Freshwater sources to the coastal ocean off northeastern North America: Evidence from $H_2{}^{18}O/H_2{}^{16}O$

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Abstract. Oxygen isotope ($H_2{}^{18}O/H_2{}^{16}O$)/salinity data identify freshwater sources along the northeastern North American continental margin. The oxygen isotope (δ^{18}O)–salinity (*S*) properties of various water types are distinguished. Sea ice formation on the Labrador Shelf is shown to influence δ^{18}O–*S* values. It is estimated that 2–3 m of freshwater is extracted from the water column to form sea ice. It is hypothesized that waters on the Scotian Shelf, Gulf of Maine, and the Middle Atlantic Bight are composed of slope water diluted by an upstream low-salinity source. This upstream source is a mixture of brine-enriched Labrador Shelf Water and St. Lawrence River water. The δ^{18}O value of the apparent freshwater component ($\delta^{18}O_{S=0}$) of waters on the Scotian Shelf and farther south is $\approx -20‰$, which has been used to suggest a sole high-latitude freshwater source. We show instead that the St. Lawrence River contributes ≈35% of the freshwater on the Scotian Shelf, in agreement with the physical oceanographic evidence. The remaining freshwater is supplied by high-latitude rivers dominated by Arctic runoff. Finally, the isotope evidence identifies Baffin Bay as an important pathway by which freshwater from the Arctic Ocean can reach the Labrador Sea.

1. Introduction

The coastal ocean off northeastern North America is strongly influenced by the large-scale coastal circulation (Figure 1) extending from the Labrador Sea to Cape Hatteras [*Fairbanks*, 1982; *Chapman et al.*, 1986; *Chapman and Beardsley*, 1989]. This circulation carries relatively cold and fresh subpolar water which influences the hydrographic properties of coastal waters downstream, such as on Georges Bank. *Chapman and Beardsley* [1989] were the first to draw attention to the critical role played by freshwater in modulating the buoyancy-driven coastal current. However, attempts to identify the freshwater sources responsible for seasonal and interannual salinity fluctuations in coastal waters have had mixed success. For example, hydrographic data suggest that Baffin Bay and Hudson Bay are important sources of freshwater for the coastal current [*Mertz et al.*, 1993; *Loder et al.*, 1998]. On the other hand, studies based on oxygen isotope data [*Chapman and Beardsley*, 1989] indicate that the margin of the Labrador Sea is the dominant source. The contribution of St. Lawrence River water to coastal waters downstream has also been debated.

In this paper, we focus on the application of the $H_2{}^{18}O/H_2{}^{16}O$ ratio as a tracer for identifying the sources that contribute to the coastal circulation. The $H_2{}^{18}O/H_2{}^{16}O$ tracer is uniquely suitable for this study because (1) source waters have well-defined δ^{18}O–salinity relationships and (2) the δ^{18}O–salinity tracer pair allows us to discriminate sea ice meltwater from river runoff as well as to quantitatively estimate the individual freshwater sources in the water column. Here we concentrate on obtaining a better characterization of upstream waters on the Labrador Shelf and in the Gulf of St. Lawrence, on the basis of salinity and mass spectrometrically determined $H_2{}^{18}O/H_2{}^{16}O$ ratios, and show how the addition of oxygen isotope data can help to resolve the source water ambiguities mentioned above. It should be stressed that our data do not resolve seasonal or interannual changes and our quantitative estimates of individual freshwater con-

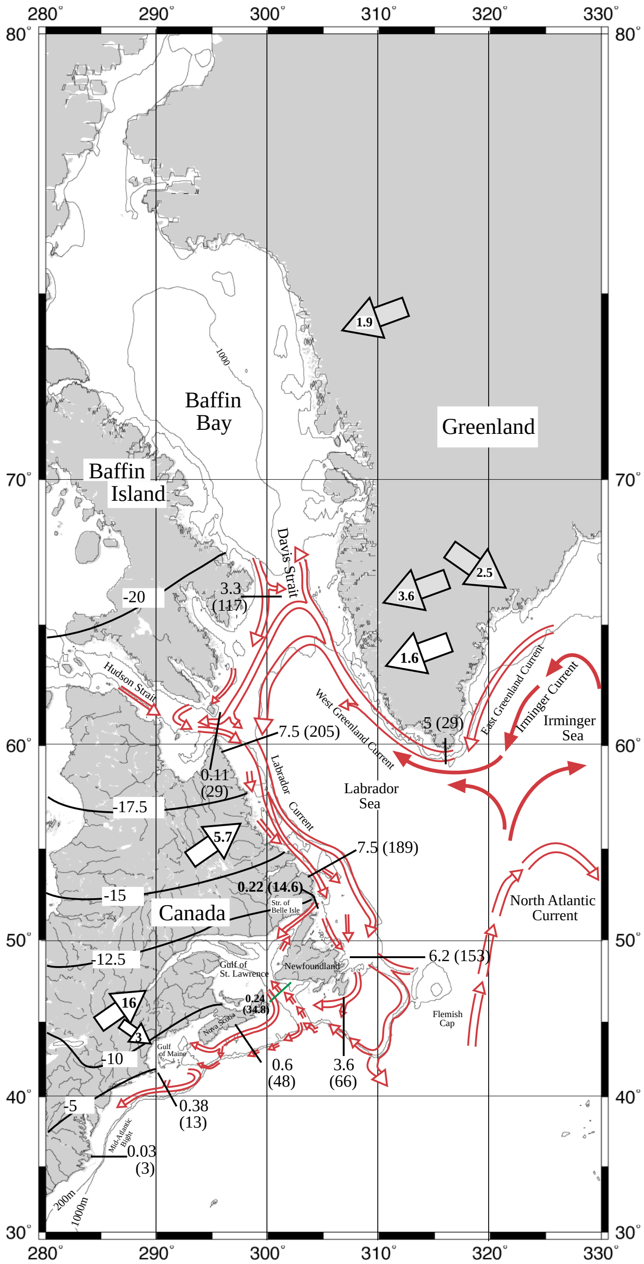

Figure 1. Schematic representation of the major circulation features in the northeastern North American coastal ocean. Adapted from *Chapman and Beardsley* [1989]. Total (freshwater) transports across key cross-shelf sections in Sv (mSv) are indicated (1 Sv=10^6 m^3 s^{-1}). Large open arrows represent runoff in mSv. Large stippled arrows represent ice discharge (mSv of water equivalent) by calving from the Greenland Ice Sheet [*Reeh*, 1985]. Note that the arrows are not scaled relatively and only indicate the general direction, not the point at which the freshwater enters the ocean. Sections extend from the coast to the 34.8 psu isohaline. Transport and runoff estimates are from *Loder et al.* [1998]. Isopleths of δ^{18}O in precipitation are shown to emphasize the latitudinal variation of oxygen isotopes [*Fairbanks*, 1982] and hence the utility of this tracer in discriminating between different freshwater sources.

tributions are tentative. Our main goal, however, is to present a qualitative picture of the coastal circulation that is consistent with both the hydrography and the available isotope data.

2. Circulation

The coastal circulation and hydrography along northeastern North America (Figures 1 and 2) have been discussed extensively elsewhere [e.g., *Chapman and Beardsley*, 1989; *Mertz et al.*, 1993; *Loder et al.*, 1998], and only a brief outline is presented here. While a fairly robust description of the large-scale coastal circulation exists, the transports shown in Figure 1 are less well constrained. In particular, fluxes as well as hydrographic properties could undergo interannual and decadal changes due to variable freshwater and atmospheric forcing [e.g., *Dickson et al.*, 1988]. These aspects, however, are beyond the scope of this paper.

The principal water sources for the Labrador Shelf are (1) the Arctic Ocean via the East/West Greenland Current System and the Canadian Archipelago, (2) outflow from Hudson Strait, and (3) outflow from Baffin Bay through Davis Strait. These sources combine to form the Labrador Current, the main branch of which is concentrated over the shelf break and upper slope. A small branch is located over the inner Labrador Shelf [*Lazier and Wright*, 1993; *Mertz et al.*, 1993], a part of which results in a small net inflow of 0.22 Sv (1 Sv=10^6 m^3 s^{-1}) [*Petrie et al.*, 1988] through the Strait of Belle Isle to the Gulf of St. Lawrence (GSL). A part of the main Labrador Current also turns eastward north of Flemish Cap. The remaining transport continues to flow southward into the Grand Banks region in two branches: a shelf-break branch carrying ≈90% of the transport and an inshore branch carrying ≈10% of the transport. The inshore branch flows south and west along the Newfoundland Shelf. Some of the offshore branch turns eastward and leaves the shelf break, while the remaining current turns westward and flows along the southern Newfoundland Shelf break. The westward flowing branches generate an inflow of ≈0.5 Sv into the GSL through the eastern side of Cabot Strait. This inflow combines with the inflow through the Strait of Belle Isle and river runoff to contribute to the circulation in the GSL. Water from the GSL flows out on the western side of Cabot Strait, joining the direct flow of Labrador Current water from the southern Newfoundland Shelf, to flow south over the Scotian Shelf in two main arteries over the inner shelf and shelf break. These waters enter the Gulf of Maine and are a primary source for Georges Bank.

