Temperature microstructure on the Bermuda slope with application to the mean flow[1]

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ABSTRACT

The oceanic conditions in the immediate vicinity of Bermuda have been studied with hydrographic data, parachute drogues, and moored current meters. The island was found to be a source of temperature and salinity microstructure with a marked azimuthal asymmetry. On one cruise, the area of most intense mixing was associated with a very strong jet across the north shore of Bermuda. The jet is depicted by the very marked deepening of the isotherms of the main thermocline as the island is approached from the north. Overall, the mean flow pattern has been determined. Very near-shore very violent time dependent motions were observed which may be associated with the step structure on the T and S curves.

I. Introduction

This study is the outgrowth of an attempt to measure internal gravity waves in the main thermocline at Bermuda (Wunsch & Dahlen, 1970). It began as an examination of the mean conditions in the immediate vicinity of the place where the internal waves were to be measured, to help understand the measurements. As the effects Bermuda was having on the mean ocean conditions around it became clear, this study was developed independently of the internal wave work, and evolved into an attempt to understand the general oceanography of the Bermuda area. We will deal with the internal wave results in a peripheral manner below.

In more general terms, the question we seek to answer is, what effects does an island have, if any, on the ocean in its vicinity? The complete answer to the question is extremely difficult, as an island does affect the ocean on many time and length scales. Hogg (1971) has presented a theoretical discussion of some aspects of the problem of a mean flow past an island, in terms of the data discussed here, and we will therefore generally limit ourselves to a brief, essentially descriptive, discussion of the oceanography of the Bermuda area. To a great extent, the data speaks for itself. Islands appear to be microcosms on an almost manageable geographic scale of many features of the physics of the ocean circulation so our results may be of general interest.

The data we have to deal with were gathered at Bermuda on three cruises, Atlantis II Cruise 47 in October 1968, Gosnold Cruise 144 in July 1969, and Gosnold Cruise 167 in July 1970. Both vessels are operated by the Woods Hole Oceanographic Institution.

II. Atlantis II Cruise 47

The first cruise, Atlantis II 47, was essentially a reconnaissance expedition to see if there were any discernible effects of Bermuda on the local oceanography. The reconnaissance was carried out as a survey of the hydrographic data with a Bissett-Berman STD system, and as an attempt to measure internal waves and the mean flow with 3 Geodyne current meters on two moorings set to the west of the internal wave array. Fig. 1 shows the positions of the STD stations and the moorings. In addition, we had available a Marine Advisers shipboard current meter.

The strategy of the STD work was to make a

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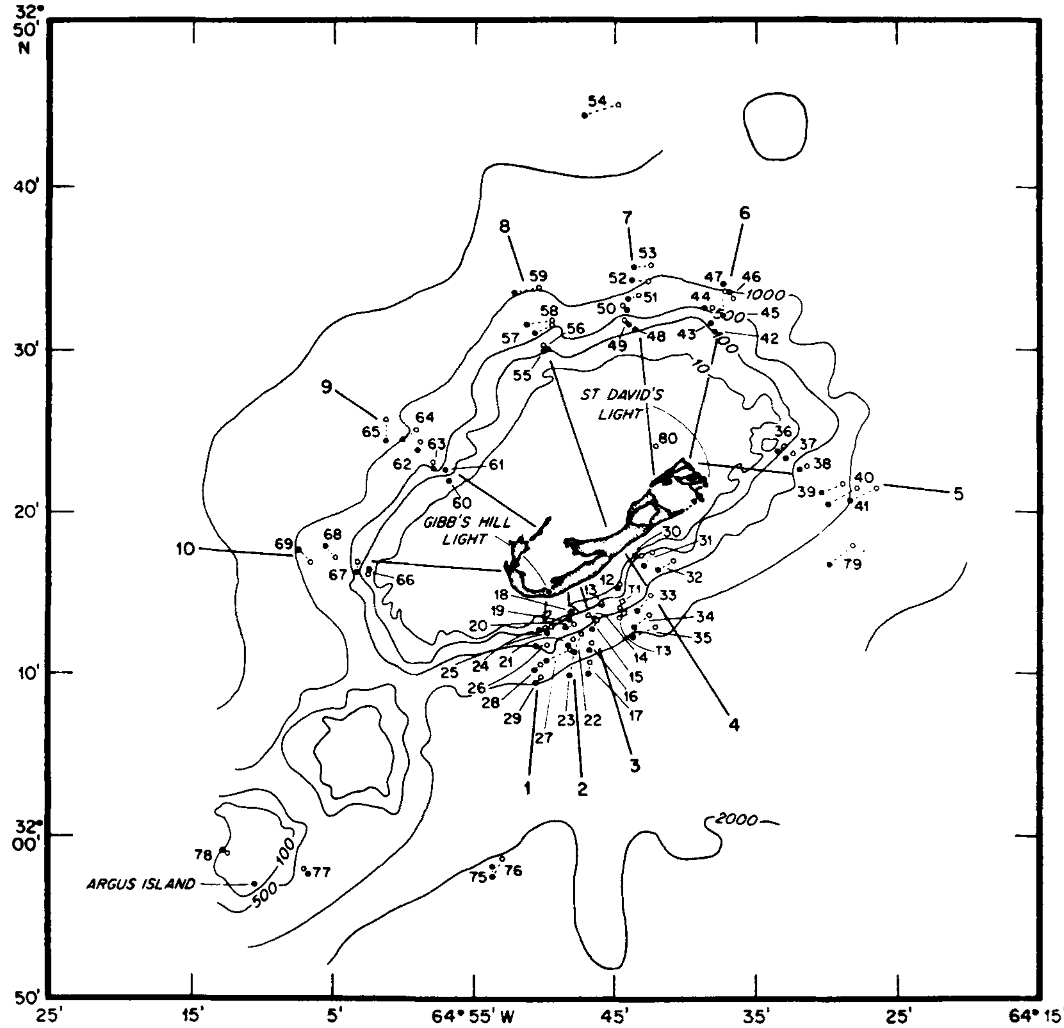

Fig. 1. STD station positions for Atlantis II Cruise 47. Solid and clear dots indicate starting and ending positions of the stations. Most of the stations are grouped into numbered "spokes". The two moorings are shown near station 12. (T1 is marked and is the "shallow" mooring.)

series of "spokes" of stations normal to the bathymetric contours of the island, as labeled in Fig. 1. During the entire period 18 October to 29 October, 1968, he ship was working around the island; the surface flow was from southwest to northeast. The ship usually drifted northeast at about 1 knot during the cruise. We will deal only qualitatively with the results of this hydrographic survey as the second cruise was more comprehensive.

In Figs. 2 to 5 we have plotted portions of the raw STD temperature tracers in representative spokes. The island is on the left in each spoke, and the traces were made at water depth intervals of 200 fathoms starting at the 100 fathom line out to 1 100 fathoms. The temperature at 300 m is given in each case to fix the curves in T–D space.

The plotting of the traces in this form makes apparent that almost without exception, the amount of temperature microsctructure increases as the island is approached. The effect is most pronounced in stations 48 to 54, but the microstructure changes are apparent in all of

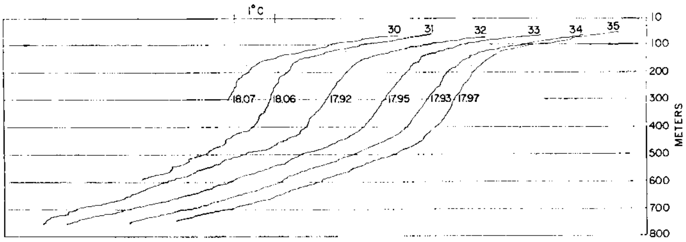

Fig. 2. Portions of temperature traces from stations in spoke 3.

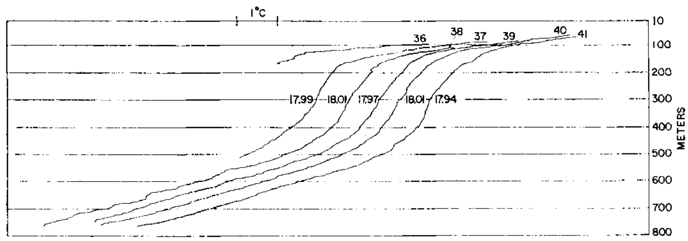

Fig. 3. Spoke 5.

the spokes. In general the trend is clearest on the north–northeast side of the island.

Some discussion of the meaning of "microstructure" is in order here. We use the term a bit loosely to indicate steplike structure present on the temperature and salinity curves in the sense used by Cooper & Stommel (1968) in this area. Examination of Figs. 2 to 5 show that the most sea-ward temperature trace is always smoother than the more shoreward traces. The effect can be quantified, but for our purposes here, the visual behavior of the curves is sufficient to make our point. The region of maximum microstructure was in the area of spoke 7 (Fig. 4).

