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Water sources for Georges Bank☆

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Abstract

The origins of Georges Bank source waters can be quantified by the oxygen isotope — salinity tracer. Regionally, water is "tagged" by freshwater of different $H_2{}^{18}O/H_2{}^{16}O$ ratios, and these waters can subsequently be identified after mixing downstream. This conservative Lagrangian tracer of source waters is useful for tracking passive plankton and larvae that may be important to sustain the Georges Bank ecosystem. The origin of Georges Bank freshwater sources is primarily in the Gulf of St. Lawrence consisting of Labrador Shelf Water, which enters via the Strait of Belle Isle, and St. Lawrence River Water. These two mix with the underlying Slope Water in the Gulf of St. Lawrence and along the Scotian Shelf. At the Northeast Channel, the input to the Gulf of Maine, there is a single freshwater endmember consisting of 5.6% St. Lawrence River Water and 94.6% Labrador Shelf Water by volume. These proportions remained constant for the years 1995–1997. The water on central Georges Bank consists of a mixture of water entering the Northeast Channel with Gulf of Maine River outflow. There is considerable interannual variation in the Maine River Water proportion, ranging from 3.3% in 1982 to 0.23% by volume in 1996. During 1995–1998 there was no correlation between Georges Bank salinity, which decreased monotonically, and the proportion of Maine River Water on the Bank. The interannual fluctuations of salinity on Georges Bank are driven by variations in upstream Scotian Shelf sources and its mixing onto the Bank and not by changes in local river outflow. © 2000 Published by Elsevier Science Ltd.

1. Introduction

Oxygen isotope studies (Fairbanks, 1982; Chapman et al., 1986; Chapman and Beardsley, 1989) have established that coastal waters in the Middle Atlantic Bight have freshwater sources derived

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from high latitudes. This is due to the large-scale coastal circulation extending from the Labrador Sea to Cape Hatteras that is thought to be buoyancy driven and trapped on the shelf by the distributed freshwater sources upstream (Chapman et al., 1986; Chapman and Beardsley, 1989). Thus, the circulation and water properties on Georges Bank may depend as much on far-field upstream influences as on local processes on the Bank and in the adjacent Gulf of Maine (Fairbanks, 1982).

The utility of oxygen isotope measurements in distinguishing meteoric and sea-ice melt freshwater has been amply demonstrated (Craig and Gordon, 1965; Redfield and Friedman, 1969; Tan and Strain, 1980; Bedard et al., 1981; Jacobs et al., 1985; Bauch et al., 1995). The fractional distillation of $H_2{}^{18}O$ and $H_2{}^{16}O$ due to their different molecular masses results in a decrease in the $H_2{}^{18}O/H_2{}^{16}O$ ratio with decreasing condensation temperature. This water isotope ratio is usually expressed in the $\delta^{18}O$ notation, defined as the per mil deviation of the $H_2{}^{18}O/H_2{}^{16}O$ ratio in the sample from that of a standard where

$$\delta^{18}O(‰) = \frac{(H_2^{18}O/H_2^{16}O)_{sample} - (H_2^{18}O/H_2^{16}O)_{standard}}{(H_2^{18}O/H_2^{16}O)_{standard}} \times 1000$$

and Vienna Standard Mean Ocean Water (Coplen, 1994) is used as the standard. Since there is a latitudinal variation in the value of $\delta^{18}O$ for meteoric water along the northeast North American continental margin (Fairbanks, 1982), $\delta^{18}O$ is an ideal tracer to identify high latitude freshwater sources. Values of $\delta^{18}O$ range from -10.5 ‰ for rivers flowing into the Gulf of Maine (Fairbanks, 1982) to -21‰ for Labrador Sea sources (Bedard et al., 1981; Tan and Strain, 1980, 1996; Östlund and Hut, 1984; Schlosser et al., 1994).

Isotopic analysis by Khatiwala et al. (1999) of water samples collected in 1994–1995 has identified freshwater sources upstream of Georges Bank, with a focus on the sea-ice melt influence in the Labrador Sea. Here we extend this work utilizing significantly more data spanning 1995–1998, which permits more precise water type definitions and examines in more detail water mixing processes in the Gulf of St. Lawrence, on the Scotian Shelf, and in the Gulf of Maine.

2. Data

Oxygen isotope data are derived from water samples collected during the GLOBEC broadscale cruises on Georges Bank and additional Canadian cruises in the Northeast Channel (courtesy, P. Smith), on the Scotian Shelf (courtesy, G. Bugden), in the Gulf of St. Lawrence (courtesy, P. Galbraith), and on the southern Newfoundland Shelf (courtesy, E. Colbourne). Representative station locations from which water was collected are shown in Fig. 1. Isotope analysis consists of measuring the $H_2{}^{18}O/H_2{}^{16}O$ abundance ratio via CO_2 equilibrium (Epstein and Mayeda, 1953) with a Micromass PRISM mass spectrometer and a Micromass Multiprep automatic sample processing system. The internal precision (1σ) of the mass spectrometer is ± 0.005‰. Analysis is performed in batches of 60 samples consisting of 12 standards and 24 water samples run in replicate. Over the course of 1 year, the external precision (1σ) of $\delta^{18}O$ for the standards is ± 0.033‰. A water sample is reanalyzed if the replicate $\delta^{18}O$ difference is greater than 2σ of the internal precision.

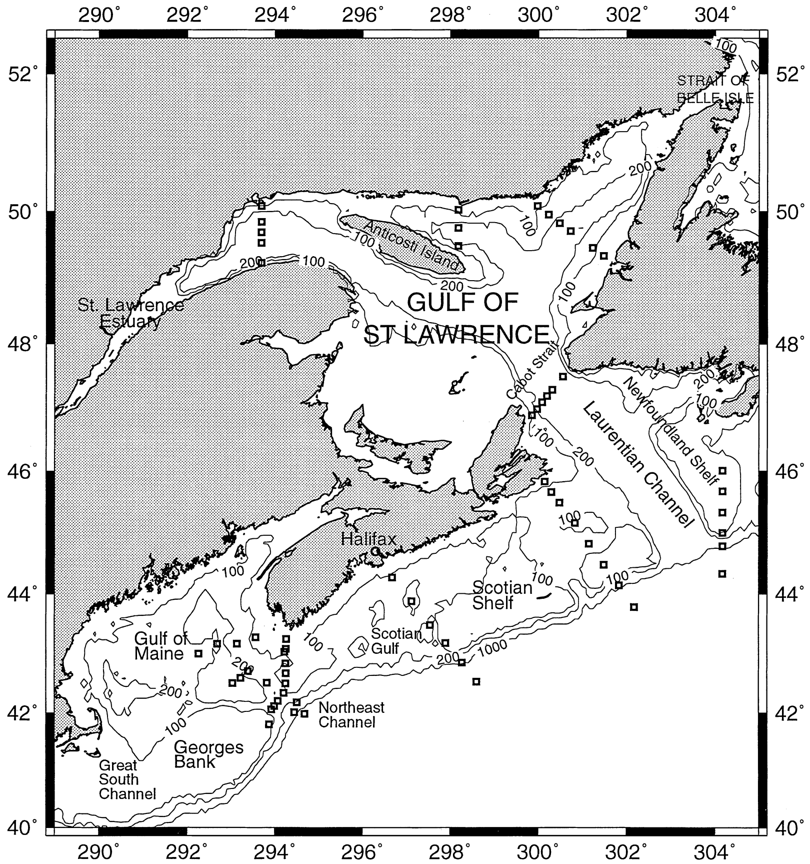


Fig. 1. Map of study area showing the hydrographic stations from which data are derived.