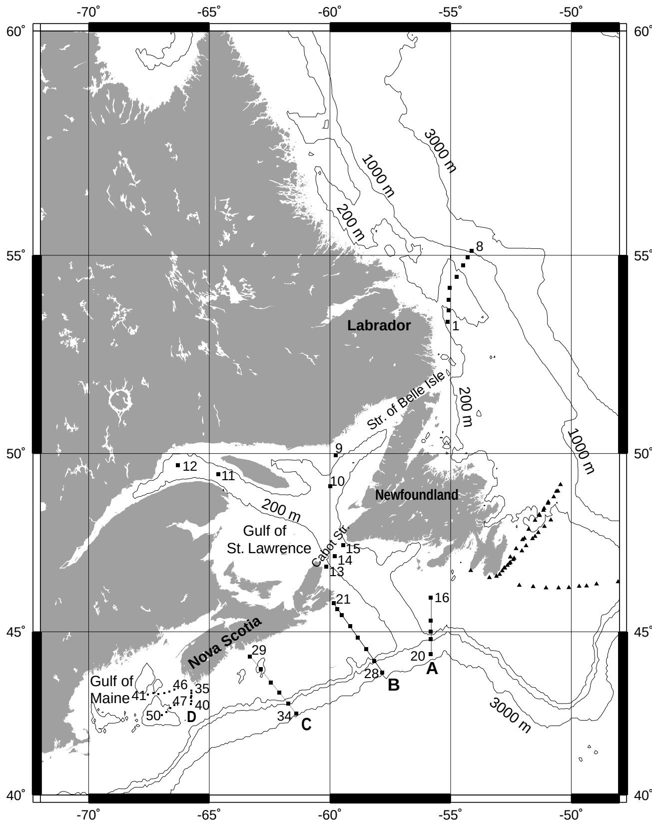

Figure 2. Locations of stations occupied on several cruises in 1995. Samples were collected from the Labrador Shelf (June) during a cruise of CSS *Hudson* and from the Gulf of St. Lawrence (October–November), South Newfoundland Shelf (November), Scotian Shelf (June and November), and Gulf of Maine (June) during cruises of CSS *Parizeau*. Station numbers and sections referred to in the text are also indicated. Solid triangles represent surface samples from the Newfoundland Shelf (March, May, June, July, October).

3. Freshwater Sources

Oxygen isotope analysis of waters from the Scotian Shelf, Gulf of Maine, and Middle Atlantic Bight suggested that the dominant freshwater input must originate at high-latitude, rather than locally [*Fairbanks*, 1982; *Chapman et al.*, 1986; *Chapman and Beardsley*, 1989]. In particular, *Chapman and Beardsley* [1989] hypothesized that river runoff and glacial meltwater around southern Greenland and the Labrador Coast are major sources of the freshwater in the Labrador Current and the Middle Atlantic Bight. In contrast, salt balance calculations made by *Mertz et al.* [1993] indicate that outflow from Hudson Bay and Baffin Bay could be the dominant freshwater sources, while runoff and glacial meltwater fluxes into the Labrador Sea are less significant. More recent work by *Loder et al.* [1998] suggests that the Baffin Island Current out of Baffin Bay is the main source of freshwater, with a freshwater transport (relative to S=34.8 psu) of $\approx$117 mSv (Figure 1). Much of this freshwater originates as runoff into the Arctic Ocean [*Aagaard and Carmack*, 1989]. The freshwater flux in the East Greenland/West Greenland Currents (transporting Arctic waters) is $\approx$30 mSv, comparable to the outflow through Hudson Strait [*Loder et al.*, 1998]. Thus, in the flux calculations of *Loder et al.* [1998] the Arctic Ocean emerges as the dominant source of freshwater to the northeastern North American Shelf. We note that precipitation exceeds evaporation by 4 cm yr^{-1} [*Ikeda*, 1987], contributing a negligible 1.3 mSv of freshwater to the Labrador Sea. Farther south, the St. Lawrence River could also contribute to the freshening of coastal water [*Sutcliffe et al.*, 1976]. *Smith* [1989] detected the influence of St. Lawrence discharge on the salinity of shelf waters off Cape Sable at phase lags of $\approx$9 months, although he found no significant negative correlation between the anomaly time series of salinity off Cape Sable and the anomaly series of St. Lawrence discharge (phase-lagged appropriately). The absence of an isotopic signature of St. Lawrence River Water on the Scotian Shelf and the Middle Atlantic Bight [*Fairbanks*, 1982], however, appeared to contradict this result.

4. Methods and Samples

Our primary tool is the tracer pair $H_2{}^{18}O/H_2{}^{16}O$ and salinity. The fractional distillation of $H_2{}^{18}O$ and $H_2{}^{16}O$ in atmospheric water vapor due to their different molecular masses results in a decrease in the $H_2{}^{18}O/H_2{}^{16}O$ ratio in precipitation with increasing latitude [e.g., *Dansgaard*, 1964]. This trend is quite pronounced along the east coast of North America (Figure 1) and allows us to differentiate between different meteoric (precipitation or river) water sources and to quantify the proportions in which they are mixed [*Torgerson*, 1979; *Fairbanks*, 1982]. The $H_2{}^{18}O/H_2{}^{16}O$ ratio is not affected by biological processes within the ocean, and thus variations in the $H_2{}^{18}O/H_2{}^{16}O$ ratio are largely a result of mixing between different water masses. Further, oxygen isotope measurements are particularly useful in distinguishing meteoric water and sea ice meltwater [e.g., *Craig and Gordon*, 1965; *Redfield and Friedman*, 1969; *Tan and Strain*, 1980a; *Bédard et al.*, 1981].

The $H_2{}^{18}O/H_2{}^{16}O$ ratio is usually expressed in the $\delta^{18}O$ notation, defined as the permille deviation of the $H_2{}^{18}O/H_2{}^{16}O$ ratio in the sample from that of a standard:

$$\delta^{18}\mathrm{O} = \left[\frac{(\mathrm{H_2{}^{18}O/H_2{}^{16}O})_{\mathrm{sample}}}{(\mathrm{H_2{}^{18}O/H_2{}^{16}O})_{\mathrm{standard}}} - 1 \right] 1000$$

The reference used in this study is VSMOW (Vienna Standard Mean Ocean Water). The $H_2{}^{18}O/H_2{}^{16}O$ ratios are measured on a VG PRISM II mass spectrometer with a precision (1σ) of about $\pm 0.03^0/_{00}$ (based on repeated analyses of an internal laboratory standard over several months).

Water samples used in this study were collected from various locations which are shown in Figure 2. At most stations, samples were collected through the entire water column at standard oceanographic (bottle) depths, with a vertical resolution ranging between 30 m and 50 m. We also use isotope data from the northern Labrador Sea and Baffin Bay reported by *Tan and Strain* [1980b]. Our approach will be first to define significant water masses in terms of δ^{18}O and salinity and then to discuss the data within the framework of those end-members.

5. Water Mass Definitions

Water mass definitions in terms of δ^{18}O–salinity (*S*) are presented in Figure 3 and summarized in Table 1. The δ^{18}O–*S* data (Figure 3) demonstrate that waters both in the Gulf of St. Lawrence and on the Scotian Shelf are a mixture of Labrador Shelf Water, Labrador Slope Water, and St. Lawrence River Water. We can use δ^{18}O and salinity mixing diagrams to quantify the fractional contribution from various sources. As seen in the corresponding potential temperature (θ)–*S* plot (Figure 4), this is not possible using traditional oceanographic temperature/salinity data in such shallow coastal environments. Temperature is useful however in distinguishing the deeper slope waters, but in this paper we concentrate on the shelf region and our principal tracers will be δ^{18}O and salinity. It should be emphasized that our data were collected from a single year and also do not resolve seasonal changes in the δ^{18}O–*S* relationships. Thus some of our water mass definitions should be seen as operational and subject to future revision as additional data become available.

The δ^{18}O isopleths in Figure 1 indicate that the high-latitude meteoric sources of freshwater to the Labrador Current should have a value of $\approx -21^0/_{00}$. As mentioned above, net precipitation to the Labrador Sea is negligible; thus rivers constitute the main meteoric source of freshwater. In particular, the large inflow of low-salinity water from the Arctic Ocean via the Canadian Archipelago and the East Greenland/West Greenland Currents (see above) has a freshwater component with $\delta^{18}O \approx -21^0/_{00}$ [*Östlund and Hut*, 1984; *Schlosser et al.*, 1994]. Oxygen isotope measurements also suggest that the typical δ^{18}O value of local glacial meltwater and river runoff into the Labrador Sea [*Bédard et al.*, 1981], Baffin Bay [*Tan and Strain*, 1980a], and Hudson Bay [*Tan and Strain*, 1996] is about $-21^0/_{00}$. Using δ^{18}O alone, we are unable to discriminate between these different freshwater sources. However, the hydrographic evidence [e.g., *Aagaard and Carmack*, 1989; *Lazier and Wright*, 1993; *Loder et al.*, 1998] suggests that the Arctic is the dominant source of freshwater. Thus we call our high-latitude meteoric end-member Arctic River Water (ARW), with the understanding that it also includes runoff into Baffin Bay and Hudson Bay. ARW is assigned a δ^{18}O value of $-21^0/_{00}$.