Salinity is less reliably measured by the STD, but in general, the salinity traces mimic the temperature so the mixing process appears to move salinity and temperature together, and in such a fashion that the local density gradient is always stable. There appears to be more structure within the 18 degree water mass than above or below, so that the generating process is inversely proportional, at least roughly, to the mean overall static stability of the water mass.

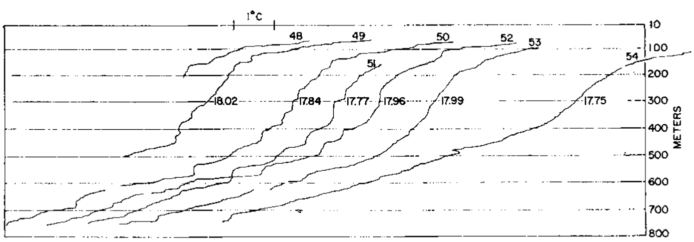

Fig. 4. Spoke 7.

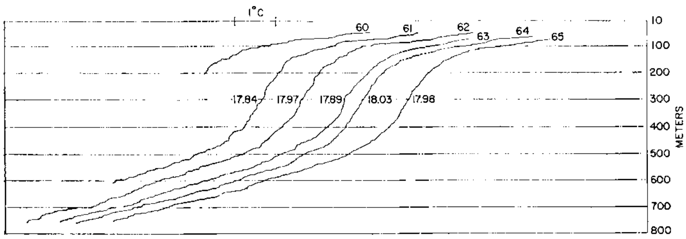

Fig. 5. Spoke 9.

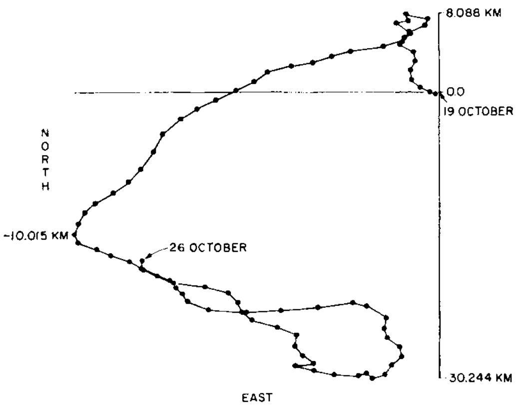

Fig. 6. Progressive vector diagram of current meter record H-880 at a depth of 610 m on shallow mooring. Dots indicate 2 hour displacements.

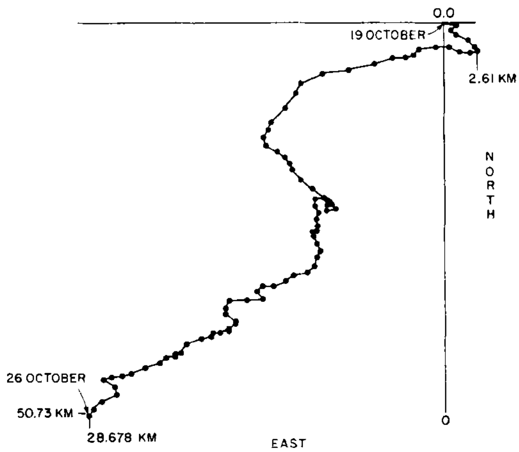

Fig. 7. Progressive vector diagram of current meter record H-881 at a depth of 700 m on shallow mooring. Dots indicate 2 hour displacements.

The large scale hydrographic structure is consistent with a rather weak flow to the northeast, with a level of no motion at 600 m. A section (not shown) of currents was made with the Marine Advisers lowered current meter. The results are consistent with the situation stated above: a weak flow at the surface to the northeast, decreasing to zero at about 600 m and then weakly to the southwest. Current profiles made at various times throughout the cruise are similar.

The current meter records from the Geodyne current meters are displayed as progressive vector diagrams of 2 hour averages in Figs. 6 to 8. The current meters operated successfully for 7 days (Table I). There are great differences in the diagrams considering how close together the moorings were.

The spectra of the west and north components of velocity from the current meters are mono-

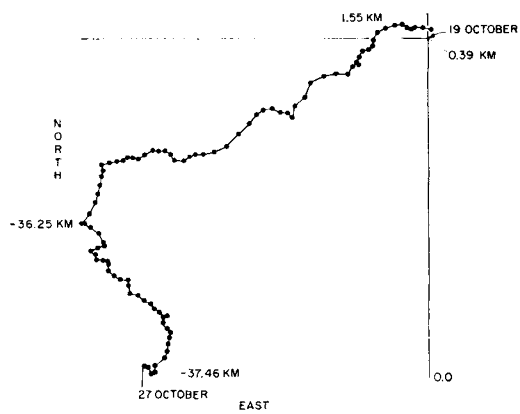

Fig. 8. Progressive vector diagram of current meter record H-879 at a depth of 690 m on deep mooring. Dots indicate 2 hour displacements.

Table 1

Current meter record	Mooring	Depth of current meter (m)	Start of record	End of record
H-880	Shallow	610	1445 19 Oct. 1968	1705 26 Oct. 1968
H-881	Shallow	700	1445 19 Oct. 1968	1705 26 Oct. 1968
H-879	Deep	690	1030 19 Oct. 1968	0950 27 Oct. 1968

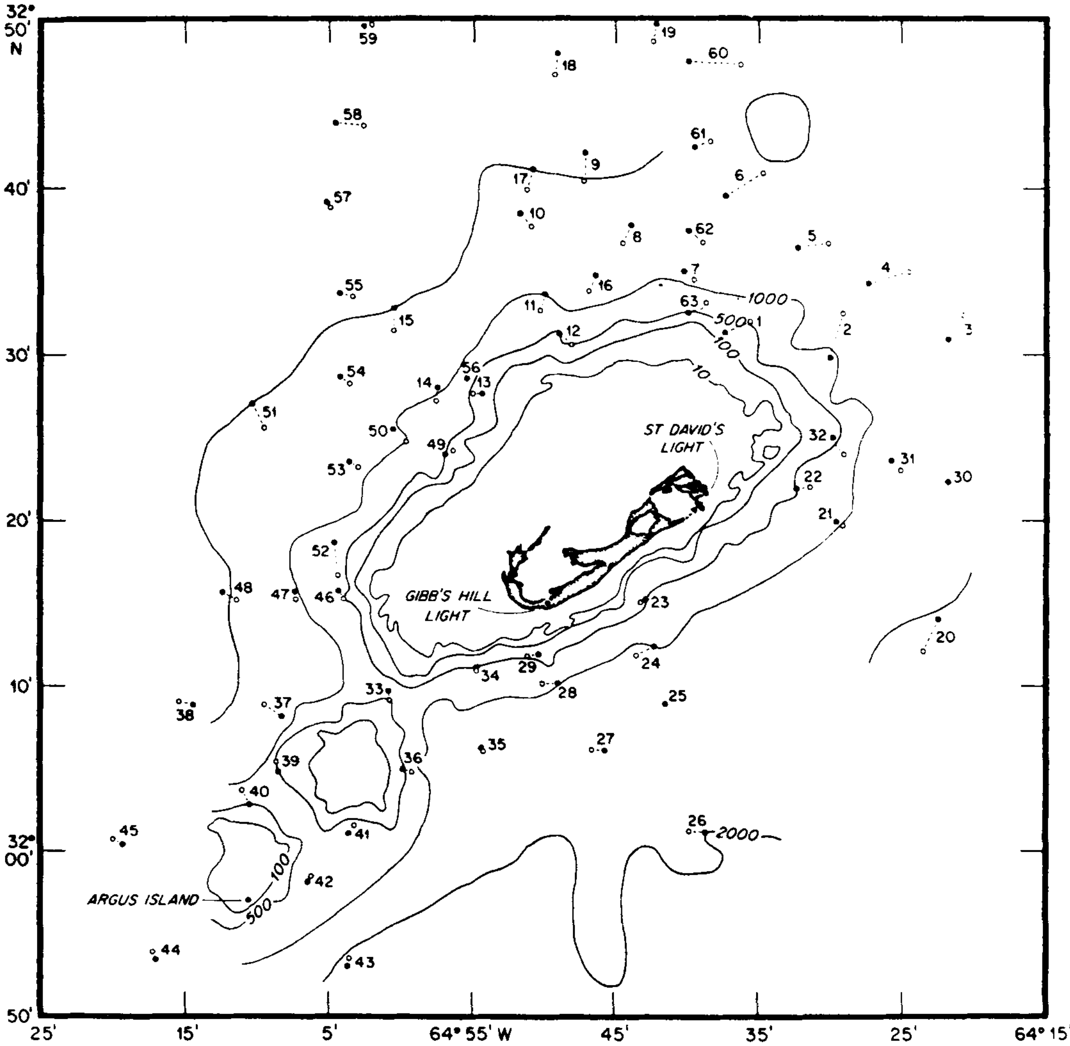

Fig. 9. STD station positions for Gosnold Cruise 144. Stations begin at black dot and end with open dot.

tonically increasing "red" and are not shown. No significant tidal or inertial peak emerges from higher resolution spectra, though there is a distinct rise in energy between 18 and 26 hours (the inertial period is 22.32 hours).

