Circulation near the Newfoundland Ridge

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ABSTRACT

Mesoscale eddies (25 to 150 km diameter) are observed to occur along the crest of the Newfoundland Ridge and have water properties that suggest an origin near the Tail of the Bank. The eddies appear to be important features of the circulation over the Ridge.

The location of the eddies and the paths of the major currents near the Newfoundland Ridge are closely associated with its topography. The latitude at which the Gulf Stream approaches the Ridge appears to be an important factor influencing the type of circulation pattern that develops further to the east. Regardless of the presence of eddies, a large transport of Gulf Stream water is observed to cross or branch around the Ridge, supporting the one gyre North Atlantic circulation scheme of Mann (1967).

1. Introduction

Two circulation patterns have been proposed for the Newfoundland Ridge area of the western North Atlantic Ocean. Worthington (1962 and 1976) concluded that the North Atlantic circulation consists essentially of two gyres separated by the Newfoundland Ridge (Fig. 1). The southeastward flow along the southern side of the Ridge is viewed as part of the Gulf Stream gyre, while the northwestward flow on the northern side is viewed as part of a separate northern gyre. Little water exchange is envisioned to occur across the Ridge. Worthington based his conclusions largely on higher oxygen values in the pycnocline on the northern side of the Ridge.

Mann (1967) proposed a different circulation pattern in which the Gulf Stream flows eastward along the southern side of the Newfoundland Ridge, and near 45W, splits into two branches (Fig. 2). One branch continues to flow southeastward, while the second curves around the Ridge, closely following the bottom topography, and then proceeds to flow northwestward in the place of Worthington's northern gyre. This branching of the Stream has been shown by Warren (1969) to be likely due to topographic steering of the current. Landward of the Gulf Stream, Mann (1967) identified a slope water current which flows around the Tail of the Bank and then northeastward.

The primary difference between these proposed circulation patterns is the transport of water across or around the Newfoundland Ridge. To further investigate

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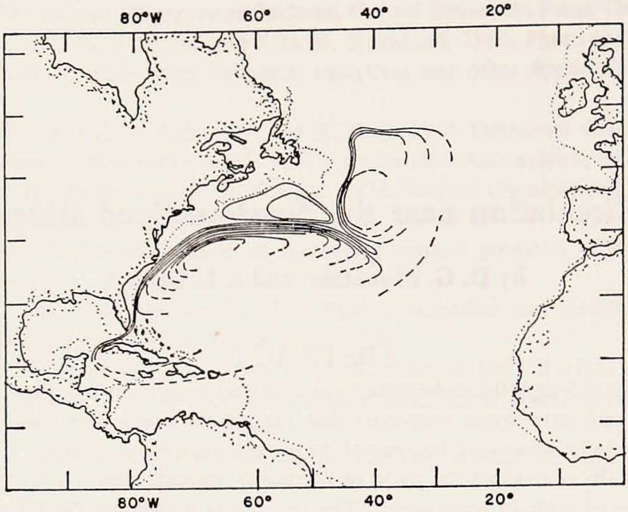

Figure 1. North Atlantic circulation (after Worthington, 1962). Each streamline represents $10^6 m^3/sec$.

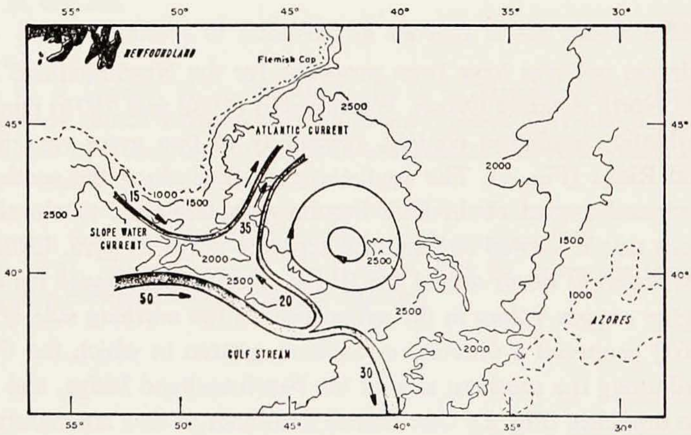

Figure 2. North Atlantic Current circulation (after Mann, 1967; depth in fathoms) Numbers indicate transport in $10^6 m^3/sec$.

these flow patterns, two STD surveys of the Ridge area were conducted in 1976 and 1977. It was hoped that improvement over previous studies would be gained by obtaining more nearly synoptic observations and by using a closer station spacing. This was accomplished by limiting observations to a depth of 1500 decibars, which is not considered a serious limitation since previous flow patterns appeared to vary little with depth (e.g. Worthington, 1976).

