NOTES AND CORRESPONDENCE

On the Origin of Shelf Water in the Middle Atlantic Bight*

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6 June 1988 and 15 August 1988

ABSTRACT

Based on a limited set of available oxygen isotope measurements, it is hypothesized that the mean flow in the Middle Atlantic Bight is part of a 5000 km-long buoyancy-driven, coastal current which originates along the southern coast of Greenland. This idea is consistent with most features of the known circulation of the region.

1. Introduction

The mean southwestward alongshelf flow in the Middle Atlantic Bight (MAB) has recently been shown to be a continuation of the mean alongshelf flow over the Scotian Shelf (Chapman et al. 1986). Although the ultimate origin and driving mechanism for the flow were not identified, the oxygen isotope data presented there suggest that the flow probably originates far to the north. That is, the meteoric diluent (i.e. freshwater) which has mixed with slope water to create the Scotian Shelf water is highly depleted in ^{18}O ($\delta^{18}O \approx -20‰$: Fairbanks 1982; Chapman et al. 1986) and is found at high latitudes. For example, the St. Lawrence River freshwater $\delta^{18}O$ is about $-10‰$ (Tan and Fraser 1976), indicating that it is not the dominant or primary freshwater source for Scotian Shelf water as previously suggested by Drinkwater et al. (1979). In this note, we present additional evidence for the origin of the MAB shelf water based on oxygen isotope data from the Labrador Sea and Baffin Bay (Fig. 1) which have been analysed and reported by Tan and Strain (1980a). Then we offer an hypothesis for the circulation and the ultimate driving mechanism leading to the MAB mean flow.

2. Oxygen-isotope tracer results

The shelf water in the MAB has been shown to consist primarily of a mixture of slope water ($S \approx 35.5‰$, $\delta^{18}O \approx 0.75‰$) and Scotian Shelf water ($S \approx 32.35‰$, $\delta^{18}O \approx -1.09‰$) which flows past the southern tip of Nova Scotia into the Gulf of Maine (Chapman et al. 1986). These two water types define what may be called the MAB mixing line: $\delta^{18}O = 0.58S - 20.0$. Both the salinity and ^{18}O content of Scotian Shelf water vary slightly seasonally, but they remain close to the MAB mixing line. Local freshwater input is significant only in nearshore surface waters adjacent to the major estuaries.

The salinity and ^{18}O content of water samples collected in the Labrador Sea (Tan and Strain 1980a) all fall very close to the MAB mixing line (Figs. 1 and 2). Data from the central Labrador Sea (station 2; open circles; water depth of 2720 m) are clustered near the slope water point, indicating the similarity between deep water here and slope water in the MAB. Data from station 1 (open squares; water depth of 497 m) and station 5 (open triangles; water depth of 750 m) occur all along the mixing line with the shallower samples located toward the Scotian Shelf water point. The regression fit for all points at stations 1 and 5 is $\delta^{18}O = 0.64S - 22.13$ (solid line) which is very similar to the MAB mixing line. (The correlation coefficient is $r = 0.94$ and the 95% confidence limits of the slope and intercept are ± 0.10 and ± 3.56, respectively). Thus, both water found in the Labrador Sea and in the MAB appear to be a mixture of slope water and freshwater with a $\delta^{18}O$ of about $-20‰$. The typical isotopic content of local glacial melt and river runoff into the Labrador Sea is about $-20‰$ (e.g. Bedard et al. 1981), which strongly suggests that the primary source of MAB freshwater is located in the northern Labrador Sea!

It is important to note that the water samples obtained by Tan and Strain (1980a) are almost entirely from locations well seaward of the continental shelf. Yet the near-surface waters at stations 1 and 5 (Figs. 1 and 2) are nearly as fresh and as depleted in ^{18}O as the Scotian Shelf water which represents nearshore water entering the Gulf of Maine shoreward of the 100

* Woods Hole Oceanographic Institution Contribution Number 6787.

