Density Current Flow into Fortune Bay, Newfoundland*

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23 January 1986 and 12 December 1986

ABSTRACT

Current meter and CTD data are presented, describing a dense bottom current which transports Labrador Current Water into Fortune Bay, Newfoundland. The effects of rotation and friction are discussed and the three-dimensional nature of the inflow is highlighted. Geostrophy alone is unable to account for the cross-channel momentum balance. The inflow may represent an important sink for the inshore branch of the Labrador Current.

1. Introduction

Dense bottom currents are an important phenomenon in aqueous environments. Experiments leading to improved dynamical understanding, particularly of the role of entrainment, were first made in the laboratory (Ellison and Turner, 1959). Studies of dense bottom currents in the ocean have been directed toward the ventilation of deep ocean basins (Smith, 1975), the removal of dense water from continental shelves (Carmack and Foster, 1975), deep water exchange in fjords (Gade and Edwards, 1980), and marine waste disposal (Hay, 1986). Dense bottom currents have also been studied in lakes and reservoirs (Hamblin and Carmack, 1978; Fischer et al., 1979, pp. 209–219).

In this paper we describe a density current which flows into Fortune Bay, Newfoundland. The Fortune Bay inflow exhibits three-dimensional characteristics partly associated with rotation, and appears to occur annually (de Young, 1984). It therefore provides an accessible coastal analogue for larger-scale oceanic density currents, such as the overflow in Denmark Strait (Smith, 1975), and differs from most fjord studies, in which two-dimensional inflows have usually been considered (e.g., Edwards and Edelsten, 1977; Geyer and Cannon, 1982). The results are also of interest because of their relevance to the fate of the inshore branch of the Labrador Current, from which the density current described here is derived, and about which little is known (see Petrie and Anderson, 1983).

2. Area description and methods

Fortune Bay is bounded by Hermitage Channel on the west and the Burin Peninsula on the east (Figs. 1 and 2). The Saint-Pierre Channel is a westward extension of the Avalon Channel, which guides the inshore branch of the Labrador Current into the region. Fortune Bay itself is 128 km long and 22 km wide, with a maximum depth of 420 m in the main basin. It is much wider than most fjords, and three-dimensional effects associated with rotation can be expected. There are three entrances to the Bay, each with a sill. The entrance of interest here, between the island of Saint-Pierre and the Burin Peninsula, has a sill at 125 m depth.

The observations presented in this paper consist of current and CTD data collected in 1982. The station positions are shown in Fig. 2. Further discussion of these and other results can be found in de Young (1984).

3. Observations

The temperature and density along the axis of Fortune Bay in June 1982 are shown in Fig. 3. This transect line runs from outside the Saint-Pierre sill to the head of Fortune Bay in Belle Bay (Fig. 2). Cold (<0°C) and relatively dense (>26.0σ_t) Labrador Current Water can be seen flowing over the Saint-Pierre sill into the Bay, first as a dense bottom current and then as a neutrally buoyant interflow. The warm water at the bottom near the head of the fjord is residual Modified Slope Water (McLellan, 1957) from Hermitage Channel.

Density and temperature data from a transect across the channel (*T* in Fig. 2) are presented in Fig. 4. On June 5 (Figs. 5a and 5b) there was a weak inflow taking place, inferred from the tilt of the isopycnals upward

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* NICOS Contribution Number 139.

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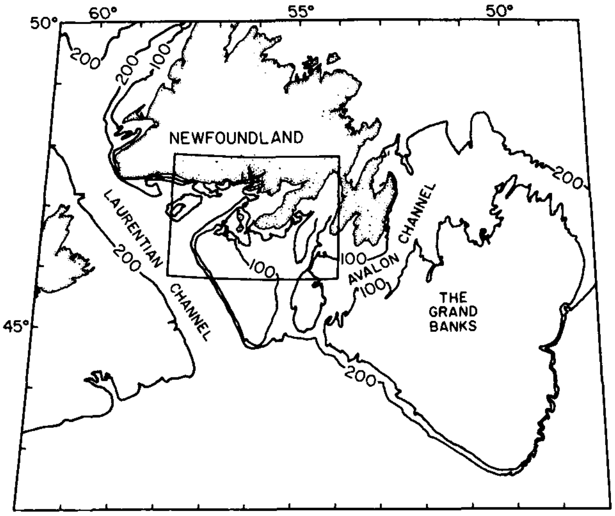

FIG. 1. Study area.

towards the right. The same transect occupied four days later (Figs. 5c and 5d) on June 9 showed a much stronger inflow with an increase in density of 0.1kg m^{-3} in the near-bottom layer. Calculation of the flow speed using the mean geostrophic equation, based on the slope of the isopycnals near the bottom, gives a value of about 40 cm s^{-1}. As will be seen, this is in fair agreement with the observed speeds, and suggests the inflow was in approximate geostrophic balance.

