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CONVECTION AT A MODEL ICE EDGE

The flow pattern near the edge of a melting ice block is modeled by heating a metal edge in a salt-stratified fluid. An unexpectedly strong, horizontal boundary current was found moving out from under the ice. Convective layers along the vertical wall were also observed.

INTRODUCTION

The presence of vast quantities of ice is one of the dominant characteristics of the polar seas. Physical processes affected by the ice include those on the largest climatic scales to those on the smallest microscales. Recently, the effects on the water circulation in the immediate vicinity of melting ice have received attention in the literature.[1-6] Laboratory investigations have been conducted to study the flow along vertical and horizontal ice boundaries in water of various temperatures and of different strengths of salt stratification.

All the studies are concerned with flow along an infinite boundary of either vertical or horizontal orientation; none investigates the flowfield near the ice edge (Fig. 1). Since sharp boundaries occur on ice of many types and sizes (glaciers, icebergs, etc.), the peculiar nature of the flow near the edges will influence both the life cycle of the ice and the nearby ocean current and density structure at certain length and time scales. The source of the water flowing upward along a vertical ice wall must be the interior fluid (i.e., the fluid away from the wall). However, if there is a horizontal bottom (Fig. 1), the source of water can be either under the ice or the interior fluid. Hence a different flowfield could result. Under an infinite horizontal ice surface, there is no asymmetry to cause the fluid to move preferentially to the left or right. However, near the edge of a horizontal ice slab, a large horizontal density gradient between the region under the ice and the open ocean can exist and may cause a strong current. The purpose of the preliminary investigation is to show that unique flow features result near an ice edge. An understanding of the flow at an infinite vertical or horizontal boundary alone is insufficient for understanding the geophysical case.

THE EXPERIMENTS

Previous results[2] have shown that many essential features of flow along a vertical ice wall in a salt-stratified fluid can be modeled by heating or cooling a metal wall for ambient temperatures well above the freezing point. Melting ice produces cold fresh water; warmer, saltier water is often underneath the ice. Although cold water is heavier, the effects of salinity can dominate, so the possible net effect is that the melt-
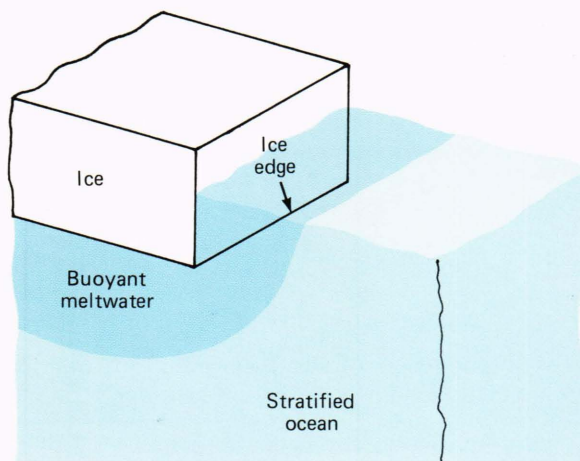

Figure 1—Sketch of the physical problem: convection at an ice edge in stratified water.

water is buoyant; it is this buoyancy that can be modeled by heating a metal wall. Although this method of modeling eliminates the actual addition of water (and therefore some phenomena that would result), the results cited above showed that flowfields near melting ice and outside a metal wall can be similar in the parameter range of interest. Since accurate experiments with ice are much more difficult than with heated metal walls, the latter approach was adopted for the preliminary experiments. First, the ice corner was modeled by flow outside a metal corner that was placed inside a 70-gallon aquarium filled with a salt-stratified fluid (Fig. 2). Inside the metal container, a reservoir of hot water was maintained at a constant temperature to drive the flow. The metal container was sealed so no water was exchanged between the hot-water reservoir and the salt-stratified region. Measurements of density were made with a profiling conductivity probe, and shadowgraphs were obtained from the flowfield.

