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Double-Diffusive Plumes in a Homogeneous Environment

J.S. Turner

Research School of Earth Sciences
Australian National University, Canberra, ACT 0200, AUSTRALIA

Abstract

Laboratory experiments using sources of salt and sugar (an analogue system for heat (T) and salt (S)) at opposite ends of a long tank containing a homogeneous solution of one solute have been used to investigate the related two-dimensional double-diffusive processes in the ocean. It has been shown that vertical gradients of T, S and density, and large-scale horizontal interleaving motions, can be generated even when the density of both inputs and the initial tank fluid are exactly the same, though the initial evolution differs depending on whether the tank contains salt or sugar solution. This difference arises because the individual input plumes are not completely equivalent. Salt diffuses rapidly out of a saline plume in a sugar tank into a surrounding sheath, producing stronger convection in the environment than a sugar plume in a salt tank. The resulting upward and downward transports of the two properties have been measured in both cases, over a range of density differences between source and tank fluid.

Introduction

Turner and Veronis [3] have addressed the problem of the stratification and motions generated by horizontal gradients of heat and salt in the ocean. There are now many observations of intruding layers bounded by both diffusive and finger interfaces that can only be explained in terms of double diffusion. The laboratory models have used horizontally separated salt and sugar sources in a tank containing salt or sugar solutions or a mixture of the two, initially homogeneous. The behaviour is quite different when the tank and the two sources contain only one solute; in that case turbulent mixing ensures that the final top to bottom density range lies within that of the two inputs, for example two salt solutions of different concentration.

With double diffusion, however, a vertical stratification is produced in which the density range is much larger than that of the input densities, and many intruding layers are formed. This is shown in figure 1 for an experiment in which there was a salt source near the bottom on the left, a sugar source near the top on the right and a 50:50 mixture of the two source fluids in the tank, with an overflow withdrawal tube at the centre (to keep the total volume constant).

Three related experiments with simple input conditions were particularly instructive. Both inputs and the withdrawal were

Figure 1. Shadowgraph of the layers formed in an experiment with separated salt and sugar sources; dye streaks added to show the shears.

at mid-depth, and the tank fluid and the salt and sugar sources had the same density, 1.100g/cm^3. The only difference between the runs was the initial composition of the solution in the tank: pure salt, pure sugar, and a 50:50 mixture of the two. All three tended to the same asymptotic distributions of salt, sugar and density after about 100 hours, with a sharp central interface and weakly stratified upper and lower layers.

The final state was stratified in the 'diffusive' sense, with a slightly higher, unstable concentration of salt in the top layer compared to the bottom and a very stable sugar distribution, with a much larger concentration in the top layer than the bottom one; the density distribution was of course very stable. The evolution of the vertical density difference for the runs with pure salt or sugar in the tank is shown in figure 2a, b. Note that although these tend to the same final state the rates of change in the early stages are very different. This observation pointed to the need to study the detailed behaviour of sugar and salt plumes feeding into homogeneous solutions of the other solute, and it has led to the research described here. The experiments reported by McDougall [1] used a similar technique, but he concentrated on the heat/salt case in his study of the vertical transports.

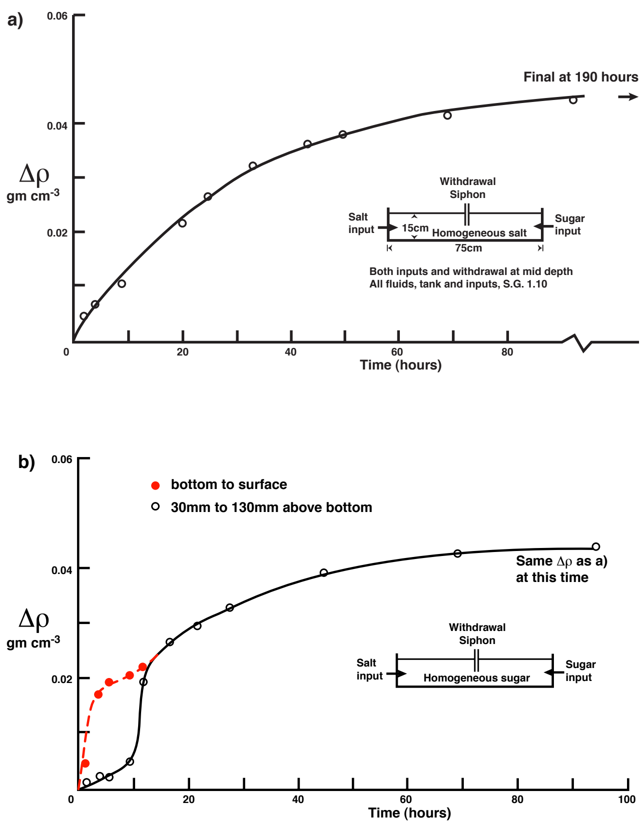

Figure 2. Evolution of the vertical density difference produced by separated salt and sugar sources. a) salt in the tank; b) sugar in the tank.