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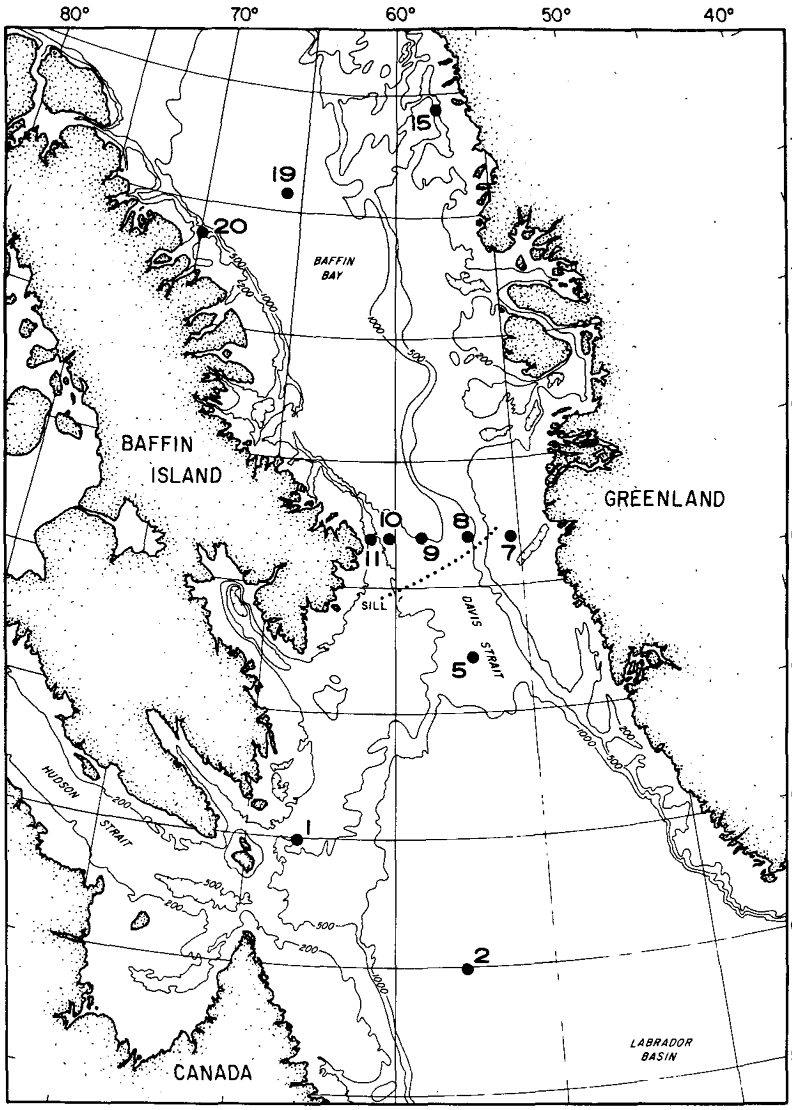

FIG. 1. Map of the northern Labrador Sea and Baffin Bay showing the station positions from which the oxygen isotope and salinity measurements used in Figs. 2–5 were obtained by Tan and Strain (1980a).

m isobath. Presumeably, the salinity and $\delta^{18}O$ content of nearshore samples in the Labrador Sea would be less saline and more depleted in ^{18}O than Scotian Shelf water (although this remains to be seen). Further, station 2, representative of deep Labrador Sea water, is consistently fresher and has lower $\delta^{18}O$ than the slope water in the MAB. All of these features are expected if the freshwater source for the MAB is in the northern Labrador Sea and a gradual mixing with more saline, higher $\delta^{18}O$ slope water occurs during the transit to the MAB.

Observations made farther north help to identify the source water. Data from samples obtained at station 7 (crosses in Fig. 3; water depth 104 m) and station 8 (open circles in Fig. 3; water depth 658 m) in the eastern part of Davis Strait near the west coast of Greenland (Tan and Strain 1980a) all fall close to the MAB mixing line with a regression fit of $\delta^{18}O = 0.53S - 18.29$ (solid line in Fig. 3; correlation coefficient $r = 0.97$; 95% confidence limits of the slope and intercept are ± 0.06 and ± 2.07, respectively). Furthermore, the samples closer to shore (station 7) fall quite close to the Scotian Shelf water point, while the offshore samples (station 8) are spread along the mixing line with the shallower samples being fresher. The most likely freshwater source is local glacial melt.