3. Results

The overall distribution of water properties in the Gulf of St. Lawrence, the Scotian Shelf, and the Northeast Channel throughout the water column is illustrated in Fig. 2. The $\delta^{18}O$–S pair defines two 2-endmember mixing lines in the Gulf of St. Lawrence corresponding to mixing of a distinct mid-depth water type with the surface and bottom water in a three-layer system. These are gradually modified through 3-endmember mixing to become a single 2-endmember mixing line the Northeast Channel. Near-surface temperatures are not conservative so the *T*–*S* diagram (Fig. 2b) is restricted to data at depths greater than 100 m to minimize scatter. The *T*–*S* diagram is used to distinguish water types, especially Labrador Slope Water (LSW) and Warm Slope Water (WSW), that are not uniquely resolved in a $\delta^{18}O$–S diagram alone. Within the Gulf of St. Lawrence, the bottom-most water has no temperature exceeding 6°C so we identify it as pure LSW that enters via the Laurentian Channel.

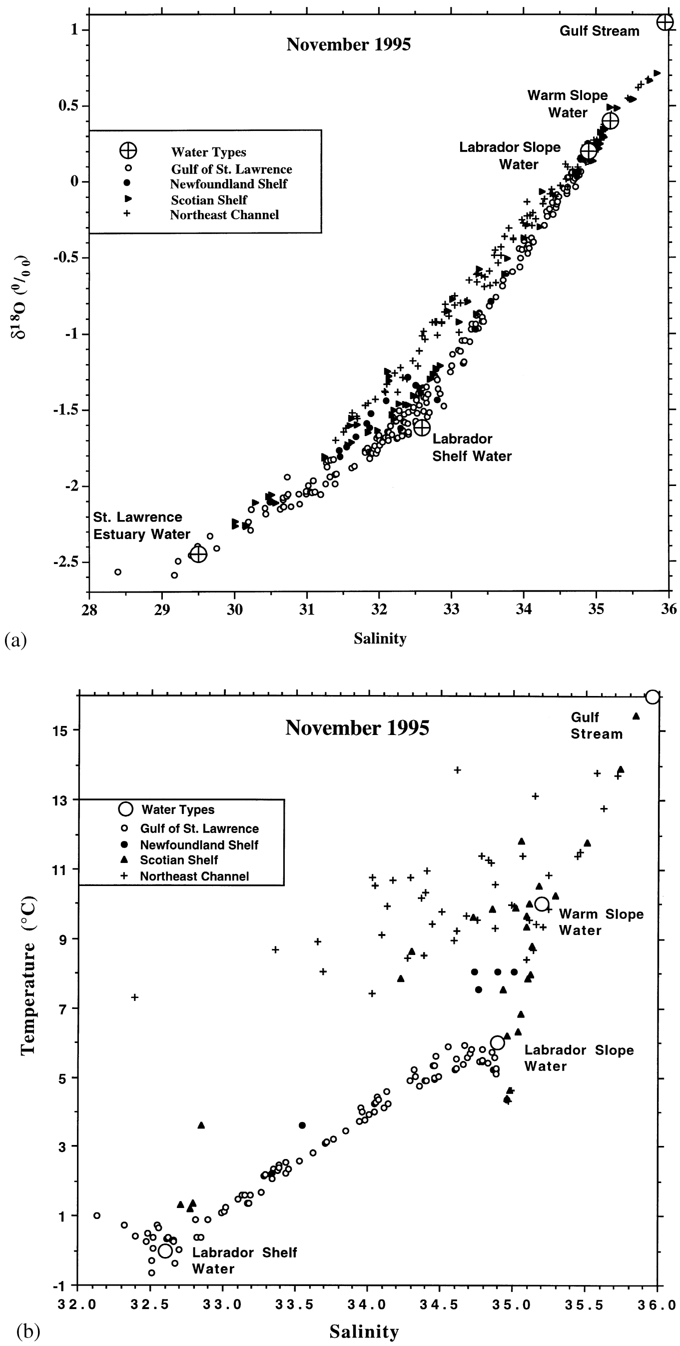


Fig. 2. $\delta^{18}O$–S distribution of all data from the Gulf of St. Lawrence, the southwest Newfoundland Shelf, the Scotian Shelf, and the Northeast Channel in November 1995. Also shown are water types (see Table 1) defined to be endmembers of mixing curves. (b) T–S distribution of same data in Fig. 2a for depths > 100 m.

3.1. Water types

The water types identified in Fig. 2 and listed in Table 1 are endmembers as defined by the mixing lines presented in Fig. 2a. These are nearly identical to those described in greater detail by Khatiwala et al. (1999). The point marked LShW in Fig. 2 represents an extrema of the data derived from the Gulf of St. Lawrence and is the most suitable endmember for the SLEW-LShW and LSW-LShW mixing lines. It represents water found at mid-depth along the section in the northeast region of the Gulf (Fig. 1). Using data from the Labrador Shelf just north of the Strait of Belle Isle, Khatiwala et al. (1999) define LShW as $S = 32.54$ and $\delta^{18}O = -1.48‰$. Here our definition of LShW is $S = 32.6$, $\delta^{18}O = -1.62‰$. It is derived from Labrador Shelf Water passing through the Strait of Belle Isle, which has a sill depth of 60 m.

St. Lawrence River Water (SLRW) influence is represented by St. Lawrence Estuary Water (SLEW) chosen to coincide with the freshest water sampled in the western Gulf. The LShW-SLEW regression projects to a zero salinity intercept of $\delta^{18}O_{S=0} \approx -10.3‰$, which is identical to the $\delta^{18}O$ value of water in the St. Lawrence River reported by Tan and Strain (1988). River water outflows along the north shore of the Gulf have $\delta^{18}O_{S=0} \approx -12.6‰$ (Khatiwala et al., 1999) because of their more northern watersheds. However, since the St. Lawrence River contributes 84% of the annual mean river runoff into the Gulf (Koutitonsky and Bugden, 1991), we take SLEW to represent the river freshwater source in the Gulf of St. Lawrence.

The two slope water types Warm Slope Water (WSW) and Labrador Slope Water (LSW) both have high salinity but originate from different regions of the North Atlantic. LSW originates from the western Labrador Sea margin, while WSW has a more southern North Atlantic origin. They are distinguished best by temperature (Fig. 2b). Their designated S and T values, chosen to be endmembers of observed mixing lines, fall within the ranges given by Gatien (1976).

The water type designated as Gulf Stream approximates the properties of warm-core ring water observed on the slope portion of the Scotian Shelf and the seaward end of the Northeast Channel.

The projection of the $\delta^{18}O$–S mixing curve to $S = 0$ is often used to identify the meteoric freshwater source. In Fig. 2a, the projection of the LShW-SLEW mixing line to $S = 0$ yields $\delta^{18}O \approx -10.3‰$, which is appropriate for St. Lawrence River Water (Tan and Strain, 1988). A projection of the LSW-LShW mixing line to $S = 0$ yields $\delta^{18}O \approx -25‰$. This is significantly

Table 1
Water- type definitions[a]

	$\delta^{18}O$ (‰)	S	T (°C)
Gulf Stream	1.05	35.95	16
Warm Slope Water (WSW)	0.40	35.20	10
Labrador Slope Water (LSW)	0.22	34.90	6
Labrador Shelf Water (LShW)	− 1.62	32.60	0
St. Lawrence Estuary Water (SLEW)	− 2.45	29.50	
St. Lawrence River Water (SLRW)	− 10.3	0	
Maine River Water (MRW)	− 10.5	0	

[a]The $\delta^{18}O$, salinity, and temperature properties for water types defined to be appropriate endmembers of mixing curves for data presented in Figs. 2a and b and for selected river inflow.