The procedure was as follows: The conductivity probe was calibrated in solutions of known salinity. The salt-stratified solution was made by filling the tank with small layers of constant salinity and waiting overnight for the density gradient to smooth by diffusion. After measuring the density gradient with the conductivity probe, the hot water reservoir was quickly (in a few minutes) filled with preheated water. The tem-
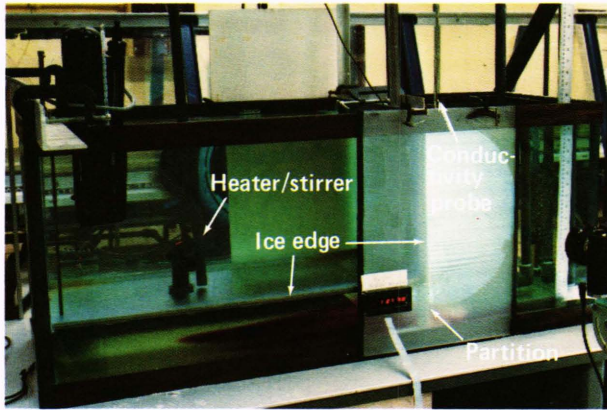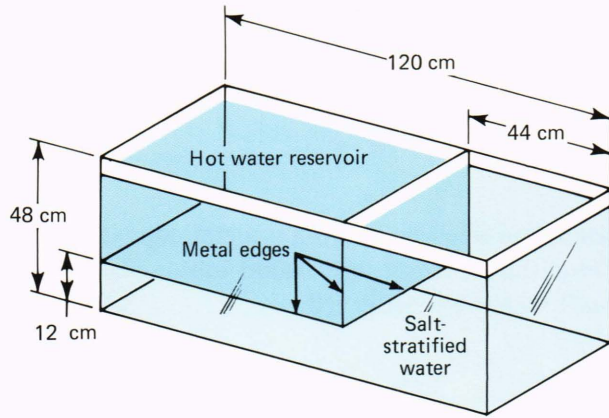
Figure 2—Experimental apparatus: (top) schematic, (bottom) photograph.

perature in the reservoir was maintained by a thermostatically controlled heater/stirrer. Shadowgraphs were taken as the flow developed. Occasionally, potassium permanganate crystals were dropped near the ver-

tical wall, and the displaced dye line was photographed to determine the velocity profile.

In the first two experiments, an impervious insulated partition was placed so as to extend the vertical wall of the metal container all the way to the bottom of the 70-gallon aquarium to eliminate the effects of the horizontal boundary and, therefore, to repeat previous results as a checkout. In the subsequent three experiments, the partition was removed, giving a height-width aspect ratio of about 1:2.

RESULTS

Five experiments were run. The temperature of the hot water reservoir, T_R, varied from 30 to 60°C, while the ambient stratified fluid was isothermal at the constant laboratory temperature, $T_\infty \sim 24$°C. A conventional measure of the strength of stratification, $\partial\rho/\partial z$, is the buoyancy period, t_B, which is the time during which a fluid particle would oscillate about its initial position if given a small vertical displacement. It is defined by

$$t_B \equiv 2\pi\left(-\frac{g}{\rho}\frac{\partial\rho}{\partial z}\right)^{-1/2},$$

where g is the acceleration due to gravity and ρ is the fluid density. As the stratification gets stronger, fluid particles oscillate more quickly and the buoyancy period decreases. The buoyancy period, due only to salinity stratification, varied from 3 to 12 seconds. The maximum salinity, S_∞, varied from 20 to 100.[7] The driving temperature difference, $\Delta T \equiv T_R - T_\infty$, varied from 5 to 28°C. Parameters for the experiments (some of which are defined in the next section) are listed in Table 1. Because of nonuniformities in the den-

Table 1—Experiment parameters.

