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Experiments on Double-Diffusive Intrusions in a Stratified Fluid

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SUMMARY Double-diffusive processes, i.e. those in which the differential diffusion of heat and salt are important, are now believed to affect the rates of vertical transport of these properties in the ocean, and to be responsible for the formation of certain types of microstructure. Relevant information has been obtained from laboratory experiments, but these have most often been one-dimensional in nature, whereas the strongest layering attributed to double-diffusion is observed when there are large horizontal gradients of temperature and salinity. The present paper aims first to summarize what is known from earlier experiments, and then to discuss some recent laboratory investigations of the intrusion of water with one set of T-S properties into an environment with different properties. The behaviour is shown to be quite different from that of a simple source of salt solution intruding into a salinity gradient at its own density level.

1 INTRODUCTION

The conditions required for double-diffusive convection to occur are now well known: a region of fluid must contain two (or more) components having different molecular diffusivities, and these components must make opposing contributions to the vertical density gradient. It is remarkable that even when the overall hydrostatic density distribution is increasing towards the bottom, strong convective notions can occur. Molecular diffusion, acting at different rates for the several constituents, makes it possible to release the potential energy in the component which is heavy at the top. Typically, this drives convection in relatively well-mixed layers, which are kept stirred by a net unstable buoyancy flux but remain separated from adjoining layers by interfaces dominated by the stably distributed component.

A series of layers and interfaces can be formed with the components distributed in either sense, i.e. with the substance of higher or lower diffusivity providing the driving energy, though the structure of the interfaces is very different in the two cases. A simple example of the first is a stable salinity gradient heated uniformly from below, which breaks up step by step into a series of layers whose thickness can be related to the initial salinity gradient and the heating rate (Turner 1968). The flux across the bounding "diffusive" interfaces is dominated by the diffusion of heat, while an excess of the more slowly diffusing salt preserves a net density step. In the opposite case, when hot salty water is placed above colder, fresher (but heavier) water, layers can also form, but now the destabilizing buoyancy flux is dominated by salt. This can occur because of the formation of "salt fingers" across the interfaces - long narrow convection cells which are maintained because of the slower horizontal diffusion of salt relative to heat.

Layers and interfaces attributed to double-diffusion have been observed in the ocean with associated T-S gradients in both senses: a good example of the diffusive case has been reported by Neal, Neshyba and Denner (1969) under an Arctic ice island. Tait and Howe (1971) found layers under the Mediterranean outflow into the Atlantic, and Williams (1974, 1975) detected fingers directly in the interfaces between layers in the same region.

As shown first by Stern and Turner (1969), essentially the same phenomena can be observed using solutes with much closer diffusivities than salt and heat, for example sugar and salt solutions. This is a convenient laboratory analogue which avoids the problems due to side-wall heat losses, and it has been used for most of the experiments described later in this paper. For more details, reference can be made to the reviews by Turner (1973, Ch.8; 1974).

2 HORIZONTAL NON-UNIFORMITIES

Though layering in the ocean was first interpreted in terms of the one-dimensional experiments described above, it has become clear that the strongest layering is associated with horizontal gradients of properties. This is also apparent from various laboratory experiments, the simplest of which is the heating of a stable salinity gradient through a side wall (e.g. Thorpe et al. 1969). In this case layers form simultaneously at all depths, with thickness comparable with the height to which the heated boundary layer can rise in the initial gradient, and move out into the interior.

Various other two-dimensional processes were explored by Turner and Chen (1974) using a tank stratified with opposing vertical gradients of sugar and salt. When an inclined boundary is inserted into a stable "diffusive" system (i.e. one having a maximum salt concentration at the top, and a maximum of sugar at the bottom), a series of layers forms as follows. Molecular diffusion distorts the surfaces of constant concentration so that they become normal to the slope, to satisfy the no-flux boundary condition there. Density anomalies are thereby produced which tend to drive flows along the incline; these cannot remain steady, but instead turn out into the body of the fluid and produce a series of extending layers. (See figure 1). This mechanism is closely related to the previous one (sidewall heating), since in both cases the motions are produced by conditions at the wall which do not match those in the interior.