The samples from the western side of Davis Strait (Fig. 4) have very different properties from those on the eastern side or to the south. Most of the data fall on a mixing line which has a freshwater endpoint much more highly depleted in ^{18}O than the MAB mixing line. Additionally, some data points are not on the

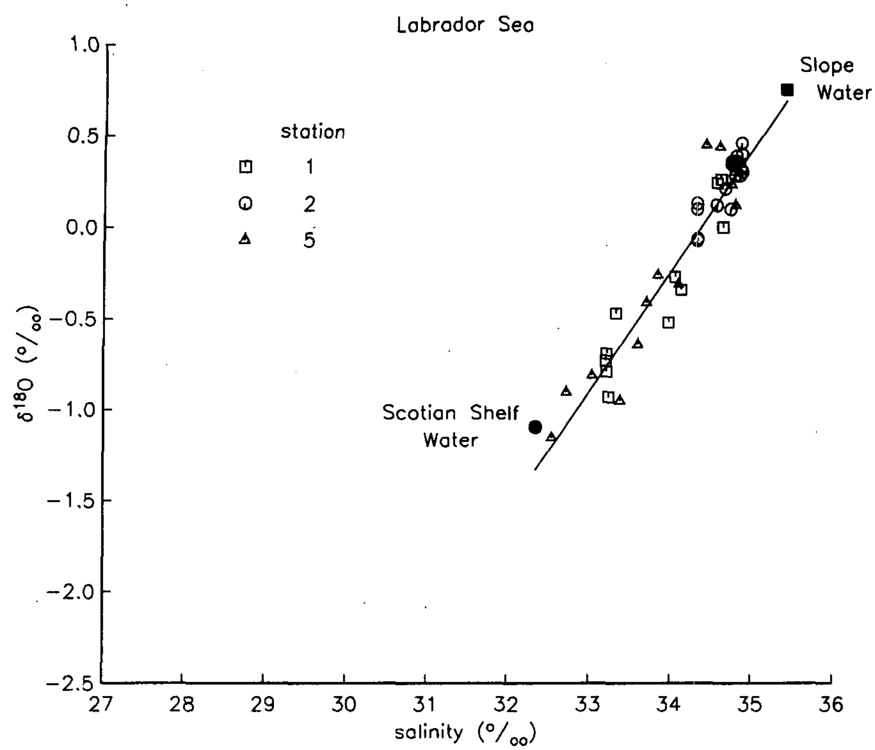

FIG. 2. Oxygen isotope depletion ($\delta^{18}O$) versus salinity for water samples from stations 1, 2 and 5 in Fig. 1. The solid square represents slope water; the solid circle represents Scotian Shelf water. The straight line is a linear regression fit to the points from stations 1 and 5 only. The measurement error for each $\delta^{18}O$ value is about 0.1‰ (Tan and Strain 1980b).

mixing line at all; these samples contain substantial amounts of sea-ice meltwater which is fresh but has the same ^{18}O content as the water from which it froze (Tan and Strain 1980b). The regression fit for the points on the western side of Davis Strait (Fig. 4) which contain little or no sea-ice meltwater is $\delta^{18}O = 1.12S - 38.93$ (solid line; correlation coefficient $r = 0.97$; 95% confidence limits of the slope and intercept are ± 0.10 and ± 3.47, respectively). Such a mixing line is typical of arctic regions (e.g. Tan et al. 1983); the higher salinity apparently resulting from the brine production during the freezing of sea water (e.g. Redfield and Friedman 1969).

Data from samples obtained at three stations in central Baffin Bay to the north of Davis Strait (Fig. 5) show similar features to those across Davis Strait (Tan and Strain 1980a). The samples obtained close to the west coast of Greenland (station 15; open squares; water depth of 214 m) fall close to the MAB mixing line. The data from the central and western parts of Baffin Bay (station 19 and 20) fall on a mixing line like that in Fig. 4 (some have substantial sea-ice meltwater and do not fall on either mixing line).

