The Near-Surface Circulation and Exchange in the Newfoundland Grand Banks Region

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ABSTRACT *Analysis of 39 satellite-tracked drifter records from the Newfoundland Grand Banks region has allowed maps of the mean and variable flows to be drawn. The variable currents are particularly large relative to the mean for the shelf, Flemish Cap and in the Newfoundland Basin. The ratio of the mean to variable flow is largest along the path of the Labrador Current. Drifters that either have been released on or migrate onto the Grand Banks remain there for an average of 71 d. A statistical study of the effect of wind on drifter motion has shown that winds can only account for about 10% of current variability. This result is examined with consideration given to data noise, aliasing and non-stationary conditions. Some drifters that were deployed in the Labrador Current moved onto the shelf and vice versa. These observations have been used to estimate the rate of exchange between the Current and the Grand Banks. Using this exchange rate in a box model, it is calculated that, over the iceberg season, 30% of the bergs will be in the Avalon Channel, 20% on the Grand Banks and 50% in the Labrador Current, in good agreement with the observed distribution. An alternative model based solely on advection is considered as well. The exchange model is also applied to the salinity budget for the Labrador Current with some success.*

RÉSUMÉ *L'étude de 39 relevés provenant de dériveurs suivis par satellite dans la région des Grands bancs de Terre-Neuve a permis de dresser des cartes représentant le courant moyen et ses variabilités. L'intensité des courants variables de la plate-forme continentale, du bonnet flamand et du bassin de Terre-neuve est supérieure à la moyenne. Le rapport entre courant moyen et courant variable est plus important le long de la trajectoire du courant du Labrador. Les dériveurs qu'on rencontre dans la région des Grands bancs y passent en moyenne 71 jours. Une étude statistique de l'effet du vent sur le mouvement des dériveurs a indiqué qu'environ 10 % seulement de la variabilité des courants sont attribuables aux vents. Au moment de l'analyse de ce résultant, on a tenu compte des bruits aléatoires, des problèmes de sous-échantillonnage dans le temps et des conditions non stationnaires. Certains dériveurs du courant du Labrador se sont rendus sur la plate-forme continentale et d'autres ont fait le mouvement inverse. Ces observations ont permis d'estimer le taux d'échange entre le courant et les Grands bancs. En utilisant ce taux d'échange dans le cadre d'un modèle systématique (box model), on calcule que pendant la saison des icebergs, 30 % d'entre eux se trouveront dans le chenal d'Avalon, 20 % sur les Grands bancs et 50 % dans le courant du Labrador, ce qui concorde bien avec la répartition observée. On a également tenu compte d'un autre*

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modèle, basé uniquement sur l'advecticn. Le modèle de l'échange permet aussi d'établir avec une certaine exactitude le bilan de salinité du courant du Labrador.

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1 Introduction

A recent study (Petrie and Anderson, 1983) of the general circulation in the Newfoundland Grand Banks area indicated that there was a dearth of direct measurements of current. After that work was completed, we collected the tracks of 39 satellite-tracked drifting buoys that were released in the region. These instruments have proven useful for mapping the mean circulation and variability in the upper ocean as shown by Richardson (1983) and Krauss and Meinke (1982). In this paper, we shall analyse the tracks of buoys in the area (Fig. 1) defined by 39–52°N and 43–54°W, which includes the Grand Banks of Newfoundland and Flemish Cap. The major oceanographic features of the region are the Labrador Current, which generally follows the 200-m isobath southward along the edge of the Grand Banks, and the North Atlantic Current to the south, which flows to the east and northeast. In addition, there is an inshore branch of the Labrador Current that flows southward near the coast through the Avalon Channel, a 100-km wide feature with an average depth of about 150 m.

The tracks will be analysed to produce maps of the mean and variable currents, to define the near-surface strength of the Labrador Current and to examine the behaviour of drifters on the Shelf. A number of buoys released in the Labrador Current were advected onto the Grand Banks and vice versa. From the probability that this will happen, we estimate the exchange between the Banks and the Current. Given this estimate, models will be developed from which we can calculate the regional iceberg distribution and the changes of the salinity of the Labrador Current.

2 Methods and observations

Thirty-four of the 39 buoy tracks were provided by the International Ice Patrol (IIP) of the United States Coast Guard. A sample track is shown in Fig. 2. Their standard instrument package consists of a 13-m drogue suspended from the buoy by a 10-m tether (Weir, 1979). On average, 3 fixes per day with a standard deviation of ±5 km (Kirwan et al., 1976; Murray, 1980, 1982) were acquired using the "RAMS" positioning system until 1979. In 1979, the IIP set up their own positioning system which was accurate to ±10 km (Murray, 1980) for that year. For the 1980 and 1981 seasons, a reference beacon was established at St John's which improved the accuracy to about ±3 km (Murray, 1982). Beginning with 1982, the IIP relied exclusively on the "ARGOS" system, which should give accuracies to about ±0.5 km based on our experience with moored satellite buoys on the Newfoundland shelf.

The data were edited and smoothed to 1 position per day fixed at 1200 GMT. The successive positions were used to calculate velocities, and it was estimated that the position error would give rise to a velocity error of 0.08 m s^{-1} based on 1 fix per day, 24 h apart. The data analysis procedures and all tracks are given by Petrie and Isenor

(1984). In the area of interest, there were 2843 daily mean current vectors in 118 $1° \times 1°$ squares, with an average of 24 vectors per square and a standard deviation of 21.5. The Grand Banks had an average of 26 (std dev. = 18) vectors per square. The data covered the period 1976–1983. Thirty-two of the 39 drifters were released during the months of March–June, the period that corresponds to the iceberg season. Thus, the results of the data analysis will be more representative of late winter and spring conditions.

For each $1° \times 1°$ square, the mean current and the variance components, in fact the root mean square (rms) amplitudes along principal axes, were calculated where there were sufficient data. Typical variance components for the Grand Banks and the deep ocean were 0.01 and 0.04 $m^2 s^{-2}$, respectively. The average number of vectors in each $1° \times 1°$ square was about 25. This would give a typical standard error of the mean current of 0.02 $m s^{-1}$ for the Grand Banks and 0.05 $m s^{-1}$ for the deep ocean. However, examination of the temporal autocorrelation functions showed significant low-frequency energy in the deep ocean. This reduces the number of degrees of freedom for the deep ocean data. A more realistic standard error would be about 0.12 $m s^{-1}$.