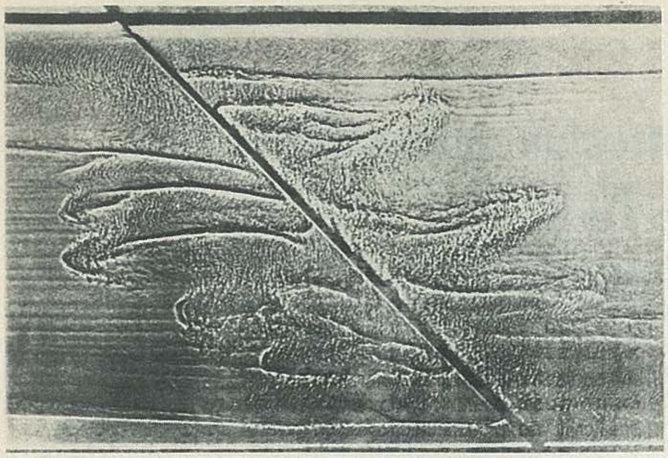

Figure 1 Layers generated by inserting a sloping boundary into a tank stratified in the "diffusive" sense with sugar and salt (Scale: the water depth is about 200 mm.)

Related processes have been observed in counter-gradient systems set up in the "finger" sense (i.e. sugar above salt); Linden and Weber (1977) again used an inclined boundary to produce a series of layers. However, Turner and Chen (1974) showed how a disturbance (produced, for example, by filling the tank past a wedge mounted on an end wall) can propagate rapidly right across a tank in the form of a wave motion, which then leads to overturning and convection nearly simultaneously throughout the affected region. Such overturned layers spread much more rapidly through a field of salt fingers than do the noses pictured in figure 1, which propagate as convective rather than wave motions.

Another method of producing strong horizontal variations of properties, which leads on directly to the new experiments to be presented, is to introduce a plume of one solution into a uniform tank of another having different T-S properties (or different diffusivity). For example, figure 2 shows what happens when a plume of sugar solution is added at mid-depth to a tank of salt solution of the same density. Because of the different diffusion rates across the plume boundary, more salt is added to the plume than sugar is removed, so the plume fluid becomes heavier and its surroundings lighter. This generates strong upward and downward vertical motions, and eventually sets up a vertical stratification through the initially homogeneous region.

Figure 2 Shadowgraph of convective motions produced by a source of sugar in uniform salt solution of the same density

3 SOURCES OF ONE FLUID IN A GRADIENT OF ANOTHER

The common situation in the ocean, where water produced in one region often intrudes at its own density level into a stratified water mass with different T-S properties, has not received much attention from laboratory experimenters. This is of course the geometry which is relevant for the Mediterranean outflow, and until it has been examined carefully, one-dimensional interpretations of the observed layer structures must be treated with caution.

The experiments are natural extensions of those illustrated in figures 1 and 2. The "noses" produced at a sloping boundary are often observed to become independent of the formation mechanism near the slope, and this suggested the present systematic study of sources in density gradients of various kinds, rather than just in a uniform fluid.

3.1 A Source of Salt in a Salinity Gradient

The basic intrusion process to which other phenomena can be compared is the flow of a uniform fluid at its own density level into a linear gradient set up using the same property. (In all cases described below the sources and the flows are two-dimensional i.e. a line source is used, extending right across the tank normal to the plane in which the motion is viewed.)

