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STRATIFICATION AND CIRCULATION PRODUCED BY HEATING AND EVAPORATION ON A SHELF

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ABSTRACT

Stratification and circulations are most commonly set up in an estuary when a river flows into its head. Less usual, but in some regions very important, is the case where property anomalies are produced by heating and evaporation at the shallow end, as in Spencer Gulf in South Australia. A series of exploratory laboratory experiments has been carried out to model such an 'inverse estuary'. Density differences and outflows were generated in a tank of homogeneous salt solution by heating and evaporation on a shallow shelf, connected to a region of uniform depth through a steep slope. Two distinct regions of circulation and types of layering developed. Counterflowing layers of hot salty water above colder fresher water were seen near the surface, with salt fingers between. The dense, warm salty water deposited by the fingers at the top of the slope, and very salty water originating on the shelf, formed gravity currents which flowed to the bottom and also away from the slope at mid-depth. This built up vertical gradients in the 'diffusive' sense; these and the circulations became quasi-steady after several days. The development and final structure were dominated by double-diffusive effects, which are quite different from those due to a simple source of buoyancy on the shelf.

INTRODUCTION

There has been a considerable amount of theoretical and laboratory work on flows driven by simple sources of buoyancy in estuaries, or shallow regions connected to deeper water bodies. The emphasis in the experiments presented here, however, is on understanding the *combined* effects of temperature and salinity anomalies. If a localized source of dense saline water is added to an initially homogeneous region of lower salinity at the same temperature, the system will evolve to a stratified state in which the range of densities always lies between those of the initial solutions, whatever mixing has taken place. This is not true when the temperature as well as the salinity of the input differs from that of the ambient fluid. Double-diffusive transports can in fact lead to an increase in the vertical density gradient.

Many ocean observations of fine- and microstructure can only be explained in terms of double-diffusive processes. When there is a systematic association between T and S, such that they have opposing effects on the density, the difference in molecular diffusivities can lead to the formation of well-mixed layers separated by sharp interfaces. These influence the vertical transports and the larger scale horizontal motions.

PREVIOUS EXPERIMENTS

Much of the detailed understanding of double-diffusive processes has come through laboratory experiments (see the reviews by Turner (1985) and Schmitt (1994)) but most of these studies have been one-dimensional i.e. they have been concerned with the vertical fluxes across established interfaces.

There are very few 'two-dimensional' experiments which take into account horizontal differences of both properties, and most of these have used the sugar/salt analogue for salinity and temperature differences. Turner and Chen (1974) explored the effects of horizontal gradients of properties in various geometries, and Turner (1978) studied intrusions produced by localized sources of salt or sugar feeding into a salinity gradient. The behaviour is very different without and with double diffusion; in the latter case strong vertical convection occurs, with the spread of intrusions at many levels.

Another configuration which has received some attention is a vertical boundary or front with different diffusive properties across it. Ruddick and Turner (1979) used the sugar/salt system to study the formation of intrusions driven by horizontal property anomalies, with identical vertical density gradients on each side of a front. In the heat-salt case there have been several studies of the layers formed by heating the side wall of a tank containing a solute gradient, and the most recent of these, Chen and Chen (1997), also summarizes the earlier work. Huppert and Turner (1980) conducted experiments on iceblocks melting into a salinity gradient, which produced both temperature and salinity anomalies. (See Fig. 1.)

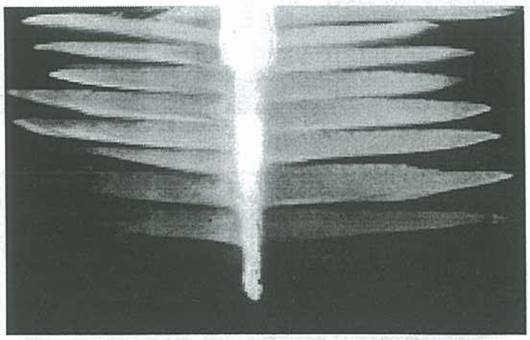

Figure 1 : Intruding layers formed by an ice block melting into a salinity gradient, marked by fluorescein frozen into the ice.

