remained to be recovered. Tracking continued on the two floats and a parachute drogue, float J being followed until a.m. April 2nd.

The results of the current measurements are summarized below. Table 1 gives all the measurements with parachute drogues and surface dye markers. The surface currents are seen to be variable in strength and direction, but generally of the order of half a knot to the north-east. The two drogue measurements at 10 m depth both show a current of the order of 35 cm/sec slightly south of east, though the direction may have been influenced by wind, which was from 330° in both cases. The measurements at 200 m and 700 m indicate a northward or north-eastward flow in the upper layers, the latter being particularly convincing since it moved upwind, though the observed current may be too small on this account.

The three deepest parachute drogues all moved approximately north-east at about 0·1 knot. Such small currents are hardly significant in view of the shear, which may be of the order of 50 cm/sec between surface and bottom. The drogues at 2700 m and 2800 m might have been expected to move south, but it is possible that the strong shear may have prevented the parachutes from reaching their full depth.

The neutrally-buoyant float results are presented in Table 2. The seven measurements at depths below 2000 m show southward movement, and although large variations were found at given depths, a general increase towards the bottom is indicated. It seems likely that the mean depths, of 2580 m for floats D, F and G, and 2840 m for H, I, J and K, are more reliable measures of the depths reached by these floats than the individual determinations are. The large scatter, from 2760 m to 2910 m at a nominal depth of 2800 m, is probably not genuine, in view of the close similarity of design of the floats and the accuracy of adjustment of densities. The very small mean current observed with float B, shows that, at that time and place, the level of no motion was very close to 2000 m in depth.

Table 3 shows the results obtained with the bottom-current meter. Fluctuations in direction, exceeding the uncertainty of measurement, were observed with both the suspended ball and the aniline drops. These may be genuine, but are more probably due to instability of the ball or to turbulence caused by the presence of the tripod framework. The velocity obtained from the deflection of the ball is comparable with that of float I nearby at 2800 m depth ; the lower velocity obtained from dispersal of the mud cloud, formed on touching the sea floor, may be due to diffusion upstream or to its being nearer the bottom.

THE METHOD OF COMPUTING THE VELOCITY PROFILES AND VOLUME TRANSPORT OF THE DEEP COUNTERCURRENT

All that has been described so far has been concerned with the direct current measurements themselves. In order to provide velocity profiles and estimates of the volume transport of the deep countercurrent, the physical data, consisting of temperature and salinity observations must be related to these direct measurements. This has been done by means of the classical geostrophic equation.

Atlantis made an initial oceanographic section to establish where the deep geostrophic gradients were strongest and subsequently made a number of sections intended to cross the deep countercurrent in such a way as to intercept the path of a drifting

Table 1. Summary of current measurements with drogues and dye-markers, March–April 1957

Time and *from*	*date* *to*	*Position* *(mean)*	*Nominal depth* (m)	*Mean current* cm/sec	*Bearing towards* °T	*Remarks*
2103/6	0130/7	*	10	33	115°	Wind 10–20 knots from 330 °T
1510/7	—	*	0	—	070°	Observation too short for speed to be estimated
0858/7	1500/9	*	1800	4·5	057°	Wind variable, 10–50 knots, 340°–240°. Exceeded 30 knots for 24 hours, from 240°–270°
1320/9	1404/9	*	0	4·5	075°	Wind 30 knots from 270 °T
0815/10	0654/11	*	700	4·5	343°	Wind decreasing 25 knots to 12 knots, from 320 °T
0900/11	0915/11	*	0	20 approx.	045°	Observation too short for reliable estimate
1738/17	1837/17	33° 08′N 75° 45′W	0	43	003°	Wind 14 knots, from 090 °T
1315/18	1410/18	33° 07′N 75° 44′W	0	20 approx.	015°	Approximate current from visual range estimate
2200/18	2200/19	33° 11′N 75° 45′W	2700	5·3	015°	Wind variable, 18 knots from 150 °T veering to 25 knots from 260 °T
1136/19	1339/19	33° 05′N 75° 45′W	0	13	295°	
1105/23	1756/23	33° 01′N 75° 43′W	10	36	129°	Wind 15 knots from 330 °T
0912/24	1453/24	33° 04′N 75° 42′W	0	9	108°	
2300/29	0400/1	33° 08′N 75° 41′W	2800	6·1	035°	Wind variable, 15 knots from 320 °T, then calm, then 15 knots from 090 °T
1015/1	1125/1	33° 05′N 75° 47′W	200	74	033°	Parachute was probably still sinking, observed current may represent average for upper 100 m