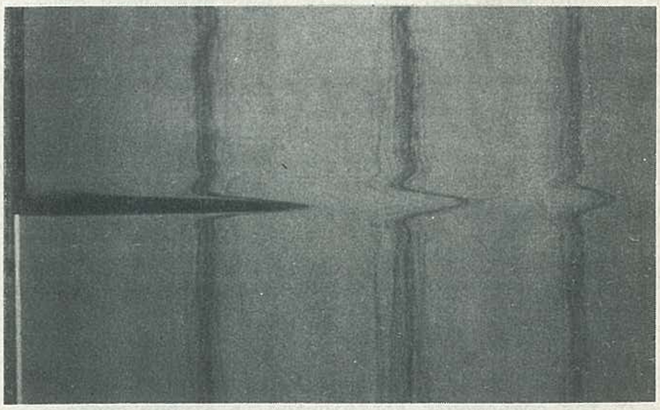

Figure 3 The intrusion of dyed salt solution into a salinity gradient at its own density level. The photographed region is about 400 mm. wide

Figure 3 shows the behaviour of a (dyed) source of salt solution flowing out as a thin layer at its level of neutral buoyancy in a linear salinity gradient. Though the details of this process are still actively being studied, qualitatively this is what we would expect: the intruding fluid just displaces its surroundings upwards and downwards, and is kept confined to a horizontal layer by the density gradient. Two points should be noted particularly. Sharp density gradients are maintained above and below the intruding fluid because of the way it distorts the environmental density distribution, and there is a considerable disturbance in the environment ahead of the advancing nose, as shown by the distortion of dye streaks. The influence of the end walls will therefore always be felt in laboratory tanks of finite length.

3.2 A Source of Sugar in a Salinity Gradient

When the source of salt is replaced by sugar solution, while the same salinity gradient is used in the environment, the behaviour is very different. (It is worth keeping in mind during the following

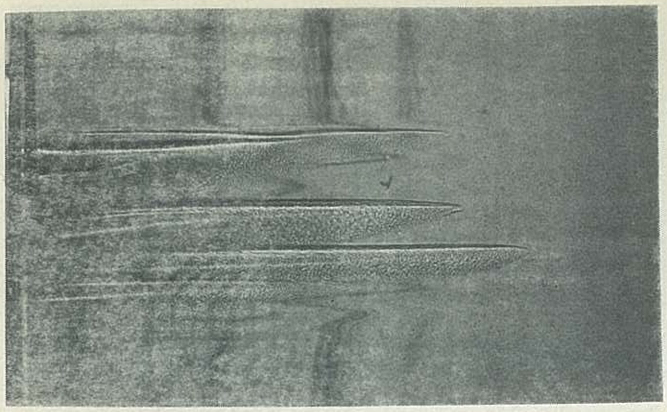

Figure 4 The flow produced by releasing sugar solution at its own density level into a salinity gradient. The density gradient and flowrate, and the scale, are about the same as in figure 3

these can be observed in figure 4. This also implies that there will be a local decrease with depth or an inversion of T through each layer, a feature which is commonly observed in the ocean.

Note too the slight upward tilt of each layer as it extends; this can be interpreted as follows. Above and below an intrusion the net density differences are small and the double-diffusive fluxes therefore large. Previous laboratory observations indicate that the transports across a finger interface (both in the sugar-salt and salt-heat cases) are larger than those across a comparable diffusive interface. Thus the flux of positive buoyancy through the fingers from below can exceed the negative flux from above, and so the layer becomes lighter and rises across isopycnals as it advances away from the source. There is also a systematic shear flow associated with the inclined layers, which can be explained using related ideas, based on the