Experiment No.	T_∞ (°C)	ΔT (°C)	t_B (sec)	S_∞ (ref.7)	h (cm)	L (cm)	h/L	Ra	V (cm/sec)	V_0 (cm/sec)	V/V_0
1	22.8	17.5	13.7	20	5.0	26.0	0.19	6.9×10^9			
2	24.3	5.25	3.5	95	0.57	0.54	1.06	2.0×10^4			
	24.3	5.25	7.0	22	1.0	1.79	0.56	5.9×10^5			
3	24.0	6.0	3.9	102	0.57	0.73	0.73	7.2×10^4	1.5×10^{-2}	1.9×10^{-3}	8.1
	24.0	6.0	7.0	10	0.86	0.42	0.42	1.0×10^6			
4	26.2	7.8	3.9	65	0.86	1.06	0.81	2.4×10^5	5.7×10^{-2}	1.3×10^{-3}	4.4×10
5	23.0	27.9	3.9	80	2.1	4.22	0.50	6.0×10^7	8.7×10^{-2}	3.3×10^{-4}	2.6×10^2

Legend:
T_∞	Ambient temperature	h/L	Nondimensional layer thickness
ΔT	Temperature difference across wall	Ra	Rayleigh number
t_B	Buoyancy period	V	Horizontal velocity
S_∞	Maximum salinity	V_0	Velocity scale
h	Layer thickness	V/V_0	Nondimensional horizontal velocity
L	Length scale		

sity gradient, there were two distinct regions of flow in experiments 2 and 3.

The flowfield in the vicinity of the corner was measured both by shadowgraph and by photographing dye-line displacements. A typical shadowgraph result is shown in Fig. 3, which is a view looking into the side of the tank. The small (about 1 centimeter) convective layers along the vertical wall develop as they have in other experiments.[3,4] However, at the corner, a very strong, thick current moves out horizontally into the open water. Velocities in the large horizontal current were an order of magnitude larger than they were in the small convective layers. Similar horizontal flows appeared in photos of the experiments by Gebhart et al.,[1] but no quantitative results were presented by them.

Shadowgraphs of the five experiments are shown in Fig. 4. The partition at the bottom of the vertical wall can be seen in Figs. 4a and 4b. Layers are formed along the vertical wall, but no strong horizontal current is developed. (The bright horizontal line in Fig. 4a, where the partition joins the heated vertical wall, is the result of a nonuniformity in the initial density gradient.) The three experiments with a horizontal boundary (Figs. 4c, 4d, and 4e) all developed strong horizontal boundary currents in addition to the convective layers along the vertical wall. (Figure 4e is the same as Fig. 3. It is included to make comparison easy.) The quantitative characteristics of these flow features are examined in the next section.

ANALYSIS

The simplest possible dimensional analysis considers the following six variables: the vertical density gradient due to the mean salinity stratification, $\partial\rho/\partial z$; the density difference due to the imposed temperature difference, $\Delta\rho$; gravitational acceleration, g; and the diffusivities of momentum, temperature, and salt, v, κ_T, and κ_S, respectively. These variables give three nondimensional parameters and three scales. The parameters are the Prandtl number (*Pr*), the Schmidt number (*Sc*), and the Rayleigh number (*Ra*), defined by

1. $Pr \equiv v/\kappa_T$ (≈ 7) is the square of the ratio of lengths to which momentum and temperature diffuse in a given time; also the ratio of time of temperature or momentum diffusion to a given length.
2. $Sc \equiv v/\kappa_S$ ($\approx 7 \times 10^2$) is the same as *Pr*, but for momentum and salt;
3. $Ra \equiv \Delta\rho g L^3/\rho\kappa_T v$ ($\approx 10^4 - 10^9$) is the square of the ratio of time scales for a fluid particle to move a distance L by buoyancy forces or by mean temperature-momentum diffusion.