*All above observations were made in vicinity of 32° 29′N, 75° 21′W (within 2 mls.).

Table 2. *Summary of current measurements with neutrally-buoyant floats, March–April,* 1957

Float	*Launched* (*time and date*)	*Last fix* (*time and date*)	*Intended depth* (m)	*Mean observed depth* ((m) ± st. dev.)	*Mean velocity* (cm/sec ± st. dev.)	*Direction* (°T ± st. dev.)	*Remarks*
B	1000/6	0743/11	2000	2040 ± 70	0·33 ± 0·11	108 °T ± 18°	
D	1715/17	0718/22	2500	*2550 ± 40	4·27 ± 0·21 1·88 ± 0·11	201 °T ± 1·4° 235 °T ± 4°	2206/17–0320/19 0636/19–0718/22
E	1527/20	1717/22	1500	1480 ± 50	6·42 ± 0·47 6·50 ± 0·29	308 °T ± 4·7° 231 °T ± 2·3°	1825/20–2135/21 0010/22–1717/22
F	0954/23	0733/25	2500	*2620 ± 80	8·99 ± 0·53	190 °T ± 2·3°	
G	2050/23	1032/26	2500	*2600 ± 50	4·41 ± 0·26 7·08 ± 0·44	218 °T ± 3·3° 203 °T ± 2·3°	0002/24–0314/25 1110/25–1032/26
H	0815/26	0605/29	2800	†2910 ± 70	18·36 ± 0·28	182 °T ± 1·0°	
I	0854/26	1040/29	2800	†2760 ± 190	6·02 ± 0·27 12·62 ± 0·39	216 °T ± 2·6° 196 °T ± 1·3°	1424/26–0555/27 1715/27–1040/29
J	1110/30	1103/2	2800	†2900 ± 120	10·24 ± 0·18 9·42 ± 0·22	204 °T ± 1·7° 185 °T ± 11°	1347/30–0034/1 0858/1–1103/2
K	1156/30	0935/31	2800	†2770 ± 200	12·95 ± 0·59	207 °T ± 5·2°	

*Mean for D, F and G = 2580 m.
†Mean for H, I, J and K = 2840 m.

Table 3. *Results of measurements with photographic bottom-current meter*

Date	*Time*	*Position*	*Depth* (m)	*Mean current* (cm/sec)	*Bearing towards* °T	*Remarks*
29/3	1613–1636	33° 07′N 75° 42′W	3230	—	173° ± 11°	From movement of aniline drops
				11·5 ± 1·5	182° ± 6°	From deflection of ball, 40 cm above bottom
				5	ca. 180°	From dispersal of mud cloud, ca. 20 cm above bottom

float. When a section successfully crossed the path of a float, only one direct measurement was available. On the basis of this one measurement, the level of no motion between the pair of stations on either side of the float could be easily determined.

This was done by first computing the velocity between the two stations relative to an arbitrary level, usually 1500 m, and drawing a curve for velocity versus depth. The observed velocity (the component of the float's drift at right angles to the pair of stations) was plotted on the same graph at the depth of the float. Then the velocity depth curve was corrected at all levels by the difference between the observed velocity and the velocity given by the original curve at the float's depth. The depth at which the corrected curve crossed the 0 velocity line was taken to be the depth of the level of no motion.