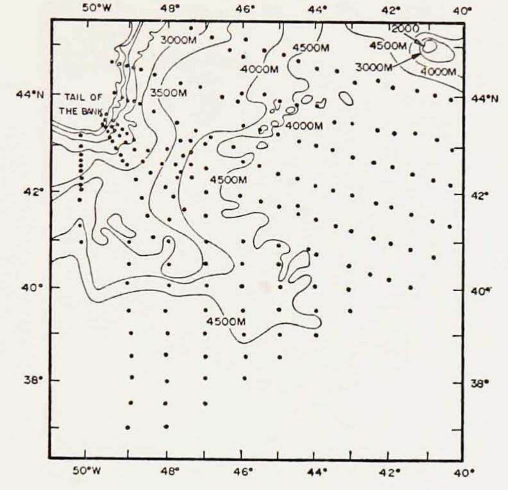

Figure 3. Station positions for summer 1976 survey (9 to 25 June 1976).

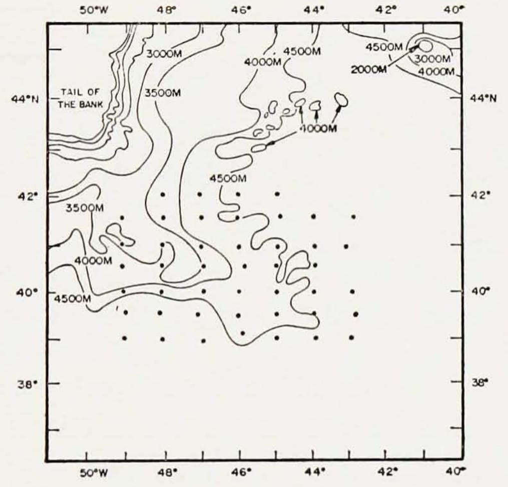

Figure 4. Station positions for summer 1977 survey (18 to 28 August 1977).

2. The data

In June 1976 two U.S. Coast Guard vessels sampled the Newfoundland Ridge area at 200 STD stations (Fig. 3). The C.G.C. *Evergreen* was engaged in work for the International Ice Patrol (IIP) along standard IIP sections. Due to operational time requirements, these observations were limited to 1000 db. Simultaneously in an adjacent region the C.G.C. *Sherman* sampled to 1500 db. every 30 miles (55 km) along tracklines approximately 45 miles (83 km) apart. Seventeen days elapsed be-

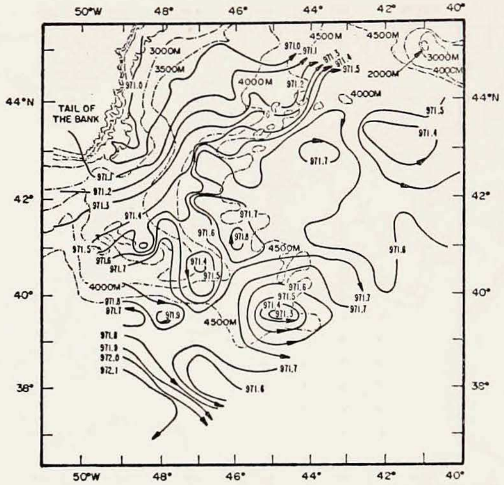

Figure 5. Surface dynamic topography for 1976 survey relative to 1000 db level (units: dynamic meters).