The cross-channel variations in near-bottom density in Fig. 4d indicate that the cross-channel momentum balance is not purely geostrophic. The core of the cold dense water is located upslope away from the channel axis. These features illustrate the three-dimensional character of the inflow.

A CTD cast through the inflow, taken in the middle of the channel on 9 June 1982, is shown in Fig. 5. The inflow appears as a 20 m thick near-bottom layer of increasing density underlying vertically homogeneous fluid. An abrupt transition between the two zones occurs at just over 170 m depth. The density profile through the inflow is approximately linear, rather than being vertically uniform as is commonly assumed and often observed (e.g., Smith, 1975). Some of the density inversions below 175 m depth are due to salinity spiking, arising from the time-constant mismatch between the conductivity and temperature sensors. The density inversions are not always associated with sharp temperature gradients, however. Those at 175 and 184 m depth, for example, may be real.

One current meter mooring was deployed at station M (Fig. 2) for a period of 8 days. Three Aanderaa RCM4 current meters were used, placed at 5, 15 and 65 m above the bottom. Stick plots of the data, together with the predicted tidal height at Saint-Pierre (Canadian Hydrographic Service, 1982) are presented in Fig. 6. The plot is oriented with north at the top. This orientation corresponds approximately to that of the channel axis.

For the first day of the record, 5 June and early 6 June, there is no mean flow into the fjord. Towards the end of 6 June the flow pattern changes; at 5 and 15 m the mean flow is directed into the fjord, and this inflow persists for the remainder of the record. The lower meter shows reduced flow speeds, perhaps a result of bottom friction. At the upper current meter, 65 m above the bottom, the flow is more variable since this meter was not always within the density current flow. The mean along-channel speeds at 5 and 15 m above bottom are about 20–25 cm s^{-1}; a factor of two smaller than the geostrophic estimate. Given the 5 km separation between the mooring location and the transect (Fig. 2), this difference could be attributable to along-channel changes in mean flow speed.

The inflow is tidally modulated, as Fig. 6 shows. The inflow is influenced by direct forcing of the dense water over the sill and by interfacial shear stress at the density current interface. The potential presence of an internal tide or an internal seiche complicates the interpretation of the record.

4. Discussion

Factors contributing to the three-dimensional character of the inflow include rotation, channel topography, lateral friction, ambient stratification in the Bay, and time dependent effects, particularly those associated with internal tides and seiches. The importance of rotation can be demonstrated by comparing the channel width with the internal Rossby radius of deformation associated with the inflow. The channel width, taken as the distance separating the 100 m isobaths, is 7 to 12 km (Fig. 2). The internal deformation

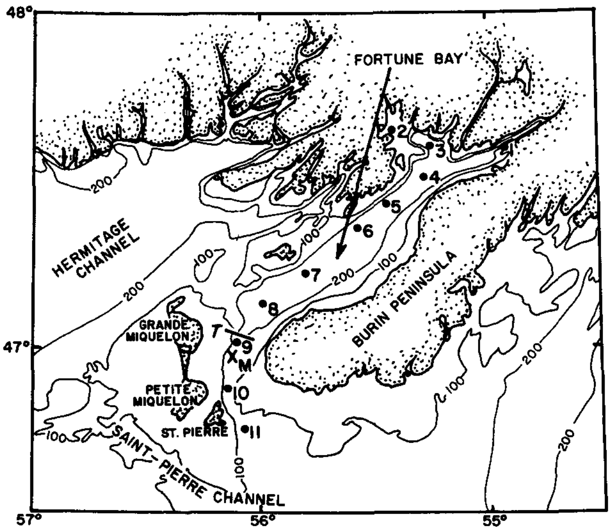

FIG. 2. Detailed study area indicating station and mooring locations.