So far, no assumptions had been made beyond those always made in dynamic computations, but in ascribing levels of no motion to other pairs of stations a further assumption was made. This was that the level of no motion between these stations fell at the same potential temperature surface as it did between stations where direct measurements were available.

The potential temperature/salinity relationship in this region is extremely reliable. The average deviation from the mean Θ/S curve is only 0·0035‰. In consequence, a potential temperature surface represents a potential density ($\sigma\Theta$) surface. These $\sigma\Theta$ surfaces sloped downwards in an offshore direction and the surfaces taken as levels of no motion in this work, always fell in a region of small vertical shear. They are in accord with Defant's (1941) requirements for the determination of the level of no motion. If one were to assume, for example, that the potential density surface at the position of the float was a constant velocity surface, the result would be that large volume transports would occur at the ends of the sections where little or no geostrophic gradients occurred.

The dynamic computations were performed according to Helland-Hansen's formula given in Proudman (1953, pp. 64 and 65), with one important exception. This was that instead of using the individual temperature and salinity, an average potential temperature vs. salinity curve was used to determine the specific volume anomaly ($10^5\,\delta$) at temperatures below the 4° isotherm, which lies at a depth of about 1500 metres in the region where the measurements were made. This was done because the Θ/S relationship is extremely reliable in this part of the Atlantic and also (since this was known beforehand) because salinity samples were not drawn on many of the stations.

The average deviation from a smooth Θ/S curve on this cruise was 0·0035‰ of salinity, (based on 538 observations below the 4° isotherm). Since this figure approaches that of the sensitivity of the Woods Hole salinometer (Schleicher and Bradshaw, 1956),* it seemed better to assume that the small irregularities which do occur are more likely to be caused by errors in the water sampling and analysis than by any real change in the Θ/S relationship in the ocean. Another reason why this method is preferred, is that error of analysis with the salinometer cannot be expected to be random. The instrument was standardized against Copenhagen Standard water at the beginning and end of each day's work, (about 125 samples). If one day's standardization differs by as little as 0·002‰ from that of the next day, a measurable difference in $10^5\,\delta$ can result; moreover, the instrument drifted during the course of a day's work by as much as 0·004‰ (average 0·003‰). Provided that this drift is at a constant rate no inaccuracy results, but it is by no means certain that the drift is constant.

Both these sources of error are of the sort which would tend toward very small but systematic error in salinity. In North Atlantic deep water, an error of 0·003‰ in salinity (at constant temperature) results in an error of 0·23 in $10^5\,\delta$. This error is negligible if it is a random error, occurring on either side of the true Θ/S curve with more or less the same frequency, but if it is a systematic error occurring only on one side of the Θ/S curve it becomes serious. An error of 0·23 in $10^5\,\delta$ compounded over a 1000 metre water column causes an error in dynamic height of 0·0023 dynamic metres. In latitude 33°, where these observations were made, this would result in a systematic velocity error of 3 cm/sec if the stations concerned are 10 km apart; this amount makes a considerable difference in determining the level of no motion. However, a random error remains even if the Θ/S curve is exact since there is an uncertainty of 0·01°C in each observation of temperature. This results in an uncertainty of velocity of 1 cm/sec, if the float is 1000 m below the reference level, and the stations are 10 km apart. An uncertainty of twice this amount (in addition to the systematic error) results if the individual temperature and salinity values are used.

Above the 4° isotherm the temperature/salinity relationship is less reliable and the values of $10^5\,\delta$ were obtained from the individual values of temperature and salinity at each Nansen bottle.

The volume transports were computed simply according to area x velocity. Transports were obtained for each standard depth interval between each pair of stations. The mean of the velocities at the top and bottom of each layer was used.

Since the observations were made across a sloping ocean floor, there were small areas adjacent to the bottom which fell below the greatest depth of observation at the inshore stations of each pair. In these cases, it was assumed that the velocity remained unchanged below the deepest standard depth. The size of these areas was determined by planimeter after the bottom contour had been drawn in. These areas were quite small since a 200 m standard depth interval was used and most of the stations extended almost to the bottom, (33 per cent of the stations extended to the bottom itself and 72 per cent to within 100 metres of the bottom).