The inner branch of the Labrador Current is the principal input at shallow and intermediate depths to the Gulf of St. Lawrence, entering the gulf through the Strait of Belle Isle. We designate this input Labrador Shelf Water (LShW). LShW continues to flow south in the Labrador Current, and as demonstrated below, its influence can be detected isotopically as far south as the Scotian Shelf. The influence of sea ice formation on the Labrador Shelf is clearly reflected in the δ^{18}O–*S* "mixing" diagram (Figure 3) and illustrated schematically in Figure 5. Formation of sea ice leads to brine rejection, as freshwater is removed from the water column. Oxygen isotopes undergo negligible fractionation during sea ice formation [*Craig and Gordon*, 1965]; therefore the isotope ratio in the resultant brine is close to that in the original water mass. A combined salinity, δ^{18}O, and mass balance can distinguish between meteoric and sea ice meltwater in the water column. On the Labrador Shelf the most brine-enriched sample (station 4, 40 m) has salinity and δ^{18}O values of 32.78 psu and $-1.53^0/_{00}$, respectively. We adopt these values as a working definition of Labrador Shelf Water. As supporting evidence, we note that both deep and surface waters in the northeastern GSL and on the Labrador Shelf appear to mix with LShW (Figure 3). This is surprising considering that samples from the Labrador Shelf were collected in June, while those from the GSL were collected in November. This leads us to speculate that LShW (more specifically, the brine enriched subsurface layer) is a more stable end-member than we might anticipate from the seasonal variation of salinity on the Labrador Shelf.

Labrador Slope Water (LSW) is defined as the most saline water found on the Labrador Slope at a depth of about 400–500 m ($\delta^{18}O=0.22^0/_{00}$, *S*=34.81 psu, θ=3.28°C). LSW, as defined here, differs from earlier definitions [e.g., *Gatien*, 1976; *Brown and Irish*, 1993] in being considerably colder. This is because we define Labrador Slope Water near its source (i.e., on the Labrador Slope) rather than farther downstream on the Scotian Slope or in the Gulf of Maine where it has already mixed with warmer and saltier waters. The solid line in Figure 3 is a theoretical mixing line between Labrador Slope Water and Arctic River Water. It is important to note that δ^{18}O–*S* data from the Labrador Shelf are not distributed along this line. South of Nova Scotia the dominant slope water is Warm Slope Water (WSW) [*Gatien*,

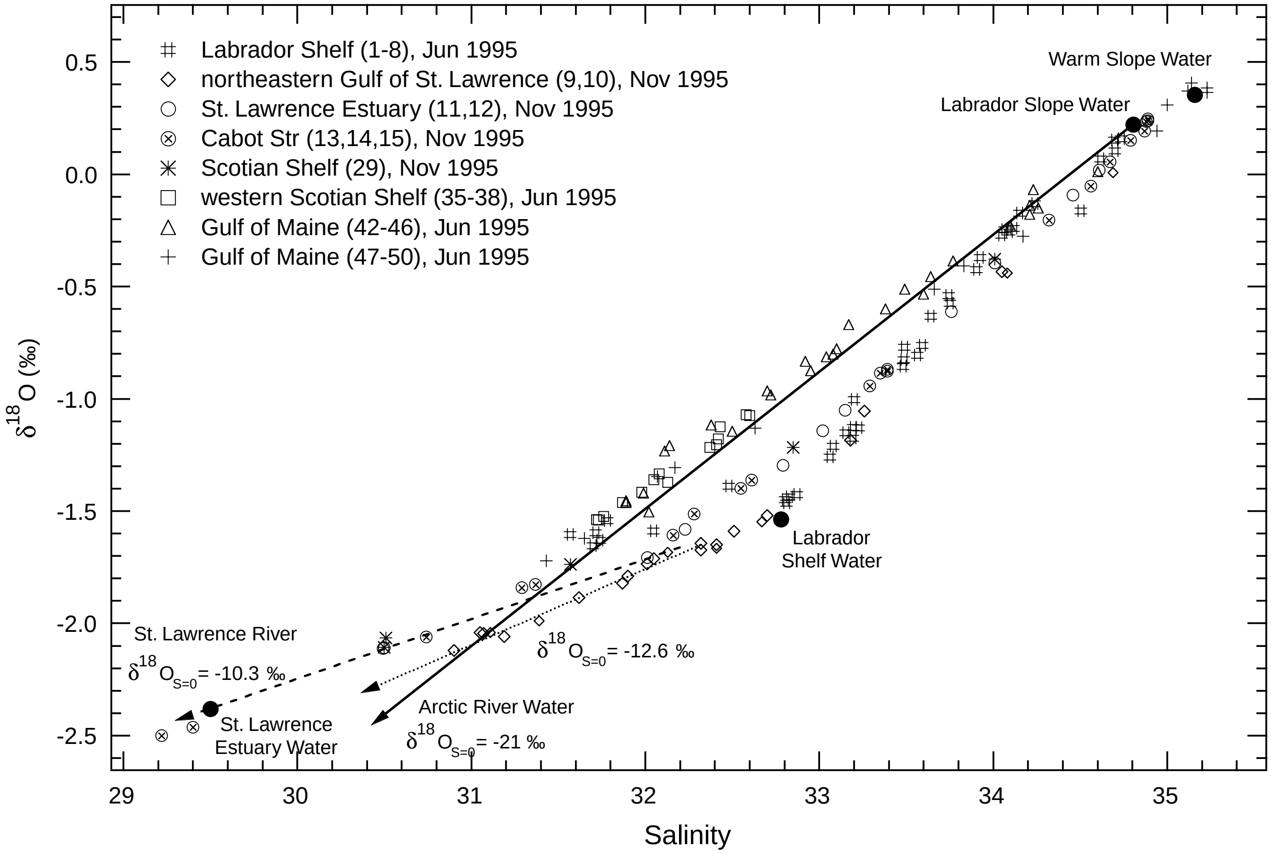

Figure 3. A δ^{18}O-salinity plot of data from selected stations used to define regional and upstream δ^{18}O–S mixing lines and end-members. Water masses defined in the text are shown as solid circles. Dashed line represents a linear regression through δ^{18}O–S measurements of near-surface samples in the St. Lawrence Estuary. Dotted line is a similar regression through data from the northeastern Gulf of St. Lawrence. Solid line is a theoretical mixing line between Labrador Slope Water and a high-latitude freshwater source (Arctic River Water).

Table 1. Water Mass Definitions

Water Mass	Abbreviation	Salinity	δ^{18}O	Potential Temperature, °C
River Water	ARW	0	-21	
Labrador Shelf Water	LShW	32.78	-1.53	
St. Lawrence River Water	SLRW	0	-10.3	
Labrador Slope Water	LSW	34.804	0.22	3.28
Warm Slope Water	WSW	35.16	0.36	11.11

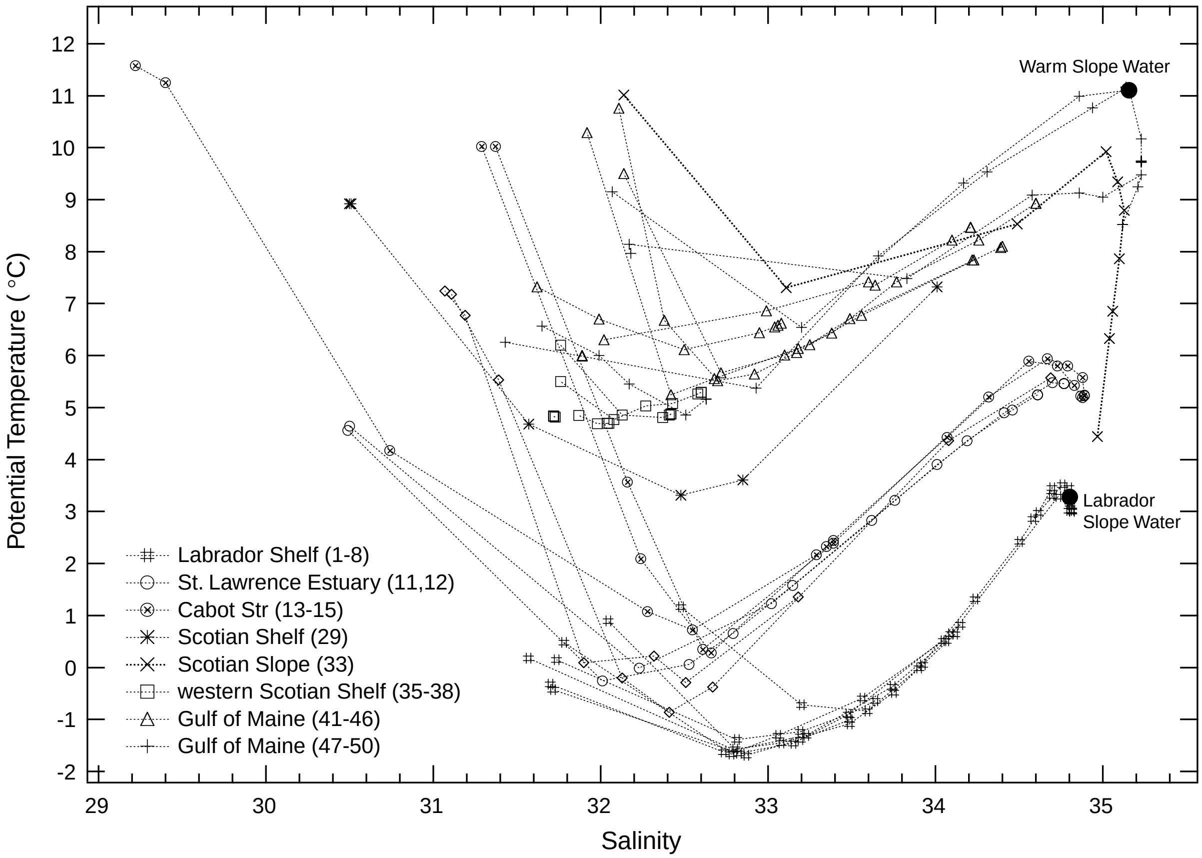

Figure 4. Potential temperature–salinity plot of data from selected stations, illustrating the difficulty of using temperature as a tracer in shallow coastal environments. Deeper slope waters (solid circles) are, however, distinguished best by temperature.