3. Proposed circulation

We hypothesize that the MAB mean alongshelf flow is actually a downstream continuation of a buoyancy-driven coastal current which originates along the southern coast of Greenland, flows cyclonically around the northern Labrador Sea, joins the Labrador Current and then feeds the Scotian Shelf mean flow. The driving mechanism is the freshwater input from Greenland glacial melt and runoff to the south of Davis Strait with additional contributions from river runoff entering through Hudson Strait and along the Labrador coast (Fig. 6). We suspect that the deep circulation associated with the subpolar gyre acts as a dynamical offshore boundary which helps keep the shelf flow confined over the shelf and upper slope [as proposed by Chapman et al. (1986) for the MAB] and does not actually drive the shelf flow. The current does not originate farther to the north along the east coast of Greenland because the $\delta^{18}O$–S relationships for water samples in the East Greenland Current near 81°N (Tan et al. 1983) are quite similar to those of western and central Baffin Bay (Figs. 4 and 5). Furthermore, the lack of shallow low-salinity water located offshore and to the east of Greenland (Ivers 1975; Worthington 1976) eliminates that region as a potential freshwater source.

This hypothesis for the source water for the MAB mean flow is consistent with both the isotope results described above and with most features of the known circulation of the region. The West Greenland Current travels north as a fairly narrow (~100 km), deep

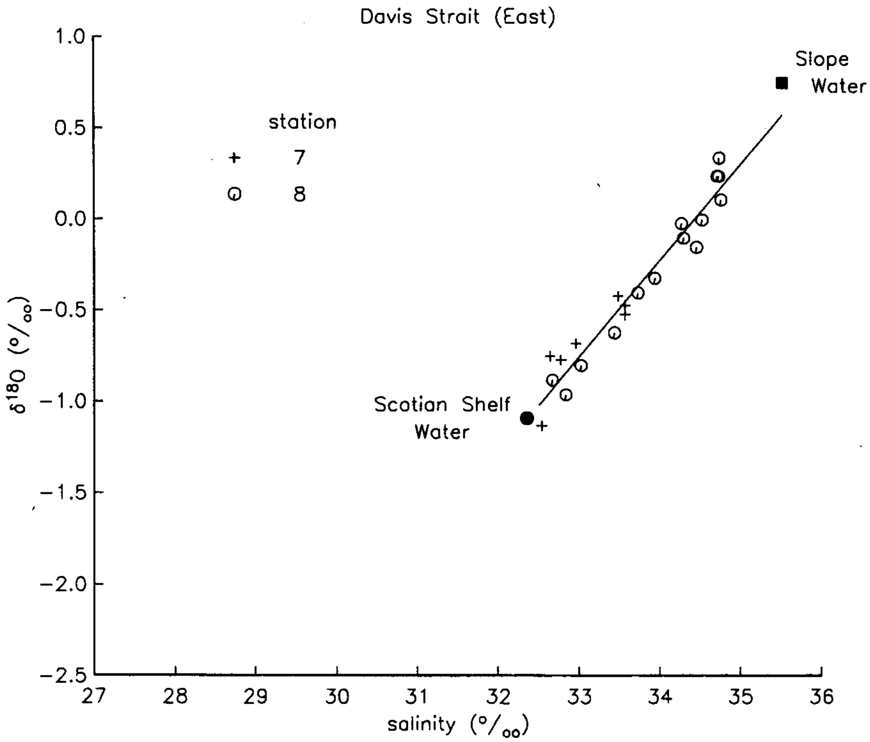

FIG. 3. As in Fig. 2 but for stations 7 and 8 in Fig. 1. The regression fit is for all points from stations 7 and 8.

