

## ICEBERG MELT-DRIVEN CONVECTION INFERRED FROM FIELD MEASUREMENTS OF TEMPERATURE

by

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### ABSTRACT

An expendable bathythermograph (XBT) survey around an iceberg grounded in 100 m of water shows that iceberg melt-driven convection significantly alters the surrounding water properties in two ways, by a general cooling of the water in the upper 40 m by as much as 3 deg and by the formation of isothermal layers with a 5 m vertical-length scale in the pycnocline. Both of these effects become more pronounced as the distance to the iceberg decreases. The overall cooling of the upper layers supports the upwelling concept of Neshyba (1977) and of Josberger and Martin (in preparation\*), while the formation of a step-like structure supports the cell formation idea of Huppert and Turner (1978) and Huppert and Josberger (1980).

Synoptic surface surveys around the iceberg show the existence of melt plumes containing water of a lower temperature than the adjacent water, and these plumes are detectable at distances of 0.5 km.

Concentrated rhodamine placed at depths of 14 and 18 m adjacent to an ice wall sloping downward at a 30° angle flowed upward along the ice. The dye reached the surface immediately next to the ice in 240 s and 540 s, respectively, to give a characteristic upward velocity of approximately 0.07 m s<sup>-1</sup>. The dye then dispersed outward away from the iceberg until it was no longer visible.

### INTRODUCTION

Recently, the convection generated by an iceberg melting in the ocean has received increased interest in the form of both laboratory and theoretical studies. However, field measurements are few and fail to confirm any of these studies explicitly. In this paper, we present the results of two field studies which show that the convection generated by a melting iceberg upwells water from below the pycnocline and produces a step-like temperature structure in the upper portion of the water column.

Neshyba (1977) suggested that upwelling by iceberg melt-driven convection could supply significant amounts of nutrients to the upper ocean. This idea received further support from the laboratory and theoretical study of Josberger and Martin (in preparation\*). In their

study, they found that for homogeneous salt water at polar temperatures and salinities, a turbulent upward-flowing boundary layer occurred next to a vertical ice wall when the vertical-length scale of the ice exceeded 0.5 m. In contradiction, Huppert and Turner (1978) and Huppert and Josberger (1980) showed that stratification limited the vertical extent of the convection and produced layers through a double-diffusive mechanism where the layer thickness is controlled by the stratification.

Direct current measurements of the melt-driven convection do not exist, due to the difficulty in making such a measurement, so the nature of the convection must be inferred from temperature and salinity measurements made as close as possible to the melting ice walls, and interpreted with the laboratory studies in mind. There are few published reports of studies carried out near icebergs or at the terminus of a tidewater glacier, which presents a similar case. Josberger (1978) reported significant cooling and dilution of the upper portion of the water column within 150 m from an iceberg in the Labrador Sea. This supports the concept of upwelling; however, the large vertical resolution of the data would not detect any layering. Jacobs and others (1979) examined the large-scale effects of glacial ice melting on the surface water of the Ross Sea in a series of hydrographic stations from the Ross Ice Shelf northward, and concluded that lateral spreading of melt-influenced water may effect the distribution of oceanographic properties. Matthews and Quinlan (1975) studied a tidewater glacier in Muir Inlet, south-east Alaska, and concluded that the presence of an ice wall at the head of the fjord enhanced the vertical circulation within the fjord. In another fjord study, Greisman (1979) studied d'Iberville Fjord, Northwest Territories, Canada, and found that melting ice had little influence on circulation. This result was probably due to the extremely cold water, very near its freezing point, in the fjord that yielded little melting and, hence, little convective activity.

(\*Submitted for publication as: "Convection generated by melting vertical ice walls".)