Some of the phenomena observed in the earlier experiments are also important in those reported here. Another significant process is the 'filling box' effect described by Baines and Turner (1969), whereby a dense plume can produce stratification in an initially homogeneous region.

EXPERIMENTAL METHOD

The experiments were all carried out in a tank 1820 mm long, 80 mm wide, 250 mm deep, filled to a depth of about 220 mm with salt solution in the range 1.03 - 1.10 SG. A typical shelf configuration was a 500 mm long plane with a slope of 1:30, placed so that so that the minimum depth over the shelf was about 10 mm, with a curved transition region leading to a slope of 45^0 inclination. In the most common type of estuary, stratification and horizontal circulations are set up when a river flows into the upper end. Less usual, but in some regions very important, is the case studied here: the 'inverse estuary' effect, in which property anomalies are produced by heating and evaporation to form warmer but denser water at the shallow end of an estuary or gulf which is surrounded by an arid region, with little runoff.

In the laboratory model, heating and evaporation were produced using two infrared lamps mounted above the shelf, and fresh water was added at the other end using a constant head device to keep the depth (and thus the mean salinity) constant. The experiments were two-dimensional and non-rotating, implying that the scales considered are such that Coriolis effects are unimportant. There was no mechanical mixing on the shelf, so any effects due to tides and winds in an estuary have also been neglected.

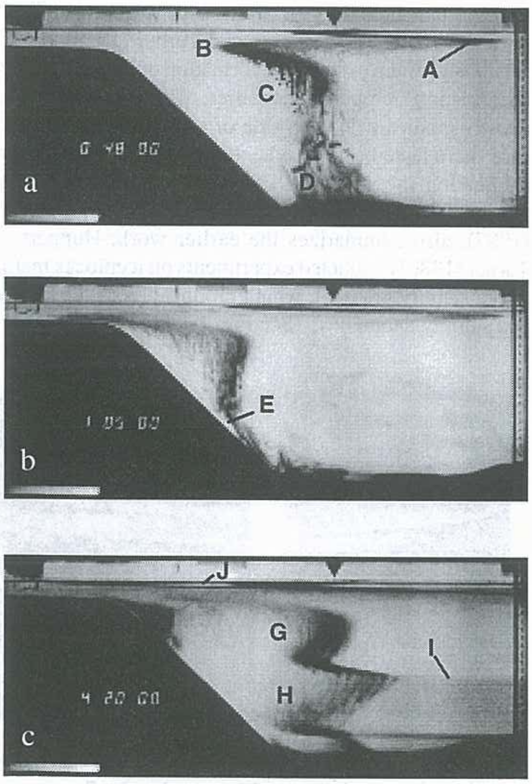

Figure 2 : Motions recorded using dye streaks in an experiment with salt solution of SG 1.05. The letters refer to features described in the text.

LABORATORY MEASUREMENTS

After the tank was filled with homogeneous salt solution, an experiment was begun by switching on the heater lamps. The motions and development of the stratification were followed by recording the distortion of dye streaks on shadowgraph pictures using still and video cameras. Salinity profiles were obtained at intervals by withdrawing samples at standard depths and measuring their density, and a few temperature profiles were also recorded using a thermistor.

Dye streak observations

In a typical experiment, steady counter-flows developed near the surface less than 30 minutes after the heating was begun. Fig. 2a, taken 48 min into an experiment, 2 min after a dye streak had been injected, shows a surface outflow (A) from the shelf, about 15 mm thick, and a slightly thicker return flow (B) below this. There was strong salt-finger convection between these layers and so the outflow was less dense, but warm and salty relative to the return layer. The salt fingers extended deeper into the nearly stagnant fluid below (C). Also seen (at D) is the upward transport of dye, driven by convection above a warm, dyed salty layer deposited on the bottom.