No coherence could be found between the records, either between u and v components of a single current meter, or between components of any pair of current meters. Most deep ocean current meter records show at least some coherence between u and v components of a single current meter (e.g. Fofonoff, 1969). Thus, the meaning of the current meter records is obscure. We should also point out that Wunsch & Dahlen (1970) found no coherence between temperature measurements 1 km apart for periods shorter than about 8 hours. The significance of these results will be discussed further below.

III. Gosnold Cruise 144

With the experience of the first cruise as a foundation, a second trip to Bermuda was made on the R/V *Gosnold* in July 1969. The plan was to make a sufficiently detailed and

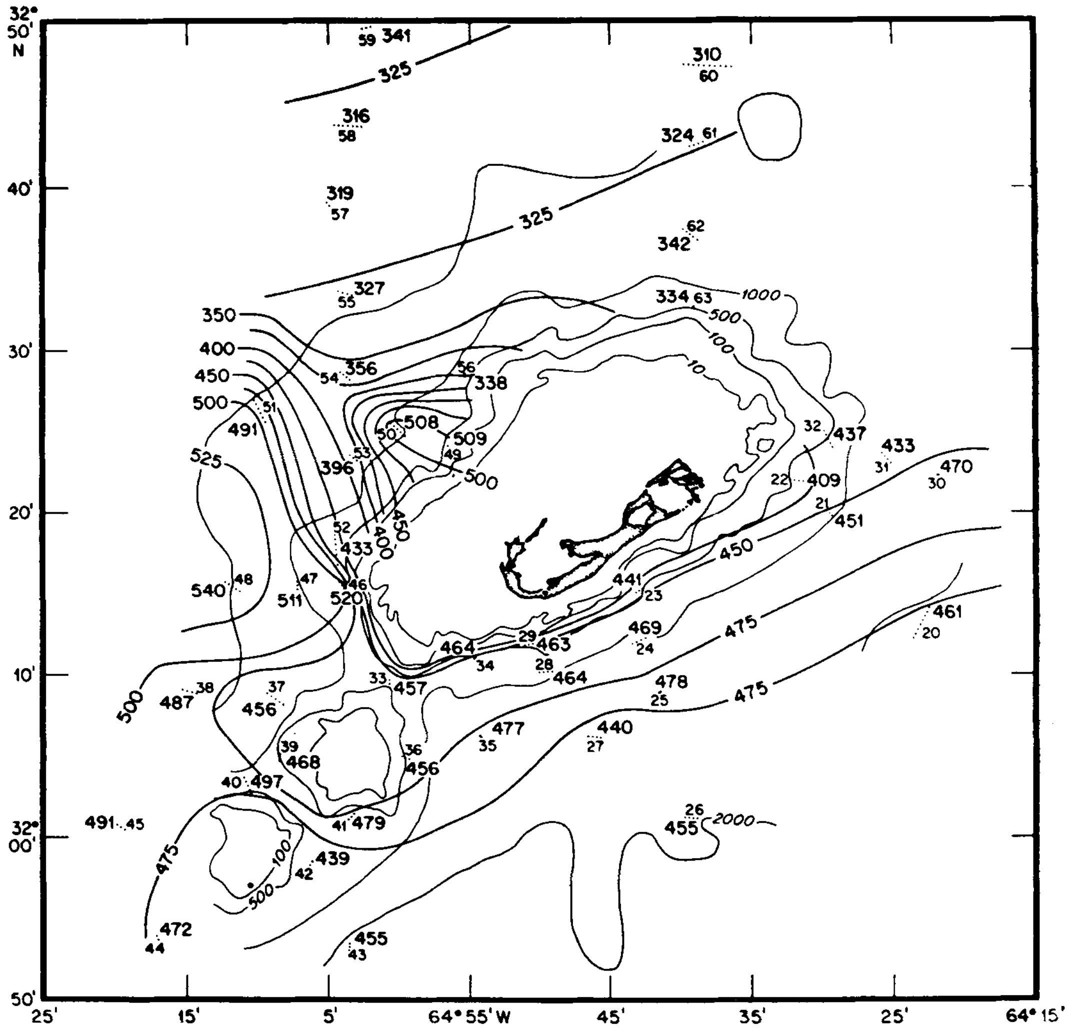

Fig. 10. A possible interpretation of the depth (in meters) of the 17°C isotherm. Note regime on north west with isotherms closing on island.

accurate STD survey of the island area so that geostrophic currents could be computed, any areas of mixing delineated, and drogues could be used to find the mean flows and as reference data for the hydrographic calculations.

The positions of the STD stations are shown in Fig. 9. As will be seen from the drogue data, the flow regime during the course of the survey which, owing to speed and endurance limitations of the ship was spread over almost 1 month, divided into two distinct states. Stations 1–19 were made during a period in which the flow at the surface appeared to be from the northeast, and the remaining stations, during a period when the surface flow was very strong and from the west. The STDs were recorded in analog form, and then were read manually at places where T and S curves changed slope. Typically, a 1 500 m deep STD station would have values read at 300 different depths. The resulting values were then adjusted to Nansen bottle calibrations.

Despite the 63 stations made within 20 miles of the 100 fathom contour, the temperature field cannot be contoured unambiguously. We

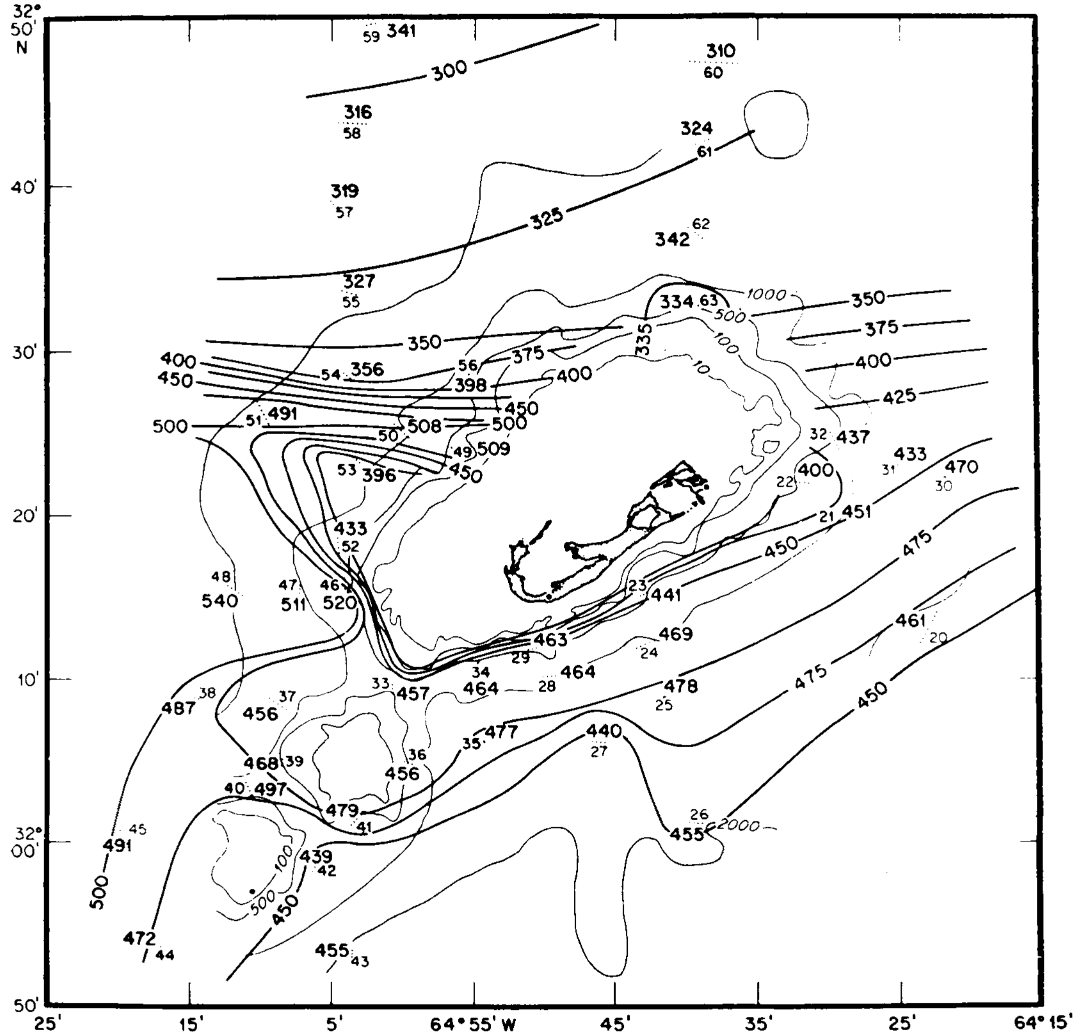

Fig. 11. A different interpretation of the 17°C isotherm depth.