The three scales are for length, time, and density. These are defined by

1. $L \equiv \Delta\rho/(\partial\rho/\partial z)$ ($\approx 10^{-2}$ meter) is the distance a fluid particle of density perturbation $\Delta\rho$ would move vertically to find its new equilibrium position in the stratified fluid;
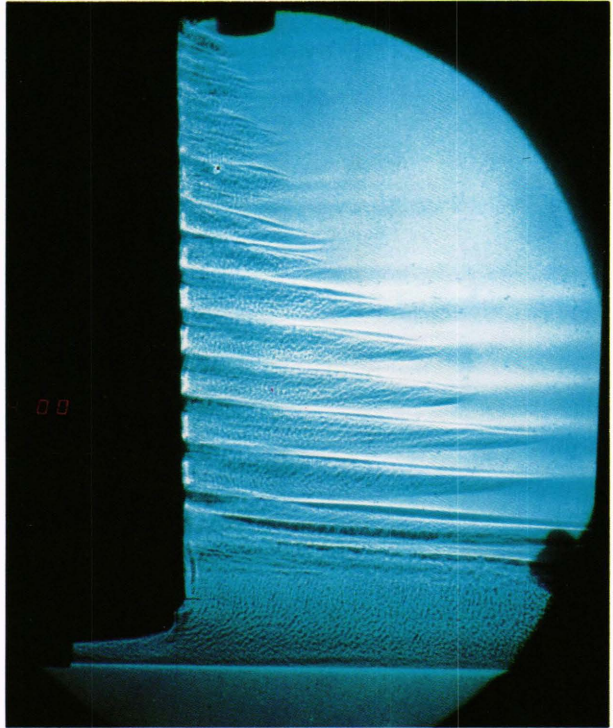

Figure 3—Shadowgraph of the flow near the edge (experiment 5) showing the strong horizontal boundary current going out from the edge and the convective layers along the vertical wall (time is 7 minutes after hot water had started to fill the reservoir).

2. $t_0 \equiv L^2/K$ (minutes to hours) is the time it takes for the imposed temperature difference to diffuse across the length scale L.
3. $\rho_0 \equiv \Delta\rho$ (≈ 10) kilograms per cubic meter is the magnitude of the imposed density perturbation. In the present experiments, this is the result of temperature differences.

The first item to consider is whether the thickness of the convective layers along the wall is affected by the horizontal boundary. The thickness, h, of the layers was measured from the shadowgraphs of Fig. 4, scaled by the length, L, given above, and plotted as a function of the Rayleigh number in Fig. 5. (The experiments shown in Figs. 4b and 4c had nonuniform density gradients. Two data points were obtained for each of these experiments, one for the upper and one for the lower group of layers. In each case, the local length scale L was used.) The sizes of the layers in the present experiment, as seen in Fig. 5, are essentially the same as those found by Huppert and Turner[3] and Huppert and Joseberger.[4] The conclusion is that flow along the vertical wall is unaffected by the horizontal boundary, except in the region that is only one or two layers thick above the corner.