The mechanism of formation of this bottom layer is made clearer in Fig 2b, taken 3 min after a dye streak was injected. In addition to documenting the surface counterflows again, it shows the flow down the slope and out along the bottom, produced by the deposition of dense fluid by the fingers. Note also the clear region (E) on the slope below the dyed downflow, which shows that even denser undyed salt solution has been delivered by fingers higher up the slope and has flowed under the marked part of the downflow.

Continuation of this downflow process produced a strong stratification in the tank, and the shear flows intensified due to the combination of horizontal and vertical property gradients set up by the injection of heat and salt near the slope. Fig. 2c shows two deeper layers (G and H) with fingers extending through them, and an interface (I) marked by dye advected up from the bottom by the 'filling box' process. Also visible is a surface layer (J) flowing away from the fresh water input, above the previously identified counterflowing layers (A) and (B) with fingers between them.

Density and temperature profiles

At intervals during each experiment, samples were withdrawn and their density determined. This was done using an Anton Paar densitometer at carefully maintained constant temperature, so that the values were a measure of the salinity, not in situ density. In a few runs a temperature profile was also obtained with a calibrated thermistor. The measurements plotted in Fig. 3 confirm the picture obtained from the dye streaks in the same run. There was a strong maximum of temperature at the level of the outflow of warm salty water off the shelf, with above it a thin, cooler fresher surface inflow. Below these was a layer 100 mm deep having a nearly uniform salinity and a stabilizing temperature gradient. Salt fingers were observed in this latter region. Below this again the salinity increased continuously to a maximum at the bottom, and there was a small secondary maximum of temperature some distance above the bottom. This temperature increase was associated with an outflow of warm salty water off the slope.

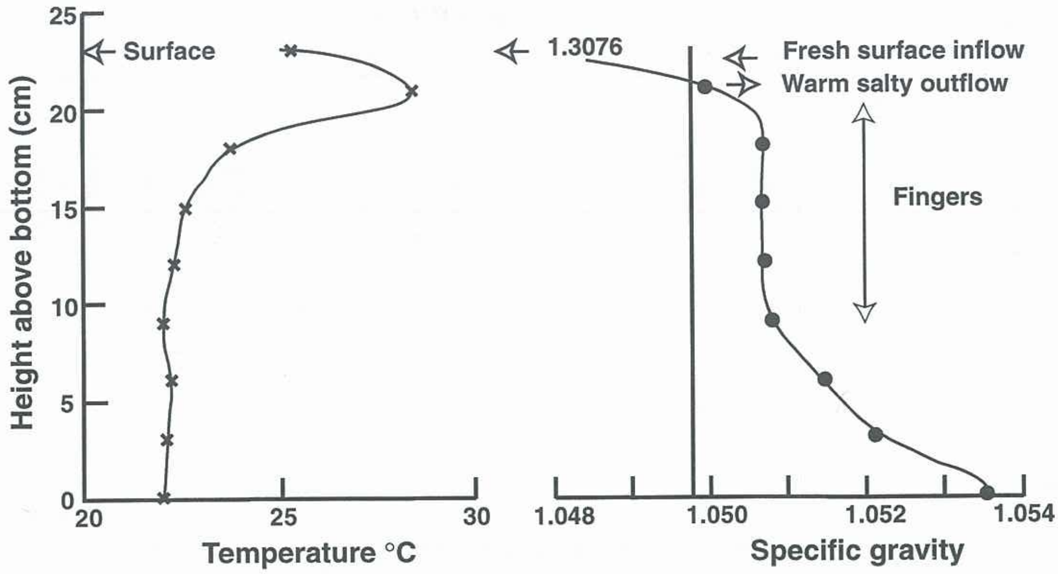

Figure 3 : Temperature and density profiles (due to salinity, at constant temperature) 28 hr after start, 300mm from top of slope; initial SG is indicated by the vertical line.