1976], which is distinguished from LSW best by temperature (Figure 4). We define WSW as the warmest water in the Gulf of Maine (θ=11.11°C) with a corresponding salinity of 35.16 psu and δ^{18}O of $0.36^0/_{00}$. LSW modified by mixing with WSW flows into the Gulf of St. Lawrence at depth via the Laurentian Channel and is an important source of salt and heat. As a result of this modification, deep waters in Cabot Strait have a higher salinity and δ^{18}O compared with Labrador Slope Water (Figure 3). This is more clearly seen in temperature/salinity space. Note that the deep waters off the Scotian Shelf or entering the Gulf of Maine are neither pure LSW or WSW. However, we expect these two water masses to span the range of δ^{18}O–*S* values found in slope waters. Where we are unable to unambiguously identify a specific slope water end-member, we call the mixture of LSW and WSW Slope Water (SLW).

The third important input to the Gulf of St. Lawrence is river water, of which the St. Lawrence is the largest (16 mSv [*Koutitonsky and Bugden*, 1991]). A linear regression through δ^{18}O–*S* measurements of near surface samples in the St. Lawrence Estuary (dashed line in Figure 3) has a zero-salinity intercept $\delta^{18}O_{S=0}$ of $\approx -10.3^0/_{00}$ (Figure 3), similar to the δ^{18}O value of water from the St. Lawrence River reported by *Tan and Strain* [1988]. This provides direct evidence of the presence of St. Lawrence River water throughout the Gulf and, as elaborated on below, farther south on the Scotian Shelf. A similar regression for data collected from the northeastern GSL has a zero-salinity intercept $\delta^{18}O_{S=0}$ of $\approx -12.6^0/_{00}$ (dotted line in Figure 3). According to *Tan and Strain* [1988] the various rivers entering the GSL have different δ^{18}O values depending on their catchment area. However, since the St. Lawrence River is by far the largest source ($\approx$65% [*Koutitonsky and Bugden*, 1991]), we use St. Lawrence River Water (SLRW) with a δ^{18}O value of $-10.3^0/_{00}$ to represent freshwater entering the GSL. This choice is further justified by the fact that outflow from the GSL sampled in Cabot Strait shows the dominant influence of SLRW (Figure 3). It is important to note that Labrador Shelf Water lies close to both regression lines, implying that shallower waters in the GSL are a mixture of

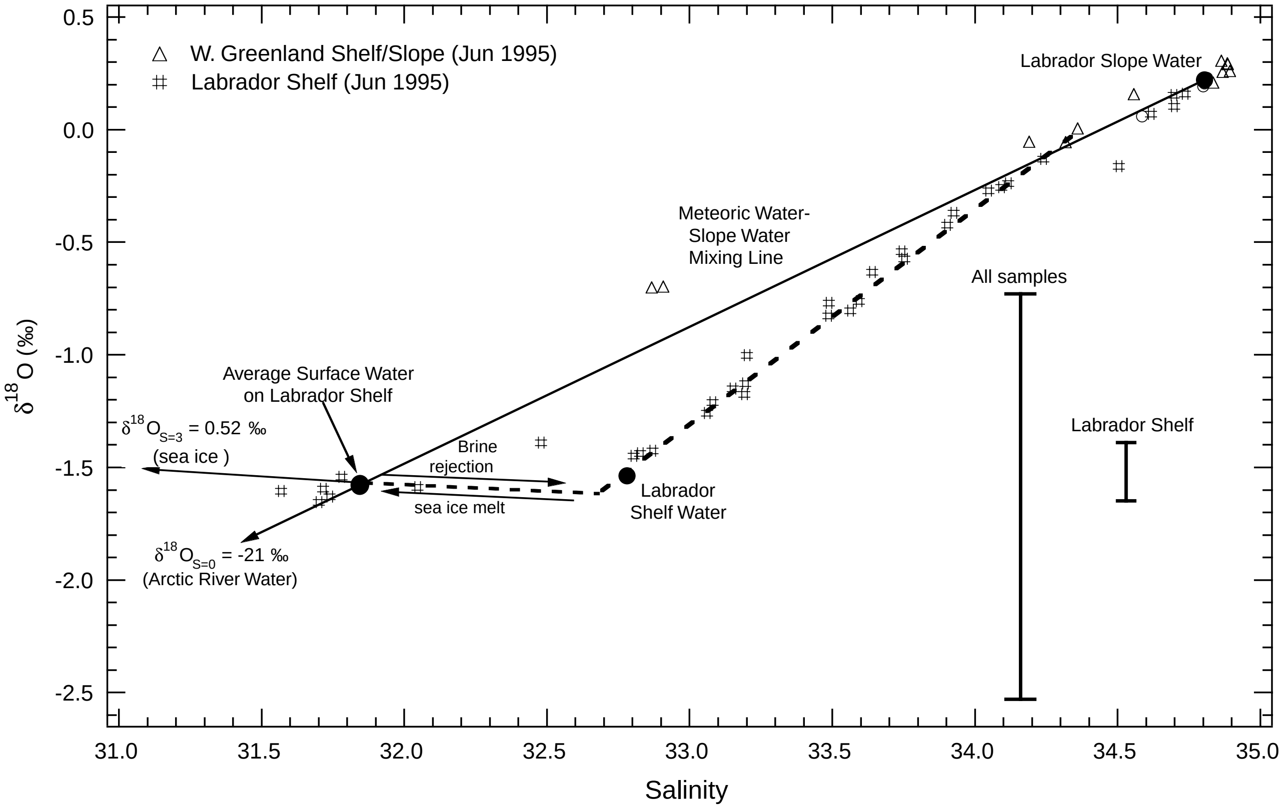

Figure 5. Schematic illustration of sea ice formation on the Labrador Shelf in δ^{18}O–*S* space. The solid line represents a mixing line between Labrador Slope Water and a freshwater source at $\delta^{18}O_{S=0}{=}-21^0/_{00}$. In the absence of sea ice formation or other sources, the δ^{18}O–*S* relationship would follow such an "undistorted" line. Freezing of seawater results in the production of brine that increases the salinity but does not change the δ^{18}O value significantly. This results in a "distorted" δ^{18}O–*S* relationship (dashed lines). The δ^{18}O of sea ice, and hence its melt, is heavier by $\approx 2.1^0/_{00}$ relative to surface waters [*Melling and Moore*, 1995]. Solid circles designate water masses defined in the text. Note the small range of δ^{18}O values in surface waters (vertical bars) from Baffin Bay and Davis Strait [*Tan and Strain*, 1980b] and the Labrador and Newfoundland shelves.

Labrador Shelf Water and river water entering the GSL. The influence of St. Lawrence River Water appears to be restricted to the upper part of the water column, a feature previously noted by *Tan and Strain* [1988]. The deeper waters fall on a mixing line between LShW and LSW. This three–layered water column maintains its structure all the way to the Scotian Shelf. It should be noted that sea ice formation in the gulf could also distort the δ^{18}O–*S* mixing line. However, the volume of sea ice involved is only $\approx$40 km^3 annually [*Dickie and Trites*, 1983], insignificant compared with the 7000 km^3 yr^{-1} of Labrador Shelf Water inflow [*Petrie et al.*, 1988; *Loder et al.*, 1998] or river runoff (600 km^3 yr^{-1}).

As stressed earlier in this section, the limited temporal coverage of the data does not allow us to resolve variations in isotope ratios corresponding to the observed annual hydrographic variations in the coastal region. Along the Labrador and Newfoundland Shelves, the annual cycle of salinity is largely due to sea ice formation and melting, with the minima in salinity at these locations occurring at the end of the melting season in July–August [*Lazier*, 1982; *Myers et al.*, 1990]. In contrast, the salinity cycle in the Gulf of St. Lawrence has a minimum in June [*Petrie*, 1990], reflecting the annual signal of runoff which peaks in May–June [*Koutitonsky and Bugden*, 1991]. The influence of these sources is complicated by sea ice melt and runoff advected from Hudson Bay and Baffin Bay. However, owing to advective lags, these upstream sources impact the Labrador, Newfoundland, and Scotian Shelves progressively later in the year [*Myers et al.*, 1990]. Mitigating these complications is the fact that the δ^{18}O–*S* properties of our principal "source" waters (ARW, SLRW, and LSW) are relatively stable. For example, the δ^{18}O values of Arctic River Water and St. Lawrence River Water are independent of any processes operating on the Labrador Shelf and do not vary except on relatively long timescales. In section 6 we discuss the oxygen isotope data within the framework of end-members developed above.