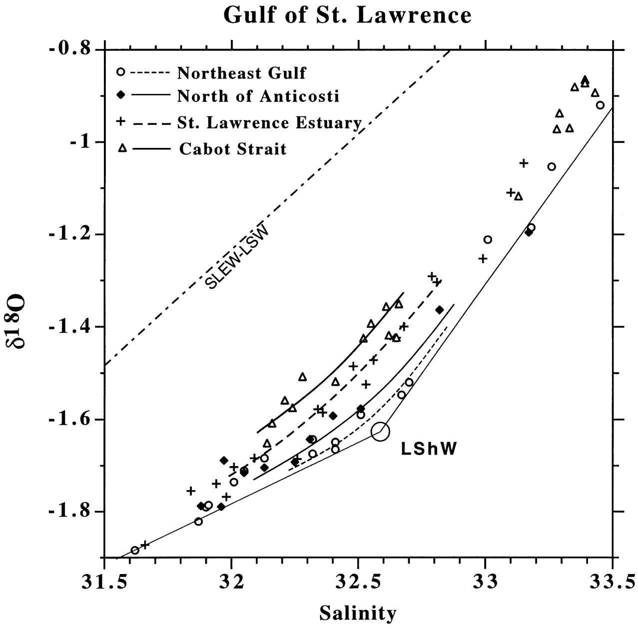


Fig. 3. Detail of the $\delta^{18}O$–S distribution from Fig. 2a to highlight the progressive mixing of Labrador Shelf Water (LShW) in a counterclockwise direction in the Gulf of St. Lawrence starting at the Strait of Belle Isle. Also shown is the mixing curve (dot–dashed line) that would result if St. Lawrence River Water and Labrador Slope Water were endmembers of a direct mixing process.

more negative than the $\delta^{18}O = -21‰$ observed for local glacial meltwater and river runoff into the Labrador Sea (Bedard et al., 1981), Baffin Bay (Tan and Strain, 1980), and the Hudson Bay (Tan and Strain, 1996) or for inflow of low-salinity water from the Arctic Ocean via the Canadian Archipelago or the East and West Greenland Currents (Östlund and Hut, 1984; Schlosser et al., 1994). This suggests that LShW is made more saline by brine rejection during sea-ice formation in the Labrador Sea (Khatiwala et al., 1999). With only November data, neither the seasonal variability of this process nor the contribution of the sea-ice formation within the Gulf of St. Lawrence can be explored.

3.2. Gulf of St. Lawrence mixing

Within the Gulf of St. Lawrence, SLEW, LShW and LSW begin to mix. The progressive mixing is illustrated in a detailed $\delta^{18}O$–S diagram (Fig. 3). In the northeast Gulf of St. Lawrence, LShW is the endmember for two separate 2-endmember mixing curves with SLEW and LSW. In the Gulf, there is very little direct mixing between surface SLEW and bottom LSW. The concentration of LShW diminishes progressively in water north of Anticosti Island, to the St. Lawrence estuary region, then to Cabot Strait. This is consistent with the large-scale counterclockwise circulation in the Gulf of St. Lawrence (Koutitonsky and Bugden, 1991; Han et al., 1999), with the Strait of Belle Isle being the primary source of LShW.

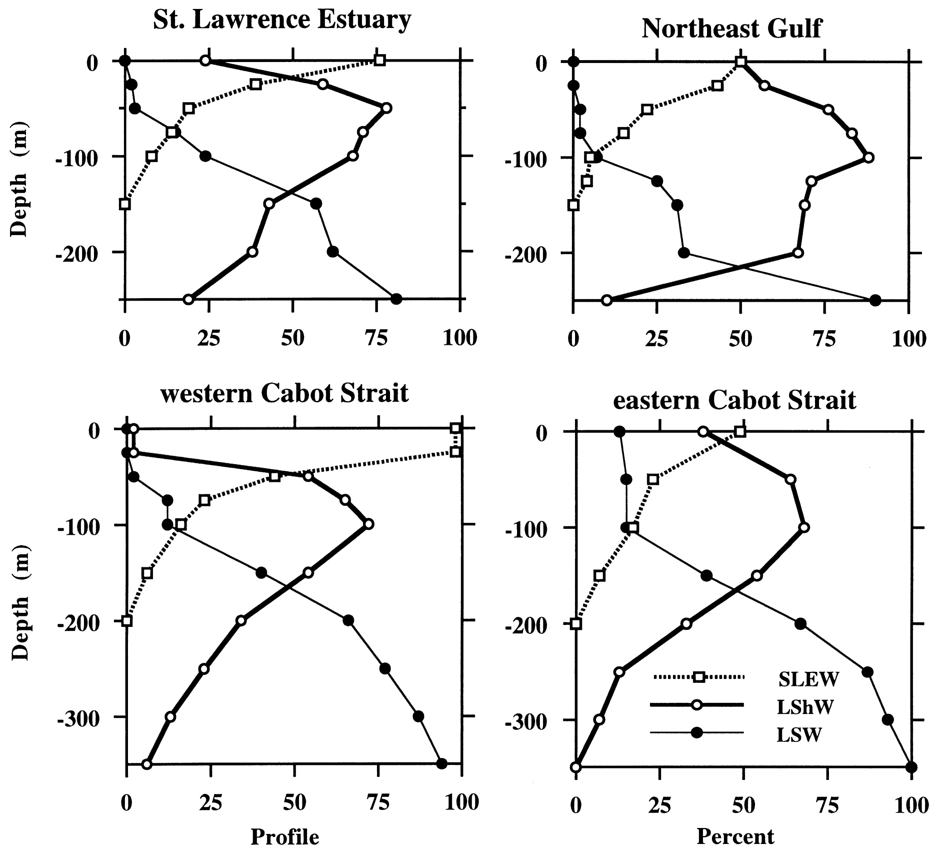


Fig. 4. Profiles of water-type composition (by percent) averaged across sections in the Gulf of St. Lawrence. Confidence interval ~ ± 10% of calculated value.

Throughout the Gulf of St. Lawrence, these three water types form a three-layer system. Except for Cabot Strait, their lateral distribution across each section is fairly uniform so that individual station profiles across the section are averaged to a single profile (Fig. 4). The water type percentages throughout the water column are calculated from 3-endmember mixing using measured $\delta^{18}O$–S values with SLEW, LShW and LSW as endmembers. At all locations, SLEW is confined to the upper 200 m, LShW has a maximum at about 100 m depth and LSW becomes the dominant constituent below 200 m.

The total volume of SLEW and LShW in the Gulf of St. Lawrence is estimated by vertically integrating these profiles then interpolating the values across the entire Gulf. For SLEW, the volume is approximately $9.8 \times 10^{12}\,m^3$. With the annual mean freshwater flux of 21×10^{-3} Sv (Sv $= 10^6\,m^3/s$) from river runoff (Loder et al., 1998), we compute a SLEW mass flux of 0.12 Sv, using a reference of $S = 34.8$, and a mean residence time in the Gulf of St. Lawrence of 2.1 yr. For LShW, the integrated Gulf volume is approximately $13.6 \times 10^{12}\,m^3$. The annual mean flux of 0.3 Sv through the Strait of Belle Isle (Han et al., 1999) yields a residence time of 1.4 yr.