The displacement of dye lines created by the crystals of potassium permanganate dropped in the fluid near the heated vertical wall was used to measure the velocity in the horizontal boundary current. A velocity scale, V_0, was formed from the length scale, L,
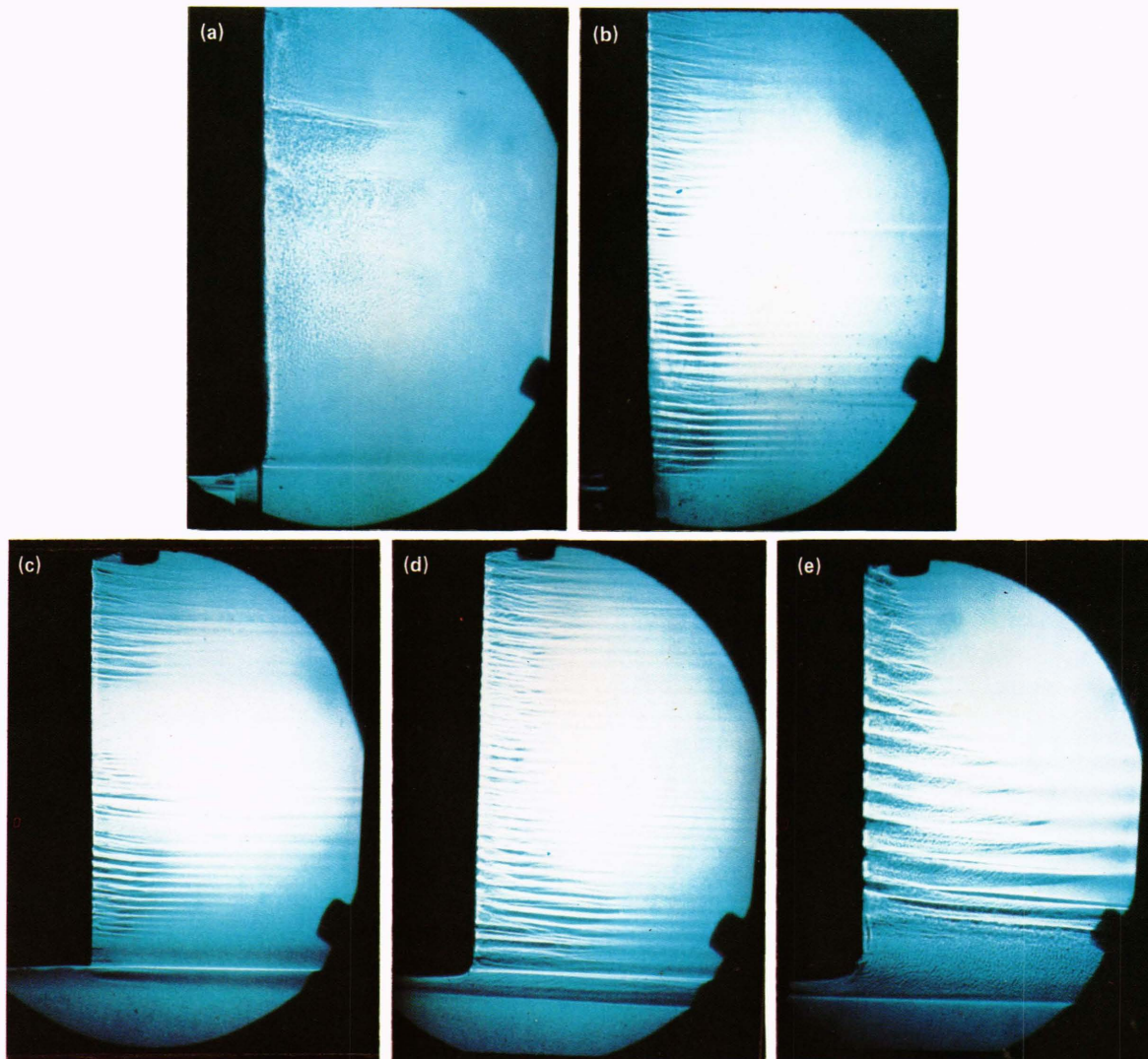
Figure 4—Shadowgraphs (a) through (e) (at times 10 to 15 minutes after start) for the parameters listed in Table 1 are for experiments 1 through 5, respectively.
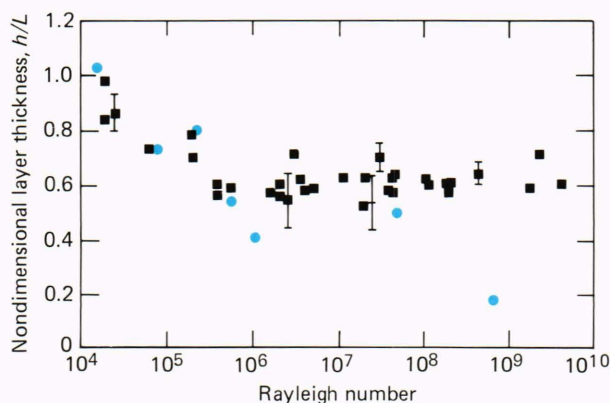

Figure 5—Layer thickness (normalized by length scale, *L*, as a function of Rayleigh number. Circled points are from the present experiments (edge flow); others are from Huppert and Turner [2,3] (vertical wall).

and the time scale, t_0, given above. Although only three data points were obtained (Figs. 4c, 4d, and 4e)

for only one aspect ratio (height/length $\approx$ 0.5), the results (Fig. 6) suggest a power law dependence of

$$V/V_0 \approx cRa^d,$$

where $d \approx \frac{1}{2}$ and $c \approx 0.08$.