THE EXPERIMENTS

To determine the nature of the convection induced by a melting iceberg, we performed two experiments around icebergs off the north-east coast of Newfoundland, Canada. The icebergs were grounded on the north-west side of Conception Bay, near Bay De Verde peninsula. In the first experiment, we used expendable bathythermographs (XBT) to measure the temperature field in the vicinity of the iceberg. Also, we performed a surface survey of the water temperature around the iceberg by holding an unlaunched XBT 0.15 m below the surface as the ship steamed around the iceberg. Figure 1 shows the location of the XBT casts relative to the iceberg, predicted tidal heights for nearby Harbor Grace for 9 June 1979, and the launch time for each XBT. The iceberg was approximately 7.5 km south-east of Low Point, and it appeared to be grounded in 90 m of water. Figure 2a shows the iceberg, which measured approximately 120 m on the water line and 35 m high; a ram projected underwater from the iceberg out to a distance of 20 m from the large blocky portion of the iceberg. Opposite the ram a narrow pinnacle showed many water-line erosional features. In the slot between the pinnacled and blocky portions, wind waves, caused by a wind of 5-8 m/s from the south-east, produced violent surges of water in the slot. Throughout the course of the experiment, the iceberg emitted cracking sounds, occasionally accompanied by ice cleaving off the portion above water.

The second experiment consisted of placing dye next to the ice at depth and observing the subsequent dispersion. A glide-out vehicle that had a glass bulb filled with concentrated rhodamine-B fastened to its nose was used. Upon impact with the iceberg the glass bulb broke and released the dye. For this experiment, we used a smaller iceberg that was approximately 40 m on

the water line and 10 m high in 45 m of water (Fig. 2b). This smaller size allowed us to work close to the iceberg, thus fulfilling the safety requirement of the glide-out vehicle. By working on the lee side of the iceberg for protection from the wind and waves, we successfully broke two glass bulbs against the downward sloping face of the iceberg at a depth of approximately 15 m. We then watched the subsequent dye dispersion.

DATA MANIPULATIONS

In order to compare the temperature profiles from each cast in the XBT study, we chose cast 5 as representative of the far-field conditions surrounding the iceberg and then subtracted this profile from the remaining profile to determine the perturbations in the temperature field. To facilitate data manipulation, a simple linear interpolation scheme determined the temperature at 0.5 m intervals. We assumed that the water in the region above the depth of the first temperature measurement was isothermal at the uppermost temperature. This assumption may underestimate the surface-cooling effects of the iceberg.

Figure 3a gives the temperature profile from cast 5, and it shows the following features. The thermocline where the temperature falls from near 6.5°C to near -0.5°C extends to a depth of 45 m, and in the depth range of 10 to 30 m there is an indication of a step-like structure. Below 45 m, the temperature remains almost constant. This uniformity shows up in all of the casts although the temperature below 45 m may vary with each cast. Because we were interested only in relative temperature changes we used this uniformity to remove the offsets of each XBT thermistor by adding a constant value to each cast such that the temperature at 60 m equaled the temperature at 60 m for cast 5.

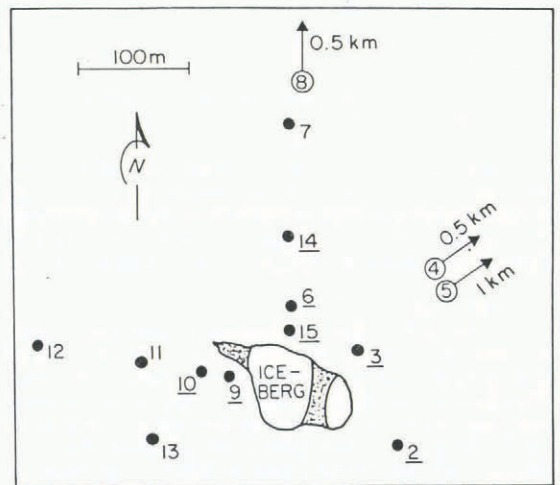
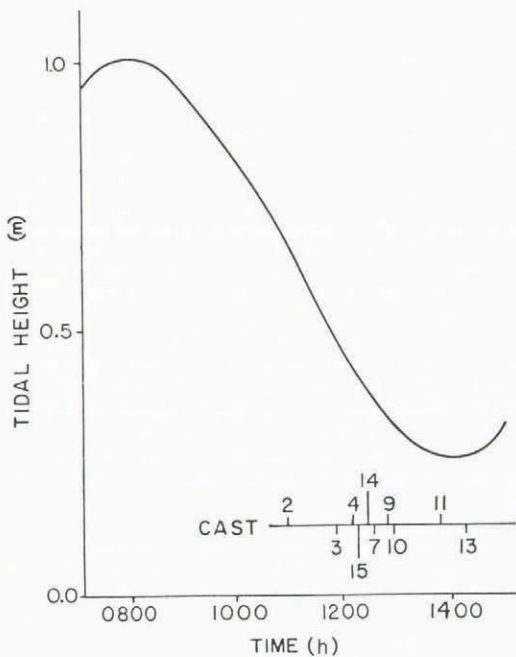


Fig.1. Tidal heights at Harbor Grace during the experimental study and the location of the XBT casts around the iceberg; the stippled portions of the iceberg were partially submerged.