restrict our attention to Stations 20–63 in what appeared to be a relatively homogeneous flow regime. It is believed that the picture is reasonably synoptic. A weakening of the flow did set in towards the end (see drogues 13 and 14) but there is no evidence for any major changes in flow field during the time stations 20–63 were made. The chief contouring difficulties are associated with the northwestern side of the island, Stations 50–54. Consider Fig. 10 the depth of the 17 degree isotherm. In this way of contouring, one has a deep "hole" of closed constant depth lines intersecting the island. This version is perhaps the simplest interpretation. A different contouring pattern of this isotherm is shown in Fig. 11. This carrying of the isotherm pattern around to the southern part of the island has been proposed by Hogg (1971) and is also compatible with the stations data. Hogg prefers this pattern as it is generally consistent with his theory of the flow. We choose to follow his lead in this, as there is at least a rationale for doing so. On the other hand, it should be pointed out that his theory takes no account of the two banks to the southwest of the island. In Figs. 12 to 14, we show the depths of several other isotherms in this area.

In these figures, the most striking feature is

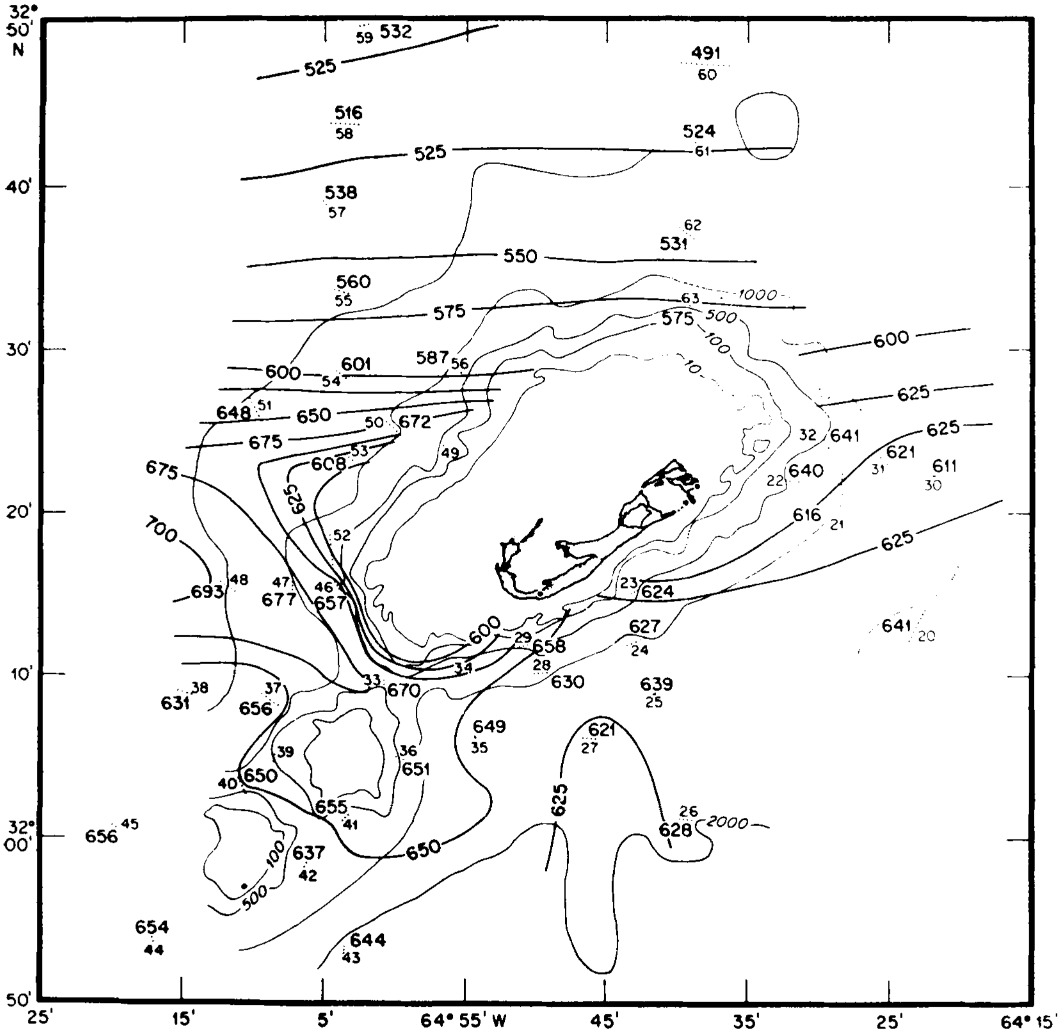

Fig. 12. Depth of 14°C isotherm.

the enormous deepening of the temperature field as Bermuda is approached from the north, e.g. the 17 degree isotherm goes from 316 m at station 58 to 540 m at station 48, a depth change of 224 m in a distance of about 30 nautical miles. On the other hand, to the south, there is almost no change in the isotherm depths. Iselin (1936) noted that at mid-depths near Bermuda, the water temperature was lower than in the surrounding Sargasso Sea. He attributed this anomaly to mixing on the island slope and deduced a counter-clockwise circulation about the island. This may indeed be the result under quiet conditions.

The field of dynamic topography associated with this mass field is shown in Figs. 15 and 16 between 500 decibars relative to 100 decibars, and 1300 decibars relative to 100 decibars. The 100 decibar level was used to avoid the complex surface distributions of salinity and temperature which changed rapidly in time. The contouring on both these topographic surfaces is incomplete in the northwest section owing to crowding of the lines. The only guiding principle used was to permit the island to approach a line of constant pressure. The large scale deepening of the isotherms to the north shows up as an area of very steep dynamic

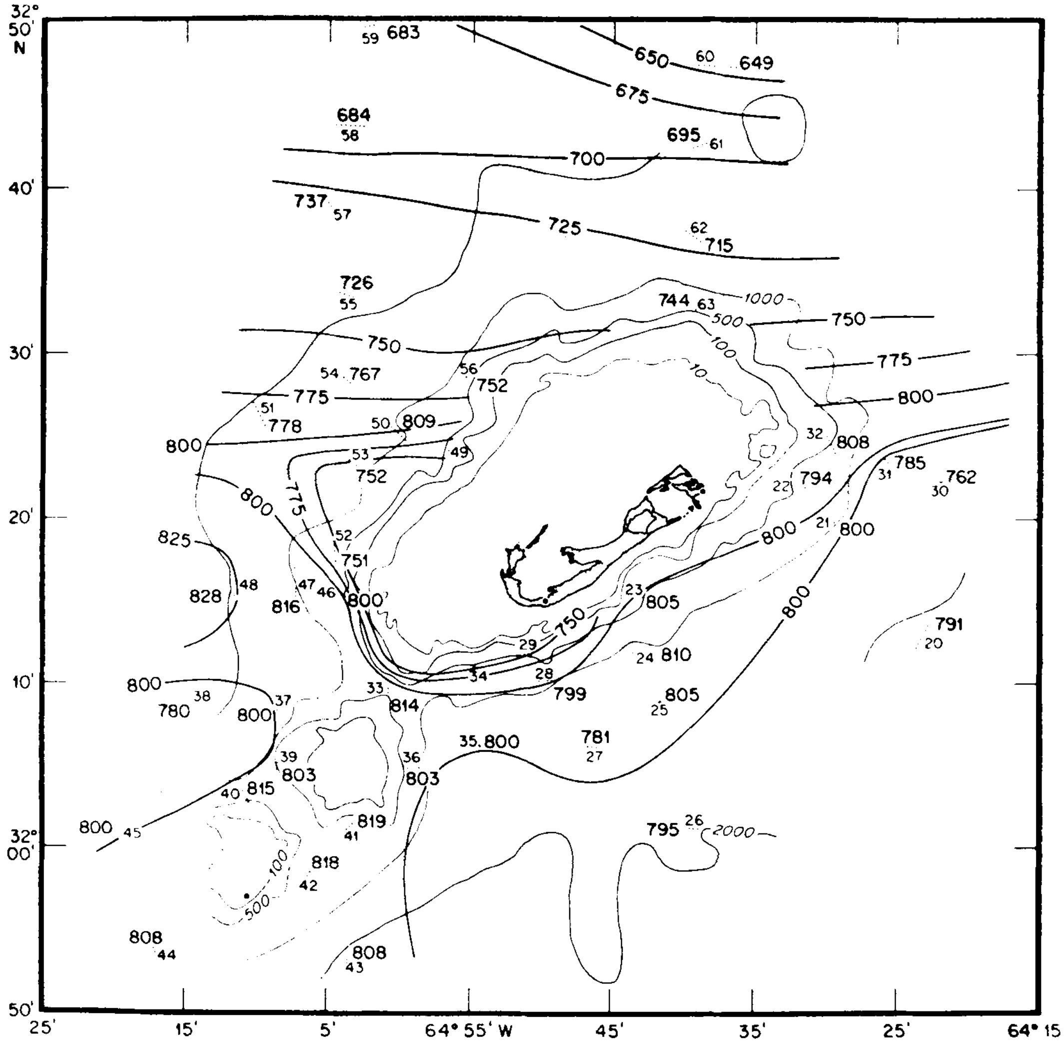

Fig. 13. Depth of 10°C isotherm.