__Flow of dense water down and away from slope__

A second mechanism of 'bottom water' formation was also apparent in several runs, namely the intermittent flow of hot very salty water off the shelf and down the slope. This process could be initiated more predictably by turning off the heater lamps. Fig. 4 shows various features of this downflow in a long-running experiment, ten minutes after the heater lamps were turned off at 23 hr 30 min . At the same time dye streaks were dropped in at 500 mm (on the shelf) and 800 mm from the end of the tank. A and B are layers spreading away from the slope near the top, while C is a thin dye layer 80 mm above the bottom which has spread right across the frame and beyond, above a thicker, more slowly intruding nose (D). These latter two layers resulted from downflows which did not reach the bottom, but were marked by dye injected much earlier, at 18 hr 50 min. The effect of the flow of dense, hot salty water off the shelf resulting from the removal of heating is seen at E. There is a clear layer against the slope, with above it a counter-flow (F), which is driven by double-diffusive heating through the interface above the bottom current and is marked by dye from the preexisting layers. Later this upflow went unstable, mixed with fluid above and below it and spread as a layer at its level of neutral buoyancy, with salt fingers below.

Thus three mechanisms have been identified which are affecting the stratification and circulation. Near the surface there are strongly sheared salt fingers below a warm salty outflow from the shelf. These fingers deposit denser fluid on the slope, leading to downflows to the bottom and intrusions at mid-depth. Very salty, hot water can also flow intermittently off the shelf and down the slope. These last two processes both contribute to the establishment of 'diffusive' T and S distributions near the bottom.

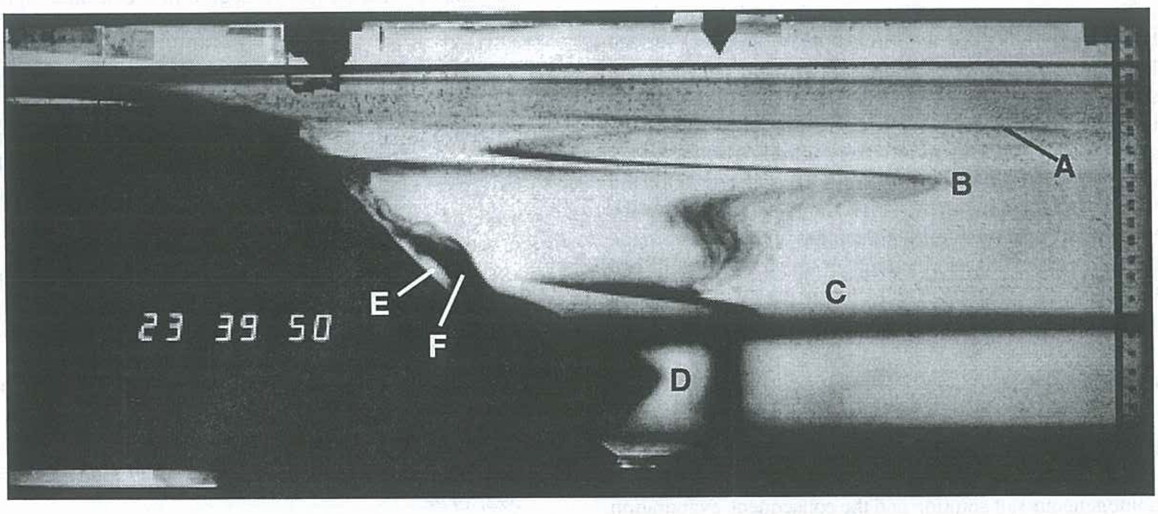

Figure 4 : Showing the flows down and away from the slope, after the heating was turned off, in run with initial SG 1.10. The letters mark features described in the text.