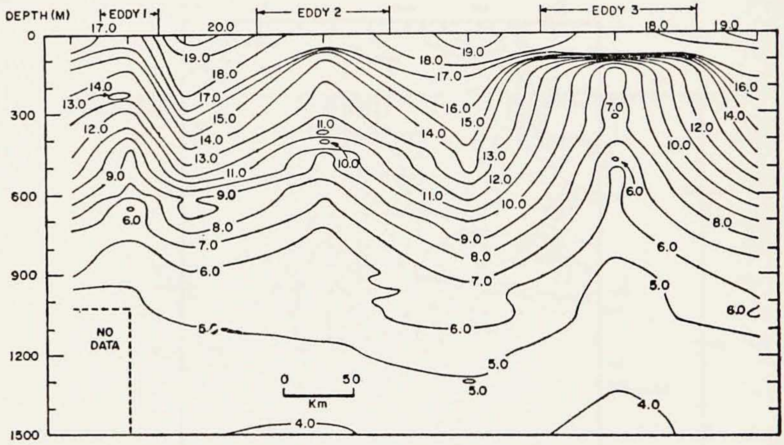

Figure 6. Temperature cross-section along the crest of the Newfoundland Ridge through the three eddies observed during the 1976 survey.

tween the first and last observations. In June 1977 the C.G.C. *Hamilton* occupied 47 STD stations over an eleven day period in a smaller area centered on the Ridge (Fig. 4). These observations were also made to 1500 decibars every 30 miles (55 km) on tracklines 45 miles (83 km) apart.

In the calculation of dynamic height a reference level of 1000 decibars was used to allow inclusion of the C.G.C. *Evergreen* data and thus make possible a direct comparison between the two years. Little difference would be noticed if a 1500 decibar reference were used.

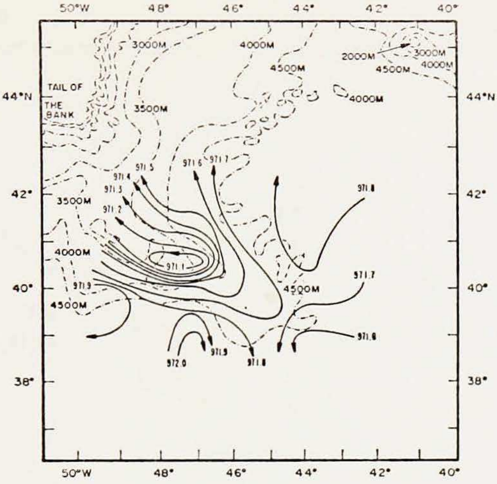

Figure 7. Surface dynamic topography for 1977 survey relative to the 1000 db level (units: dynamic meters).

1976 Circulation Pattern—An analysis of the surface dynamic topography for June 1976 (Fig. 5) indicates a strong flow to the southeast along the southern boundary of the survey area, and a major northeast flow in the northwestern portion. Between these two major flows are smaller scale features, the most prominent being three cyclonic eddies lying along the crest of the Ridge (Eddy 1 at 48°30′W, Eddy 2 at 47W, and Eddy 3 at 45W). The diameter of the eddies and the magnitude of their center depression increase from west to east. The smallest eddy (<25 km diameter), to the west, is identified by only one station, the middle eddy (100 km diameter) by two stations, and the largest (150 km diameter), to the east, by four stations within closed contours.

A temperature section along the crest of the Ridge (Fig. 6) shows the eddies to extend to at least 1500 decibars. The eddies are obvious in the temperature field only below 100 m due to their near surface thermal manifestation being quite small.

In contrast to Mann (1967), the Gulf Stream during this survey does not branch around the Ridge near 45W, although a considerable portion of the Stream does flow across the western portion of the Ridge. The northeastward transport, $37 \times 10^6 m^3 s^{-1}$ (referenced to 1000 decibars), is comparable to Mann's (1967) $35 \times 10^6 m^3 s^{-1}$ (reference to 2000 decibars) for the combined slope water current and the Gulf Stream branch.