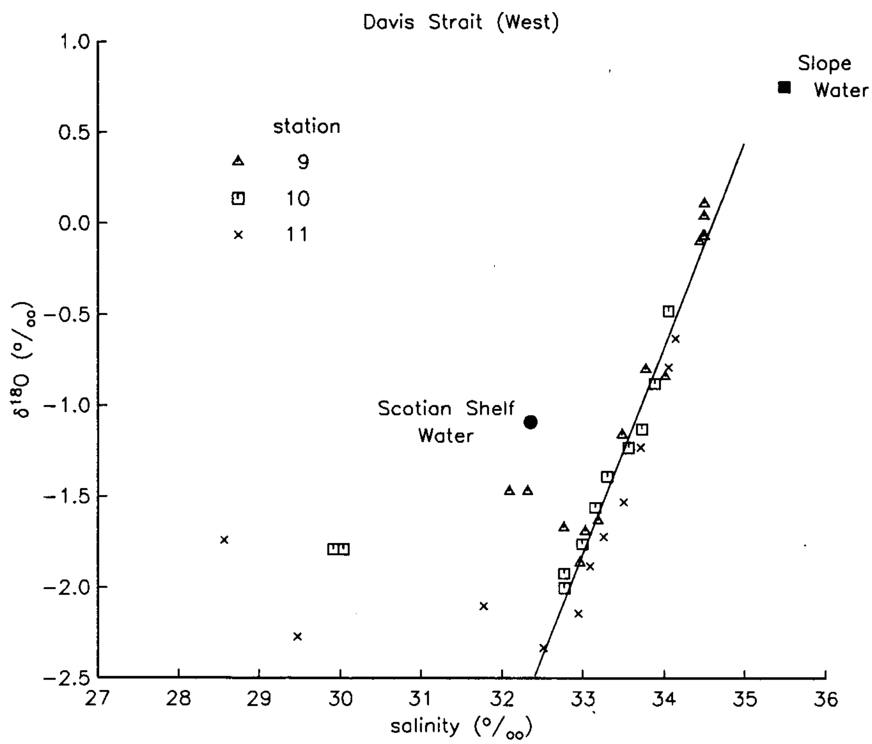

FIG. 4. As in Fig. 2 but for stations, 9, 10 and 11 in Fig. 1. The regression fit is for all points from stations 9, 10 and 11 except the seven points which are substantially fresher than those near the line.

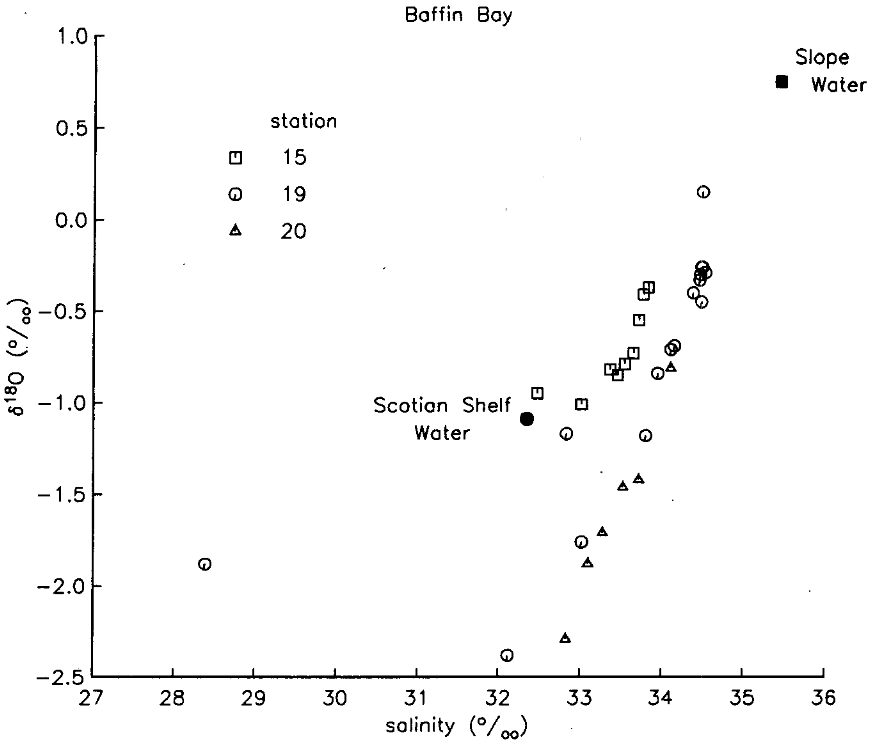

FIG. 5. As in Fig. 2 but for stations, 15, 19 and 20 in Fig. 1.