3 Mean, variable and wind-driven currents

a *Mean Currents*

Figure 3 shows the mean currents derived from the drifter observations. Several features are noteworthy. The Gulf Stream and the North Atlantic Current are quite evident in the lower portion of the figure as a strong flow to the east, which then veers to the northeast with speeds of up to 1 $m s^{-1}$. The next important feature to examine is the Labrador Current. Fifteen buoys launched north of 48°N and west of 46°W seemed to follow two routes. Six drifters that tracked eastwards north of Flemish Cap give rise to the strong flow between 48 and 49°N that is evident in Fig. 3. Nine buoys drifted through Flemish Pass. The apparent splitting or alternating of the flow around Flemish Cap and through Flemish Pass has been noted by others (Smith et al., 1937). In the Pass, the Labrador Current appears to parallel the 200-m isobath from north to south with speeds to about 0.25 $m s^{-1}$. Since the Current (see Petrie in Benoit and Mungall, 1983) is about 50 km wide and has horizontal excursions normal to the 200-m isobath of at least 60 km, and the resolution of the $1° \times 1°$ grid is at best 75 km, we expect the speed of the Labrador Current to be underestimated. We reanalyzed 11 drifters that apparently were in the Labrador Current and cut off their tracks at the points where they began to move to the northeast in the North Atlantic Current. The average speed of the flow from the northern Grand Banks along the 200-m isobath to the Tail of the Bank was 0.30 $m s^{-1}$. The currents on the Grand Banks (< 200 m) are somewhat haphazard and generally less than 0.10 $m s^{-1}$. This is quite different from the picture presented by Smith et al. (1937), who show a well-defined circulation pattern.

b *Variable Currents*

The so-called eddy kinetic energy per unit mass (Richardson, 1983) was calculated (Fig. 4) by using $EKE = 0.5\,(U'^2 + V'^2)$, where U' and V' are the departures from the

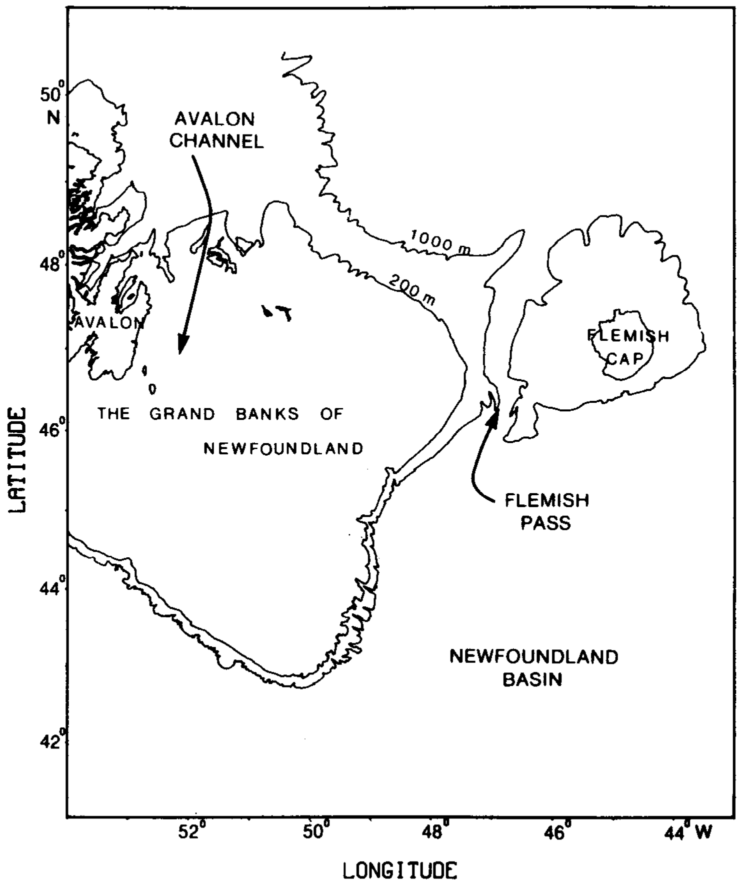

Fig. 1 The study area showing the 200- and 1000-m isobaths.

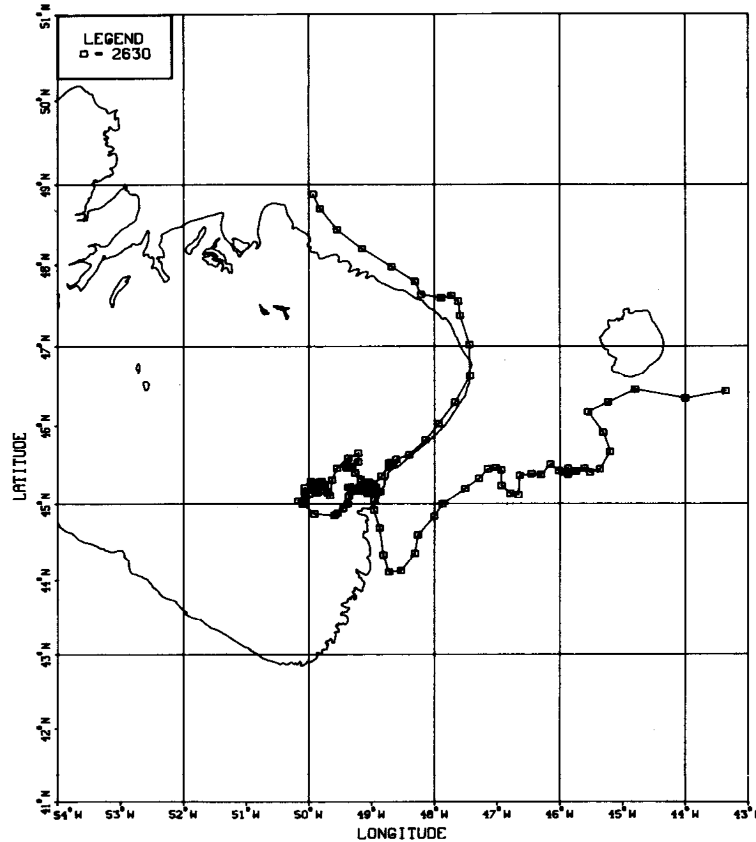

Fig. 2 Track of IIP drifter 2630, which was released March 29 and stopped transmitting on 17 July 1980. A hollow square marks the drifter's position at 1200 GMT every day. A solid square marks every tenth day. The 200-m isobath is also shown.