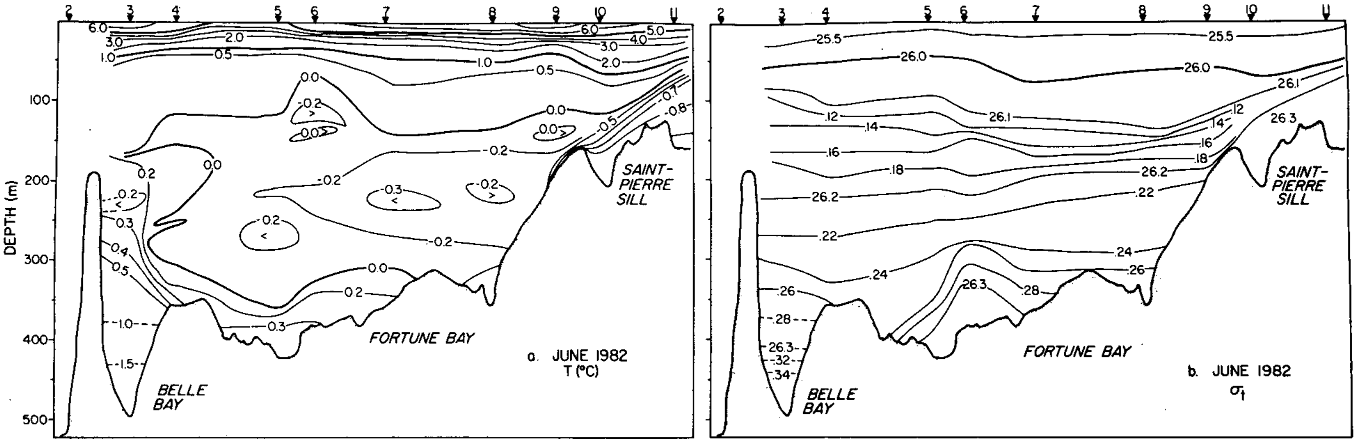

FIG. 3. Temperature and sigma-*t* along the axis of Fortune Bay in June 1982.