THE ATLANTIS SECTIONS

2–4 *March*

The first section (stations 5476–5483) was made by *Atlantis* before the arrival of *Discovery II*. Its purpose was to establish where the strongest deep pressure gradients were to be found, so that the floats could be properly placed. The best spot seemed to be at about 32° 30′N 75° 20′W; here the slope of the deep isotherms was the steepest. The depth at this position is 3700 metres, which is well up the continental slope from the abyssal plain (5200 m) as had been expected from the Cape Romain section (Fig. 1).

6 *March*

The first successful float, B, was launched in this region and remained there, almost stationary, at a depth of 2070 metres for four and a half days.

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*It can be appreciated that salinity values obtained by Knudsen titration would be entirely useless for dynamic computations of this kind since the errors of that method are about 7 times as large.

6–7 *March*

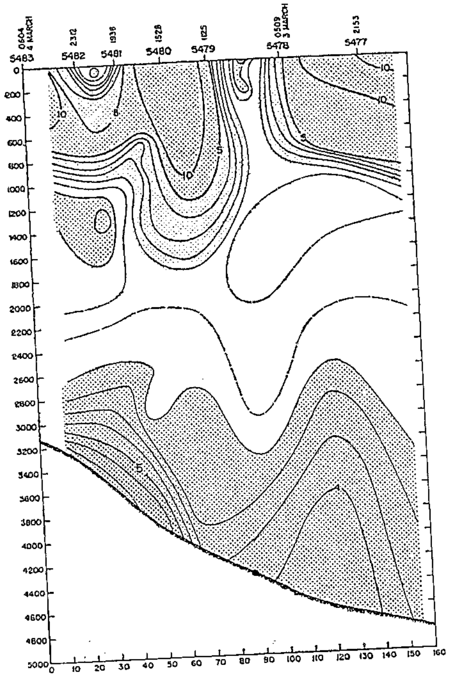
While this float was drifting at this level, Section II (stations 5484–5489) was made across the position of the float, bracketing it between stations 5485 and 5486. The level of no motion was assumed to be 2070 metres between these stations as indicated by the float. A potential temperature of 3·44° was found at 2070 metres at the float (the average potential temperature of stations 5485 and 5486 at that depth) and this potential temperature surface was assumed to be motionless between the other pairs of stations on this section, as described in the previous chapter on methods of computation. The resulting velocity profile (FIG. 6) shows a consistent southerly current below the reference level. The volume transport of this current was 3·5 million m³/sec. Most subsequent sections showed larger volume transports and it may be that the section was too short. This was the only section in the first part of the cruise which crossed the track of a float. However, two more sections (I and III) were made before both ships went into Charleston. Section I was the exploratory section already described and Section III was made at the conclusion of the first half of the cruise to see whether the deep gradients were any stronger to the north.

It seems reasonable to assign the same temperature to the reference level on these two sections, particularly since the first two sections made after leaving Charleston showed a potential temperature of 3·43° at the reference level, a change of only 0·01°. The velocity profile of Section I (FIG. 7) shows a stronger southerly current than that of Section II. The current seems to be divided into two halves with almost no transport taking place between stations 5479 and 5480. The total transport of the undercurrent in the section was 6·8 million m³/sec. It is possible that the offshore half of the current is not the undercurrent proper (its salinities are slightly higher at the same potential temperature). If this is taken to be the case, the volume transport (stations 5479–5483) is reduced to 4·1 million m³/sec, a figure in better agreement with those of subsequent sections. These were admittedly shorter.