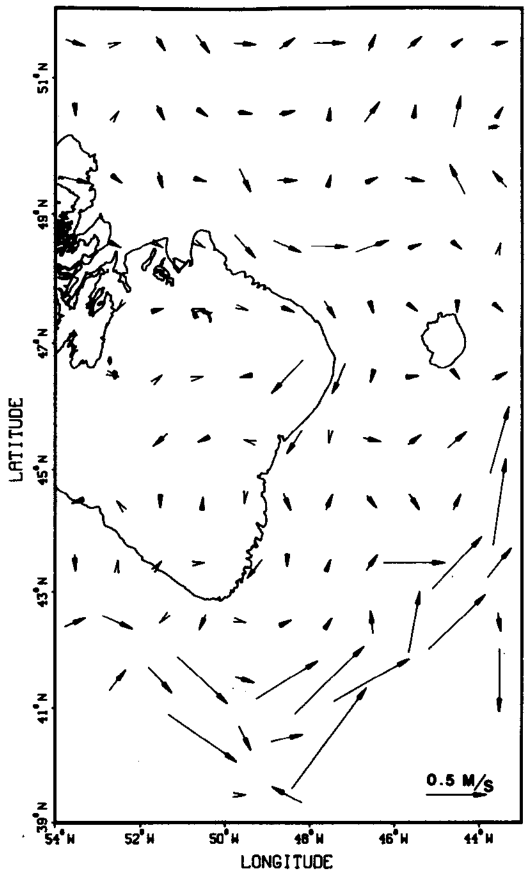

Fig. 3 Map of the mean current vectors for each 1° × 1° square. Open and solid arrowheads signify currents between 0 and 0.05 m s^{-1}, and between 0.05 and 0.10 m s^{-1}, respectively. We estimate that a representative standard error of the mean for the shelf would be 0.02 m s^{-1} and for deeper water would be ~0.12 m s^{-1}.

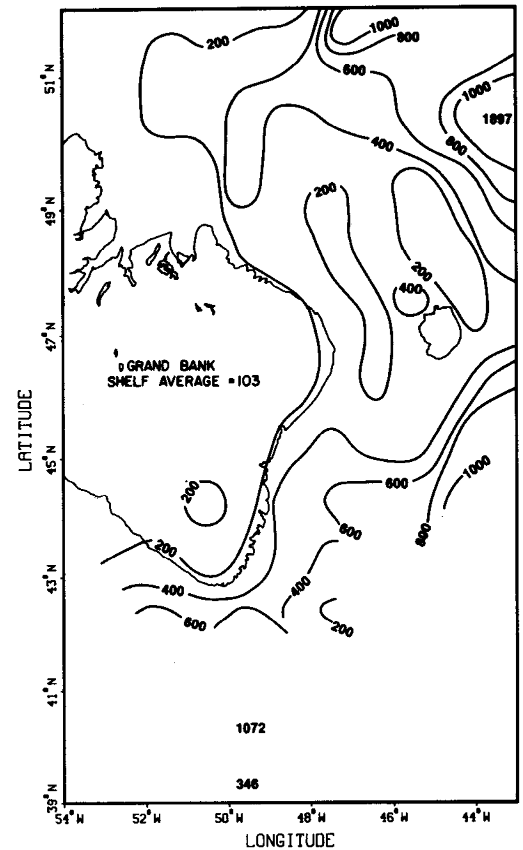

Fig. 4 Contours of the eddy kinetic energy in units of 10^{-4} m^2 s^{-2}. The 200-m isobath is also shown.

TABLE 1. Drifters on the Banks

ID Number	Year	First Day on Banks	First Day off Banks	Number of Days
2605	1979	61 (March 2)	199 (July 18)	138
2630	1980	101 (April 10)	164 (June 12)	63
2632	1980	187 (July 5)	253 (September 9)	66
2633A	1980	284 (October 10)	317 (November 12)	33
2596	1979	113 (April 23)	318 (November 14)	205
2611	1983	135 (May 15)	140 (May 20)	5
		147 (May 27)	165 (June 14)*	18
2633B	1983	127 (May 7)	166 (June 15)*	39

*The buoy, while still on the Banks, was picked up on this date.

means of the eastward and northward velocities, respectively. We have used data from 1° × 1° boxes that contain at least 10 observations. The shelf area has the lowest variance with an average of $100 \times 10^{-4}\,m^2\,s^{-2}$ for the Grand Banks. Note that in the next section we estimate that position uncertainty can give rise to an EKE of up to $70 \times 10^{-4}\,m^2\,s^{-2}$. The $200 \times 10^{-4}\,m^2\,s^{-2}$ contour follows the 200-m isobath and therefore the path of the Labrador Current for the greater part. Areas of high eddy kinetic energy are located to the south and east of the Grand Banks and to the northeast of Flemish Cap. These areas correspond to the path of the Gulf Stream and North Atlantic Current (Krauss and Meinke, 1982). Although the eddy kinetic energy is least on the Grand Banks, the mean currents are also lowest there so that the ratio of the mean current to the rms current is 0.34. The mean flow is more dominant (the ratio is greater than 0.5) along the 200-m isobath and between 48 and 49°N from 50 to 44°W, i.e. the area north of Flemish Cap. These paths correspond generally to the route taken by the Labrador Current.

c *Effect of Wind*

The dominance of variable currents on the shelf and the potential application of these data to questions of iceberg drift, residence time and dispersion prompted us to investigate the effect of wind on drifter movement. Of the drifters that were on the Banks (Table 1), it is fortunate that the one (2596), for which contemporaneous shelf winds were available from drillings rigs, was always within 300 km of a wind-measuring site and spent the most time (205 d) on the Grand Banks. In fact, there were 194 d (22 April–1 November) when simultaneous wind and position data were available. We have calculated the simple correlation of daily mean currents, derived from the drifter track, and the daily mean wind. The results are shown in Table 2. Wind can only account for about 5% of the variance of the eastward (u) current and about 10% of the variance of the northward (v) component. Note that the relationship between the cross components of wind and current is as one would expect if the response were in the Ekman sense: b_2 is positive for u and b_1 is negative for v. We also note that the magnitude of the coefficients are about what one would expect. However, the collinear coefficients are comparable and only 10% or so of the current variance is accounted for by wind.

Before concluding that the wind does not appreciably affect current on the Banks,

TABLE 2. Relationship between the daily mean components of the wind (U, V) and current (u, v) on the Grand Banks, along with their variances ($\overline{u^2}$, $\overline{v^2}$, $\overline{U^2}$, $\overline{V^2}$), based on the drift track of IIP drifter 2596. $u, v = b_0 + b_1 U + b_2 V$.