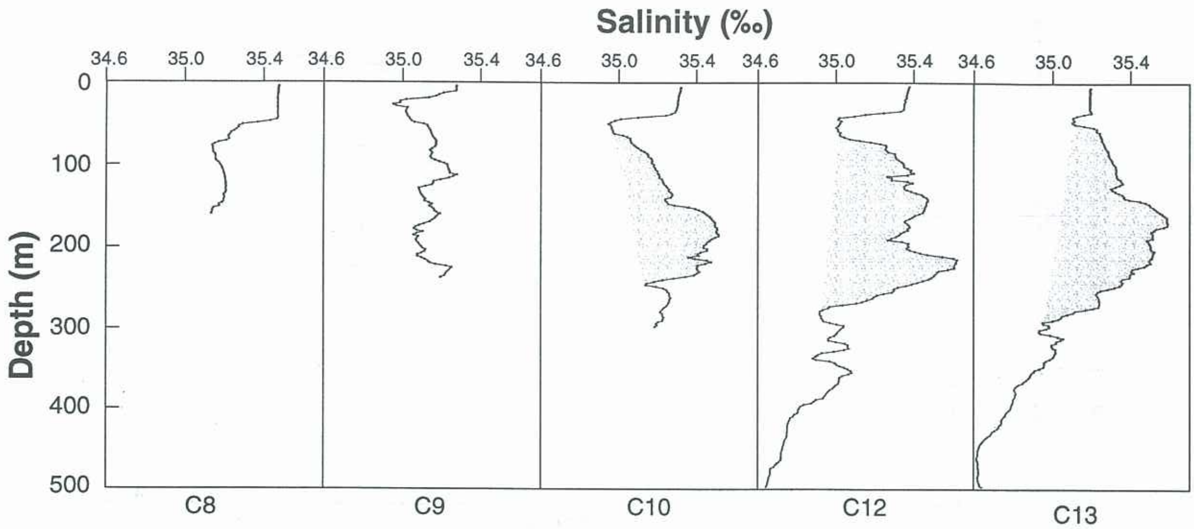

Figure 5 : Salinity profiles obtained on the Australian NW Shelf in January 1995. Shaded areas show the extent of the high-salinity intrusion as it moved off the slope.

COMPARISON WITH OCEAN DATA

CTD data from the Australian Northwest Shelf, obtained during a study of internal tides, exhibit some features comparable to those observed in the laboratory. The processes on the Shelf are more complex than the model (which omits mechanical mixing) but the double-diffusive nature of the flows seems very clear. The five profiles plotted in Fig. 5 are the first casts at the stations given in the Table; they were obtained within three days and are the best measure available of a synoptic cross-shelf section.

Station	C8	C9	C10	C12	C13
km from C1	63.5	76.3	89.3	122.8	140.8
Depth (m)	162	242	302	764	1382

The temperature gradient was in each case strongly stable, with the highest T at the surface and superimposed fluctuations and reversals of gradient associated with saline intrusions. The salinity profiles are the most graphic indicators of the process of interest, and only these are shown here. There is a clear well-mixed salty (and hot) surface layer in each profile, extending away from the shelf and across the slope. At C8 there is also a salinity maximum near the bottom, consistent with the deposition of salt by salt fingers. At C9 there are many intruding saline layers over the whole depth. At section C10 a thicker intrusion has developed, leaving the slope some distance above the bottom. Its salinity is greater than that of the surface value here, so it must have formed higher up the shelf. C12 and C13 show a thickening of this outflowing layer, extending away from the slope at a depth of about 200 m.

CONCLUSIONS

The results of the (mainly qualitative) experiments described here have shown that even in a simple geometry of shelf, slope and a deeper tank, the heating of an initially homogeneous salt solution and the consequent evaporation in the shallowest region can produce large scale motions and strong stratification. The effects depend essentially on the coupled changes in temperature and salinity, and could not occur if dense fluid due to only one of these properties had been supplied at the shelf. The striking similarity to the ocean observations presented suggests that the processes documented in the laboratory can be effective on the larger scale.

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