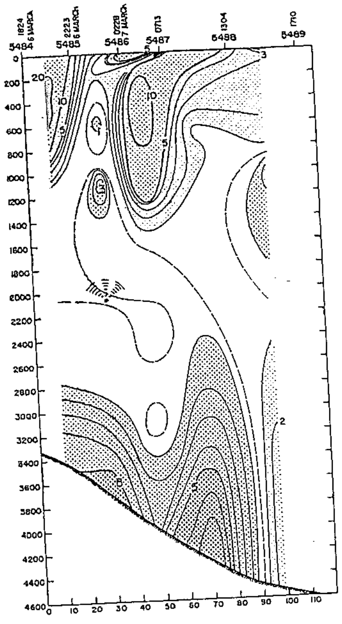
11–12 *March*

Section III (FIG. 8) revealed that the gradients were indeed stronger to the north of the first working area and it was decided to move to the neighbourhood of this section for the second half of the work. The current was far narrower and swifter than before although roughly the same volume transport was computed; 4·4 million m³/sec. The surface velocities of the Florida Current were much stronger as was to be expected but were not, as it turned out, sufficiently strong to hamper the deep measurements.

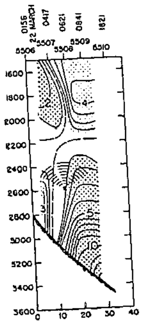
During the second half of the cruise, most of the stations consisted of one series of eleven bottles which extended from 1500 metres to the bottom in most cases. It was clearly desirable to make the stations as rapidly as possible, since in many cases two floats were adrift at the same time, and it was felt that the undercurrent lay wholly below the 1500 metre level. In retrospect, it would perhaps have been better to have extended these stations up to the 1200 metre level in order to include more of the northward flowing water but this would have decreased the density of the observations in the undercurrent itself.