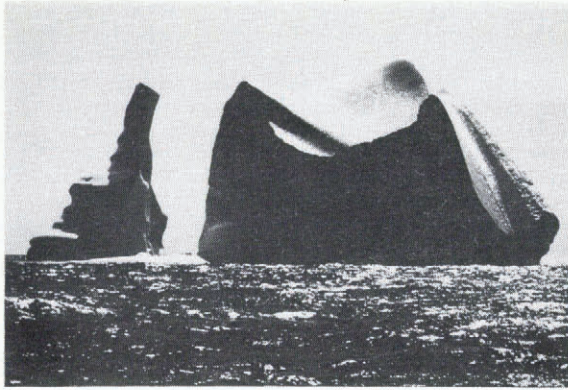


Fig.2a. The iceberg used in the XBT study.



Fig.2b. The iceberg used in the dye study.

RESULTS

Figures 3a, b, and c show the temperature residual as a function of depth for all of the profiles. Figures 3a and b are the casts that comprise sections one and two, respectively shown on Figure 1, while Figure 3c shows the casts that do not fall on either of the two section lines.

In all cases, Figure 3 shows that below 45 m the temperature perturbation is nearly zero, while above 45 m temperature perturbations can be as large as 2°C and always negative, which indicates cooling only. Also as expected, the amount of cooling decreases with increasing distance from the iceberg. Table I gives the depth-integrated temperature perturbation, Q,

for all of the casts integrated to a depth of 60 m. Hence Q represents the total amount of cooling when compared to the far-field cast 5. In general, Q decreases with increasing distance from the iceberg but fluctuates at constant distance from the iceberg, which indicates that the cooling is not horizontally isotropic.

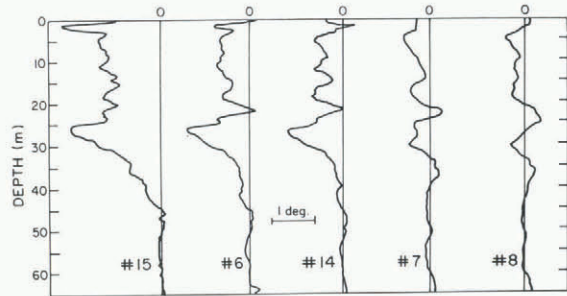


Fig.3b. Temperature differences for casts 15, 6, 14, 7, and 8.

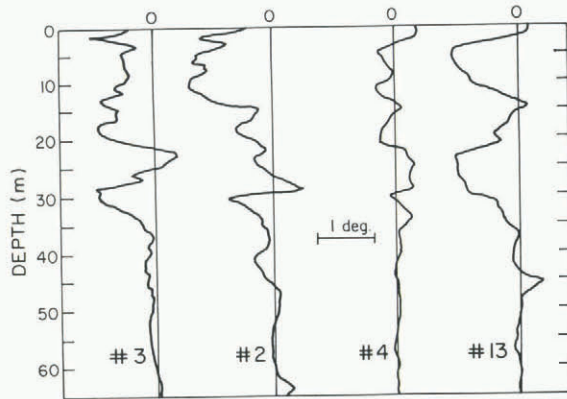


Fig.3c. Temperature differences for casts 3, 2, 4 and 13.

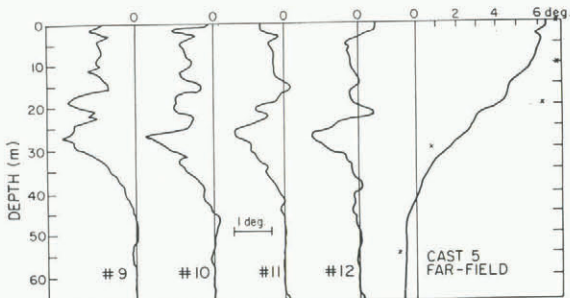


Fig.3a. Temperature differences for casts 9, 10, 11 and 12; and the far-field cast 5; "x", data from I. Borthwick.