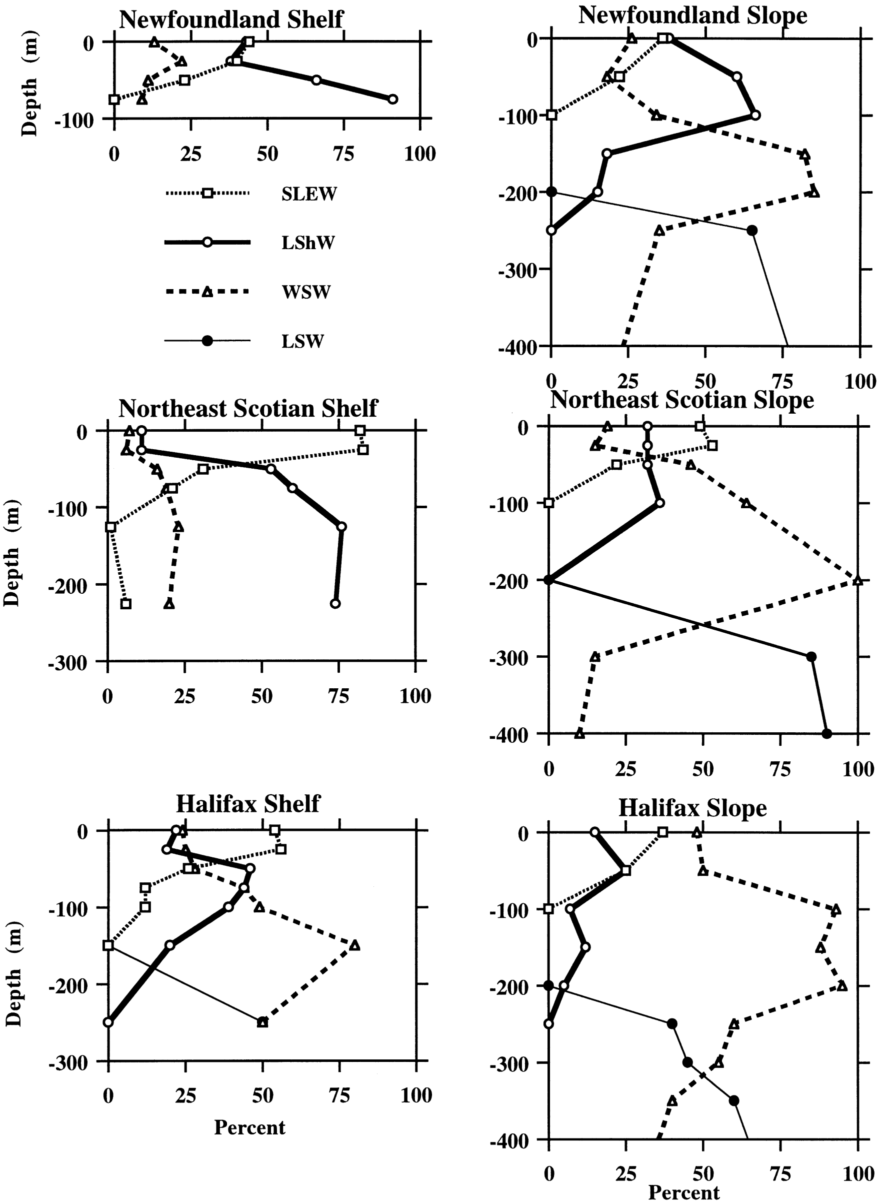


Fig. 5. Profiles of the water-type composition (by percent) averaged over shelf and slope regions south of Newfoundland and on the Scotian Shelf. Confidence interval $\sim \pm 10\%$ of calculated value.

The data presented in Fig. 4 (and Fig. 5) were collected in November 1995. This is the season when inflow through the Strait of Belle Isle is greatest and the cyclonic circulation in the western Gulf of St. Lawrence is strongest (Han et al., 1999). The fact that the greatest concentration of SLEW is observed in the western Cabot Strait rather than in the St. Lawrence Estuary must be due to the southward advection along the western margin of river outflow that peaks in the summer.

3.3. Scotian-Newfoundland shelf

For the sections across the Scotian and southwestern Newfoundland Shelves, the data are partitioned into the shelf region (water depth < 250 m) and the deeper slope region offshore. Profiles of the water-type composition on the shelf (an average of 4–5 stations) and slope (average of 1–2 stations) are shown in Fig. 5. A fourth water type, Warm Slope Water (WSW), now appears on the shelf and at mid-depth (100–200 m) over the slope. Here *T–S* properties are combined with δ^{18}O–S values to resolve WSW from LSW. Since at most only 3 of the 4 water types are present at any depth, 3-endmember mixing calculations using the δ^{18}O–S properties are used to determine the percentages given in Fig. 5. Throughout the region SLEW is confined to the upper 200 m with the greatest concentration at the surface, LShW is confined to the upper 200 m with maximum concentration at 100 m, WSW has a maximum concentration at 150–200 m, and LSW is found below 200 m. At 100 m depth at the outermost station of the northeast Scotian Slope section (not shown) there was Gulf Stream Water presumably derived from a warm-core ring incident on the slope region.

From the along- and cross-shelf variations in the water composition, we infer the sources and exchange of coastal waters along the shelf and through Cabot Strait. For example, although WSW is the dominant constituent over the slope, none is present at Cabot Strait where the deep inflow is LSW. In the upper water column at Cabot Strait, where there is outflow at the western end and inflow at the eastern end (Koutitonsky and Bugden, 1991), SLEW and LShW are exported onto the northeast Scotian Shelf. Topographic steering of this outflow (Hannah et al., 1996); Loder et al.,1997; Han et al., 1999) brings these waters in significant concentrations to the Scotian outer Shelf and Slope.

The source and then destination of water on the southwestern Newfoundland Shelf is more ambiguous. SLEW and LShW are observed on both the shelf and slope region in concentrations similar to those observed in the eastern Cabot Strait. Most likely this water originates from the eastern Newfoundland Shelf. Recent model results (Han et al., 1999) suggest that Newfoundland Shelf water can both enter the Gulf of St. Lawrence via Cabot Strait or cross over the Laurentian Channel directly to the Scotian Shelf. However, there is significant seasonal variability and model uncertainty. High concentrations of LShW on the Newfoundland Shelf suggest a significant contribution to the LShW budget in the Gulf, but this is difficult to quantify. Our data are from November when the flux through the Strait of Belle Isle (SBI) is maximum and much of the inflow through Cabot Strait recirculates cylonically just inside the Strait (Han et al., 1999). Our assertion that the SBI is the primary source of LShW in the Gulf, based on the observed monotonic decrease of LShW concentration clockwise from the SBI may be correct only for the fall and winter.

Along the Scotian Slope, the LShW concentration diminishes to the southwest as it mixes while moving away from its source. Likewise, LSW diminishes to the southwest while WSW increases consistent with a more southern source for the latter. At 700 m depth (not shown) the water is 100% LSW. A consequence of this alongshelf gradient is that the deep inflow to the Gulf of St. Lawrence through Cabot Strait is LSW, while further downstream, the inflow into the Gulf of Maine through the Northeast Channel consists of both WSW and LSW with significant interannual variation in their relative proportions (Smith et al., 2001).

Moving southwest along the inner Scotian Shelf two changes take place: a significant increase in WSW at mid-depth, and the appearance of LSW at the bottom. Most likely this water entered the shelf region through the Scotian Gulf and then circulated cyclonically around Emerald Basin as described by Hannah et al. (1996) and Loder et al. (1997). In the upper 100 m, there is a progressive mixing of SLEW and LShW.