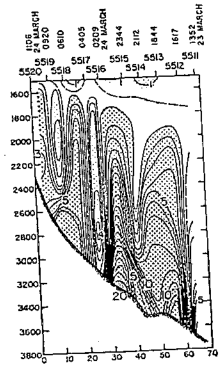
SECTION I, 2-4 MARCH



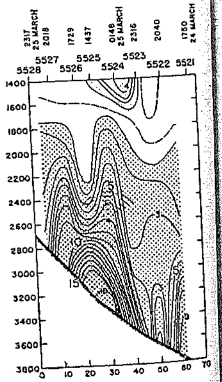
SECTION II, 6-7 MARCH



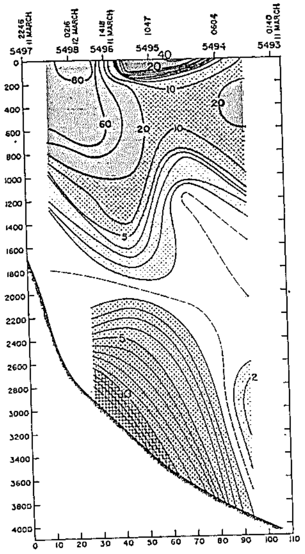
SECTION V MARCH 22



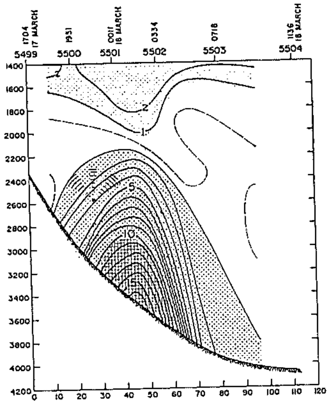
SECTION VI, 23-24 MARCH



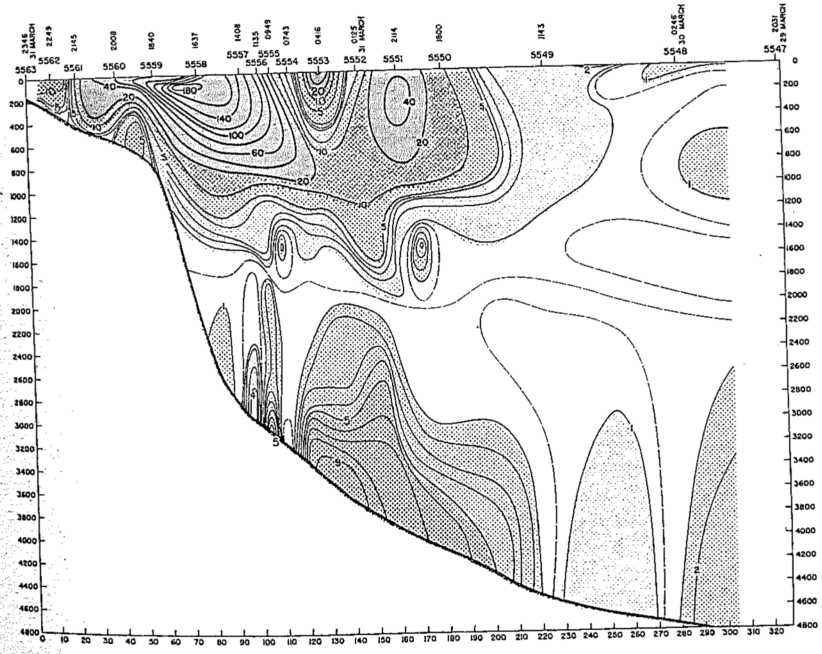
SECTION VII, 24-25 MARCH



SECTION III, 11-12 MARCH



SECTION IV, 17-18 MARCH



SECTION VIII, MARCH 29-31

16 *March*

After leaving Charleston, *Discovery II* preceded *Atlantis* to the new operating area which was centred at 33° 03′N, 75° 45′W. Section III had indicated that the strongest deep currents should be found above the 3150 metre depth contour.

17–18 *March*

Float D was launched at this contour and *Atlantis* made her fourth section (stations 5499–5504) across the path of this float, bracketing it between stations 5500 and 5501. The southerly component of velocity at right angles to these stations was measured by the float as 3·7 cm/sec at 2580 metres. The level of no motion between these two stations was 1950 metres and the potential temperature at that depth was 3·43°. The velocity section (Section IV, FIG. 9) shows a remarkably steady and symmetrical southerly current; this is probably due in part to the somewhat wider spacing of stations, (about 18 km). The volume transport of this current was computed at 4·1 million m³/sec. The float was not in the swiftest part of the undercurrent which seemed to have meandered about 20 km offshore between the times of Section III and Section IV.

The next section was delayed partly by bad weather and partly because *Atlantis* took an injured scientist from *Discovery II* in to Morehead City for medical treatment. By this time, float D was still working but it was drifting much more slowly.

22 *March*

Atlantis made a short section (No. V, stations 5506–5510, FIG. 10) across the path of float D making no effort to cross the entire current but getting another estimate of the level of no motion. Float D's track was crossed between stations 5507 and 5508 and it showed a velocity component of 0·91 cm/sec at right angles to a line drawn between these stations. The computations gave a level of no motion at 2150 metres and the potential temperature surface used for this section was 3·43°, the same value as that of the previous section.

23–24 *March*

Following this *Atlantis* made two sections, one at 33° 10′N and the other at 33° 03′N. The intention was to cross the undercurrent both north and south of floats F and G, which had been launched on 23 March. However, insufficient allowance was made for the southerly drift of these floats which was double that of float D. Consequently, the northerly section of the two (stations 5511–5520) did not approach the track of either float closely enough to calculate a reference level from it. The reference level, therefore, was assumed to lie at the same potential temperature surface (3·68°), as the southerly section which immediately followed it.

The northerly section (No. VI, FIG. 11) is the most complicated. This is due in part to the close spacing of the stations, which averaged 8 kilometres, but there is no question about the reality of the streakiness in the crosscurrent pressure gradients. No navigational error can be expected to cause a reversal in the computed current direction such as appears between stations 5516 and 5517, and the highest velocity values are found between the most widely spaced pair of stations, 5516 and 5517, which is the reverse of what one would expect from a navigational error. The computed volume transport of this section was 4·4 million m³/sec.