Component*	Multiple Correlation Coefficient r	Regression Coefficients b_0	b_1	b_2	Variance ($m^2 s^{-2}$)
u	0.23	0.012	0.0021	0.0010	6.1×10^{-3}
v	0.32	0.002	−0.0026	0.0023	5.5×10^{-3}
U					50
V					65

*u and U are positive eastwards; v and V are positive northwards.

we must consider the sources of error. A typical standard deviation of position for these data could be as large as ±5 km as noted earlier. This gives rise to a noise variance of the daily currents of $6.7 \times 10^{-3}\,m^2\,s^{-2}$, which we shall take as equally distributed between both components ($3.35 \times 10^{-3}\,m^2\,s^{-2}$). A typical current variance is $5.8 \times 10^{-3}\,m^2\,s^{-2}$ (Table 2). Assuming that the noise is not correlated with buoy position or with wind we estimate that the correlation coefficient would be degraded by 0.11. We also considered the effects of non-stationary conditions – the water column was nearly well mixed when the buoy was first deployed, stratified during spring and summer, and began to mix up again toward the end of the buoy's track in November. We considered an idealised model that included Ekman dynamics operating on a mixed layer that varied sinusoidally from 80 m deep in April to 20 m in midsummer and back to 80 m in November. The model was forced by a periodic wind stress. Several cases were run with periods in the range of 3–7 d. The dynamics coupled wind stress and current exactly. However, because of the varying mixed layer conditions, the correlation between wind and current was 0.90. Clearly, there are numerous variations of this calculation that one can try, such as forcing with several components of wind, including tides, inertial period motions, or more relevant mixed layer dynamics. We did try most of these combinations but the smallest degradation of the correlation coefficient that we found was 0.10. It is quite easy to vary the models to get considerably larger values. Using current-meter data from the shelf for the same time period, we estimated the variance due to inertial period motions as $2.2 \times 10^{-3}\,m^2\,s^{-2}$ for one component. However, the contribution will be reduced because of the daily averaging and the random (relative to the tides) inertial motion phase. At these energy levels, the inertial period motions will degrade the correlation coefficient by about 0.01. Tides have a negligible effect on r. Therefore we expect that the maximum correlation from these data would be in the range 0.75–0.80. Given the simplicity of some of our estimates, the non-stationary conditions, for example, this would be an upper bound. We have not dealt with non-local effects such as shelf waves or even coastlines. In addition, we have implicitly assumed that our wind data are error-free and that our daily averaging constitutes a perfect filter. We conclude that it will require considerably more sophisticated models and better data sets to determine the nature of the wind-Lagrangian motion coupling.

4 Drifters on the Grand Banks, onshore-offshore exchange, and iceberg distributions

a *Probability of Exchange From the Data*

Seven drifters (Table 1) spent time on the Grand Banks. Of these, five were launched outside the 200-m isobath and two, numbers 2596 and 2633B, were deployed just off Avalon Peninsula. Buoys 2605, 2630 (Fig. 2), 2632 and 2611 appeared to be in the fast-moving Labrador Current before moving onto the Bank, whereas buoy 2633A did not. The number of days spent shoreward of the 200-m isobath ranged from 5 to 205 with a mean of 71 d and a standard deviation of 68 d. All values shown in Table 1 have been used in this calculation, giving an underestimate of the mean since two drifters were recovered while still on the Bank.

Let us consider now the exchange between the shelf and offshore waters. There were 18 drifters launched in the Labrador Current, one deployed west of the Current in an area north of the Grand Banks, and one launched on the Banks themselves, for a total of 20 drifters. Of the 18 buoys deployed in the Current, three of them (2605 in 1979, 2630 in 1980 and 2611 in 1983) clearly moved from the Current to the Banks (see Fig. 2 for a sample track and Table 1 for the number of days each buoy remained on the Banks). In fact, drifter 2611 (see Table 1) may have undergone two exchanges but the first was quite brief (5 d) and we shall only count the second event. Of the remainder, two drifters (2601 and 2604 in 1979) simultaneously showed very little movement over a 10–12 d period while near the 200-m isobath and separated by 140 km. One buoy (2636 in 1980) was reported to be launched west of the Labrador Current on the northern slope of the Grand Banks (U.S. Coast Guard, 1981). It described a circle of about 30-km diameter for 10 d before moving into the Labrador Current. For these last three drifters, we consider there is less certainty that exchange took place. Twelve drifters deployed in the Labrador Current clearly did not undergo exchange along the northern or eastern edge of the Grand Banks. The two buoys (2633 in 1980 and 2596 in 1981) that were launched well to the west of the Labrador Current spent 33 and 25 d, respectively, on the Banks within a 50-km wide strip inshore of the 200-m isobath before they were caught up in the Current. This is comparable to the travel time of the Labrador Current from the northern slope to the Tail of the Grand Banks, which we estimate as ~31 d ($=800\,\mathrm{km}/0.3\,\mathrm{m\,s^{-1}}$). Thus, we include these as drifters that have undergone exchange. In summary, of the 20 buoys that could have undergone exchange between the shelf and the Current, 5 were clearly exchanged and 3 may have been. This gives an estimate of the probability of exchange ranging from 1 in 4 to 2 in 5. We shall take 1 in 3 as a first guess and examine the sensitivity of the model, which we shall now describe, to this factor later.

b *Conceptual Model*

Consider the conceptual model sketched in Fig. 5. Icebergs are being fed into Avalon Channel and the Labrador Current, which has a width w and velocity v. Petrie and Anderson (1983) indicate that, north of the Grand Banks, the Labrador Current splits into two branches with about 10% of the transport flowing through the Channel and 90% staying offshore. The offshore branch is, of course, a much deeper flow. For the upper 100 m, we calculate 30% of the transport flows through Avalon Channel

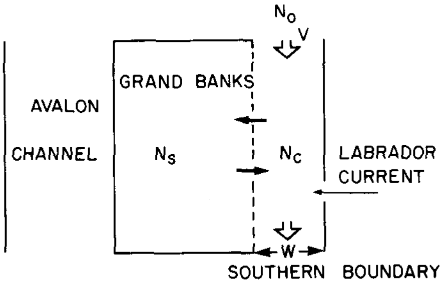

Fig. 5 Box model of iceberg concentrations for the Grand Banks region.

and 70% offshore. These estimates are based on an array of current meters deployed in Avalon Channel from June to October, 1980 by the Bedford Institute, and the geostrophic computations of Smith et al. (1937) and Husby (1969). Given a number of icebergs carried to the area by the Labrador Current, a rough first estimate would have 30% going into Avalon Channel. The remaining 70% would stay in the Current.

The bergs are advected southwards by the Labrador Current but during their passage may be carried onto and off the Grand Banks. Note that for this model there is no exchange between the Grand Banks and Avalon Channel. We define the following variables:

N_0 the concentration of icebergs north of the area
N_c the concentration in the Labrador Current
N_s the concentration on the Grand Banks
A_c the area of the Labrador Current box
A_s the area of the Grand Banks box
w the width of the Labrador Current
v the speed of the Labrador Current; and
α the exchange rate between the boxes (in $m^2 s^{-1}$).