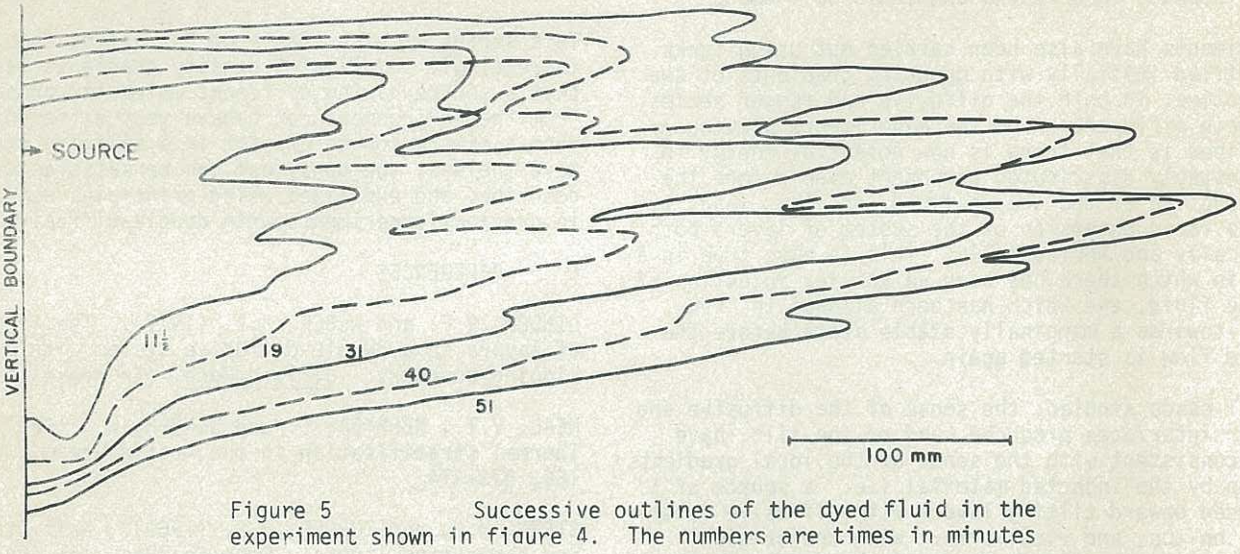

Figure 5 Successive outlines of the dyed fluid in the experiment shown in figure 4. The numbers are times in minutes

descriptions that sugar is the analogue of salt in the heat-salt system, since it is the substance with the lower diffusivity, while salt is here the analogue of heat. Thus this experiment corresponds to the intrusion of a layer of warmer, saltier water into a stable temperature gradient. To avoid confusion it has become customary to denote the substance having the higher diffusivity by T and the lower by S.)

As shown in figure 4, there is strong vertical convection near the source, produced by the mechanism illustrated in figure 2 for a source in a uniform fluid of different diffusivity. The vertical spread is now limited by the stratification, and "noses" begin to spread out at levels above and below the source. The process of vertical convection continues, and further layers appear as the first layers formed extend away from the source. The region of fluid affected by mixing with the input increases markedly in the course of time, both horizontally and vertically, as is shown by the tracing of successive outlines of dyed fluid (figure 5). The total volume of this fluid is many times that of the input, confirming that the intrusions are overtaking and incorporating the environment, rather than just displacing it as in the experiment of figure 3.

Each individual nose as it spreads contains an excess of S relative to its environment, so that conditions are favourable for the formation of a diffusive interface above and fingers below, and

horizontal density anomalies set up by the net negative buoyancy flux.

3.3 A Source of Salt (T) in a Gradient of sugar(S)

Corresponding experiments have been carried out in the opposite case, with a source of salt solution flowing at its own density level into a gradient of sugar solution. Figure 6 shows what is observed when the density gradient and flow rate are the same as those used in figure 4.

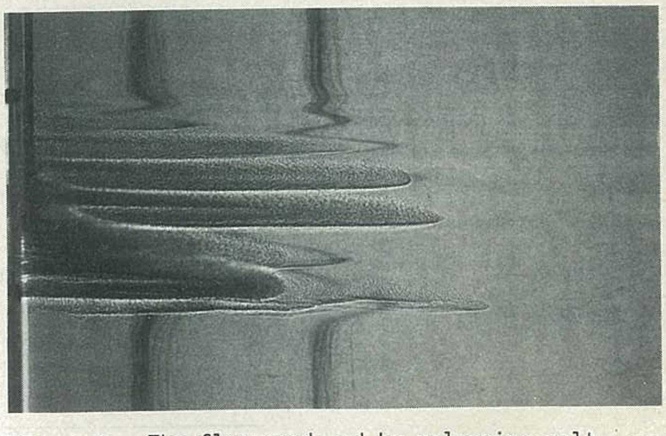

Figure 6 The flow produced by releasing salt solution into a gradient of sugar (using conditions comparable with, but the inverse of, those shown in figure 4)