6. Interpretation of Oxygen Isotope Data

6.1. Influence of Sea Ice

As discussed in section 5, the influence of sea ice on the water column of the Labrador Shelf and even farther downstream is significant. This is not surprising given the large amount of sea ice formed annually in this region. For instance, the total sea ice extent in Baffin Bay, Davis Strait, and the Labrador Sea reaches a seasonal maximum (in March) of about 1.45 $\times$ 10^6 km^2 [*Gloersen et al.*, 1992]. Most of the sea ice in this region is single-year ice. Sea ice extent in Hudson Bay is almost as large (1.16 $\times$ 10^6 km^2 at the annual maximum), although it is not clear what proportion of the freshwater leaves the system via Hudson Strait to contribute to the Labrador Shelf. In this section we use isotope data to compute the inventory of sea ice meltwater and meteoric water on the Labrador Shelf. The conservation equations for mass, salinity, and oxygen isotopes are [*Östlund and Hut*, 1984]

$$f_{\rm L} + f_{\rm I} + f_{\rm R} = 1 \qquad (1)$$

$$f_{\rm L}S_{\rm L} + f_{\rm I}S_{\rm I} + f_{\rm R}S_{\rm R} = S_{\rm m} \qquad (2)$$

$$f_{\rm L}\delta^{18}{\rm O}_{\rm L} + f_{\rm I}\delta^{18}{\rm O}_{\rm I} + f_{\rm R}\delta^{18}{\rm O}_{\rm R} = \delta^{18}{\rm O}_{\rm m} \qquad (3)$$

where $f_{\rm L}$, $f_{\rm I}$, and $f_{\rm R}$ refer to the fraction of Labrador Slope Water, sea ice meltwater, and Arctic River Water in any parcel of water, respectively and $S_{\rm L}$, $S_{\rm I}$, $S_{\rm R}$, δ^{18}O$_{\rm L}$, δ^{18}O$_{\rm I}$, and δ^{18}O$_{\rm R}$ are the corresponding salinity and δ^{18}O values. $S_{\rm m}$ and δ^{18}O$_{\rm m}$ are the measured salinity and δ^{18}O values, respectively; δ^{18}O–*S* values for Labrador Slope Water and Arctic River Water were specified in section 5. Values for sea ice meltwater were chosen as follows: Given the large seasonal cycle of sea ice extent in Baffin Bay, Davis Strait, and on the Labrador Shelf [*Gloersen et al.*, 1992] and the fact that much of the meltwater is advected southward, we do not know precisely where the sea ice fraction was formed. We therefore use the δ^{18}O values of surface waters to derive the δ^{18}O value of the sea ice meltwater [*Schlosser et al.*, 1994]. We assume that both surface waters and the brine were advected southward to the region in the Labrador Current. Then the use of surface δ^{18}O values to derive sea ice meltwater isotope ratios can be justified because (1) both surface water and brine are advected into the area from the same region (although, in general, at different velocities) and (2) an examination of available surface ocean measurements of δ^{18}O [this study; *Tan and Strain*, 1980b] from the Newfoundland Shelf, Labrador Shelf, Davis Strait, and Baffin Bay indicates a relatively small range of δ^{18}O values. The δ^{18}O values for those samples range from $-2.53^0/_{00}$ to $-0.73^0/_{00}$, with a mean of $-1.58^0/_{00}$ (vertical bars in Figure 5; see also Figure 6). For samples collected from the Labrador Shelf, surface δ^{18}O values range between $-1.65^0/_{00}$ and $-1.39^0/_{00}$ with a mean of $-1.57^0/_{00}$. Using a fractionation factor of 1.0021 and $S_{\rm I}$=3 psu [*Melling and Moore*, 1995], we estimate δ^{18}O$_{\rm I}$=$0.52^0/_{00}$ (i.e., $2.1^0/_{00}$ heavier than average surface ocean δ^{18}O).

Equations (1)–(3) were solved for $f_{\rm L}$, $f_{\rm I}$, and $f_{\rm R}$, and the fractions were integrated down the water column to the depth of the deepest available sample, resulting in the inventory of sea ice meltwater, Arctic River Water, and Labrador Slope Water in the upper water column (Table 2).

The calculations presented above indicate that 2–3 m of freshwater (3 psu) has been extracted from the water column to produce sea ice. However, the observed average mean thickness of sea ice on the Labrador shelf is $\approx$1 m [*Ice Climatology Services*, 1992]. A possible explanation for this discrepancy is that sea ice is continuously exported from the region. As a result, the total amount of sea ice formed at any given location (reflected in our mass balance calculations) will be greater than the amount of sea ice present at any given time. The latter likely corresponds to a quasi steady state balance between formation and export. It is also possible that the larger δ^{18}O-based results reflect advection of brine-enriched waters from the north where sea ice is generally thicker. Thus our estimate of sea ice production should be considered an upper bound.

6.2. Sources of Freshwater in the Labrador Current

Additional isotope measurements from the Labrador Shelf allow us to resolve the discrepancy between isotope-derived and hydrographic estimates of freshwater sources contributing to the Labrador Current. In particular, oxygen isotope data [*Chapman and Beardsley*, 1989] were used to rule out a significant freshwater contribution from Baffin Bay, while hydrographic and current meter data suggest that Baffin Bay might be an important source of freshwater [*Lazier and Wright*, 1993; *Mertz et al.*, 1993; *Loder et al.*, 1998]. *Chapman and Beardsley* [1989] showed that the mixing line for δ^{18}O–*S* from the northern Labrador Sea (dashed line in Figure 6) had a zero-salinity intercept of $\approx -22^0/_{00}$ which is characteristic of glacial melt and river runoff along the West Greenland Coast. In contrast, data from western Davis Strait and Baffin Bay showed an apparent δ^{18}O$_{S=0}$ value of $\approx -40^0/_{00}$ and was clearly influenced by sea ice formation (Figure 6). Since δ^{18}O–*S* data from the northern Labrador Sea showed no effect from sea ice formation, they

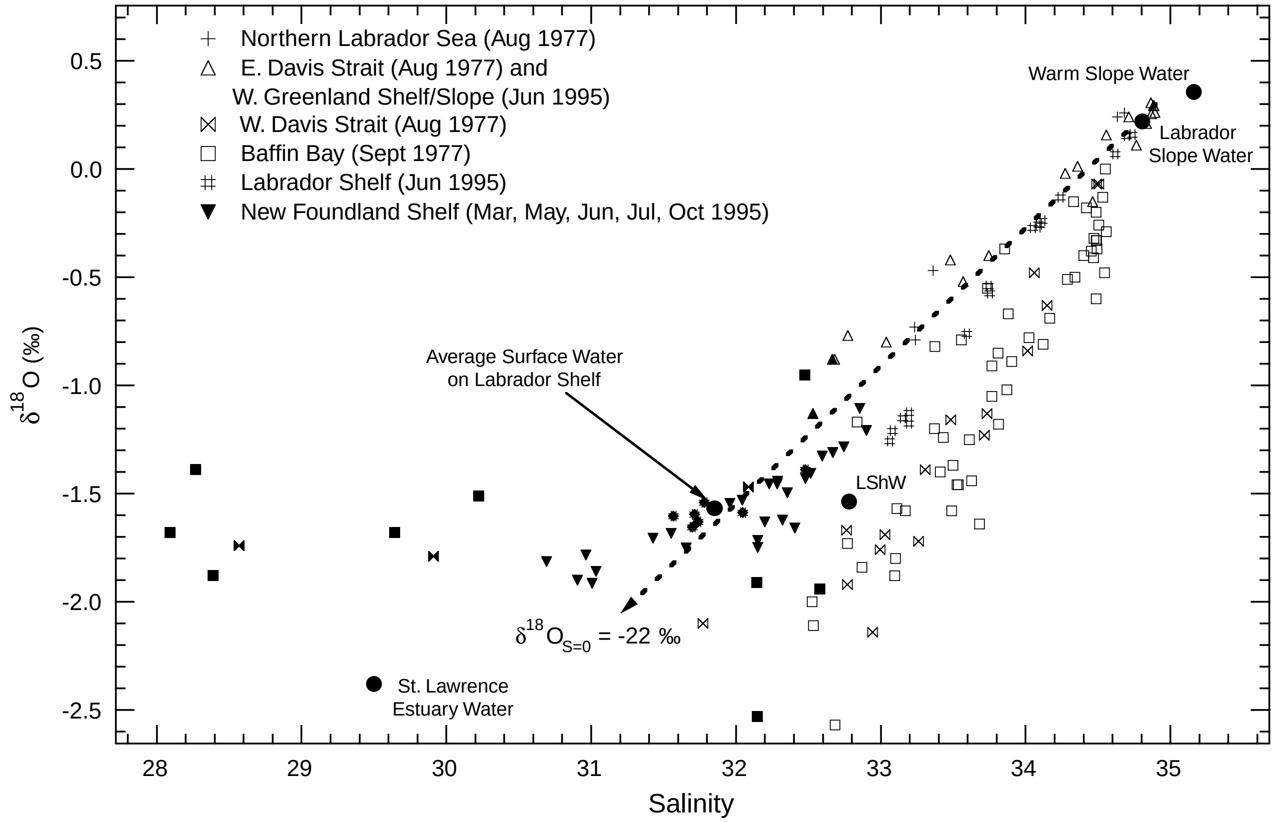

Figure 6. The δ^{18}O–*S* data for various locations from the Labrador and Newfoundland Shelves, Davis Strait, and Baffin Bay to show the influence of sea ice in the coastal environment off northeastern Canada. Near-surface samples are represented by solid symbols. Also shown is average surface water on the Labrador Shelf. Note that waters on the West Greenland Shelf and Slope and eastern Davis Strait are relatively undistorted by sea ice formation. Dashed line is a linear regression to data from the northern Labrador Sea [*Chapman and Beardsley*, 1989].