24–25 *March*

The southerly section (No. VII, stations 5521–5528, Fig. 12) is not so streaky although the station interval averaged only 9 km. For this section the drift of float G was used since F was already more than 11 km to the south before the section crossed its track. Float G passed between stations 5524 and 5525 at a depth of 2580 m with a velocity of 7·08 cm/sec at right angles to the stations. The calculated level of no motion was 1640 metres and the 3·68° potential isotherm was used as a reference level for the remainder of the section. The southerly volume transport of the undercurrent relative to that surface was 5·0 million m^3/sec. It is difficult to see any continuity of current between these two sections. The high velocity zone between stations 5515 and 5516 on Section VI can probably be connected with the high velocity zone between 5524 and 5525 on Section VII. Other highs and lows can be connected but with decreasing reliability.

26 *March*

On the morning of 26 March, *Discovery II* launched floats H and I loaded for 2800 metres and *Atlantis* began a square pattern of stations intended to cross the tracks of these floats. Bad weather forced her to stop after 4 stations, all to the east of these floats. Fortunately, two of these stations 5529 and 5532 crossed the path of float G, 6 km apart. It was consequently possible to get another estimate of the level of no motion, which fell at 1820 metres and at a potential temperature of 3·54° a figure well within the limits of the previous measurements.

27 *March*

A whole day was lost by *Atlantis*, hove to in heavy weather, but before midnight on 27 March she was able to resume work.

27–28 *March*

Three pairs of stations (5533–5534, 5535–5538 and 5536–5537) were made across the paths of floats H and I but unless the level of no motion lay much shallower than 1500 m the spacing of these stations was too wide to measure the true slopes of the isobaric surfaces and in consequence the computed currents are far slower than the observed. The narrowest spacing (13 km) was between stations 5533 and 5534 where the computed southward velocity (relative to the 3·68° potential isotherm) was 4 cm/sec at 2840 m the depth of floats H and I, whereas, the observed component of velocity at right angles to these stations was 17 cm/sec for float H and 12 cm/sec for float I. It can be seen from Fig. 12 that a station spacing of 13 km would result in diminished calculated velocities and a broader, slower flow.

28 *March*

Immediately following these stations, a section was made with an average station interval of 3 km, (stations 5538–5542). The southward computed velocities at 2840 m were 23 cm/sec between 5538 and 5539 and 12 cm/sec between 5539 and 5540. These velocities would go very well with floats H and I respectively, although the value of 23 cm/sec is rather too high for float H, but unfortunately both pairs of stations would have to be moved about 3 km to the west in order to cross the track of the floats. (These velocities were calculated relative to the 3·68° isotherm as before).

Float H was already 20 km to the south at the time the stations were made and float I was 4 km to the south since *Atlantis* again made insufficient allowance for the southerly drift of the floats. In consequence, all that the closely spaced section did establish was that geostrophic currents sufficiently strong to carry the floats at their maximum velocity could be calculated from the distribution of density. The high value of 23 cm/sec is possibly due to navigational error since stations 5538 and 5539 were only 1·9 km apart, the shortest station interval of the cruise.

Aboard *Atlantis* only rapid and rudimentary current calculations were made and the importance of bracketing the floats closely in time as well as in space was not properly appreciated. This apparently caused no great damage to the measurements involving the shallower floats, B to G, but the oceanographic observations on the deeper (2840 m) floats, H to K were not adequate since at that depth the pressure field evidently fluctuates more rapidly with time.

On the morning of 29 March, *Atlantis* left the working area in order to start the final oceanographic section. This section, it had been agreed, was to include the entire Florida Current as well as the deep undercurrent. The first station, 5547 was at 33° 01′N, 73° 30′W, about 220 km east of the working area. The stations consisted of two series except on the shelf and while crossing the tracks of floats J and K when only one series was made. Again, it seems, the oceanographic measurements were not adequate ; only half the velocity of these floats could be accounted for by the dynamic calculations unless the level of no motion were raised to 1000 m. While this could possibly have been the case, it seemed more sensible to assume that the true slopes of the isobaric surfaces were missed by *Atlantis* and that the level of no motion lay at some greater depth. The potential isothermal surface of 3·56°, a median value obtained from earlier measurements, was used as a reference level for this section.