1977 Circulation Pattern—The surface dynamic topography for June 1977 (Fig. 7) reveals a circulation similar to that proposed by Mann (1967). The Gulf Stream flows eastward along the southern side of the Ridge and apparently branches near 46W. One branch continues southeastward and the other curves around the Ridge

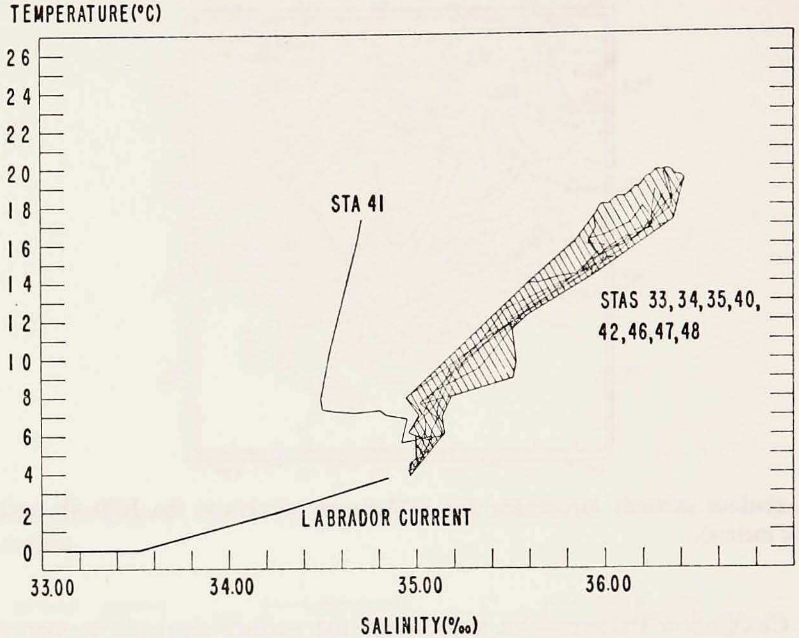

Figure 8. Temperature-salinity diagram for the station in the center of the easternmost eddy observed in 1976 (STA 41) and for the stations surrounding that eddy (cross-hatched envelope).

to the northwest. A closed contour on the crest of the Ridge suggests the presence of an eddy-like feature.

3. Water properties of the eddies

The temperature-salinity properties of the waters near the eastern edge of the Grand Banks in 1976 and 1977 were similar in pattern to those commonly observed (e.g. Bullard *et al.*, 1963). Cold low salinity Labrador Current water was located over the steep continental slope at the eastern edge of the Grand Banks. Further offshore (approximately located seaward of the 971.1 dynamic height contour in Figure 5) the water properties were characteristic of the North Atlantic current. Between the two water masses was a narrow region of mixed water with intermediate temperature-salinity properties.

Two exceptions to the above described pattern occur within the eddies observed in 1976 and in 1977. The water properties within the largest eddy in 1976 (station 41 in Fig. 8) appear to result from a mixing of Labrador and North Atlantic current waters, while those within the 1977 eddy (stations 8 and 19 in Fig. 9) appear to be nearly pure Labrador current water. In Figures 8 and 9 the observations surrounding both eddies lie within T/S envelopes characteristic of the North Atlantic current

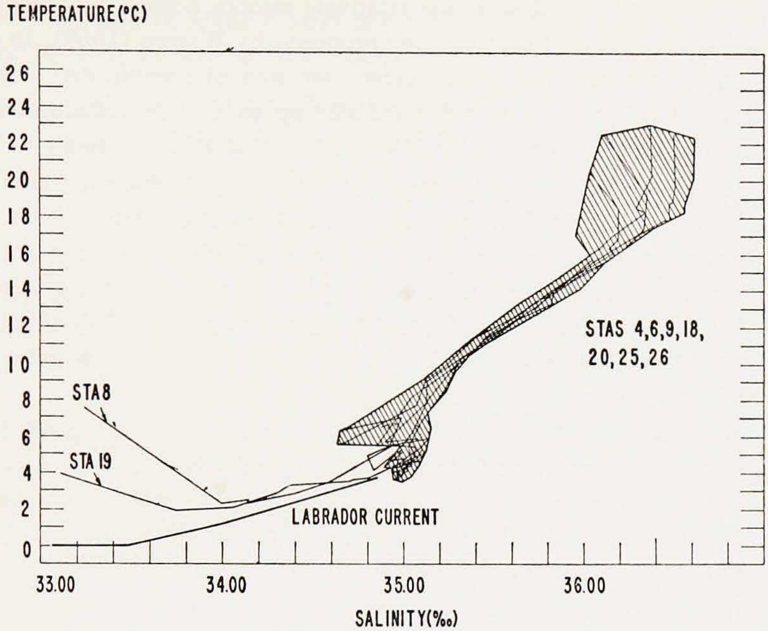

Figure 9. Temperature-salinity diagrams for those stations within the eddy observed in 1977 (STA 8 and STA 19) and for the stations surrounding that eddy (cross-hatched envelope).

water. The upper 50m of the water columns has been excluded in these figures to eliminate local, nearsurface effects. The presence of isolated Labrador Current water more than 200 km from its normal extent suggests that the eddies may have originated near the Tail of the Bank and moved or were advected southeastward along the crest of the Newfoundland Ridge.