Two equations describe the rate of change of iceberg concentration:

$$dN_c/dt = (wv/A_c)N_0 - (\alpha/A_c)N_c + (\alpha/A_c)N_s - (wv/A_c)N_c \quad (1)$$

$$dN_s/dt = (\alpha/A_s)N_c - (\alpha/A_s)N_s \quad (2)$$

where in (1) the first term on the RHS represents the input from the north, the second (third) represents the loss (gain) to (from) the shelf and the fourth represents the advection out of the southern boundary.

Let $K_1 = (wv/A_c)N_0$ and $K_2 = (wv/A_c)$ and substitute (2) into (1) to get:

$$d^2N_s/dt^2 + \gamma\, dN_s/dt + \beta N_s - \delta = 0 \quad (3)$$

where

$$\gamma = (\alpha/A_s) + (\alpha/A_c) + K_2 \quad (4)$$

$$\beta = \alpha K_2/A_s \quad (5)$$

$$\delta = \alpha K_1/S_s \quad (6)$$

The general solution of (3) is given by

$$N_s = a\,e^{m_1 t} + b\,e^{m_2 t} + c \quad (7)$$

where,

$$c = \delta/\beta \quad (8)$$

and

$$m_{1,2} = [-\gamma \pm (\gamma^2 - 4\beta)^{1/2}]/2 \quad (9)$$

The solution for N_c is given by

$$N_c = a[1 + (m_1 A_s/\alpha)]e^{m_1 t} + b[1 + (m_2 A_s/\alpha)]e^{m_2 t} + c \quad (10)$$

c *Solutions for Constant Iceberg Flux*

Let us now use these solutions and estimates of the various terms to determine the iceberg distribution. We take the width w of the Labrador Current as 50×10^3 m, the velocity v as 0.3 m s^{-1} (Section 3a), and the area A_c as 4×10^{10} m^2 (the length of the Current along the edge of the Grand Banks is taken as 800×10^3 m; this gives an advection time of 2.7×10^6 s). The drifter tracks indicate that about 1 in 3 drifters undergo exchange (we shall examine the sensitivity of iceberg distribution to this estimate later); thus, we get an exchange rate α of 5×10^3 m^2 s^{-1} $(=(1/3)\,(A_c/2.7 \times 10^6))$. Stated explicitly, we assume that in order to have one third of the drifters exchange during the advection time of the Current, we require one third of the area of the Current to be exchanged. The entire area of the Banks under consideration is 8×10^{10} m^2 but probably only half of the Banks has icebergs with any consistency; therefore we take $A_s = A_c = 4 \times 10^{10}$ m^2. This will have two effects. Firstly, it accounts, in a crude way, for the observed higher density of bergs on the outer portion of the Grand Banks. Secondly, Eqs (1) and (2) can be written in simpler form depending only on the exchange probability and the input concentration N_0 if we non-dimensionalize by letting $t = \tau t'$ where $\tau = L/v$ and L is the length of the Labrador Current. However, at this point we would prefer to retain the more general equations and examine the effect of unequal areas later. The average number of bergs that pass south of 48°N, based on data from 1946–78 (U.S. Coast Guard, 1979), was 265, with 33 for March, 90 for April, 89 for May, and 53 for June. For simplicity, we shall consider this first as a constant flux of icebergs into the Labrador Current. We have

$$N_0 = 265/w\,v\,T = 1.7 \times 10^{-9} \text{ bergs m}^{-2}$$

where $T = 4$ months. Using Eqs (4)–(6), (8) and (9) we find

$$c = 1.7 \times 10^{-9} \text{ m}^{-2}$$

$$m_1 = -8.7 \times 10^{-8} \text{ s}^{-1}$$

$$m_2 = -5.4 \times 10^{-7} \text{ s}^{-1}.$$

Applying the boundary conditions $N_c = N_s = 0$ at $t = 0$, we calculate,

$$a = -2.0 \times 10^{-9} \text{ m}^{-2}$$

and

$$b = 3.3 \times 10^{-9}\ \mathrm{m}^{-2}.$$

The solutions, (7) and (10), are shown in Fig. 6 where we have plotted the number of bergs on the shelf, in the Labrador Current, and the *total* ($= \int_0^t w\, v\, N_c\, dt$) advected out of the system as a function of time. Icebergs enter the system for days 0–120 which correspond to 1 March–30 June at the rate of about 11 bergs every 5 d. The source is cut off at day 120. We show, as well, plots of the solutions, based on (1) and (2) with $N_0 = 0$ and appropriate matching boundary conditions at day 120, for days 120–150. This brings the corresponding real time to the end of July. Figure 7 shows the percentage ratio of bergs on the shelf to the total number in the system as a function of time. The average for the first 120 d is 23.5%. For the first 150 d, the average is 29%. Thus, we expect that, starting with a given number of bergs, over the iceberg season 30% would be in Avalon Channel and 70% carried into the Labrador Current. The 70% would be distributed such that 20% (70% × 0.29) would be on the Grand Banks and 50% in the Current. These figures can be compared with the observed percentages.

To determine the actual distribution of icebergs, we examined 69 IIP aerial reconnaissance reports for the period 1970–1982. Our statistics based on these reports give the mean (standard error of the mean) number of icebergs for the areas as follows: 7.9 (2) for Avalon Channel, 12.6 (3) for the Grand Banks and 28 (5) for the slope region. This yields percentages of 16, 26 and 58 to compare with the estimates of 30, 20 and 50. This agreement is certainly acceptable; in fact, it is better than we would have expected given the additional effect (Garrett et al., 1985) that wind has on icebergs compared to water, the uncertainties in our transport estimates and our implicit assumption that all icebergs on the Grand Bank proper come from the offshore branch with none coming from Avalon Channel. We have also assumed that each IIP survey gives a reliable estimate of the iceberg population and covers a representative area. We did select surveys that had extensive flight paths but we do not know how good the visibility was. We do not have a good estimate of the accuracy of berg counts.

d *Solutions for a Time-Varying Iceberg Flux*

We would now like to consider the changes in the results of the model using a more realistic time-varying berg input. Solutions for a sinusoidal source function which gives 39, 94, 94 and 39 icebergs for March, April, May and June, respectively, are shown in Figs 8 and 9. For the time-dependent case, the mean percentage of bergs remaining on the shelf for more than 150 d is 28%, hardly any different than for the constant input. In Fig. 9, we have plotted the percentage of icebergs on the Grand Banks from aircraft reconnaissance flights in 1972, a year when there were 1584 icebergs reported south of 48°N, and the average percentage for the period 1970–1982. The time-dependent behaviour of the population in 1972 is not quite that predicted by the model though the overall percentages (28% for the model, 23% for the data) are comparable. The agreement for the 1970–1982 average is much better especially for days 50–120.