TABLE I. THE TEMPERATURE ANOMALY INTEGRATED TO 60 M FOR ALL OF THE CASTS AND THE DISTANCE OF EACH CAST FROM THE ICEBERG

Cast No.	Q (°C/m)	Distance to iceberg (m)
2	-25.5	50
3	-20.2	25
4	- 0.3	500
6	-25.8	50
7	-10.0	200
8	- 2.9	500
9	-42.2	25
10	-27.4	50
11	-18.6	100
12	- 8.8	200
13	-20.4	100
14	-19.0	100
15	-49.8	20

More interesting and informative is the structure of the temperature perturbation in the upper 45 m. Within 25 m from the iceberg, there is a large pool of colder water, with the spikes in the profiles indicating interleaving. Further from the iceberg, the pool of cooled water becomes smaller, as indicated by the decreasing values of  $Q$ , but in some cases the interleaving appears to become more organized and pronounced. A prominent feature in all of the casts is the large cold spike between 25 and 35 m, below which there is no evidence of any cooling. Examination of the density structure in Conception Bay provides insight into the convective processes that yield the observed temperature perturbation distributions. Due to ship problems we were unable to measure the salinity during the XBT study, but Dr I. Borthwick of the Memorial University of Newfoundland was able to supply salinity and temperature data from Conception Bay two days after our experiment. Figure 4 shows these data and the resulting density structure; the temperature data are also plotted with our far-field temperature data in Figure 3a, which show very similar temperature conditions. Therefore we assume that the density structure two days after our experiment is representative of conditions during it. The density structure consists of an isopycnal layer 10 m deep on top of a highly stratified region,  $(1/\rho)\partial\rho/\partial z = 3.3 \times 10^{-5} \text{ m}^{-1}$ , down to approximately 50 m. Below 50 m, the stratification decreases and  $(1/\rho)\partial\rho/\partial z = 5.8 \times 10^{-6} \text{ m}^{-1}$ . In the lower region,  $S \approx 33.5\text{‰}$  which gives a

freezing point of  $-1.83^\circ\text{C}$ , and hence the temperature elevation above the freezing point is approximately 1.2 deg. For no stratification, Josberger (1979) and Josberger and Martin (1980) show that, at these temperature and salinity conditions, an upward flowing boundary layer forms next to the ice for vertical-length scales greater than 0.5 m, and there is no outward horizontal flow away from the ice. Because the temperature difference profiles show no significant cooling events below 45 m, we infer that the flow is upward and unaffected by the ambient stratification. As this flow progresses up past 45 m into the lighter overlying water, a large fraction of the water at the outer portion of the boundary layer reaches its own density level and then flows horizontally outward to form the large spike between 25 m and 35 m. This cold spike is not only due to water being cooled by the melting process but also to the advection of cold water below into the region of warm water above by the upward convective flow.

In the upper region above 25 m, the temperature perturbation profiles show cooling of approximately 1 deg that is highly variable with depth. The higher temperatures, approximately  $6^\circ\text{C}$ , will increase the melt rate which should make temperature perturbations easier to measure and the high stratification should have a large influence on the convective motions. The jaggedness of the profiles indicates interleaving and layering, but these measurements are insufficient to determine if it is double diffusive layering as described by Huppert and Josberger (1980), a simple interleaving process, or both.

These results of Huppert and Josberger predict, for the lower region, a vertical layer scale of 6.4 m and, for the upper region, a layer scale of 3.6 m. Because no layering was observed in the lower layer, where a 6.4 m layer scale is predicted, the layering in the upper region probably results from simple interleaving and not a double diffusive effect; however, the larger gradient in the upper region may be sufficient to produce double diffusive layering as described by these authors. In either case the temperature difference profiles indicate that significant amounts of colder deeper water are upwelled.