On the basis of the existing stations, no satisfactory level of no motion could be obtained by using the deep floats, H-K. This is thought to be due mainly to the streakiness of the currents at 2840 m which required station intervals to be much closer than they were both in position and, particularly, timing.

30–31 *March*

This final section (No. VIII, Fig. 13) took two days to complete and gave a computed volume transport for the Florida Current (*above* the reference level) of 63·6 million m^3/sec, stations 5549–5561. The volume of the southerly undercurrent (stations 5549–5558) came to 6·7 million m^3/sec, and that of the shallow inshore countercurrent 0·5 million (stations 5561–5563). The net northerly transport through this section was, therefore, 56·4 million m^3/sec.

At first glance, it does not appear that an undercurrent of only 6·7 million m^3/sec can be of much importance to the water budget of the western North Atlantic, but it becomes extremely important when the net transport of 56·4 million m^3/sec is compared to the value obtained when the bottom is used as a reference surface.

If the direction of the southerly undercurrent is reversed by using the bottom as a reference surface, the northerly volume transport becomes 7·2 million m^3/sec (a slightly larger figure because the vertical shear is usually greater towards the bottom). In addition to this, between each pair of stations the transport above the intermediate reference level must be increased by an amount equal to the area included between the stations (above the reference level) times the velocity at the intermediate level. This comes to the more substantial figure of 16·2 million m^3/sec.

Accordingly, the net transport relative to the bottom in this section is 63·6, + 7·2, + 16·2, − 0·5 (the inshore countercurrent), or 86·5 million m^3/sec, an increase of 30·1 million. This increase is roughly equal to Montgomery's (1941) estimate of the total volume transport of the Florida Current between Key West and Havana. The establishment of the level of no motion can be seen to be of profound importance in estimating the water budget of the western North Atlantic in spite of the rather small volume of water transported by the deep countercurrent.

SUMMARY AND CONCLUSIONS

The direct measurements of currents, described above, show that southward velocities in the range 9–18 cm/sec can be found in the region of steep temperature gradients in the deep water off the Blake Plateau. The steadiness of these velocities, observed over periods of several days, and the consistent finding of a southward movement at depth, whether directly or indirectly observed, at each attempt during a period of a month, suggest that the southward flow may be a permanent feature of the circulation in that area.

In other regions, where weak temperature gradients are found, and where a few direct measurements of current at comparable depths have been made (Swallow, 1957, Swallow and Hamon, 1959) the observed velocities have been in the range 0–5 cm/sec, and variable in direction. The fast-moving southward deep currents off the Blake Plateau stand in a similar ratio to these weaker observations as does the surface Gulf Stream velocity to typical surface currents in the open ocean, and they may therefore perhaps, on account of their magnitude, be fairly described as a deep western boundary current.

Whether a continuous current can be traced in the deep water along a substantial part of the western Atlantic remains to be decided by further observations. Remarkably similar velocities have been computed by Wüst (1958) at the western boundary of the South Atlantic.

On the assumption that the flow is geostrophic, velocity profiles have been computed between pairs of hydrographic stations bracketing the tracks of the floats, using the directly-observed velocity as a reference, and hence estimates have been made of the depth of the level of no motion. On the further assumption that the surface of no motion is a surface of constant $\sigma\Theta$, velocities and volume transports have been computed between other pairs of hydrographic stations, leading to estimates of the total transport in the deep southward current and, in one case, of the transport in the Gulf Stream itself.

The level of no motion has been shown to lie at a depth of about 1900 m, off the Blake Plateau. This intermediate reference surface is consistent with that chosen by Defant (1941), but difficulties are encountered in extending the use of this reference surface to larger areas.

Stommel's (1957) thermohaline model of the Atlantic circulation, which inspired the measurements here described, is strongly supported by the demonstration that fast-moving southerly currents can exist in the deep water at the western boundary of the North Atlantic.

Contribution No. 1129 *from the Woods Hole Oceanographic Institution.*

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