4. Discussion

Substantial temporal variation occurs in the general circulation pattern near the Newfoundland Ridge. The eddies encountered over the Ridge are features not included in the circulation schemes of Mann (1967) and Worthington (1962 and 1976). Some of the variation may be an artifact of the different sampling grid spacings. For example, if the observations along 46W in the 1976 survey were omitted, dynamic height contours similar to those presented by Mann (1967) could be drawn. A similar remark also applies to the circulation pattern described by Worthington (1962 and 1976), which was based on sections spaced over 200 km apart and taken over an eleven year period.

Both the branching of the flow around the Newfoundland Ridge and the existence of eddies along the ridge crest seem associated with the bottom topography. In the various surveys discussed, the eastward flow around the Tail of the Bank and along the south side of the Ridge follows the relatively smooth bottom topography. This is consistent with the topographic steering proposed by Warren (1969). In contrast the eddies are observed on the ridge crest—an area of complicated topography where eastward flowing water would encounter up to a 45% reduction in water depth in 200 km distance (5100 m at 52W to 2800 m at 49°30′W along 41N).

A major difference between the surveys is the latitude at which the Gulf Stream enters the Newfoundland Ridge area. As a result the bottom topography that the eastward flow encounters also differs. In Mann's (1967) circulation pattern (Fig. 2) the Gulf Stream enters the region at 39N along the south side of the Ridge. In the 1976 and 1977 observations (Figs. 5 and 7) the northern edge of the Gulf Stream is near 42 and 41N, respectively, such that the Ridge topography is more directly encountered by the Stream.

Direct current measurements by Clarke and Reiniger (1973) along 49°30′W indicate that the currents near the Ridge do extend to the bottom with near bottom velocities of 10 to 15 cm/sec, making plausible the proposed topographic influence. The same measurements show that the Gulf Stream at the western edge of the Newfoundland Ridge can move 60 km northward in three days. Assuming a topographic influence in the current pattern development to the east, such movement suggests that the time scale (ca. three days) of major change can be less than the advection time (ca. ten days) through the Ridge area. Thus even the two week sampling period used in 1976 and 1977 may be too long to yield an acceptably synoptic picture of the flow field in some instances.

Despite the presence of eddies and the variation between surveys, the implications of the 1976 and 1977 measurements for the large scale North Atlantic circulation are the same as concluded by Mann (1967). A large transport of water crosses or branches around the Newfoundland Ridge, and therefore the circulation on the north side of the Ridge is not isolated from the Gulf Stream system. This conclusion is based on the assumption that the flow is geostrophic, a point questioned by Worthington (1976) on mass balance considerations. Future work in this area should combine drifting buoys and hydrographic measurements to insure that the flow is predominately geostrophic.

5. Conclusions

The presence of mesoscale eddies along the crest of the Newfoundland Ridge implies temporal and spatial variability in the current patterns near the Ridge on scales smaller than resolved in previous surveys. The circulation pattern varied from one of the Gulf Stream branching around the Ridge to one with a portion of the Stream flowing across the Ridge and eddies lying along the Ridge crest. A strong topographic influence is indicated.

The large transport of water observed to cross or branch around the Ridge supports the conclusion of Mann (1967) that the circulation to the north of the Newfoundland Ridge is not separate from the Gulf Stream system.

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Corrigendum

In Hinga, Sieburth, and Heath, The supply and use of organic material at the deep-sea floor, Vol. 37, 557-579, the following corrections should be made:

Table 6: "Organic Carbon" should be replaced with "Organic matter (assuming 50% carbon)."

Page 577: The sedimentation rate of "6.8 cm per year" should be 6.8 cm per 1000 years."