Table 2. Water column inventories of Labrador Sea Water, River Water, and Sea Ice Meltwater

Station	Maximum Depth, m	Labrador Slope Water	River Water	Sea Ice Meltwater
1	180	169.6	12.8	-2.5
2	270	258.3	14.8	-3.2
3	140	131.7	10.1	-1.8
4	150	142.4	9.8	-2.2
5	180	171.9	10.3	-2.2
6	230	219.8	11.8	-1.6
7	350	342.2	10.0	-2.2
8	910	909.1	2.0	-1.1

In meters.

concluded that waters in and north of Davis Strait did not contribute significantly to the Labrador Current. The wider geographic coverage of our data shows that sea ice meltwater is isotopically detectable on the Labrador Shelf (as discussed in section 5). Furthermore, the persistence of brine on the Labrador Shelf and the calculations presented in section 6.1 suggest an important contribution from Baffin Bay consistent with hydrographic data [*Lazier and Wright*, 1993; *Loder et al.*, 1998].

6.3. Source Waters for Scotian Shelf and Middle Atlantic Bight

Fairbanks [1982] showed that the δ^{18}O–salinity properties of coastal waters in the Gulf of Maine and the Middle Atlantic Bight are distributed along a "mixing line" between "Slope Water" and "Scotian Shelf Water" with an apparent zero-salinity intercept $\delta^{18}O_{S=0}{\approx}-20^0/_{00}$ (Figure 3). Because meteoric water entering the Labrador Sea has a $\delta^{18}O{\approx}-20^0/_{00}$, he concluded that the freshwater in the Gulf of Maine, on Georges Bank, and along the Middle Atlantic Bight was predominantly derived from the Labrador Sea rather than the St. Lawrence River, as suggested by *Sutcliffe et al.* [1976]. However, the apparent absence of an isotopic signature of St. Lawrence River Water ($\delta^{18}O{\approx}-10.3^0/_{00}$) has been a puzzle.

The greater upstream scope and resolution of the isotope data presented here identify the contribution from the St. Lawrence River, as inferred from the δ^{18}O–*S* data shown in Figures 7a–7f. Figure 7a is a plot of δ^{18}O–salinity data from stations south of Newfoundland (section A in Figure 2). The δ^{18}O–*S* relationship closely follows a mixing line between LShW and SLW. The near-surface data also show the influence of a third source, either St. Lawrence River Water or runoff from Newfoundland. Figure 7b is a plot of data from the eastern Scotian Shelf just south of Cabot Strait (section B in Figure 2). The δ^{18}O–*S* relationship for most stations on this section follows a mixing line between LShW and SLRW with the exception of the two shelf-break stations (stations 27 and 28). The δ^{18}O–*S* relationship at station 27 appears to follow a mixing line between LShW and WSW, although the near-surface data once again show the influence of SLRW. Station 28, farthest offshore, follows a mixing line between SLW and an apparent freshwater source with a δ^{18}O value of $\approx-19.3^0/_{00}$ (close to the high-latitude Arctic River Water end-member defined above). Note, however, that data from the Labrador Shelf and Slope (upstream of the Newfoundland and Scotian Shelves) showed that the δ^{18}O–*S* relationship was distorted by sea ice formation (Figures 3 and 6). The presence of a high-latitude freshwater source with $\delta^{18}O{\approx}-21^0/_{00}$was indirectly inferred from our knowledge of the behavior of oxygen isotopes under the influence of sea ice formation/melting as well as the δ^{18}O values expected in high-latitude runoff. To explain this discrepancy, we propose the following hypothesis. The Labrador Shelf Water defined here is not simply slope water diluted by meteoric water but is influenced by sea ice formation and is therefore saltier because of brine rejection. As it flows south, the brine-enriched Labrador Shelf Water is freshened by the addition of St. Lawrence River Water (the resultant mixture will of course lie on the mixing line between LShW and SLRW). We then expect the δ^{18}O–*S* relationship of waters downstream to lie on a "mixing line" between slope water and this low-salinity LShW–SLRW mixture. It is important to note that the zero-salinity intercept of this mixing line does not represent a real freshwater end-member. The fact that it is close to the δ^{18}O value of a high-latitude freshwater source is simply an artifact. The influence of SLRW and LShW further south on the Scotian Shelf is seen in Figure 7c (section C, Figure 2). The δ^{18}O–*S* data from the nearshore station (station 29) are aligned along a "mixing line" between LShW and SLRW. The properties of waters deeper than 80 m lie along a "mixing line" between LShW and SLW. As mentioned in section 5, this vertical structure is formed in the GSL and maintained all the way to the Scotian Shelf. Farther offshore, the δ^{18}O–*S* data are distributed between LShW and WSW, but once again they show the influence of a fresher dilutent which is a mixture of LShW and SLRW. Samples collected farther south at the western end of the Scotian Shelf (Figure 7d; section D in Figure 2) and the Gulf of Maine (Figures 7e and 7f) no longer show the individual influence of LShW and SLRW. The δ^{18}O–*S* data appear to define mixing lines between slope water and a freshwater end-member whose δ^{18}O ranges between $-18^0/_{00}$ and $-21^0/_{00}$. As noted earlier, however, the zero-salinity intercepts are not meaningful and, if interpreted literally, would appear to imply a single freshwater source for the Scotian Shelf, Gulf of Maine, and Middle Atlantic Bight originating at high-latitude, precluding any contribution from the St. Lawrence River.

We conclude by calculating the relative contributions of the two main freshwater sources (Arctic River Water and St. Lawrence River Water) from the δ^{18}O–*S* data. The calculation proceeds in two steps. First, the proportion of Arctic River Water in LShW is found to be ≈8%. This is done by solving equations (1)–(3), with LSW, ARW, and sea ice meltwater as the three end-members. Second, any water parcel downstream of the Labrador Shelf is then considered to be a mixture of Slope Water, Labrador Shelf Water, and St. Lawrence River Water. Since the proportion of freshwater (ARW) in LShW is known, we can compute the relative contributions of ARW and SLRW in any water parcel. Table 3 shows the column-integrated proportions of SLRW

Table 3. Freshwater Contribution From St. Lawrence River Water and Arctic River Water

Station	St. Lawrence River Water, %	Arctic River Water, %
	Section A, Southern Newfoundland Shelf (Nov. 1995)	
16	28.9	71.1
18	27.5	72.5
19	18.3	81.7
20	15.1	84.9
	Section B, Eastern Scotian Shelf (Nov. 1995)	
21	47.4	52.6
22	42.3	57.7
23	32.7	67.3
24	42.1	57.9
25	27	73
26	40.2	59.8
27	23.8	76.2
	Section C, Central Scotian Shelf (Nov. 1995)	
29	38	62
30	35.2	64.8
31	41.2	58.8
32	34.6	65.4
33	21.6	78.4
34	32.8	67.2
	Section D, Western Scotian Shelf (June 1995)	
36	42.8	57.2
37	40.8	59.2
38	43.7	56.3
39	42.1	57.9
40	39.7	60.3
	Gulf of Maine (June 1995)	
41	48.2	51.8
42	47.5	52.5
43	42.6	57.4
44	35.8	64.2
45	40.9	59.1