topography on both levels; the change from station 58 to 48 amounts to 24 dynamic centimeters at the 1 300 decibar level. To the south of Bermuda the topography is virtually flat. The considerations given by Scarlet & Wunsch (1971) concerning the statistical significance of hydrographic data indicate that on a 10 km scale, a difference of one dynamic centimeter is probably significant. The region to the south showing a closed contour on the 1 300 decibar surface is thus marginal. For the same reasons, the isotherm topography in this region is also of dubious significance.

As expected the dynamic topography is associated with very strong currents to the north of Bermuda in this period. Fig. 17 and Table II indicate for drogues 6, 7, 8, 9 a strong flow of 1.3 to 1.7 knots at a nominal depth of 400 m of the drogues. The drogues consisted of a large drag parachute plus pilot chute, 100 pound sash weights, surplus BT wire, and a styrofoam float with flag and radar reflector. The depths indicated are nominal, and the chutes probably did not quite reach these depths. On the other hand, the geostrophic velocity computed between STD stations 60 and 61, shows almost no shear between 300 and 500 m depth. Thus, assuming that the chutes were

Table 2. *Drogue positions, Gosnold 144*

Drogue no.	Depth (m)	Date (1969)	Time (Local)	Position Lat. (N)	Position Long. (W)	Av. speed since last fix (Knots)	Av. speed overall (Knots)
1	300	7/14	1700	32°-32.7′	64°-31.6′		0.32
		7/15	0812	32°-31.5′	64°-28.3′	0.22	
		7/15	1852	32°-29.0′	64°-25.9′	0.30	
		7/17	1215	32°-13.3′	64°-19.3′	0.40	
		7/18	1612	32°-07.5′	64°-24.7′	0.26	
2	300	7/16	1330	32°-27.7′	64°-55.8′		0.36
		7/16	1518	32°-26.9′	64°-56.0′		
		7/16	1827	32°-26.0′	64°-55.5′		
3	600	7/15	1411	32°-33.5′	64°-30.0′		0.31
		7/17	1055	32°-22.3′	64°-19.2′	0.31	
		7/18	1817	32°-14.4′	64°-12.0′	0.31	
4	300	7/21	1500	32°-08.8′	64°-53.7′		0.06
		7/22	1300	32°-09.1′	64°-54.9′	0.05	
		7/23	0532	32°-10.5′	64°-54.7′	0.10	
		7/23	1438	32°-11.0′	64°-52.0′	0.14	
		7/25	1507	32°-12.2′	64°-50.5′	0.04	
5	300	7/21	1805	32°-09.4′	65°-04.1′		0.32
		7/22	1109	32°-08.5′	65°-10.1′	0.32	
		7/23	0332	32°-03.7′	65°-12.7′	0.32	
6	400	7/24	0331	32°-41.7′	65°-01.0′		1.3
		7/24	2253	32°-43.9′	64°-32.7′	1.3	
7	400	7/24	0440	32°-42.4′	64°-55.7′		1.4
		7/24	2200	32°-44.9′	64°-27.5′	1.4	
8	400	7/24	0553	32°-42.1′	64°-49.5′		1.6
		7/24	2100	32°-44.9′	64°-21.9′	1.6	
9	400	7/24	0658	32°-42.2′	64°-42.3′		1.7
		7/24	0800	32°-42.5′	64°-40.5′	1.8	
		7/24	0900	32°-42.9′	64°-38.1′	2.1	
		7/24	1000	32°-42.8′	64°-35.5′	2.1	
		7/24	1100	32°-43.3′	64°-32.8′	2.5	
		7/24	1150	32°-43.3′	64°-30.7′	2.3	
		7/24	1300	32°-43.6′	64°-29.0′	1.5	
		7/24	1400	32°-43.6′	64°-27.3′	1.5	
		7/24	2012	32°-45.3′	64°-16.9′	1.5	
0	400	7/25	0609	32°-28.1′	64°-56.0′		0.40
		7/25	1000	32°-27.1′	64°-57.6′	0.40	
1	400	7/25	0804	32°-21.7′	65°-02.6′		1.0
		7/25	1245	32°-17.5′	65°-04.2′	1.0	
2	400	7/29	1347	32°-35.7′	64°-47.7′		1.15
		7/29	1609	32°-36.1	64°-42.2′	1.2	
		7/29	1939	32°-36.8′	64°-39.6′	1.1	
3	400	7/29	2330	32°-24.0′	64°-58.0′		1.3
		7/30	0030	32°-24.7′	64°-56.9′	1.3	
		7/30	0427	32°-25.5′	64°-55.7′	0.3	
		7/30	1321	32°-32.0′	64°-45.9′	1.2	
		7/30	2133	32°-34.6′	64°-31.6′	1.6	
		7/30	2310	32°-34.9′	64°-27.7′	2.0	
		7/31	0010	32°-34.9′	64°-25.6′	1.7	
		7/31	0100	32°-35.1′	64°-23.5′	2.2	
4	400	7/29	1518	32°-30.3′	64°-50.5′		0.75
		7/29	1724	32°-30.7′	64°-48.3′	1.0	
		7/29	2110	32°-31.1′	64°-46.3′	0.5	
5	400	7/31	2150	32°-38.3′	64°-50.1′		0.86
		8/1	0526	32°-38.0′	64°-42.0′	0.9	
		8/1	0752	32°-37.3′	64°-40.5′	0.6	
		8/1	1000	32°-37.1′	64°-38.1′	1.0	

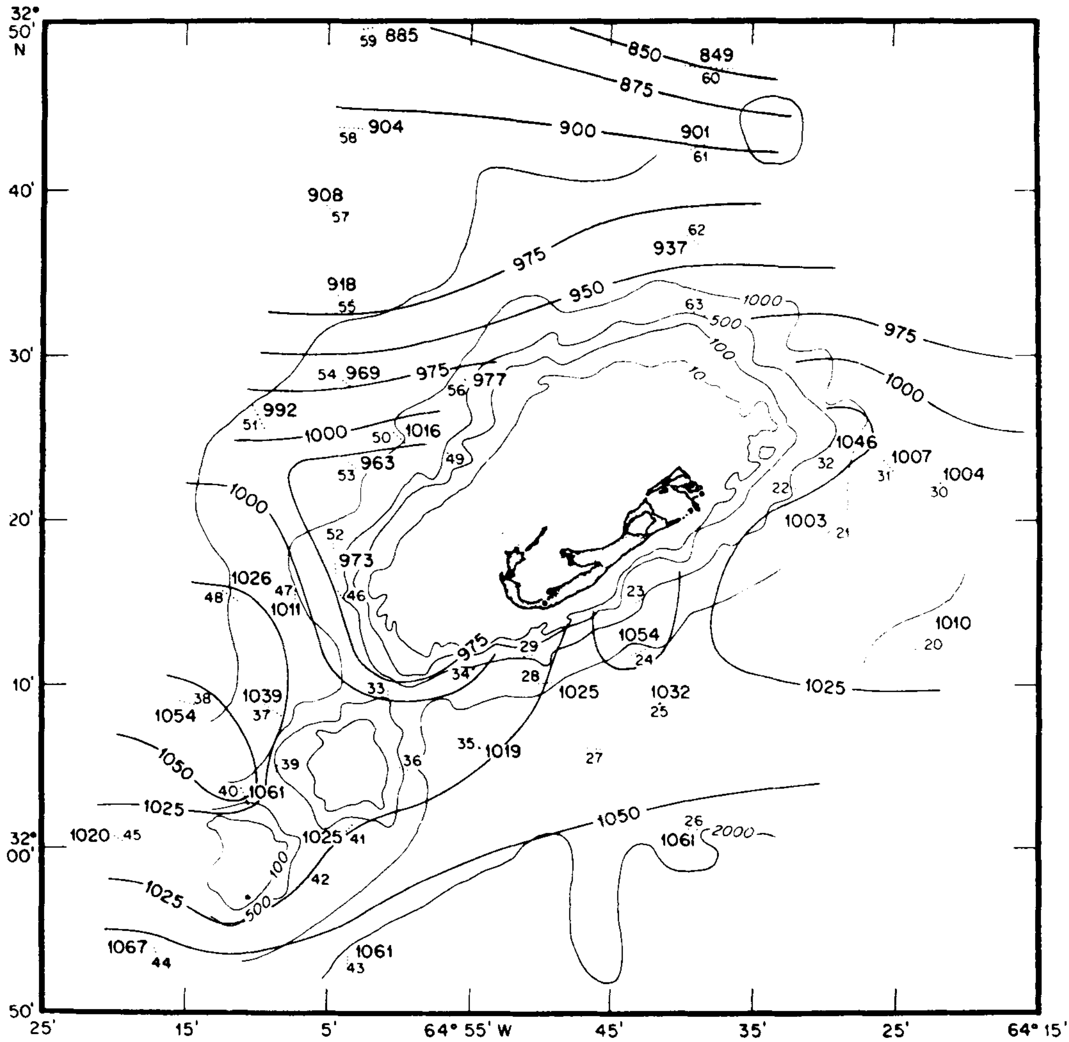

Fig. 14. Depth of 6°C isotherm.

fully open, the drogues are probably an excellent measure of the local water velocity.