The observed motion is just the inverse of that shown previously, and supports all the explanations given above of the processes which maintain it. Vertical convection near the source is again followed by the spread of noses at various levels, but now with diffusive interfaces below and fingers above, corresponding to the excess of T in the noses relative to their S environment. There is a systematic downward tilt as the noses advance, due to the dominance of the buoyancy flux at the finger interfaces, which now causes the layers to become heavier as they extend. The sense of the internal shear is also consistent with this picture: the motion is inclined slightly down and away from the source at the bottom of the fingers and above the diffusive interfaces, indicating again that there is an increase in density due to the continuing flux in the fingers.

4 SOURCES IN OPPOSING GRADIENTS OF T AND S

Experiments have also been carried out using tanks stratified initially with opposing gradients of two properties, in both the diffusive and finger senses. The main difference from the experiments previously described is that there is now potential energy in the unstably distributed component even before the introduction of the source fluid, and this leads to a more rapid extension of the system of layers both vertically and horizontally. This is also true in a tank in which there has been an earlier injection of source fluid, and which has been allowed to "run down" towards a marginally stable state before the source flow is started again.

In all cases studied, the sense of the diffusive and finger interfaces produced, and of the tilt, have been consistent with the sense of the local gradients set up by the injected material i.e. a source of S produced upward tilting layers with diffusive interfaces on top, and vice versa. With the original gradients in the diffusive sense, salt fingers are nevertheless prominent in the extending noses. This is of course consistent with the nature of the input fluid, as already mentioned, but the greater speed with which new layers form and extend suggests that the source fluid just acts as a trigger in this case, to overturn the environment and draw on local potential energy. As discussed in connection with the noses shown in figure 1, these can propagate well away from the slope at which they began, so they are evidently driven locally rather than from behind. We deduce that overturning to produce fingers may be the most efficient way to release the potential energy in the environment.

The most rapid spreading observed in this series of experiments was obtained using a tank stratified with nearly compensating gradients of sugar and salt in the "finger" sense, so that fingers initially extended through the depth of the tank. Even when the fingers had been allowed to "run down" for some hours (and thus were approaching the marginally stable state), layers formed very rapidly and regularly with a greater relative vertical spread than previously, probably reflecting the higher flux rate in fingers (see figure 7). Note too the strong regular shearing motions produced in this experiment, as shown by the distortion of the initially vertical dye streak.

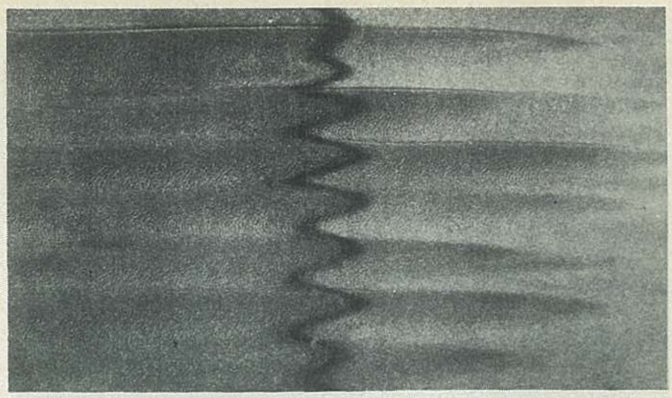

Figure 7 The multiple layer system produced by a source of sugar solution in a tank stratified with opposing gradients of sugar and salt in the "finger" sense. Note the strong shearing motions

5 CONCLUSIONS

This series of experiments on intrusions into increasingly complicated density gradients has shown that a source having different molecular properties from the environment can behave very differently from a simple source of salt in a salinity gradient. Nevertheless, the behaviour can be satisfactorily described and explained using principles established in previous experiments with double-diffusive fluids.

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