Observations of double-diffusive plumes

The most striking feature of sugar plumes flowing into salt solution or salt plumes into sugar is the fact that they can split near the source, leading to strong vertical convection in both senses. Earlier descriptions of this process (such as that given in [3]) were too simplistic; they merely stated that this happens when the densities of tank and input fluids are the same. The careful measurements of the vertical transports of properties presented below show, however, that even small density differences can have a big effect on the fraction of input fluid transported up and down, and that sugar and salt plumes behave differently.

Two shadowgraph photos (taken in the tank described in the next section) will illustrate this point. Figure 3 shows a salt plume slightly denser than the tank of sugar into which it flowed (by 6 parts in 10^4), 100min after the flow was turned on at the rate of 5ml/min. The initial flow is downwards, as expected, but vigorous upward as well as downward convection is seen, and there is evidence of stratification in the two layers. The measured amounts of salt in the top and bottom layers are nearly equal, but a little larger in the top.

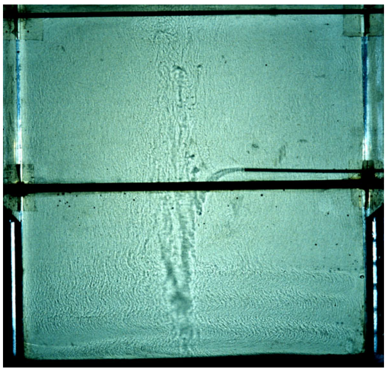

Figure 3. Shadowgraph of a slightly denser plume of salt solution flowing into a homogeneous tank of sugar solution.

Figure 4 shows a slightly lighter sugar source (by 8 parts in 10^4) feeding into salt solution, again at the rate of 5ml/min. This photo was taken at 80min after the start, 2min after a dye streak was added near the position of the source. Again the initial flow is in the expected sense (upwards), and this is followed by strong convection both up and down, with evidence of stratification and outflows both in the shadowgraph and in the dye distribution. In this case, however, the later quantitative measurements showed that substantially more sugar was transported down than up, which is not obvious from the visual observations.

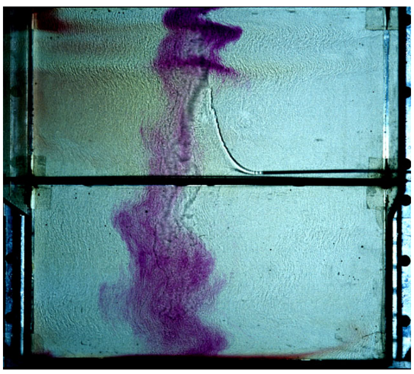

Figure 4. Shadowgraph of a slightly less dense plume of sugar solution flowing into a homogeneous tank of salt; dye streak shows the shears.

Experimental Method

The experiments were carried out in a perspex tank 300mm x150mm in cross section. At 150mm above the base it was fitted with a partition, sliding through a waterproof slot in the front (300mm) wall and in grooves in the side (150mm) and back walls. This partition was left open during the period of a run, then closed to isolate the upper and lower compartments. (The tank was much deeper than the portion used and photographed in these experiments; the extra depth above the water surface had no effect on the results.) The input fluid was supplied through a hypodermic tube (3mm O.D., 2mm I.D.) inserted through the side wall 10mm above the partition. Some of these features are visible in figures 3, 4, 7 and 8.

For each run the tank was filled to a depth of 300mm with either salt or sugar solution, of specific gravity close to 1.100, measured using an Anton Paar densitometer (to 1 part in 10^5). The input solution of the other solute was prepared, with its density varied systematically on either side of the density of the tank fluid. This was supplied to the input tube through a peristaltic pump. Four series of experiments were conducted using input rates of 5ml/min and 20ml/min for both sugar and salt plumes. The inflow was continued typically for 30min at the higher flow rate and 100min at the lower, long enough for a sufficient concentration of source fluid to be built up for accurate measurement. Detailed results will be presented here only for the lower flow rates, concentrating on the runs with small density differences.

At the conclusion of a run the partition was closed and the upper layer stirred and sampled, to provide a measure of the total upward transports. This layer was then drained, the partition opened and the lower layer stirred and sampled to give the corresponding downward transports. The density of the samples was measured in every case, and also optical rotation for the experiments with a sugar input or conductivity for runs with a salt input. This second property was chosen because it was in each case the most sensitive measure of a low concentration of the input fluid in the concentrated tank solution. The fraction of the input fluid transported up and down was deduced using direct calibrations, based on known dilutions of the input solution with the tank fluid for each run. Alternatively, this quantity was calculated using the inversion procedure developed by Ruddick and Shirtcliffe [2] and this also makes it possible to deduce how the solute (which was initially homogeneous) was redistributed in the tank.