($\geq$1000 m) and swift ($\sim$40 cm s^{-1} at the surface) flow (Smith et al. 1937; Lazier 1980). The current splits near the sill of Davis Strait, with one component continuing northward into Baffin Bay and the rest of the current turning westward (Smith et al. 1937; Collin and Dunbar 1964). This split is fairly clear in a sequence of hydrographic sections across the Labrador Sea (Grant 1968) and is consistent with the similarity in $\delta^{18}O$ values in the eastern part of Davis Strait and the Labrador Sea (stations 5, 7 and 8 in Figs. 2 and 3). Once within Baffin Bay, the West Greenland Current water mixes, perhaps freezes and rapidly loses its original character (Sverdrup et al. 1942, p. 665; Collin and Dunbar 1964).

The westward flowing part of the West Greenland Current joins the Baffin Current flowing south out of Baffin Bay north of Hudson Strait (Smith et al. 1937; LeBlond et al. 1981). At first glance, the $\delta^{18}O$ data from the western part of Davis Strait (Fig. 4) seems inconsistent with this pattern. However, stations 9, 10 and 11 were actually located *north* of the sill separating Baffin Bay and the Labrador Sea (see Fig. 1). This suggests that at least some of the flow there could turn eastward and remain within Baffin Bay (Smith et al. 1937). Further, observations indicate that, north of Hudson Strait, the Baffin Current flows close to the coast (Grant 1968; LeBlond et al. 1981) and is fairly weak; less than $\sim$10 cm s^{-1} at the surface. Such a nearshore flow would not be detected in the $S - \delta^{18}O$ properties at station 1 which is well offshore at the 500 m isobath. The ultimate fate of the southward flowing part of the Baffin Current is unclear; perhaps its identity is lost through mixing within Hudson Strait. In any case, the Baffin Current apparently does not significantly influence the salinity and $\delta^{18}O$ properties observed farther south, where the bulk of the southward flow is located farther offshore and is composed mainly of the westward extension of the West Greenland Current (Smith et al. 1937; LeBlond et al. 1981).

The southward flow is accelerated as it passes Hudson Strait (Smith et al. 1937; LeBlond et al. 1981; Peterson 1987), due both to the southward convergence of the outer shelf and upper slope bathymetry and to additional freshwater input through the southern side of Hudson Strait which should have roughly the same ^{18}O content as Greenland glacial melt [based on the distribution of ^{18}O in meteoric waters over North America (Fairbanks 1982)]. This flow joins the Labrador Current which continues south along the continental margin of Labrador and Newfoundland (receiving additional freshwater runoff) until encountering the Grand Banks. The Labrador Shelf topography is quite complex, with a series of banks and cross-shelf channels or saddles separating a nearshore marginal trough from the shelf break. Although the Labrador Current exhibits a banded structure with the stronger currents occurring over the outer shelf and upper slope, the complex bathymetry allows some cross-shelf ex-