3.4. Northeast Channel

At the Northeast Channel (NEC), the δ^{18}O–S properties of all the water passing into the Gulf of Maine are distributed along a single mixing curve (Fig. 6), with WSW the saline endmember. Occasionally, higher salinity Gulf Stream water is observed at 100-m depth at the seaward-most station, indicating the presence of a warm core ring intrusion. At some stations LSW appears at depths > 200 m. A regression of this mixing curve projects to $\delta^{18}O \approx -19.5‰$ at $S = 0$. From similar regressions Fairbanks (1982), Chapman et al. (1986), and Chapman and Beardsley (1989) inferred a sole high latitude (Labrador Sea) freshwater source, estimated to have to $\delta^{18}O_{S=0} \approx -21‰$. But here we have shown in detail, as first reported by Khatiwala et al. (1999), that the freshwater endmember is a mixture of SLEW, i.e., St. Lawrence River Water, and LShW. It is only because LShW is made more saline, presumably because of sea-ice formation, that a SLEW-LShW mixture can produce a freshwater endmember that projects to $\delta^{18}O_{S=0} \approx -19.5‰$, which is indistinguishable from a Laborador Sea meteoric source and masks the SLEW contribution.

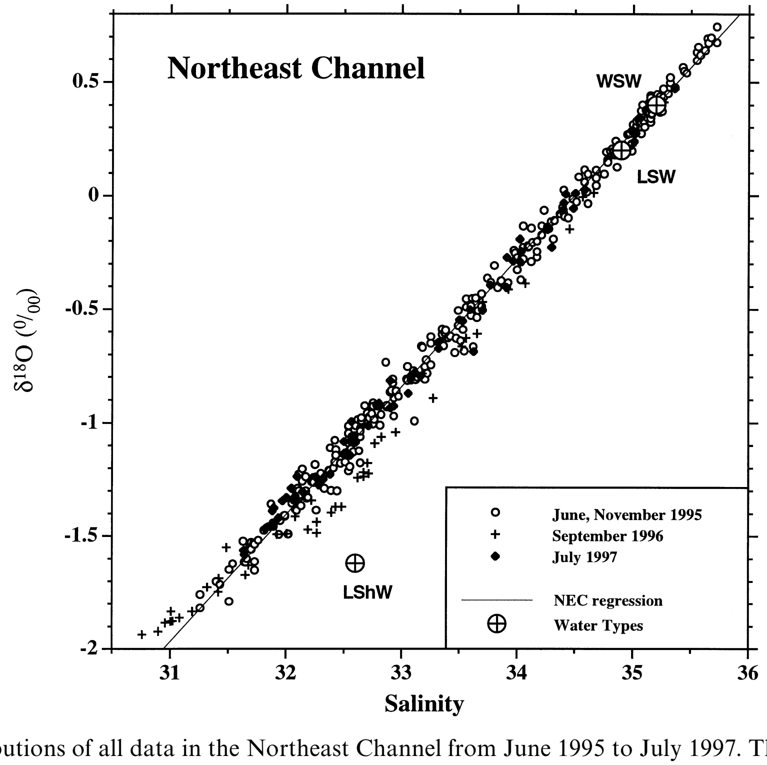


Fig. 6. δ^{18}O–S distributions of all data in the Northeast Channel from June 1995 to July 1997. The linear regression of the June–November 1995 data shown as a solid line.

Between the salinities of 31 and 34, the regression line shown in Fig. 6 is indistinguishable from a constant mixture of $39 \pm 6\%$ LShW and $61 \pm 6\%$ SLEW by volume, i.e., the ratio of LShW/SLEW $= 0.64 \pm 0.15$. The data scatter along the regression line in Fig. 6, much greater than the analysis precision, is due to water sampling variability. This ratio is equivalent to a mixture of 5.6% SLRW and 94.4% LShW by volume. Relative to $S = 34.8$, the freshwater content of LShW is

$$((34.8 - 32.6)/34.8) \times 100 = 6.3\%.$$

So the St. Lawrence River contribution to the freshwater entering the Gulf of Maine is

$$(5.6/(5.6 + 0.063 \times 94.4)) \times 100 = 48 \pm 8\%.$$

This is comparable to the estimate by Koutitonsky and Bugden (1991) and Loder et al. (1998) that the St. Lawrence River contributes 55% of the freshwater input into the Gulf of St. Lawrence. For the years 1995–1997, the δ^{18}O–S regression for Northeast Channel water was virtually constant. The apparent exception for 1996 is discussed below.

The progressive mixing of LSW, WSW, LShW and SLEW during their passage from the Gulf of St. Lawrence to the Northeast Channel is illustrated in Fig. 7. The 3-endmember mixing in the Gulf

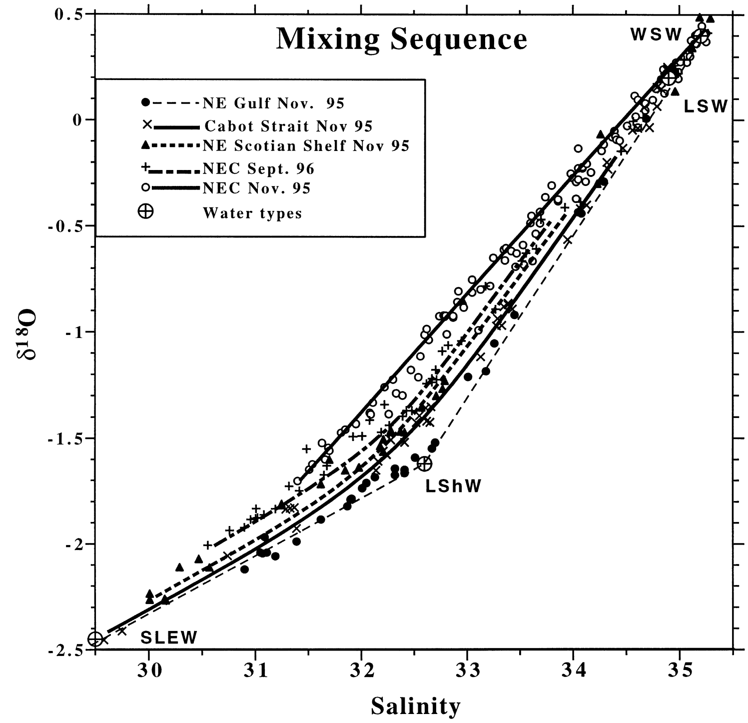


Fig. 7. δ^{18}O–S distributions showing the progressive mixing of SLEW and LShW with Slope Water. The succession of curves are: initial mixing of LShW with SLEW, a proxy for St. Lawrence River Water, and with Labrador Slope Water (LSW) in the Gulf of St. Lawrence (thin, dashed); outflow at Cabot Strait (bold, solid); on the Scotian Shelf (bold, dashed); outer Northeast Channel, Sept. 1995 (bold, dot–dashed); Northeast Channel regression (bold, straight line), same linear regression as shown in Fig. 6.

of St. Lawrence and on the Scotian Shelf contracts into a 2-endmember curve in the Northeast Channel where tidal mixing is particularly vigorous. The water property distribution converges to the NEC regression line for which the LShW/SLEW volume ratio is 0.64. The salinity of the surface water, which is least in the St. Lawrence estuary region and then increases downstream, varies depending on the degree of mixing with deep Slope Water. Northeast Channel data for September 1996 (Fig. 6) deviated from this NEC regression line and thus were first thought to represent an interannual variation in the inflow water properties to the Gulf of Maine. However, additional data from stations on the Gulf side of the Northeast Channel do fall on the regression line. So it appears that the NEC September 1996 data shown in Fig. 6 represent a water column in which SLEW and LShW are not yet fully mixed, a condition normally characteristic of the southwestern Scotian Shelf. Water properties of the inflow into the Gulf of Maine for 1995–1997 are indeed represented by the NEC regression line (Figs. 6 and 7).