Drogues 6 to 9 were set in the pattern shown based on the assumed flow pattern found in the first days of the cruise, generally from the north. It was anticipated that the drogues would separate and go around the island on different sides. Plainly, an entirely different flow pattern has established itself which appeared steady over most of the remainder of the time. Many of the remaining drogues were set in an effort to find the "stagnation point", or position of division of the flow to the south around the island. The problems of interpretation are made apparent by the tracks of drogues 10 and 13 on the northwest side. A portion of the track of drogue 13 is dashed in the figure because the inferred straight line track would have taken it into water too shallow for the parachute to clear the bottom. Presumably, the average speed should be somewhat higher than indicated to take the drogue around the contour. Drogue 10, tracked for only a short time, proceeded southwest, as did drogue 11. There appears to be a dividing streamline in the flow on the northwest end of the island. Notice that drogue number 4 south of the island hardly moved at all (average speed 0.06 knots)

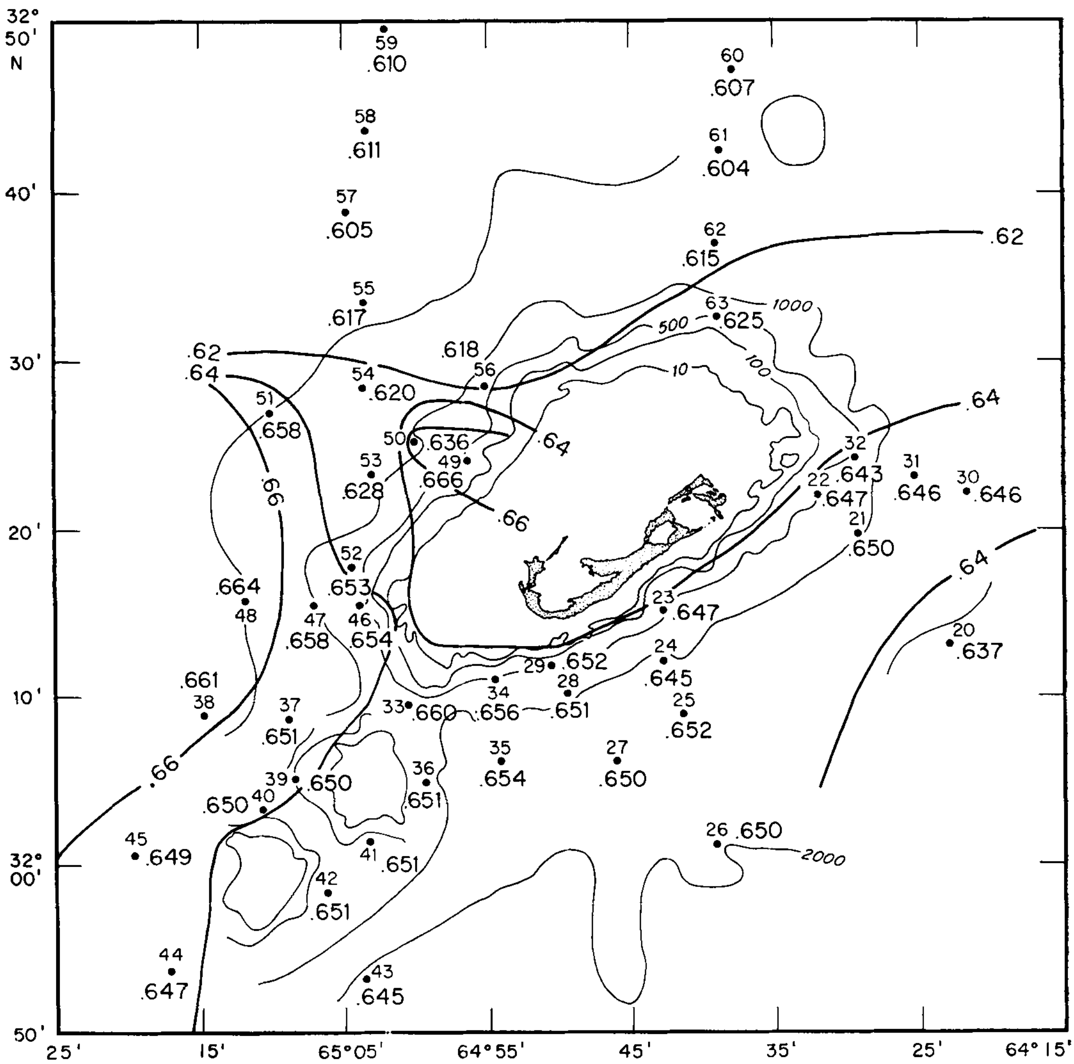

Fig. 15. Height of 100 decibar surface relative to 500 decibars (in dynamic meters).

over a 5 days period. The region to the south of the island and to the east of the banks appeared to be virtually stagnant. The sill depth between the northern bank (Challenger bank) and the island is in excess of 100 m, though the passage is considerably constricted. Drogue 4 was probably simply in the lee of the banks.

We might remark here that reference to Table II will show that drogue 9 increased its velocity as it passed over the small seamount to the north of Bermuda. The published chart shows a minimum depth of 1 360 m but we found isolated regions where the depth was much less.

In the region to the north of the island where drogue 6 to 9 moved so rapidly, Hogg's (1971) solutions become non-linear, and we may note that based on a flow velocity of 75 cm/sec, and an island diameter of 45 km the Rossby number of this flow as shown by the drogues is about 0.2, indicating a somewhat non-linear regime.

Perhaps it is appropriate to point out here that none of the drogue tracks, with the possible exception of number 1, shows the behavior discussed by Longuet-Higgins (1970), i.e. there