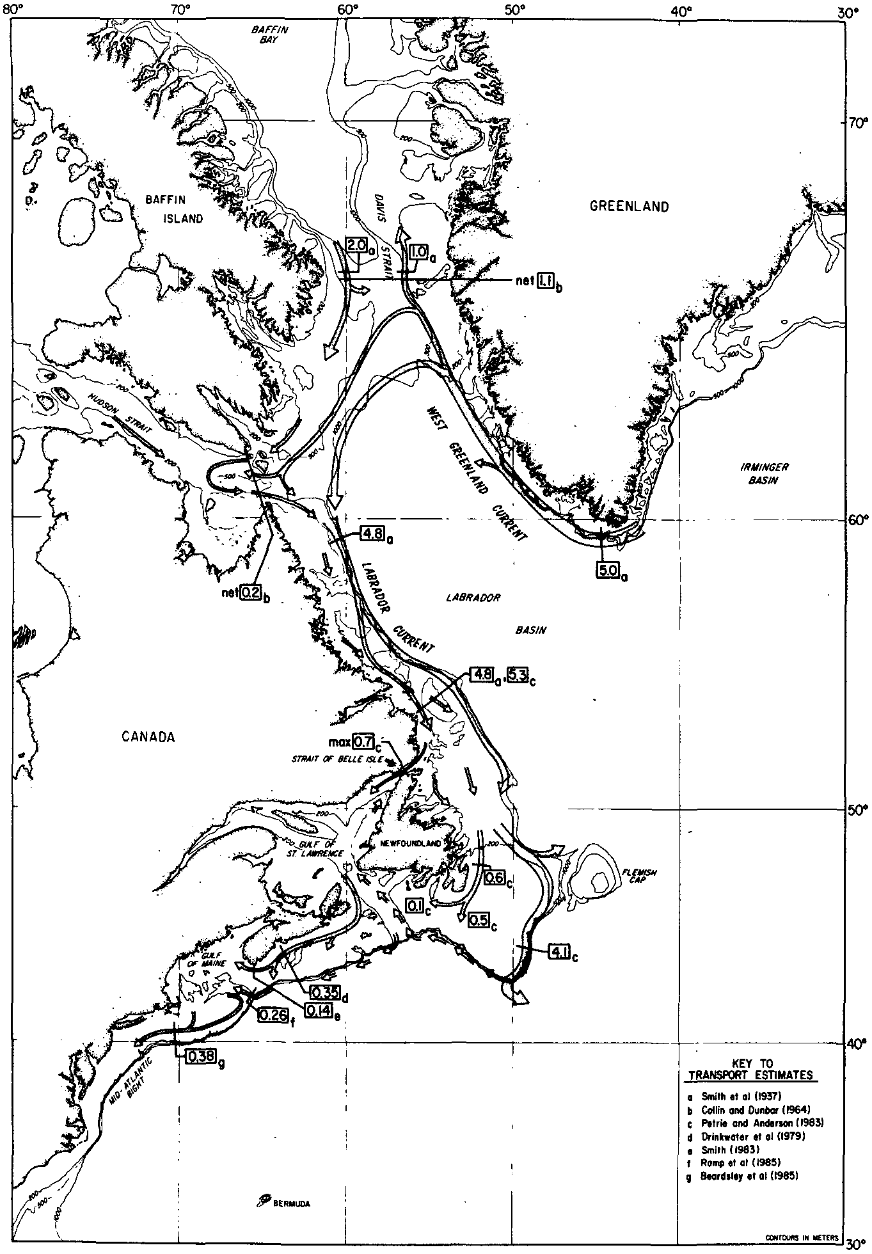

FIG. 6. Proposed circulation pattern showing possible pathways for coastal water from the West Greenland Current to the MAB. Broader arrows denote regions of higher current concentration, and broken arrows correspond to deeper flows. The numbers shown in boxes are transports in units of 10^6 m^3 s^{-1} taken from the different sources listed in the key. Most of the transports listed north of 50°N are geostrophic estimates with a reference level of 1500 m. No attempt has been made in this figure to conserve transport. This figure represents an extension to the north and west of the mean circulation picture for the Newfoundland shelf presented by Petrie and Anderson (1983).

change so that both local runoff and deeper Labrador Current water are found near shore (Iselin 1930; Smith et al. 1937; Peterson 1987).