Figure 5 shows the results of two surface temperature surveys made by holding an XBT 0.15 m below the surface and steaming around the iceberg. The first survey at 450 m from the iceberg took place at 10 30 h and although incomplete shows two plumes with cooling anomalies of approximately 0.5 deg. The second survey at 50 to 100 m from the iceberg took place at 14 35 h and shows the following features: the most significant cooling occurs in the south-east to south-west quadrant where the temperature falls in places by as much as 1 deg. The greatest cooling occurs in the south-east, where there is an abrupt drop in temperature from the water further to the east. The fluctuating temperature to the west of the iceberg indicates some effect of the iceberg but not as great as the effect on the southern side of the iceberg. The location of the cool water is puzzling because the wind was out of the south-south-west which should carry the surface water to the north-east, but the tidal height reached its minimum at 14 00 h so that the flooding tide

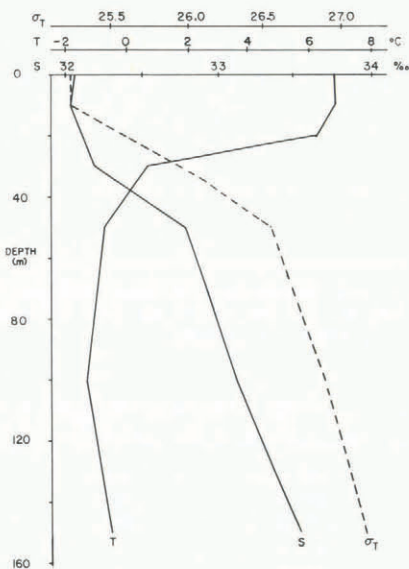


Fig.4 Temperature, salinity, and density in Conception Bay two days after the XBT study, supplied by I. Borthwick.

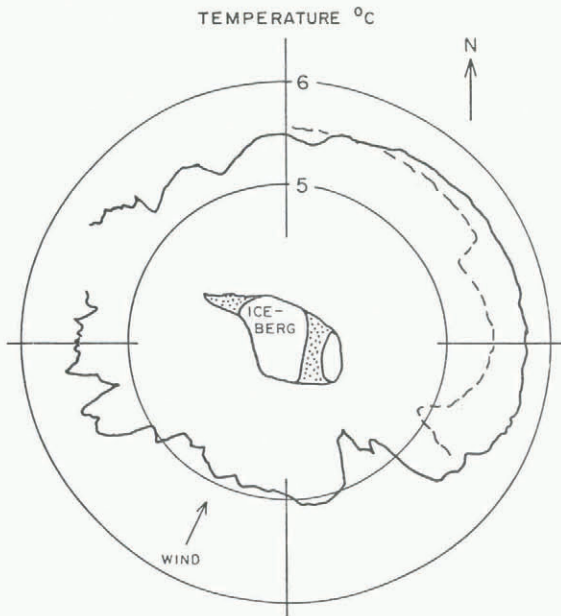


Fig.5. Surface temperature surveys,  
 ---- 10 30 h, 480 m from the iceberg;  
 ——— 14 35 h, 50 to 100 m from the iceberg.

may have been carrying this water to the windward side of the iceberg.

Finally for the 1979 study, we twice deployed rhodamine-B dye on the lee side of a small iceberg grounded in 46 m of water. Despite the large density of the concentrated dye ( $1.133 \text{ gm cm}^{-3}$  at  $16^\circ\text{C}$ ), the dye from the first deployment at 14 m reached the surface in approximately 240 s while in the second deployment, at approximately 18 m, the dye reached the surface in approximately 540 s. In both cases, the dye reached the surface as follows: When the canister had ruptured, the dye dispersed in a cloud of approximately one meter in diameter and subsequently flowed up the sloping ice face with no visible downward motion. On reaching the surface close to the iceberg, the dye moved downward until it was no longer visible. In the second experiment only, a vertically-rising plume was observed directly over the impact site in addition to the dye moving up the slanting ice wall. These observations indicate upward velocities of the order of  $0.05 \text{ m s}^{-1}$ .

#### CONCLUSIONS

The results of this study show that the convection caused by a melting iceberg has two effects on the local water characteristics. The first is to create a pool of colder water surrounding the iceberg; this partially results from upwelling. The second is to produce a step-like temperature structure in regions of large density gradients. The step structure results from interleaving and may only occur for density gradients above a minimum value, in this case  $(1/\rho)\partial\rho/\partial z = 5.8 \times 10^{-6} \text{ m}^{-1}$ . Hence, in the Antarctic, we conclude that significant upwelling will occur near large vertical ice walls because the stratification here is generally

less than that in Conception Bay. However, the colder water temperatures in the Antarctic will produce a less vigorous convection that might be limited by the weaker stratification. Future studies near icebergs in weakly stratified water are needed to resolve this problem completely.

#### ACKNOWLEDGMENTS

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