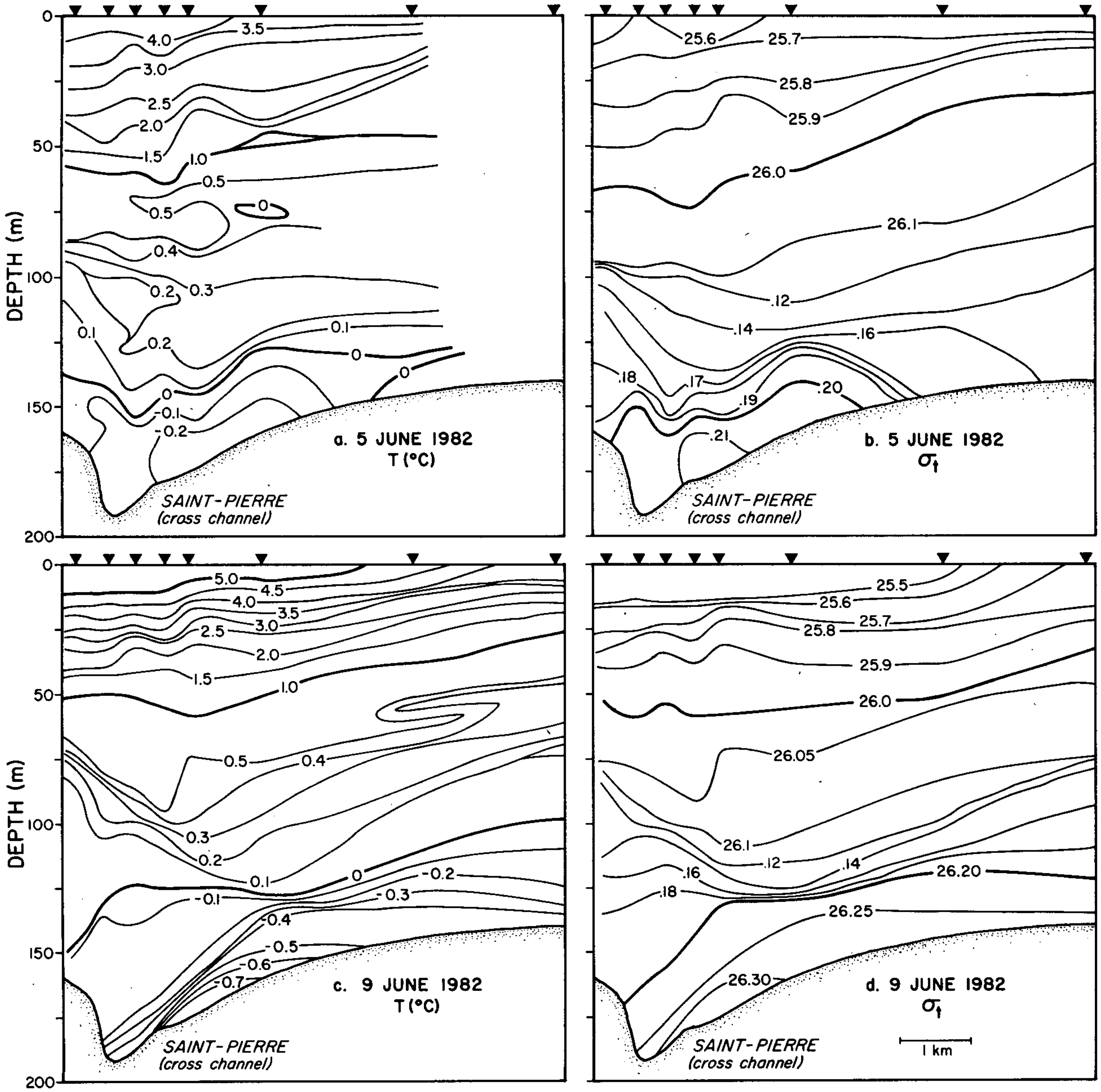

FIG. 4. Temperature and sigma-*t*, plotted along transect T (see Fig. 2), looking into the fjord on 5 and 9 June 1982.

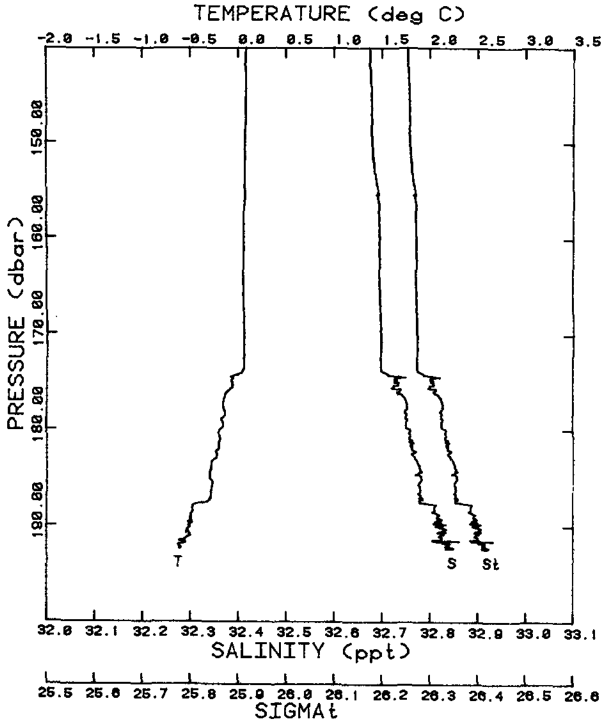

FIG. 5. The bottom section of a CTD cast, in the middle of the channel, at 1612 UTC 9 June 1982. The station is the third from the left in Fig. 4. Note that 1 db = 1 m.

radius is given by $a' = (g'h)^{1/2}/f$. Here $g' = (\Delta\rho/\rho)g$, $\Delta\rho = \rho' - \rho$ is the excess density of the inflow, h is the thickness of the density current, and f is the Coriolis parameter. The CTD data show that $h = 20$ m and $\Delta\rho = 0.2$ kg m^{-3} maximum (Figs. 4d and 5). These values give $a' = 2$ km, which is much less than the channel width, and is comparable to the half-width of the cold-water core (Fig. 4c).

Comparisons can be made between our observations and existing theory. Application of fully three-dimensional calculations, however, is beyond the scope of this paper. We choose instead to use two-dimensional theory as a first approximation. This is equivalent to assuming that three-dimensional effects can be ignored at lowest order.

Steady two-dimensional density currents have been investigated in the laboratory (e.g., Ellison and Turner, 1959; Middleton, 1966). The results of these and other studies have been reviewed by Bo Pedersen (1980). The along-channel momentum balance is between buoyancy and friction, and is given by the usual modified Chezy equation,

$$U = \left(\frac{g'h \sin\beta}{C/2}\right)^{1/2}, \qquad (1)$$

where β is the bottom slope and C is a dimensionless friction coefficient. The bottom slope inside the Saint-Pierre sill is 0.6°. Bo Pedersen estimates that at this slope the friction coefficient spans the range $2 \times 10^{-3} < C/2 < 3 \times 10^{-2}$. Upon substitution into Eq. (1) we find $11 < U < 45$ cm s^{-1}, which encompasses both the geostrophic estimate and the observed mean speeds (Fig. 6).