Hydrographic and direct current observations (summarized by Petrie and Anderson 1983) show that the Labrador Current splits into two branches near 48°N, with most (~90%) of the current continuing to flow toward the southeast along the northern edge of the Grand Banks while much of the remaining water flows south around the tip of Newfoundland in a nearshore branch through Avalon Channel. Some of this nearshore branch (~20%) continues westward into the

Gulf of St. Lawrence. The offshore branch further splits, with much of its transport eventually turning eastward near 42°N, but with some flow continuing around the perimeter of the Grand Banks toward Cabot Strait. Some of this westward flow enters the Gulf of St. Lawrence as a deep flow through Cabot Strait (El-Sabh 1977) while the remainder flows southwestward along the continental slope toward the Gulf of Maine. This southwestward flow is the "Labrador Slope Water" described by Gatien (1976) which apparently contributes substantially to the mean flow into the Gulf of Maine through the Northeast Channel (Ramp et al. 1985). In addition, some Labrador Current water enters the Gulf of St. Lawrence via the Strait of Belle Isle, mixes with St. Lawrence River water and the deep inflow from Cabot Strait, and eventually flows onto the Scotian Shelf. This combined transport of Labrador Current water flowing westward past Newfoundland and onto (and along) the Scotian Shelf and upper slope either directly or indirectly (via the Gulf of St. Lawrence) is more than adequate to supply the 0.4×10^6 m^3 s^{-1} mean transport in the MAB (Beardsley et al. 1985).

A simple salt budget provides additional evidence that the primary source water for the MAB mean flow is not the St. Lawrence River. There appears to be basically two sources of inflow to the Gulf of Maine which in turn provide the mean flow to the MAB; the nearshore mean flow around the southern tip of Nova Scotia (Smith 1983) and the deep mean inflow through the Northeast Channel (Ramp et al. 1985). Both inflows are appreciably fresher than the neighboring slope water. Chapman et al. (1986) have used salinity and oxygen isotope measurements to argue that the deep channel inflow contains a combination of shelf and slope water which was mixed over the Scotian Shelf and upper slope before entering the Northeast Channel. If we assume that both inflows are formed by a mixture of fresh water ($S = 0‰$) and slope water ($S = 35.5‰$), then an estimate of the total freshwater contribution can be obtained as

$$F_f = V_f - S_f/35.5‰$$

where F_f is the freshwater flux, V_f the total volume influx, and S_f the total salt influx. For the nearshore inflow, we have used the mean and annual cycles for velocity and salinity reported by Smith (1983, his Table 1) to compute V_f and S_f, which yields $F_f = 0.017 \times 10^6$ m^3 s^{-1}. For the deep channel inflow, we used a mean flow of 0.26×10^6 m^3 s^{-1} reported by Ramp et al. (1985), and we assumed a salinity of 34.7‰ based on their Fig. 10. This results in $F_f = 0.006 \times 10^6$ m^3 s^{-1} for a total freshwater flux of 0.023×10^6 m^3 s^{-1}. This is about twice the freshwater outflow of the St. Lawrence River (Sutcliffe et al. 1976), and therefore is consistent with the need for a more distant upstream source. The St. Lawrence River does, however, represent a significant freshwater source. We suspect that some St. Lawrence freshwater may be lost from the shelf in near-surface exchange at the shelf/slope front, and that the mixing in the Gulf of St. Lawrence and over the Scotian Shelf proper is so thorough that its signature in the salinity and δ^{18}O characteristics of the water ultimately entering the MAB is lost.

4. Conclusion

The limited available oxygen-isotope measurements suggest that freshwater input from glacial melt and river runoff around southern Greenland (with additional freshwater input through Hudson Strait and along the Labrador coast) generates a buoyancy-driven coastal current which continues southward, around Newfoundland, over and along the Scotian Shelf and finally into the MAB; by far the longest coastal current known (over 5000 km). This hypothesis for the origin of the MAB shelf water and the driving mechanism for the mean alongshelf flow in the MAB is consistent with most features of the known circulation of the region. Many of the details of the flow (e.g. the ultimate fate of both the southward flowing Baffin Current and the St. Lawrence River freshwater outflow), as well as the flow dynamics, will require a more complete data set and analysis and modeling efforts before they will be completely understood.

Acknowledgments. We thank Mike McCartney for several valuable discussions. During the course of this research, we have been supported by the National Science Foundation under Grants OCE85-21837 (DCC) and OCE84-17769 and OCE87-16937 (RCB).

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