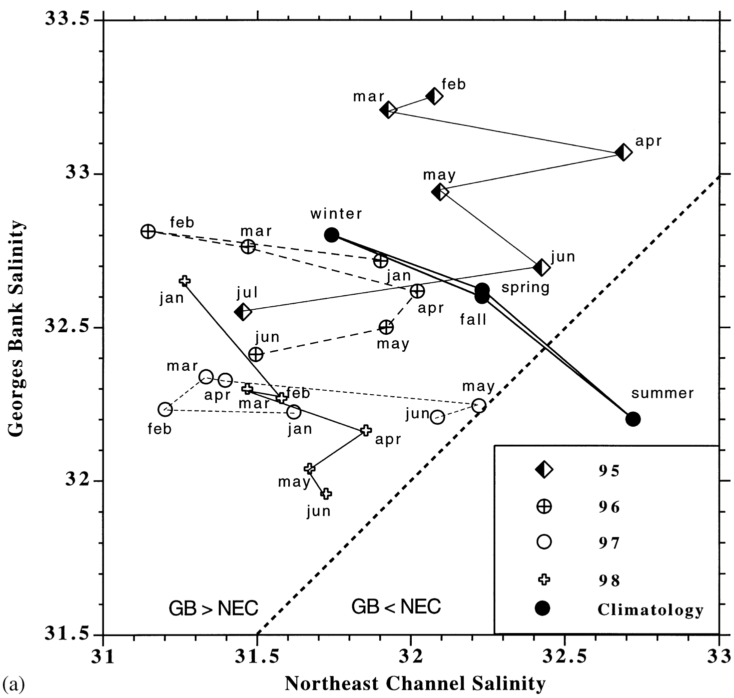
3.5. *Gulf of Maine— Georges Bank*

The properties of the water entering the Gulf of Maine via the Northeast Channel are distributed along a linear regression (Figs. 6 and 7). The surface salinity varies seasonally along this regression with a minimum in February (Smith, 1989). On Georges Bank, the minimum salinity is in the summer (Flagg et al., 1982). This could be due to the lag by the advection of the peak outflow of rivers discharging into the Gulf of Maine, which we designate as Maine River Water (MRW), in spring or the cyclonic transit of the Scotian Shelf February salinity minimum around the Gulf of Maine. The climatological annual cycle of the salinity on Georges Bank is one-half the amplitude and out of phase with that of the inflow from the Scotian Shelf via the Northeast Channel (Fig. 8a). In contrast, the interannual variation at both locations during 1995–1998 is in phase and approximately the same amplitude (Fig. 8b). The monthly variations (Fig. 8a) have the annual cycle superimposed on a freshening trend. In 1997, the salinity annual cycle on Georges Bank was virtually absent.

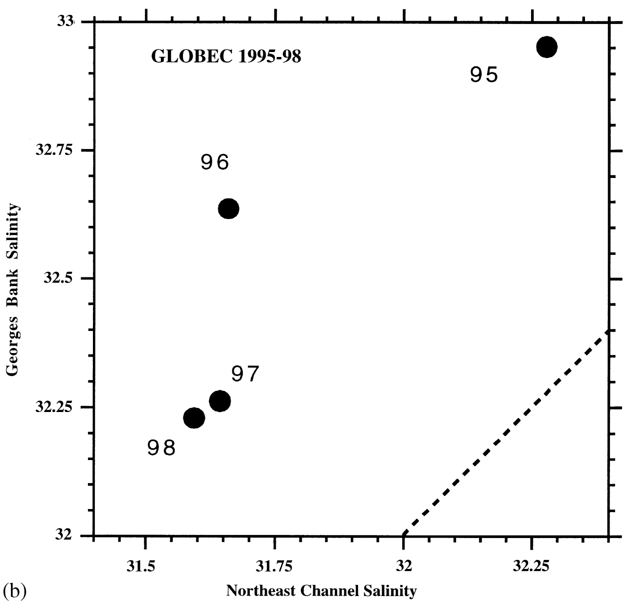
River runoff in the Gulf of Maine, which we will designate as Maine River Water (MRW), has an isotopic value of $\delta^{18}O \approx -10.5‰$ (Fairbanks, 1982). Therefore, any water in the Gulf of Maine or on Georges Bank with $\delta^{18}O$ properties more positive than the NEC regression, where $\delta^{18}O_{S=0} \approx -19.5‰$, must be derived from mixing with these local river sources. The data distribution suggest that MRW mixes with water on the NEC regression line at $S \approx 33.8$, which represents water in the Gulf of Maine at 100–150 m depth and which we will designate as Maine Intermediate Water (MIW). An example from the June 1994 broadscale survey, in which MRW influence on the Bank is greatest, is shown in Fig. 9. The data are partitioned into the regions on Georges Bank shown in Fig. 10. All of the data lie between the NEC regression line and the MRW-MIW mixing line. For the 1997 January–June broadscale surveys (Fig. 11), virtually all of the data are distributed along the NEC regression. The only significant local river influence is on the northwest flank in May and June. This local river influence does not extend onto the central portion of Georges Bank.

3.6. *Central Georges Bank*

We define central Georges Bank Water by the broadscale stations (4,11,12, 30 and 32) that are on the cap of the Bank in water depths < 55 m. These stations are removed from the gradients at the



(a)



(b)

Fig. 8. (a) Monthly mean salinity of central Georges Bank vs. Northeast Channel (defined by the average upper 40 m of the water column at GLOBEC broadscale station #25, on the east side of the Northeast Channnel) for the years 1995–1998. Also shown is the climatological seasonal cycle where Georges Bank values are the mean for 1975–1979 (Flagg, 1987) and Northeast Channel values are 1978–1985 averages of the upper 50 m from mooring C2 on the southwest Scotian Shelf (Smith, 1989). Since the Northeast Channel data are derived from a single station in a region with strong horizontal gradients, its variance is greater than the Georges Bank data, which is a 5 station average in a more homogeneous region. (b) Annual mean salinity, calculated from the six monthly broadscale surveys each year.

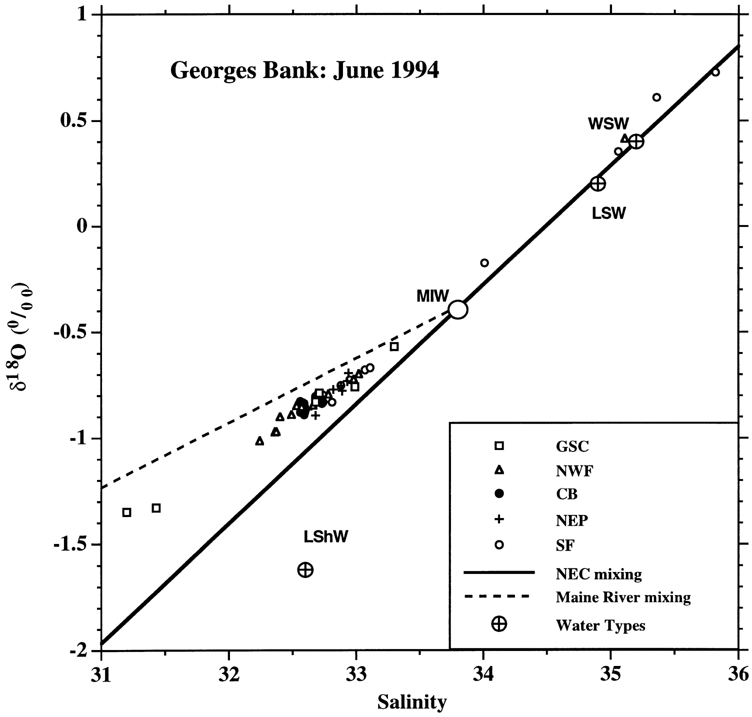


Fig. 9. The δ^{18}O–S distribution on Georges Bank in June 1994 with data partitioned by regions defined in Fig. 10: Great South Channel (GSC), northwest flank (NWF), central Bank (CB), northeast peak (NEP), and southern flank (SF). Also shown is the Northeast Channel (NEC) regression (solid line) and mixing between Maine River Water and Maine Intermediate Water (MIW) (dashed line).