Quantitative measurements

The procedure adopted once the separate contributions of salt (αT) and sugar (βS) to the density have been deduced (using the inversion process developed in [2]) will now be described. Assume for example that sugar (S) is the input fluid. The calculation of the vertical transports of both S and particularly the tank solute T needs to be carried out carefully.

Since the plumes have a finite volume flux, as well as carrying the input solute (S), the volume of fluid in the tank is increased during an experiment. Thus the sampled volume V_2 above the partition is larger than V_1 below, and the measured concentration must be corrected before it can be compared with that in the lower layer. Defining

$$r = V_2/V_1 \quad \text{and} \quad R = r\,\beta S_2/\beta S_1\,, \qquad (1)$$

which can be calculated directly from the measured quantities, the fractions of the input solute in the two layers are:

$$\text{bottom layer} = 1/(1 + R) \ \text{ and } \ \text{top layer} = R/(1 + R). \qquad (2)$$

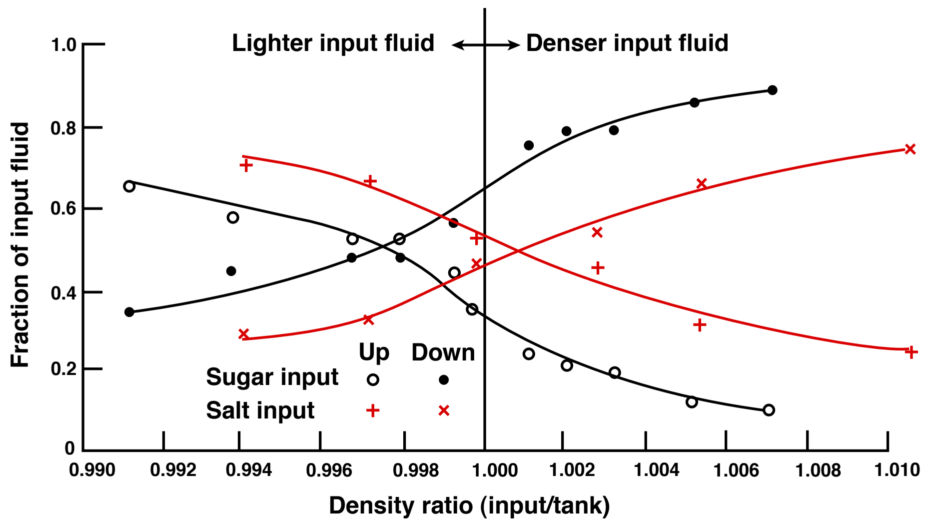

Figure 5. The fraction of input fluid transported up and down by sugar plumes in a tank of salt and salt plumes in a tank of sugar (flow rate 5ml/min), over a range of density ratios between the input and tank fluid

In the case where salt (T) is the input fluid the procedure is the same, with αT replacing βS wherever it occurs.

The fractions of plume fluid transported up and down are plotted in figure 5, for the runs with the smallest density differences on either side of zero and both sugar and salt inputs. At this stage many more runs in the range plotted have been carried out with sugar plumes than with salt plumes. The density ratio between the input and tank fluids (rather than the density difference), has been chosen for this plot. The values derived from the direct calibrations show little systematic difference from those found using the inversion; they too need to be corrected for the larger volume in the upper layer. They have a larger scatter since the two values are determined independently, rather than necessarily summing to unity, as imposed by the relations (2).

It is clear that there is a substantial difference between the behaviour of sugar and salt plumes. There are equal up and down transports of salt at a density ratio corresponding to a predominantly downward sugar flux, while the transports of sugar are equal only for a considerably lighter sugar input.

The upward and downward transports of the solute initially in the tank (T say) can be calculated in essentially the same way, once it is recognised that the source flow is associated with a negative anomaly of tank solute. Denote the measured values of the input fluid properties by ρ_i, S_i and T_i, those of the tank fluid by ρ_0, S_0 and T_0 and the values in the lower and upper layer by subscripts 1 and 2 respectively. Suppose that (as in the experiments) the initial volumes in the upper and lower layers are equal (= V_1) and that the (measured) total volume V_i of source fluid is added during an experiment. Then the mass conservation equation is

$$V_i\rho_i + 2V_1\rho_0 = V_1\rho_1 + V_2\rho_2 \qquad (3)$$

The corresponding equations for the solute anomalies from the initial values in the tank are

$$V_i\rho_i\,(S_i - S_0) = V_1\rho_1\,(S_1 - S_0) + V_2\rho_2\,(S_2 - S_0) \qquad (4)$$

$$V_i\rho_i\,(T_i - T_0) = V_1\rho_1\,(T_1 - T_0) + V_2\rho_2\,(T_2 - T_0) \qquad (5)$$