DISCUSSION

Since the experiments were designed only to demonstrate the effect of the edge on the flow, many important questions about the variability, strength, extent, and time scales remain unanswered. Although the effect of ice melting on upwelling has been discussed before,[2,6] the magnitude and details of the upwelling remain to be measured. The present experiment implies that for a horizontally finite block of free ice, upwelling would be enhanced by the strong horizontal current at the edge. The important dependencies of the boundary current on distance from the edge and the details of the return flow (via upwelling or other-
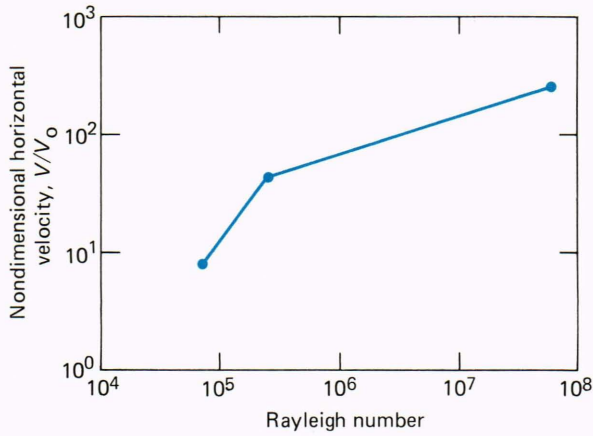
Figure 6—Speed of the horizontal boundary current (normalized by L/t_0) as a function of the Rayleigh number.

wise) were beyond the scope of the present experiments.

The fact that the corner flow eliminated the first one or two layers along the vertical wall could be important in the geophysical case if the layer thickness is similar to the ice thickness. Huppert and Turner[3] estimated convective layers of fluid to be at least 1 meter thick in the Arctic. If that estimate is correct, the present results imply that horizontal current below the ice will dominate the flow for ice thickness less than about 2 meters.

The horizontal current at the edge will certainly affect the melt rate of the ice and could be an important component of the heat budget of the ice and of the upper ocean below the ice.[1] The question of three-dimensional effects (instabilities and interactions with currents and waves along the ice edge) has not been addressed in these experiments. Several useful steps logically follow the present study: to repeat the experiments using real ice, to study the boundary layer flow numerically and theoretically, and to obtain some detailed measurements in the field near all types of ice edges.

REFERENCES and NOTE

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[7] This nondimensional new standard salinity scale, called "practical," is numerically equivalent to the old o/oo unit.

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JACK CALMAN has been on the staff of the Submarine Technology Department since joining APL in 1980. He was born in New York City in 1947 and attended City College of New York (B.S. physics, 1969) and Harvard University (S.M., 1970; Ph.D., applied physics (oceanography), 1975). His career has included positions at MIT and the Weizmann Institute of Science, Environmental Research and Technology, Inc., and NASA's Goddard Space Flight Center. The subjects of his previous work were instabilities of ocean circulation, the fluid dynamics of solar ponds, theoretical methods of interpreting ocean current spectra, pollution problems of oil spills and jet aircraft exhaust, and climate studies of sea-surface temperature. After joining APL, Dr. Calman worked on small-scale ocean turbulence for several years and on drag reduction briefly. He is now interested in application of satellite altimetry to studies of ocean circulation. He has published extensively and is a member of the American Geophysical Union, the New York Academy of Sciences, the American Physical Society, and the Committee for International Freedom of Scientists.