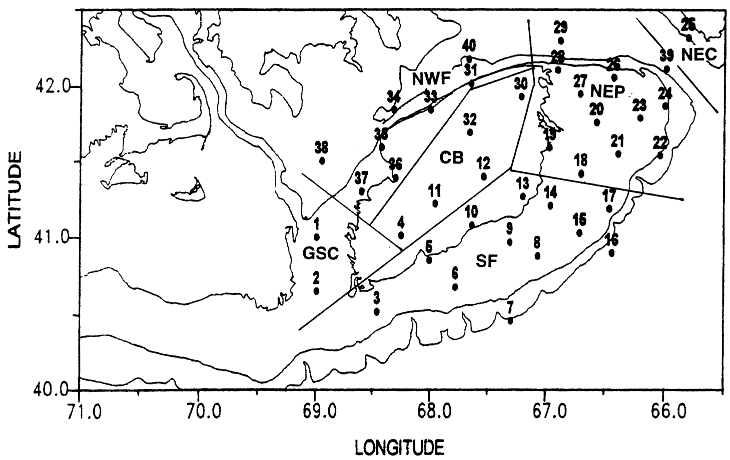


Fig. 10. A map of Georges Bank showing the GLOBEC broadscale standard station locations and the regional partitioning used in Figs. 9 and 11.

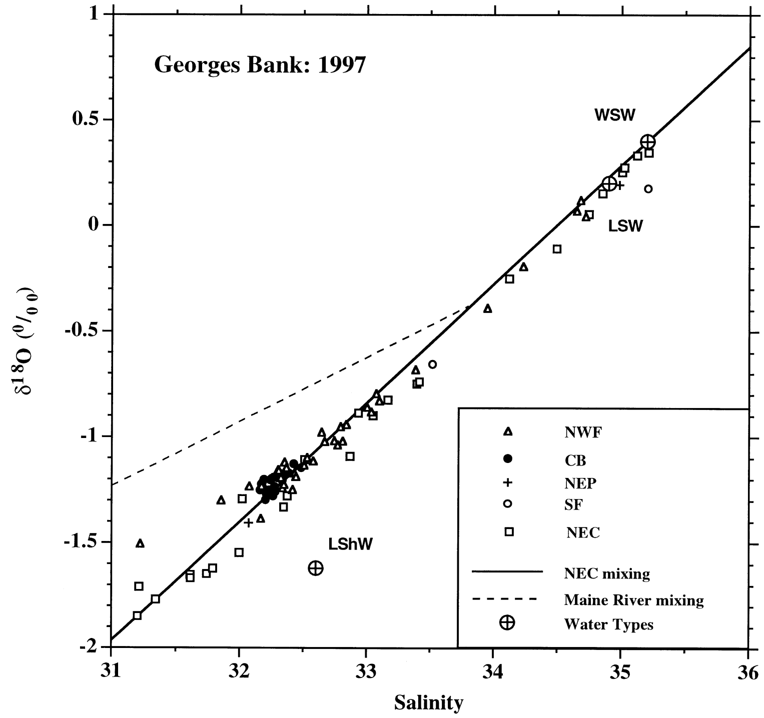


Fig. 11. Same as Fig. 9 for a subsample the data from the six GLOBEC broadscale surveys in 1997. Included is an additional region: Northeast Channel (NEC), broadscale station #25.

perimeter of the Bank and are situated in the more homogeneous, tidally mixed water on the cap of the Bank. They represent the water properties at the center of the Bank.

Monthly mean values of central Georges Bank water for GLOBEC 1994–1998 and for the National Marine Fisheries Service Marine Resource Monitoring, Assessment, and Prediction (MARMAP) program 1981–1982 are shown in Fig. 12. All data are positioned between the NEC regression line and the MRW-MIW mixing line as expected since these are the only available water sources. Thus, the water properties on the central Georges Bank are derived from the mixing of a point source, MRW, and a distributed source, the inflow through the Northeast Channel. The resulting salinity will depend on the fraction of MRW, the salinity of Scotian Shelf water entering the Northeast Channel, and the degree of vertical mixing within the Northeast Channel and Gulf of Maine.

The contribution of MRW to the water on the central Georges Bank was determined by 3-endmember δ^{18}O–S mixing calculations using MRW, MIW and the freshwater endmember of the NEC mixing line as endmembers. There is considerable interannual variation of this contribution (see Table 2) with the greatest in 1981–1982 and the least in 1996–1997. The percent of freshwater, relative to $S = 34.8$, supplied by MRW and the percent of MRW by volume on the central Bank for these years is given in Table 2. The contribution of freshwater on Georges Bank by MRW ranges from 55 to 3.7%. For comparison, Loder et al. (1998) estimate that on average Maine

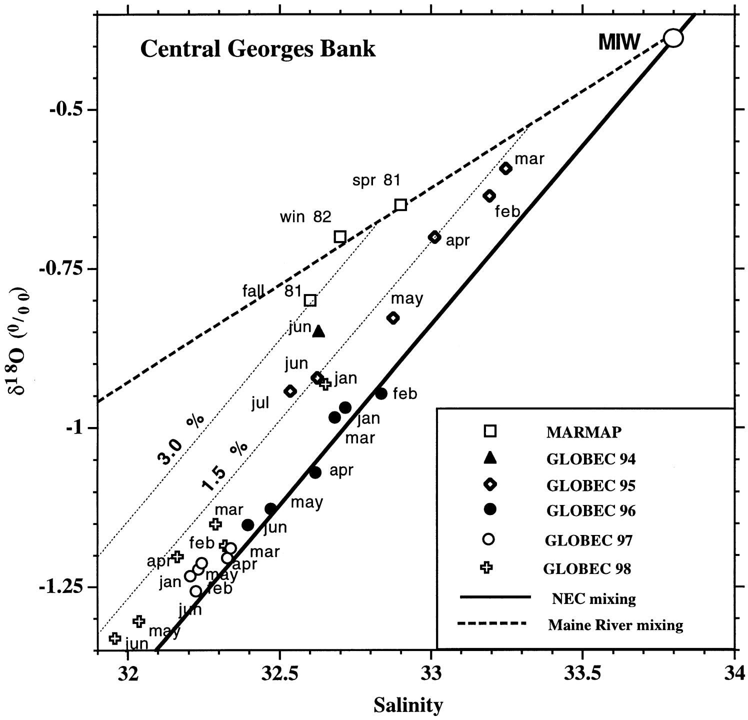


Fig. 12. $\delta^{18}O$–S distribution of monthly mean central Georges Bank data for MARMAP 1981–1982 and GLOBEC 1994–1998. Dotted lines show the locus of constant percent of MRW (by volume).