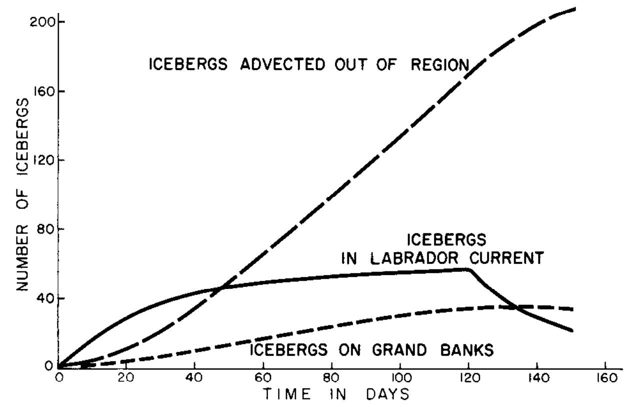

Fig. 6 Plots of the number of bergs on the shelf and in the Labrador Current, and the total number that have been advected out the southern boundary as a function of time. Day 0 corresponds to 1 March. The flux of bergs into the region stops on day 120.

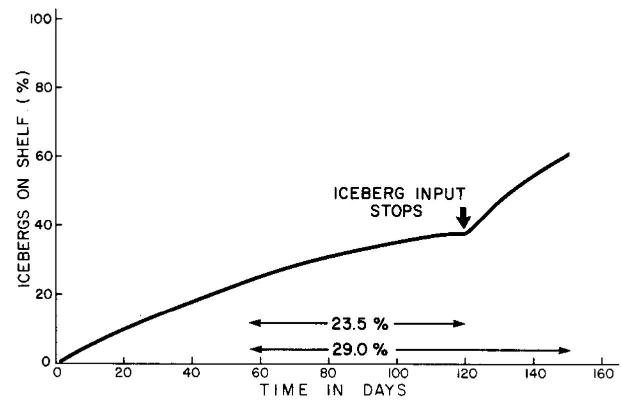

Fig. 7 Plot of the percentage of bergs on the shelf ($= (N_s A_s \times 100)/(N_s A_s + N_c A_c)$) as a function of time.

e *Model Sensitivity*

Finally, for the exchange model, we show the sensitivity of the percentage of bergs on the shelf to the exchange rate α in Fig. 10. Reducing α by a factor of 10 from our first estimate of 5×10^3 m^2 s^{-1} reduces the percentage of bergs on the shelf from about 29 to 7% averaged over 150 d. Increasing α by a factor of 2 increases the percentage to 35%. We think that neglecting processes such as melting, wind, advection and exchange with Avalon Channel and the North Atlantic Current could be processes that are as important to consider as variations in the exchange rate. In fact, allowing exchange between Avalon Channel and the Grand Banks should bring model results more in line with observations.

In Section 4c we noted that the solutions have some dependence on the areas of the Labrador Current and the Grand Banks, and we also considered the case where the two areas were equal. In 1972 and 1973, icebergs were plentiful (1584 and 850 bergs, respectively, south of 48°N) and covered nearly the entire Grand Bank. We would

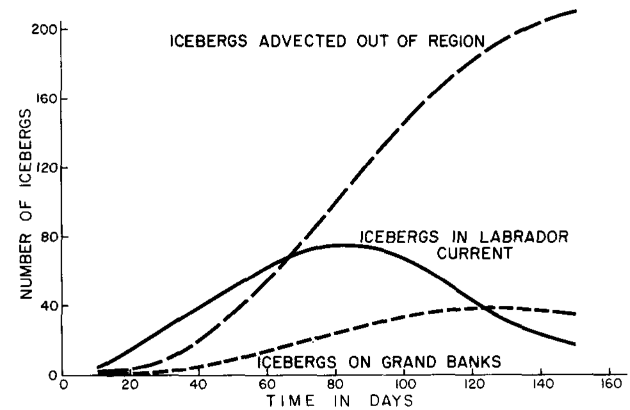

Fig. 8 Same as Fig. 6, except for a sinusoidal input of icebergs that is zero at days 0 and 120 and a maximum on day 60.

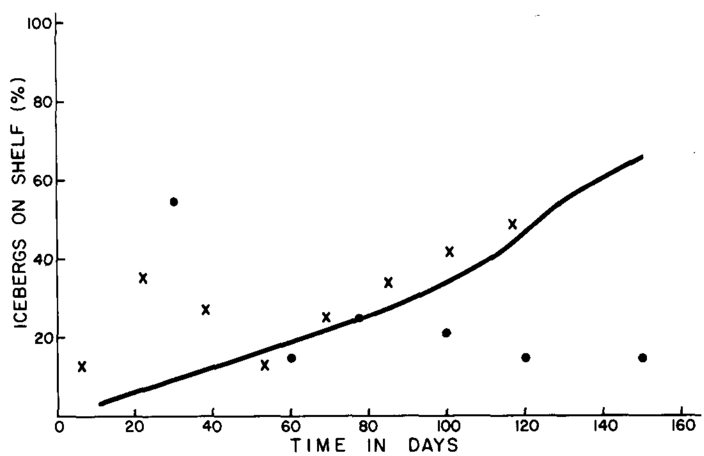

Fig. 9 Same as Fig. 7, except for a sinusoidal input. The circles show the percentage of bergs on the shelf for the year 1972. The percentage averaged over the years 1970–1982 is designated by an "x."

like to consider the change in the solutions by taking the area of the Grand Bank affected by icebergs as 8×10^{10} m^2, twice that previously considered. The changes are not large and show an increase in the percentage of bergs on the Grand Bank. For the constant (sinusoidal) flux case with $\alpha = 5 \times 10^3$ m^2 s^{-1}, the average percentage over 150 d with $A_s = 8 \times 10^{10}$ m^2 was 32.8% (31.4%) compared with 29.0% (28.0%) for $A_s = 4 \times 10^{10}$ m^2. Differences of this magnitude are not significant.

Some drifters became entrained in the North Atlantic Current (see Fig. 2) before reaching the Tail of the Bank. The average distance for all buoys in the Labrador Current was 650 km. For $\alpha = 5 \times 10^3$ m^2 s^{-1} and $A_s = 4 \times 10^{10}$ m^2, the percentage of bergs on the Grand Banks over 150 d for a constant (sinusoidal) flux was 33.9% (32.8%) for a 650-km Labrador Current versus 29% (28%) for an 800-km Current. Again these differences are not significant.