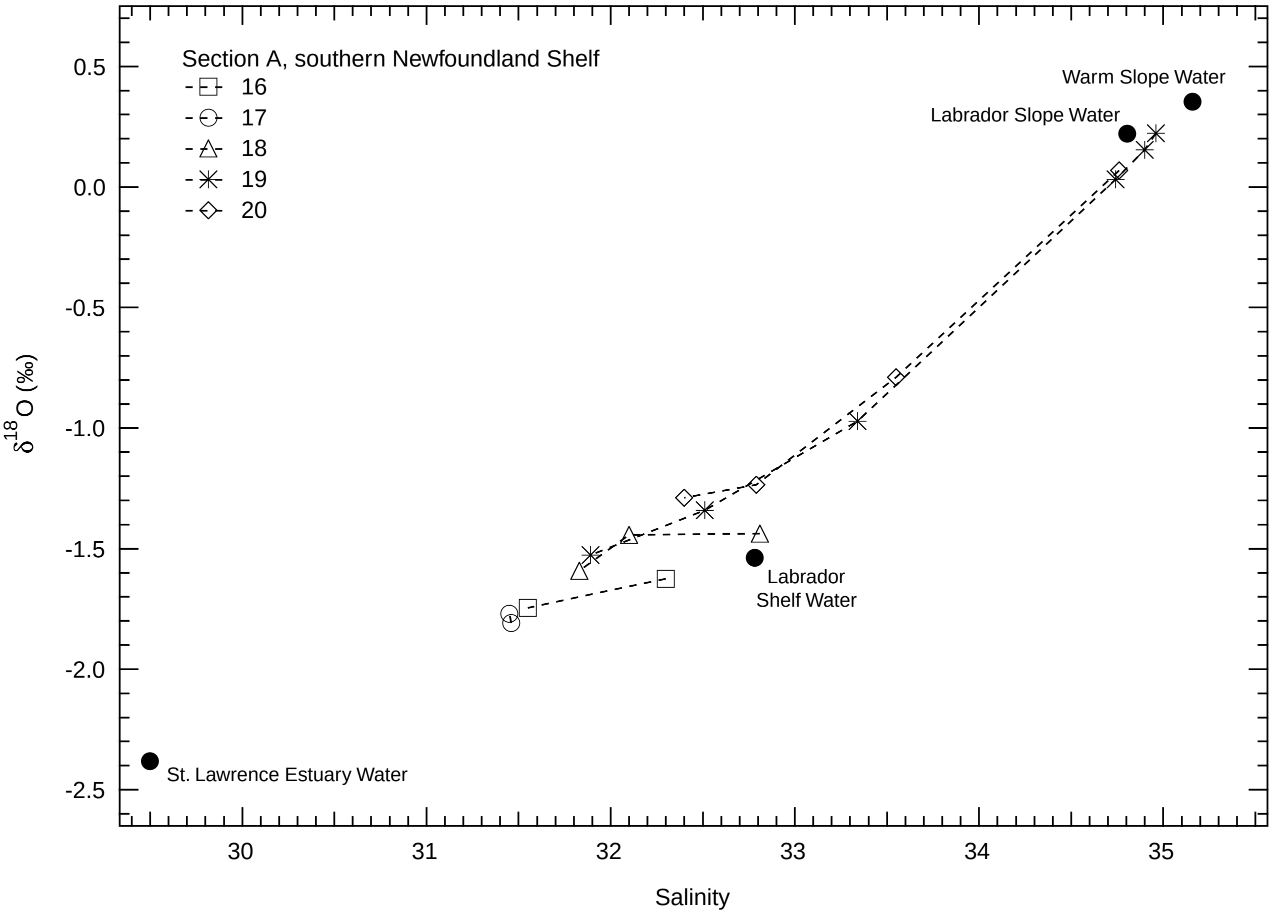

Figure 7a. A δ^{18}O–S plot for various locations along section A, southern Newfoundland Shelf. For station positions, see Figure 2.

and ARW for stations along sections A, B, C, and D and in the Gulf of Maine. There are three main results to note. First, the calculations for sections A, B, and C (occupied in November) are fairly robust and consistent with what we might expect from the circulation. For example, stations 16–20 on the southern Newfoundland Shelf show the lowest proportion of SLRW, and the contribution from SLRW generally decreases offshore on all three sections. The variability present is not surprising given the complicated cross-shelf flow structure. Second, *Loder et al.* [1998] show that the southward freshwater transport on the Scotian Shelf is 48 mSv, ≈1/3 of which (16 mSv) comes from the St. Lawrence River. Our results for the Scotian Shelf (section C) show that St. Lawrence River Water contributes ≈35% of the freshwater, consistent with the flux estimates of *Loder et al.* [1998]. Third, waters on the western Scotian Shelf (section D) and in the Gulf of Maine show a much higher proportion of SLRW (40–50%). However, note that these stations were occupied in June. Thus the difference might be due to the fact that both St. Lawrence runoff and the flow along the Labrador Shelf [*Lazier and Wright*, 1993] vary seasonally with different phase lags and also impact downstream regions at different advective lags. Additionally, runoff into the GSL also shows substantial interannual variability [*Koutitonsky and Bugden*, 1991]. These complications will be addressed in future work as more data become available and our knowledge of seasonal variations in δ^{18}O–S on the Labrador Shelf is refined. An effort is also underway to collect isotope data from multiple years to study interannual changes in freshwater fluxes.

7. Conclusions

It is clear that hydrographic variability in coastal waters off northeastern North America owes its origins to upstream fluctuations in various freshwater sources. The oxygen iso-

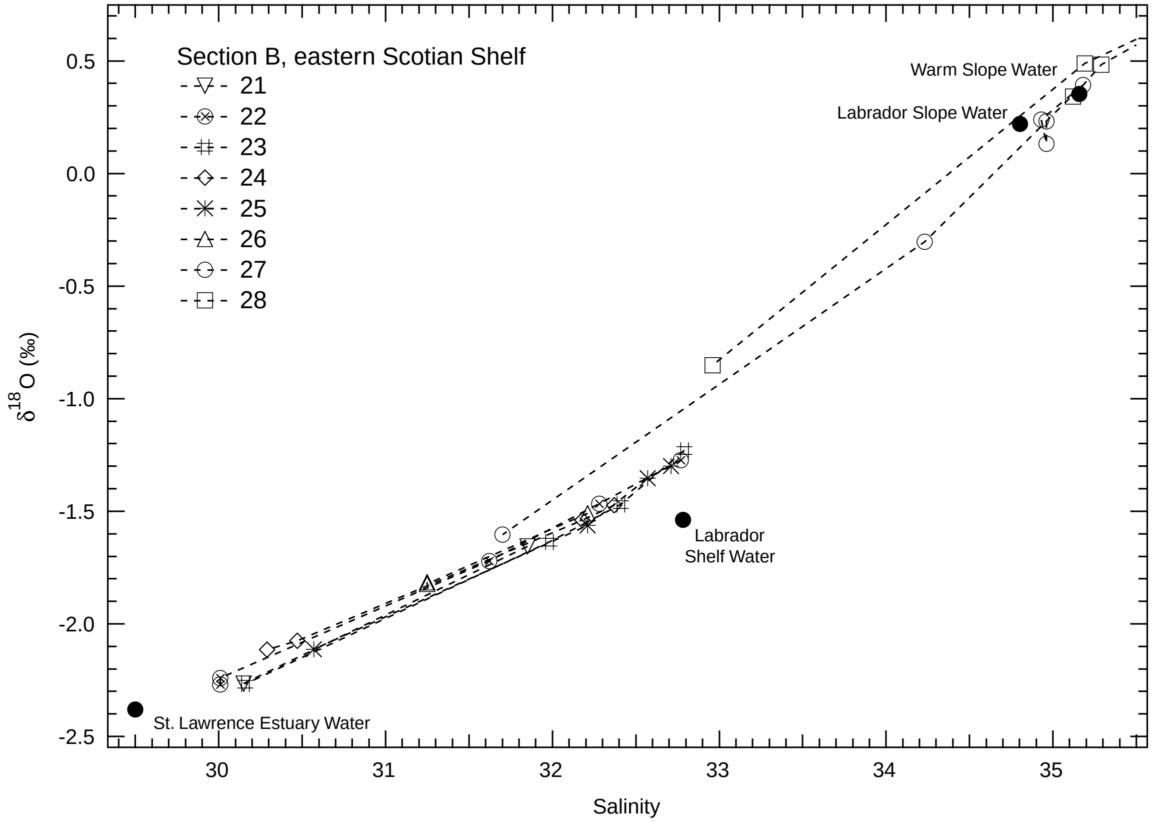

Figure 7b. A δ^{18}O–*S* plot for various locations along section B, eastern Scotian Shelf. For station positions, see Figure 2.

tope measurements presented in this paper have allowed us to identify and quantify the primary upstream sources to the Scotian Shelf, Gulf of Maine, and Middle Atlantic Bight. These sources are Labrador Shelf Water, St. Lawrence River Water, and Labrador Slope Water. The two main sources of freshwater are high-latitude runoff (originating in the Arctic) and the St. Lawrence River, in a 2:1 ratio. In addition, the δ^{18}O data demonstrate the pervasive influence of sea ice on the Labrador Shelf and identify Baffin Bay as an important conduit for freshwater from the Arctic Ocean to reach the Labrador Sea. These results are consistent with the recent estimates of *Lazier and Wright* [1993], *Mertz et al.* [1993], and *Loder et al.* [1998], based on salinity, geostrophy, and current meter measurements.

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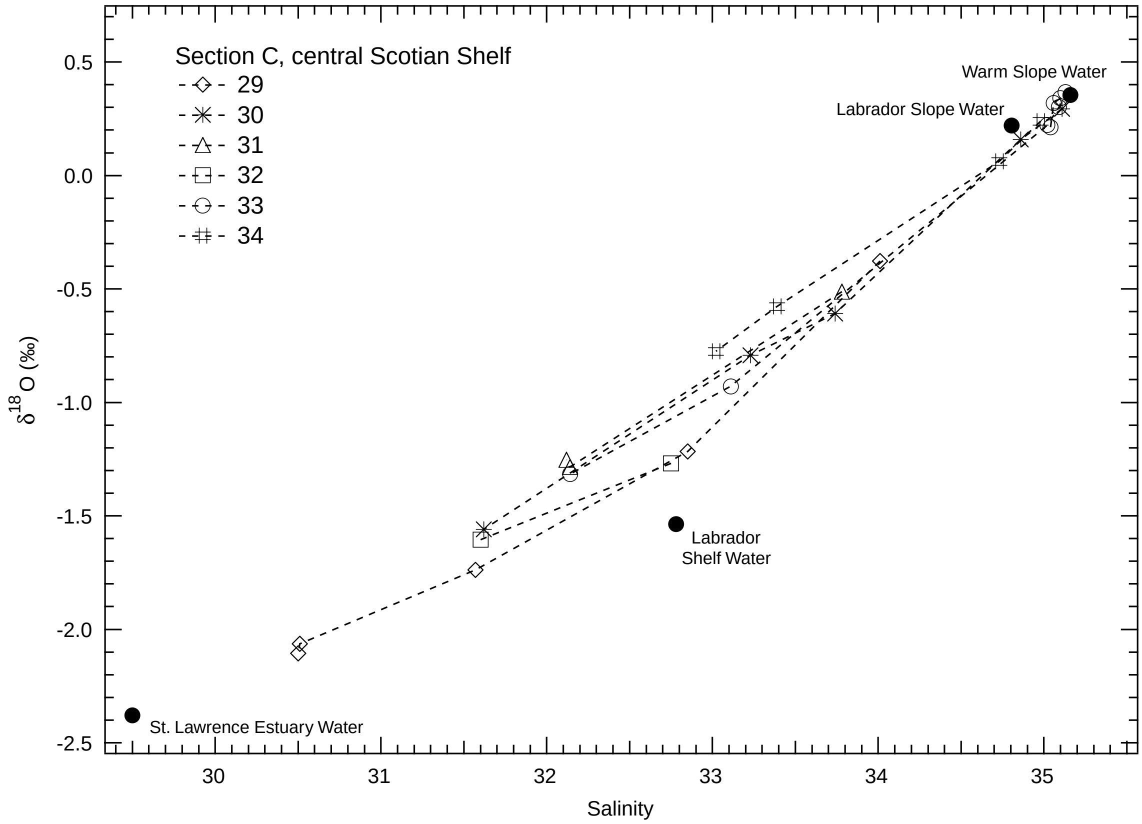

Figure 7c. A δ^{18}O–*S* plot for various locations along section C, central Scotian Shelf. For station positions, see Figure 2.