Table 2
Maine River Water on central Georges Bank[a]

	% by vol.	% freshwater
Spring 1981	2.76	50
Fall 1981	3.07	48
Winter 1982	3.32	55
June 1994	2.40	38
Feb.–July 1995	1.37	25.5
Jan.–June 1996	0.23	3.7
Jan.–June 1997	0.36	5.3
Jan.–June 1998	1.06	15.5

[a] The percent, by volume and freshwater fraction relative to 34.8, contributed by Maine River Water to central Georges Bank water for years 1981–1982, using MARMAP, and for 1994–1998, using GLOBEC data.

River runoff contributes 19% of the freshwater, relative to $S = 34.8$, in the Gulf of Maine. There is no reason to expect MRW to mix uniformly throughout the Gulf of Maine or to be on Georges Bank in the same proportion as much of it remains in the coastal current and exits over Nantucket

Shoals or through the Great South Channel. In Fig. 12, the locus of constant percent (by volume) of MRW in central Bank water is given by lines parallel to the NEC regression line. So, in 1995, the percent of MRW by volume was approximately constant during February–June with a slight increase in July.

4. Discussion

Previous studies of Gulf of St. Lawrence hydrography using only *T–S* properties described an intermediate cold layer (Lauzier and Bailey, 1957; Forrester, 1964; Banks, 1966), which in summer is identified by a temperature minimum ("the cold layer") centered at approximately 100 m depth. It appears that this layer is synonymous with the LShW we have identified. Forrester (1964) estimated its wintertime volume to be $9.2 \times 10^{12}\,m^3$, slightly smaller than our estimated LShW volume. However, since temperature is non-conservative, the cold layer thickness varies seasonally, disappearing by fall, and attempts to partition its source between in situ cooling and Strait of Belle Isle inflow gave mixed results (Banks, 1966; Lauzier and Bailey, 1957). More recent analysis by Petrie et al. (1988) estimates that this inflow contributes 53% of the water in the cold layer. Using the conservative $\delta^{18}O$ tracer, we are able to identify the structure of this layer independent of its changing temperature and estimate its residence time.

The regression observed in the Northeast Channel represents the mixing of two fresher water sources (SLEW and LShW), each of finite volume, with a reservoir of saltier Slope Water. More precisely, at the Northeast Channel, the two freshwater masses are removed from their origin, which is primarily the Gulf of St. Lawrence, while a Slope Water source is distributed along the entire continental margin. The ratios of Gulf of St. Lawrence freshwater sources are given in Table 3. In the Gulf of St. Lawrence, the ratio of the volumes of LShW and SLEW is 1.4, but since their residence time is not the same, the outflow will not be in the same proportion. The ratio of the mass flux of LShW and SLEW into the Gulf of St. Lawrence is 2.1 or 3 times the mixing ratio measured at the Northeast Channel.

The above estimates of sourcewater volume ratios may be misleading for several reasons. At the Northeast Channel, the ratio of LShW/SLEW along the mixing line appear to be constant at least to $S = 34$ or approximately 100 m depth. Below this depth, the LShW proportion may be greater although the scatter in the data precludes a quantitative estimate. That there may be more LShW

Table 3
Freshwater source ratios[a]

	LShW	SLEW	LShW/SLEW
Volume ($10^{12}\,m^3$) in the GSL	13.6	9.8	1.4
Mass flux (Sv) into the GSL	0.30	0.14	2.1
Northeast Channel: % by vol.	39	61	0.64

[a]A comparison of LShW and SLEW volumes and fluxes in the Gulf of St. Lawrence (GSL) with their volume ratio in the upper water column of the Northeast Channel.

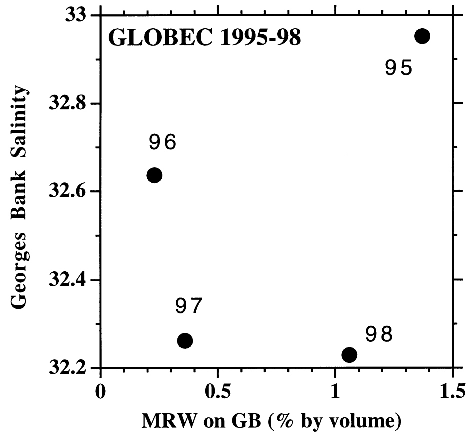


Fig. 13. Annual mean, calculated from the six monthly broadscale surveys each year, salinity and percent (by volume) of Maine River Water (MRW) on Georges Bank.

at depth is not surprising since the SLEW source is near surface while LShW is centered at 50–150 m depth. If half the LShW mixed downward, it would not contribute to the Northeast Channel regression in the upper 100 m of the water column and bring the source and regression mixing ratios closer.

The seasonal variation of these source waters also could alter their volume ratio. The St. Lawrence River outflow varies by a factor of 2, with peak values in May–June (Koutitonsky and Bugden, 1991). The seasonal cycle of the Strait of Belle Isle inflow is less certain and appears to vary from a peak of 0.5 Sv in November–December to 0.1 Sv in July–August (Han et al., 1999). Since the residence time in the Gulf of St. Lawrence of both water types is greater than 1 year, some of these fluctuations might be filtered out. However, throughout the upper 100 m at the southwestern end of the Scotian Shelf, the annual cycle of salinity is pronounced and has an amplitude of 0.4 with a minimum in February (Smith et al., 2000). This represents a 9-month lag in the peak outflow for the St. Lawrence River and indicates that the seasonal cycle of the Gulf of St. Lawrence freshwater sources persists downstream. It is therefore surprising that for the months of June–November over a 3-yr interval, the ratio of LShW and SLEW in the upper 100 m at the Northeast Channel is virtually constant. A deviation by a factor of 2 would be readily detected.

The interannual variation of the percent of Maine River Water on Georges Bank is shown in Fig. 13. For the GLOBEC years 1995–1998, this variation is not correlated with the salinity on Georges Bank. Instead, interannual variation of Georges Bank salinity is correlated with the Northeast Channel salinity (Fig. 8b). Thus, interannual fluctuations of salinity on Georges Bank are driven primarily by variations in upstream sources and not the presence of local river water.

5. Conclusions

From oxygen isotope analysis, we conclude that freshwater on Georges Bank is derived primarily from two sources: St. Lawrence River Water and Labrador Shelf Water that enters the

Gulf of St. Lawrence via the Strait of Belle Isle. By the time this water enters the Gulf of Maine at the Northeast Channel, water properties are distributed along a single 2-endmember mixing curve. For the years 1995–1997, the composition of the freshwater endmember was virtually constant, consisting of 5.6% SLRW and 94.4% Labrador Shelf Water by volume. Relative to 34.8, SLRW supplies 48% and LShW 52% of the freshwater entering the Gulf of Maine through the Northeast Channel.

Within the Gulf of Maine, the local river outflows are an additional source of freshwater. During 1981–1982, the water on Georges Bank contained $\sim 3\%$ local river water by volume. During GLOBEC, the volume of local river water on the Bank diminished from 2.4% in 1994 to a negligible value in 1996–1997 then increased in 1998. Thus, the percent of freshwater relative to 34.8 supplied by MRW to Georges Bank varied from 55 to 3.7%.

During 1995–1998, the monotonic decrease in salinity on Georges Bank correlates with the salinity of the surface inflow through the Northeast Channel (Fig. 8b). In contrast, Georges Bank salinity does not correlate with the percent of MRW on the Bank, In fact, in 1995 when the percent of MRW was greatest, Georges Bank salinity was also greatest. Thus, the water-type composition on Georges Bank is not a simple function of these water sources but may involve variations in the circulation and mixing within the Gulf of Maine which are not yet fully understood.

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