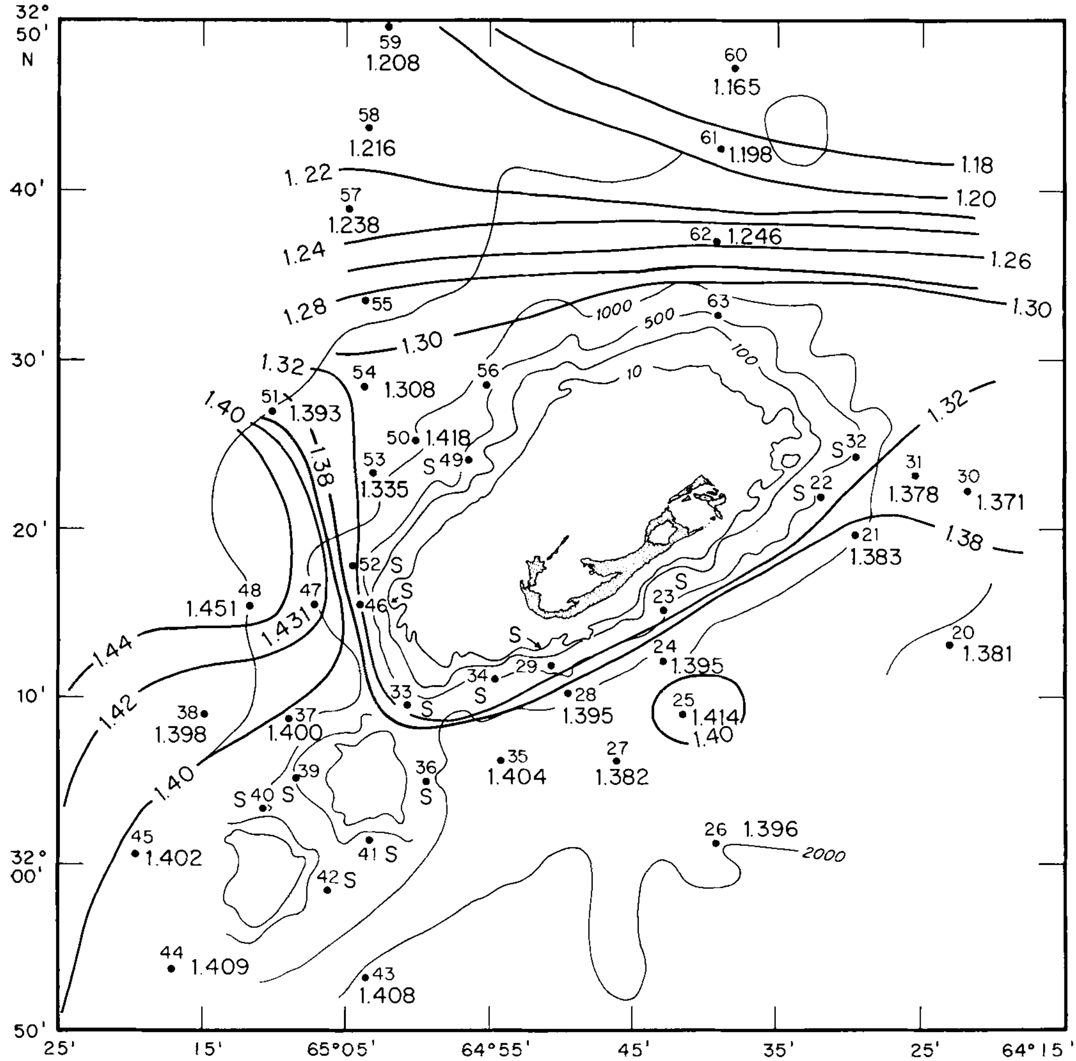

Fig. 16. Height of 100 decibar surface relative to 1 300 decibars. *S* indicates that the station was shallower than 1 300 decibars.

is no apparent circulation about Bermuda at this time. The mean flow is probably too strong to permit such a circulation to establish itself by the Longuet-Higgins mechanism.

In section II we noted that during the Atlantis II cruise the island appeared to be a source of microstructure. Figs. 18 and 19 show two similar temperature sections taken from the Gosnold cruise. The effect of approaching the island is again plainly apparent. The salinity traces are similar.

This discovery of a microstructure source, a local one, is in some ways the most striking of our results. Some inquiry into cause and effect is in order. The simplest explanation is to postulate an incoming field of internal waves that break up and mix on the Bermuda slope. The problem has been explored by Wunsch (1969), Wunsch & Dahlen (1970), and Cacchione (1970). Wunsch & Dahlen (1970) estimated the amount of incoming internal wave energy available for mixing, and Cacchione (1970) showed graphically in a laboratory tank that microstructure would actually be generated by

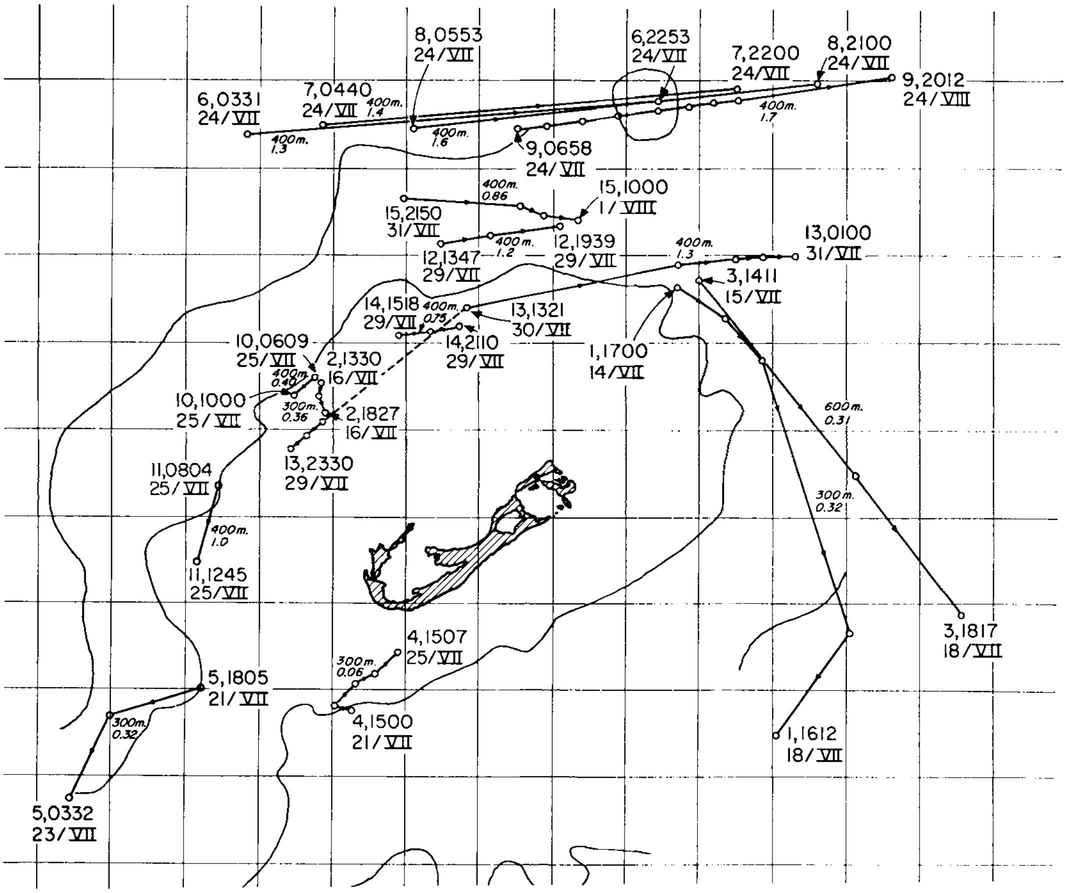

Fig. 17. Drogue tracks from Gosnold Cruise 144. The beginning and end positions are labeled with the drogue number, time and date of fix. Intermedate positions are also shown and are detailed in Table 2. Nominal drogue depth and average speed over the entire track are also indicated.

this mechanism. In the Atlantis II data, sufficient energy is probably available in the internal waves to account for most of the mixing. On the other hand, in the Gosnold data, this hypothesis is much less appealing. The degree of mixing to the north in this cruise is considerably greater than that to the south, and leads to the necessity of a highly asymmetric internal wave field.

The flow on the north side is much stronger than on the south (see drogue 4) and so is the microstructure. While more intense mixing could drive a stronger current (Wunsch, 1970), it seems reasonable to conclude that probably

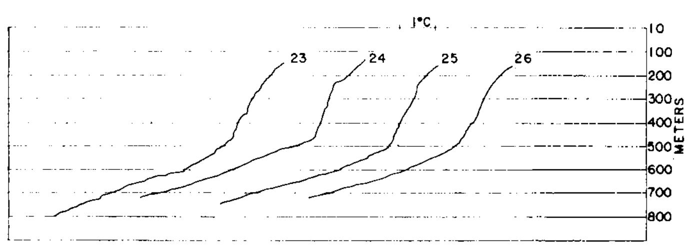

Fig. 18. STD temperature traces from Gosnold Cruise 144. The station positions are shown in Fig. 12. The island is to the left.

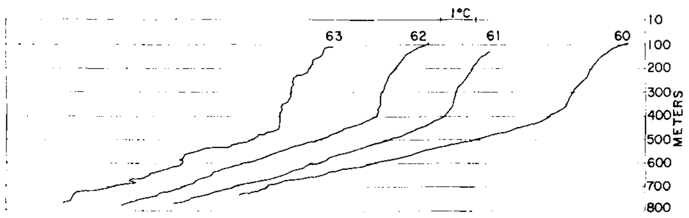

Fig. 19. STD temperature traces from Gosnold cruise 144. The station positions are shown in Fig. 12. The island is to the left.

the strong northern current is the cause, rather than the effect, of the mixing process.

The simplest explanation of the process is to postulate a shearing instability of the mean flow. The geostrophic shear is shown in Fig. 20 for stations 60 and 61. Defining the Richardson number to be:

$$\mathrm{Ri} = \frac{N^2}{(\partial U/\partial z)^2}$$

where N is the Brunt-Vaisala frequency, and $\partial U/\partial z$ the shear, we can estimate this number in the region north of Bermuda. Taking 100 m averages about a depth of 650 m, for stations 60 and 61, we obtain Ri = 23. In many parts of the profiles, especially in those resembling Station 63 (see Fig. 19), the STD cannot tell if the water is locally even statically stable; specifically, the value of N is so close to zero in places that the resolution of the STD, owing to the characteristics of the salinity sensor, is inadequate to resolve the issue. In these places the value of the Richardson number approaches zero. It seems inevitable that one must conclude that the flow is locally unstable at least part of the time whether or not the Richardson number criterion is completely appropriate.