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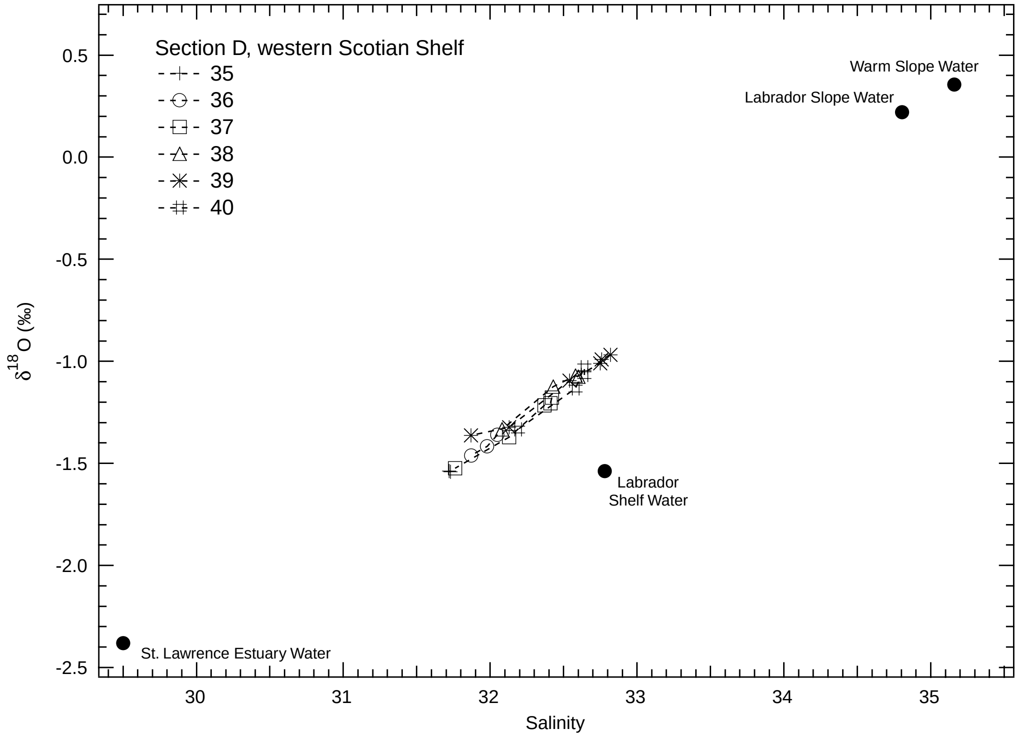

Figure 7d. A δ^{18}O–S plot for various locations along section D, western Scotian Shelf. For station positions, see Figure 2.

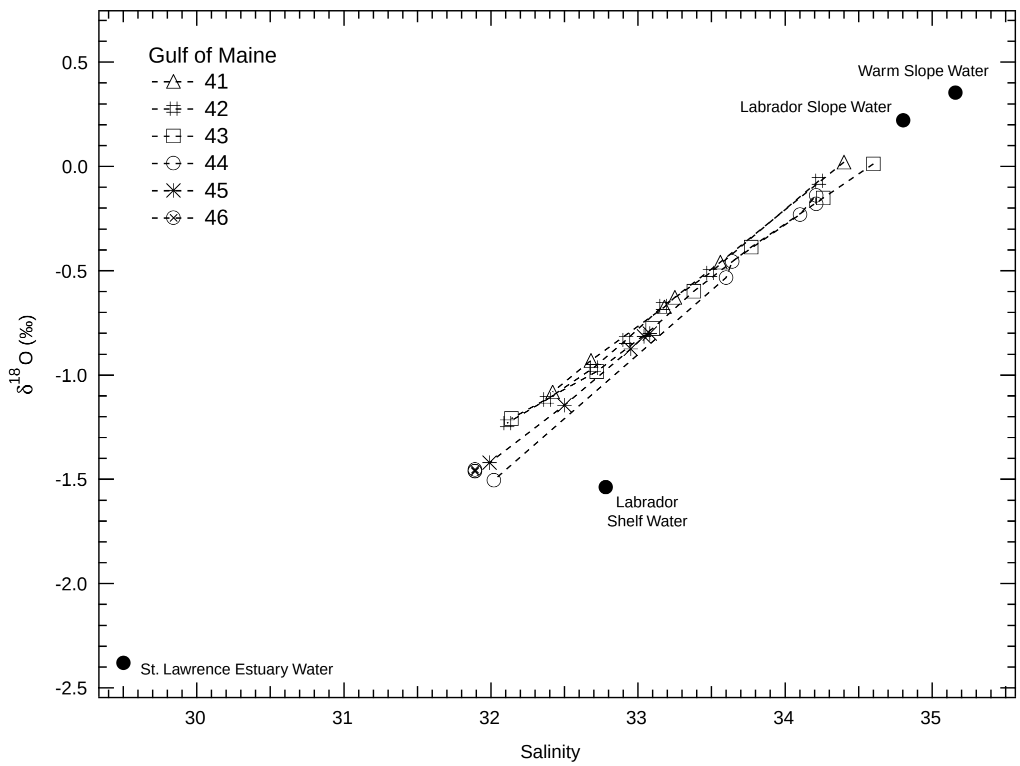

Figure 7e. A δ^{18}O–S plot for various locations from the Gulf of Maine. For station positions, see Figure 2.

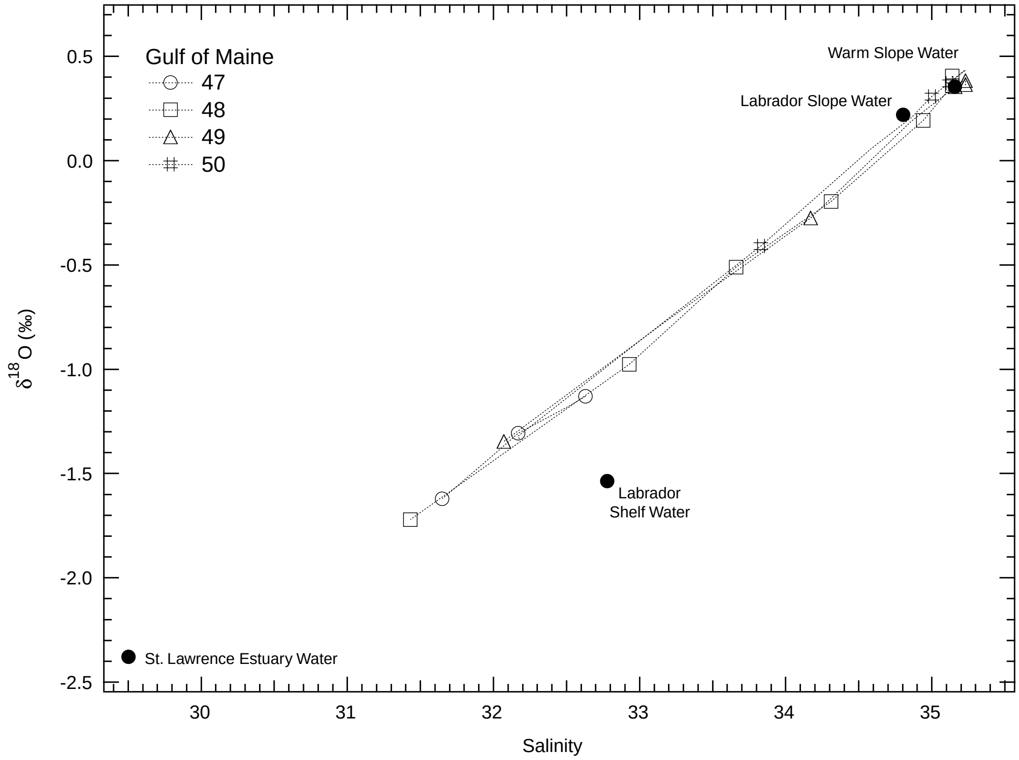

Figure 7f. A δ^{18}O–S plot for various locations from the Gulf of Maine. For station positions, see Figure 2.

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