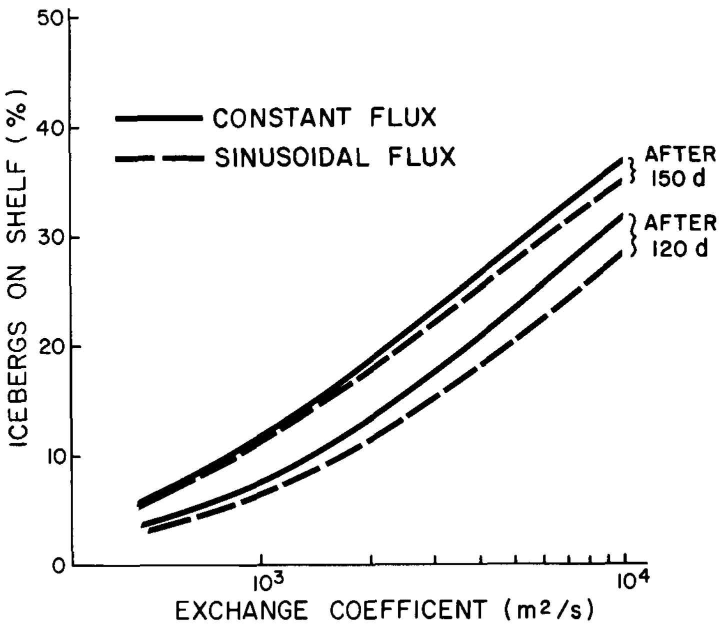

Fig. 10 Plot of the sensitivity of the percentage of bergs on the shelf to variations in the exchange coefficient, α. The average percentage of icebergs on the shelf is shown after 120 and 150 d for both the constant and sinusoidally varying fluxes of icebergs.

f *Advection Model of Iceberg Distribution*

Before leaving the iceberg distribution problem we would like to consider an alternative hypothesis. Petrie and Anderson (1983) pointed out that over the broad expanse of the Grand Banks, the currents are relatively weak and at 47°N, 49°W Petrie (1982) finds a nearly barotropic flow of 0.02 m s^{-1} to the south based on one year of current data. We would like to consider the conceptual model shown in Fig. 11, which displays a 300-km northern shoulder of the Grand Banks and an on-bank flow of 0.02 m $^{-1}$. We show in Figs 12 and 13 the diagrams for this model equivalent to Figs. 6 and 7 for the exchange model. Two cases are shown in Fig. 13, one with an on-bank flow of 0.02 m s^{-1} and the other with a flow of 0.01 m s^{-1}. These indicate that even weak on-bank advection could account for the iceberg distribution. At this point we do not have sufficient data to choose between the two models or a combination of them that could explain the observations.

g *Effect of Winds*

Garrett et al. (1985) determined by statistical methods the direct effect of wind on icebergs. Icebergs were found to drift downwind at 1.8 ± 0.7% of the wind speed. Thompson and Hazen (1983), using 26 years of data, give the mean wind over the Grand Banks for March–May as about 2 m s^{-1} towards the east. Combining these two results, we calculate that from Flemish Pass to the Tail of the Bank, a distance of about 500 km, the mean wind would tend to move the icebergs offshore a distance of

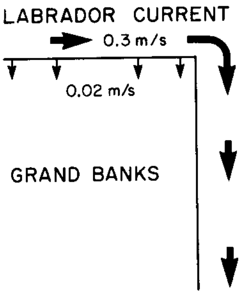

Fig. 11 Box model of iceberg concentrations for the Grand Banks region with advection and no exchange.

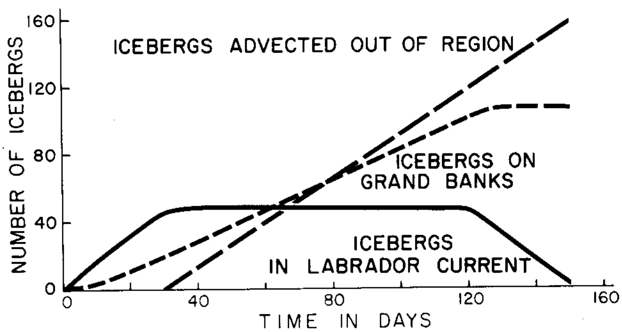

Fig. 12 Same as Fig. 6, except for on-bank advection of bergs at the rate of 0.02 m s^{-1} and for a constant flux of bergs.

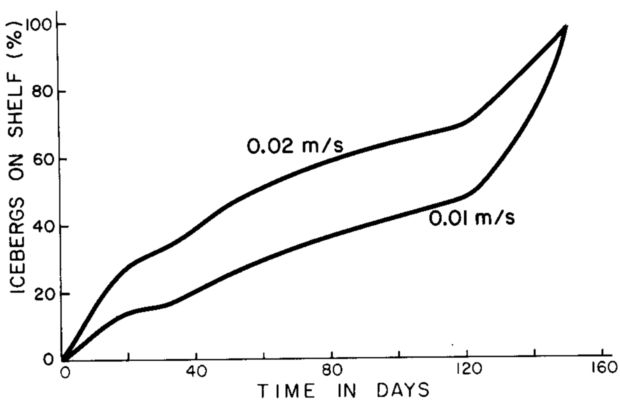

Fig. 13 Same as Fig. 7, except for the advection model. Two cases are shown, for on-bank flows of 0.02 and 0.01 m s^{-1}.

$$x = 2 \text{ m s}^{-1} \times 0.018 \times (500 \times 10^3 \text{ m}/0.3 \text{ m s}^{-1})$$
$$= 60 \text{ km}.$$

Thus, the effect of the mean wind is to keep icebergs off the Banks. Other mechanisms that would tend to put bergs onto the Banks would have to overcome this effect.

TABLE 3. Mean and perturbation salinities ($\bar{S}$, S') and phase of salinity minimum (θ) for the input current and the Grand Banks

Location	$\bar{S}$	S'	θ* (rad.)
Input current	33.32	0.256	3.5
Grand Banks	32.75	0.154	4.4

*The phase corresponds to the time of year when the salinity minimum occurs. For example, a phase of 3.5 corresponds to a minimum at $(3.5/2\pi) \times 12 = 6.6$ months or mid-July.

h *Salinity Budget*

We would like to return to the exchange model now and consider a box model of salinity S_c in the Labrador Current similar to that depicted in Fig. 5. However, in this case, we shall consider the salinity S_s in the Grand Banks box as a boundary condition that has a mean $\bar{S}_s$ and a time varying part S'_s. Similarly, the input flow to the Labrador Current has a mean $\bar{S}_0$ and a time varying part S'_0.