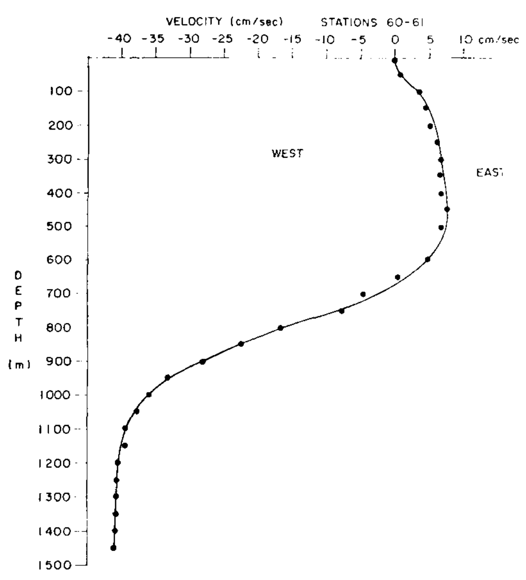

Fig. 20. Geostrophic shear between Gosnold stations 60 and 61. The surface has been chosen as the reference level.

What are the large scale dynamical consequences of mixing by any mechanism? Wunsch (1970) examined a model in which mixing was parametrized into an Austausch coefficient and explored the consequences of the wall boundary conditions. More generally, let H be the vertical scale of mixed fluid. Then we must have an adjustment of the interior temperature and mass field to those values. The effect of these mass inhomogeneties will make themselves felt at a distance $L \sim NH/f$ into the interior, the Rossby radius of deformation. Within the actual mixing region, the dynamics might have a buoyancy boundary layer character as discussed by Veronis (1967) or Wunsch (1970), but in any event will be turbulent and difficult to interpret. In the interior region, by the model, the flow is essentially geostrophic, and the effect of the mixing (Wunsch, 1970) is to increase the geostrophic shear within a deformation radius of the island, perhaps leading to further instabilities.

In this picture of a turbulent mixing field, the near shore temperature and velocity fluctuations are forced either by the mean flow, or by breaking internal waves and need not necessarily behave like free propagating internal waves. This is one interpretation of the incoherence of the current meter components reported here. That is, there is no simple propagating field. The "mean flows" so close to shore indicated by the progressive vector diagrams probably have little to do with the mean motion of the water, but must be interpreted only as Eulerian means with large spatial derivatives (Longuet-Higgins, 1969; Wunsch, 1971).

IV. Gosnold Cruise 167

This cruise was carried out in cooperation with Peter Hacker of the Scripps Institution of Oceanography, and Arthur Voorhis and Douglas Webb of the Woods Hole Oceanographic Institution in July 1970. The detailed findings will be discussed elsewhere by these participants, and we will confine ourselves here to a few general remarks.

The flow about the island was much more weak and variable than on either previous cruise, but the surface layers appeared to flow towards the southwest on the average. The "mixing" region was detectable primarily on the southern side in contrast to previous conditions. This finding is consistent with the ideas outlined above and Hogg's solutions, and makes the internal wave source a much less attractive hypothesis, since it would require ad hoc azimuthal sources.

A number of vertical current meter (VCM) Swallow floats (Voorhis, 1970) were set in the main thermocline southeast of the island. In general, floats set 100 m apart in the vertical separated rapidly, indicating a strong vertical shear. Some of the floats tended to move shoreward, at least one coming within 50 m of the bottom. The floats that moved into shallow water underwent very strong vertical excursions, dragged by violent fluid motions. The behavior of the floats is in accord with the picture obtained previously of an intense mechanical stirring process in the near shore region.

V. Conclusions

The flow in the immediate vicinity of Bermuda is distorted in a number of ways from that of mean ocean conditions. The island acts as an obstacle to the stratified shear flow and an inviscid theory (Hogg, 1971) succeeds reasonably well in describing the large scale features of this near field. These features can be described as a complicated tilting of the isopycnals as the flow adjusts to the necessity of going around the island obstacle, with a finite Rossby number effect primarily manifested when the island is to the right of the flow, in an area where a great deal of microstructure is apparent.

Some kind of mechanical mixing process is associated with the island slope. To an extent, this mixing may be derived from an incoming internal wave field (Wunsch, 1969; Wunsch & Dahlen, 1970), but the asymmetry of the microstructure in azimuth about the island indicates that the dominant effect is associated with the mean flow itself. The general tendency for T and S to mix together probably indicates that the mixing process is probably primarily mechanical, as does the remarkable behavior of the VCM in the vicinity of the shoreline.

The surveys of Bermuda reported here must be regarded as in the "near-field" of the flow. Exactly how the flow features delineated fit into the overall pattern of the surrounding Sargasso Sea may only be guessed. The high velocities seen in drogues 6, 7, 8 and 9 presumably do not extend indefinitely far from Bermuda, but there is no indication of curvature of the tracks or a decrease in velocity as they moved east. The direct effects of the mixing process, outlined schematically above, and the non-linear effects would diminish as the island is left. Unfortunately, there is insufficient information to be certain. Probably, the mean flow is from the west, a stagnation point is formed at the western edge of the island, the flow to the north is intensified by topographic effects, mixing, and finite Rossby number, and would diminish if pursued further eastward or northward.

Despite the difficulties of interpreting the small-scale features of the flow field, the overall flow pattern seems clear. The Gosnold 144 survey is reasonably synoptic, and the adjustment of the flow field to the island is apparent.

It may be worthwhile at this point to consider the small literature that exists on islands in general, and on Bermuda in particular in the light of our observations. Wyrtki et al. (1967) and Patzert (1969) have discussed the eddy-like motions that appear in Hawaiian waters. These eddies are on a much larger scale than we have considered at Bermuda. Patzert ascribes the eddy formation to very strong local winds in the inter-island passages. This seems an unlikely phenomenon at Bermuda.

White (1971) has discussed the flow of a homogeneous fluid past an island, in which a linear Rossby wave wake is formed in a well known process. The ratio of the beta terms, in the vorticity equation for a homogeneous fluid, to the advective terms, is easily shown to be:

$$\beta L^2/U$$

where L is the island scale, and U is a typical flow velocity. With $\beta \sim 10^{-11}$, $U \sim 10$ cm/sec, it is clear that the beta terms are much less than the inertial terms unless $L \gtrsim 10^6$ m. Few islands are this large. White's solution may have some relevance to possible laboratory flows however.

At the other extreme, Drazin (1961) considered a stratified shear flow past a hemispherical island in a non-rotating fluid. His approach was similar to that of Long (1955) for two-dimensional flows, and despite some difficulties with non-uniformities, Drazin's solutions are probably applicable to very small islands with very high Rossby numbers.

We have mentioned Longuet-Higgins' (1970) hypothesis of mean circulation about islands generated by wave streaming. As noted, there was no clear sign of a circulation in our data, but under different conditions such a circulation might be set-up. Longuet-Higgins (1970) points out that measurements by Stommel (1954) at Bermuda lend some support to his theory. Stockmann (1966) considered an entirely different mechanism for generating a circulation about a very large island through an interaction of gradients in the mean wind with the oceanic boundaries.

Boden (1952) discussed the apparent summertime circulation about the Bermuda islands, and Boden and Kampa (1953) the winter circulation. They assume the flow is primarily baroclinic in both cases. Boden (1952) shows that in the summer, the water in the Bermuda lagoon tends to be warmer than in the surrounding ocean, setting up an anti-cyclinic vortex. He postulates a convergence around the island where the two water masses meet and mix. The physics of the mixing is not made clear. In winter, Boden & Kampa (1953) show that it is plausible that the opposite happens, a cyclonic vortex is set up by the much cooler water in the lagoon. The summertime circulation they postulate is consistent with the measurements of Gosnold 144, though we would tend to identify their "convergence zone" with mechanical mixing on the slope.

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МИКРОСТРУКТУРА ТЕМПЕРАТУРЫ НАД БЕРМУДСКИМ ШЕЛЬФОМ С ПРИМЕНЕНИЕМ К СРЕДНЕМУ ТЕЧЕНИЮ

При использовании гидрографических данных и данных, полученных на плавучих буях и заякоренных измерителях скорости, были изучены океанические условия в непосредственной близости от острова Бермуда. Найдено, что остров является источником микроструктуры с заметной азимутальной асимметрией в полях температуры и солености. По данным одного рейса область наиболее интенсивного перемешивания была связана с сильным струйным течением поперек северного склона о. Бермуда. Это течение характеризуется очень заметным углублением изотерм главного термоклина по мере того, как оно приближается к острову с севера. Определена также средняя картина потока. В непосредственной близости от берега наблюдались быстропеременные во времени движения, которые можно связать со ступенчатой структурой кривых T и S.