Entrainment of water into the density current critically affects the mass and momentum balances. Rough estimates of the entrainment rate can be made from the scalar properties of Fortune Bay bottom water and the Labrador Current Water at the Saint-Pierre sill. Previous work indicates that the entrainment rate depends on flow speed and bottom slope. Expressing the entrainment rate in terms of a vertical velocity, this dependence takes the form (Ellison and Turner, 1959; Bo Pedersen, 1980):

$$W_e = KU \sin\beta, \qquad (2)$$

where K is a constant, provided the bulk Richardson number is constant, as implied by Eq. (1). Bo Pedersen suggests that $K = 0.072$. According to Eq. (2) and using this value of K, about 30% of the water reaching the bottom of Fortune Bay is entrained ambient fluid. Using the observed temperatures and salinities of the water at the sill, and in the fjord at mid-depth and the bottom, it is estimated that the actual amount of entrained fluid is 55% (see Table 1). Given the empirical nature of the theory and the uncertainty in the parameters used, this may be considered reasonable agreement.

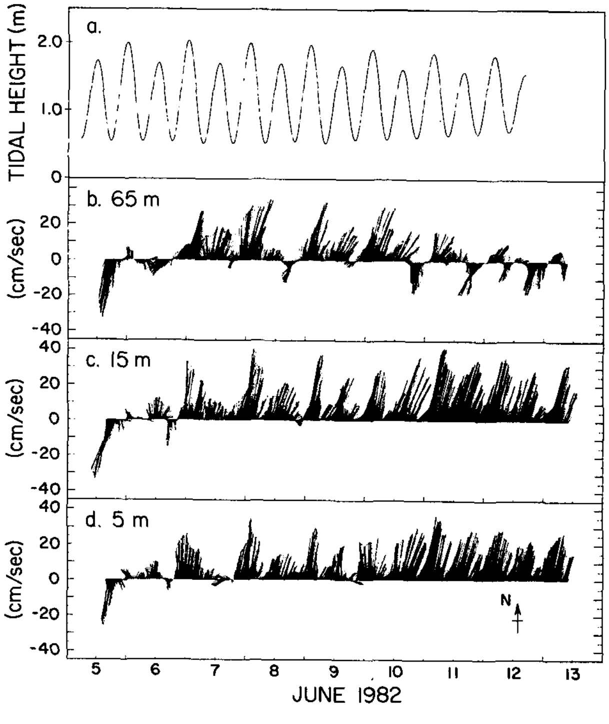

FIG. 6. (a) The predicted tidal height at Saint-Pierre in m. (b), (c) and (d) Stick plots of current at 5, 15 and 65 m above the bottom at station M.

TABLE 1. Temperature and salinity of water in Fortune Bay at middepth (FBM) and at the bottom (FBB), and of Labrador Current Water (LCW) outside the Saint-Pierre sill, in June/July 1982. Salinities are taken from de Young (1984). For either temperature or salinity, FBM = 0.45 LCW + 0.55 FBM.

	Temperature (°C)	Salinity
Mid-depth Water (FBM)	0.0	32.70
Inflow Water (LCW)	−0.9	32.85
Resultant Bottom Water (FBB)	−0.4	32.80

These results can also be used to estimate the volume transport of Labrador Current Water into the fjord. Using a 20 cm s^{-1} mean speed, a flow thickness of 20 m and a channel width of 2 km at the entrance gives a volume transport of roughly 10^4 m^3 s^{-1}. This is 10% of the estimated annual Labrador Current transport through the Saint-Pierre Channel (Petrie and Anderson, 1983). We conclude that Fortune Bay may at times represent a significant sink for the inshore branch of the Labrador Current.

5. Conclusions

A set of observations has been presented which demonstrate the occurrence of a dense bottom current in Fortune Bay. The inflow is derived from the inshore branch of the Labrador Current, and may drain as much as 10% of the water transported by the inshore branch in this region. Comparison of measured mean currents with speeds estimated from the cross-channel isopycnal slopes indicate that the cross-stream momentum balance is approximately geostrophic. The observed mean speeds are also within the range estimated by assuming an along-channel balance between friction and buoyancy. Significant departures from steady two-dimensional density current flow are observed. The cross-stream density gradient indicates the influence of rotation and other three-dimensional effects. The inflow is tidally modulated, although the nature of the tidal control of the density current inflow has not been determined.

The Fortune Bay inflow represents a fjord analog for oceanic density currents. The coastal location and its annual occurrence make it possible to study the dynamics of this phenomenon on a smaller scale.

Acknowledgments. The work of many people at Memorial University went into this project and it is a pleasure to acknowledge their efforts. The officers and crews of the vessels CSS Dawson, CGS Shamook, CGS Marinus and MV Pandora II were indispensable. Funding assistance to A.E.H. came from a Canadian Department of Fisheries and Oceans subvention grant and Natural Sciences and Engineering Research Council operating grant (A-8446).

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