The equation describing the variation of the salinity in the Labrador Current is given by

$$dS_c/dt + k_1 S_c - k_2(\bar{S}_0 + S'_0) - k_3(\bar{S}_s + S'_s) = 0 \qquad (11)$$

where

$$k_1 = (V_{EX} + vwH)/V_c$$

$$k_2 = vwH/V_c$$

$$k_3 = V_{EX}/V_c$$

and V_{EX} is the volume exchange (in $m^3\ s^{-1}$) between the shelf and the Labrador Current; v and w are the velocity and width of the Current; H is the depth considered in the model; and V_c is the volume of the Labrador Current in the model area.

We take the length of the Current as 800 km, the width as 50 km and the depth as 100 m. Husby (1969) gives the transport of the upper 100 m of the Current as $0.93 \times 10^6\ m^3\ s^{-1}$ with a standard deviation of $0.46 \times 10^6\ m^3\ s^{-1}$. Thus, a representative velocity for the upper 100 m is $0.2\ m\ s^{-1}$. As before we expect about one third of the Labrador Current water to be exchanged in a time $T = 800 \times 10^3/0.2 = 4 \times 10^6$ s. Therefore $V_{EX} = V_c/3T = 3.3 \times 10^5\ m^3\ s^{-1}$. This assumes that the cross-isobath exchange is uniform with depth. We suspect that the exchange may be more intense at the surface where the buoys are located and that this value may be high. The general solution of (11) is given by

$$S_c = ae^{mt} + b + c \sin \omega t + d \cos \omega t \qquad (12)$$

since we take the time varying fields S'_0 and S'_s to have the form

$$-S \cos(\omega t - \theta) \qquad (13)$$

where ω corresponds to a period of one year; S, the amplitude of the time varying part; and θ, the phase.

TABLE 4. Results of the salinity box model for the Labrador Current. Variables are the same as in Table 3.

Source	$\bar{S}$	S'	θ (rad.)
Data	33.22	0.22	3.9
Model	33.18	0.19	4.1

The values (K. Drinkwater, Bedford Institute of Oceanography, pers. comm) of the inputs are shown in Table 3. Substituting (12) into (11), we can find the value of the unknown coefficients. The results are shown in Table 4. We have a difference of 0.04 in salinity for a range of 0.57 with the Labrador Current being slightly too fresh. This indicates that we have too much exchange. The time-dependent salinity shows reasonable agreement in amplitude and phase. This comparison gives us some added confidence in our estimates of exchange between the Banks and the Labrador Current.

i *Mechanisms*

These box models do not give us any idea concerning which processes may be responsible for the exchange. We shall explore that question a little further now. Eddies have been observed in the Labrador Current by LeBlond (1982) off Labrador. The possibility of barotropic or baroclinic instability and subsequent eddy formation has been discussed by Mountain (1980) for the Current on the eastern edge of the Grand Banks. Moreover, four series of satellite infrared photos from 1977, 1982 and 1983 (2 series) have been brought to our attention (J. Loder, Bedford Institute of Oceanography, pers. comm). They show 2, 6, 0 and 4 eddy-like features at the edge of the Grand Banks with diameters of 20–40 km.

Consider an eddy with a diameter D of 30 km and a depth of 100 m. To achieve a volume exchange of 3.3×10^5 m^3 s^{-1} requires one eddy to cross from the Current to the shelf every 2.5 d (= eddy volume/exchange). To us this seems excessive indeed, and we suspect that we are overestimating the exchange. For example, the front between the Labrador Current and the shelf waters, if it were not renewed, would be eliminated on a time-scale of 33 d (=800 km × 2.5 d/2D). However, the entire upper 100 m of the Labrador Current is replaced through advection in 46 d (=800 km/0.2 m s^{-1}). Thus, relatively large exchanges caused by eddies cannot be ruled out.

We can make another independent estimate of eddy transport at the front between the Current and shelf water using the methods of Garrett and Loder (1981). The transport per unit length of shelf due to baroclinic eddies $T_{\text{b.e.}}$ is given as

$$T_{\text{b.e.}} = \xi(g'H)^{1/2}H \tag{14}$$

where $\xi = 0.0055$, a constant; g' is the reduced gravity; and H is taken as 100 m. We calculated g' on a monthly basis for the data compiled by Keeley (1981). The average $T_{\text{b.e.}}$ was 0.55 m^2 s^{-1}, a factor of 15 greater than that calculated by Garrett and Loder (1981). An 800-km outer shelf length gives a transport of 4.4×10^5 m^3 s^{-1}, the same order as we found from drifter exchange. Using a variable H based on the pycnocline depth reduces the value to 1.9×10^5 m^3 s^{-1}.

We conclude from these rough calculations that baroclinic eddies are an important process of exchange between the Labrador Current and the shelf. We intend to investigate the stability of the Current with modelling and analyses of some current-meter observations taken in the flow.

5 Concluding remarks

A few concluding remarks are warranted at this point. Our maps of mean and fluctuating currents, although not ideal from the point of view of long, fixed-location time series, have been useful to derive and begin to fill in some of the gaps in our knowledge of the circulation on the Grand Banks. They indicate that the circulation on the Banks may be more irregular than that depicted by Smith et al. (1937). The relationship of winds and currents must be explored more thoroughly and perhaps with better and more data than we have at present. The box models that we have examined indicate that eddy exchange plays an important role in sorting out iceberg populations and salinity budgets. However, other mechanisms deserve investigation. For iceberg distributions, some examples are wind effects, melting, iceberg grounding (the drafts may exclude some bergs from the Banks), and exchange between the Grand Banks and Avalon Channel. We have shown that a weak on-bank mean flow could account for the iceberg distribution just as well as the exchange model. For a salinity budget, exchange between the North Atlantic Current and the Labrador Current is potentially important. Our neglect of these exchanges reflects our lack of knowledge of the magnitude of these processes; furthermore we have been developing a first-order model that we want to keep as simple as possible. The available data may not be sufficient or even of the right type to discriminate between the various mechanisms and correctly determine the importance of each.

Acknowledgements

C. Garrett encouraged us to expand our treatment of the box model, which resulted in a short note becoming a reasonably long paper. J. Loder's concern about the exchange probability and rate resulted in several useful discussions. G. Symonds thoroughly checked the model formulation. These three also provided other helpful comments for which we are grateful. The authors thank J. Benoit for raising the issue of iceberg draft, and A. Hay for comments that helped clarify sections of the paper. We would also like to thank the U.S. Coast Guard International Ice Patrol for their drifting buoy data, and Lieutenant Commander Alan Summy for his efforts. Finally, thanks are due to K. Drinkwater who provided the salinity data used in Section 4. Financial support for this work was provided by the Office of Energy Research and Development of Energy, Mines and Resources Canada.

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