The terms on the RHS of (4) are those that have already been used in (1) and (2) to find the distribution of the input solute

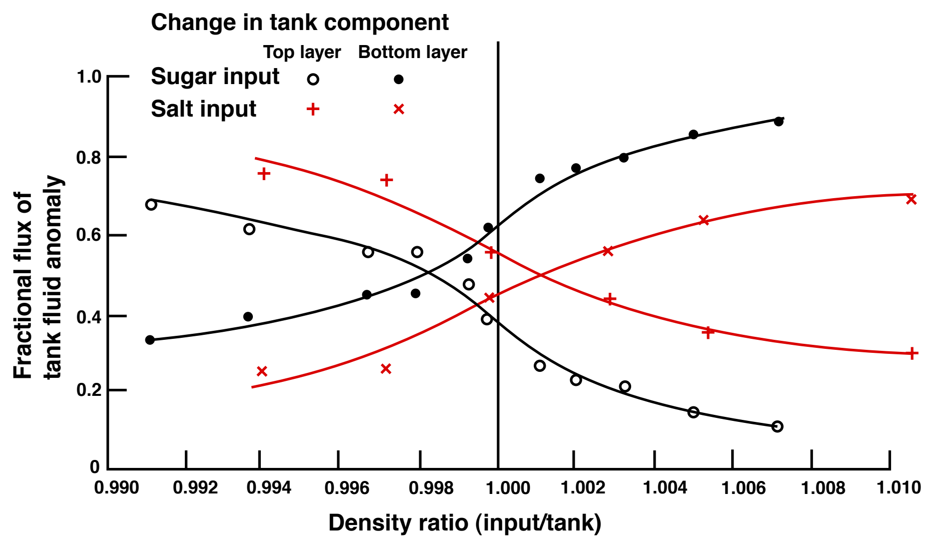

Figure 6. The fraction of tank fluid anomalies transported up and down, produced by convection set up by plumes of salt or sugar in a homogeneous tank of the other property. (c.f. figure 5)

S and to plot figure 5. More care is needed in the calculations for the tank solute T. The terms on the RHS of (5) are less precisely known since they involve small differences between large concentrations that are not so accurately determined by the inversion procedure. However the knowledge of the input parameters on the left makes it possible to adjust T_1 and T_2 to achieve consistency, and in particular to ensure that in the T-S plane the final mean values in the tank (T_m, S_m) lie on the straight line joining (T_0, S_0) and (T_i, S_i) and also on the line joining (T_1, S_1) and (T_2, S_2).

The proportional transports up and down of the negative solute anomalies of tank solute, calculated in this way, are shown in figure 6, again for density ratios close to and on either side of unity, using the same symbols as in figure 5. The scatter is larger than for the input fluid, particularly for the experiments with salt plumes, in spite of the adjustments made using (5). Again there is a systematic variation with density ratio and a difference between the sugar and salt plumes. The upward and downward transports, of the tank solute anomaly in figure 6 and the input solute in figure 5, are equal at close to the same values of the density ratio.

Further work in progress

The analysis and interpretation of these results is continuing, and further experiments have been carried out to extend the range of the measurements. Of particular interest is the way the upward and downward transports change as the density of the plumes becomes very much larger or smaller than that of the tank fluid. An extreme example is shown in figure 7 for a sugar plume flowing into a tank of salt, again at 5ml/min. The ratio of input to tank densities was 0.9777 and the plume rose very strongly to the top, producing the array of salt fingers shown in the photo taken one hour after the start. Nevertheless about 8% of the input sugar was measured in the bottom layer, and strong convection was visible below the interface located just above the level of the partition.

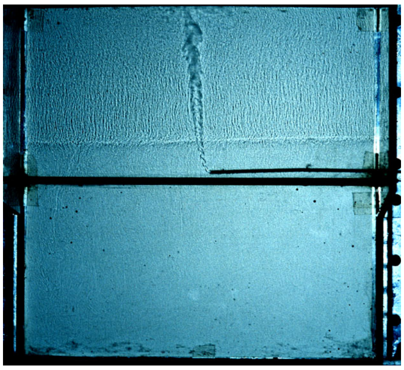

Figure 7. Shadowgraph of the structure produced after one hour by a very light plume of sugar flowing into salt solution at 5ml/min.

A second set of experiments has been carried out using a larger flow rate, namely 20ml/min. The general picture of a systematic difference between sugar and salt plumes has been confirmed. Figure 8 shows an experiment with a denser sugar input (density ratio 1.0059) at the larger flow rate. After 16min the strong downward sugar flux has produced layering in the diffusive sense in the lower layer, with upward convection through the interface on the left, shown by the mixing of a dye streak put in 2min earlier. Later measurements showed that 6% of the input sugar had been transported upwards. There are substantial differences in the detailed behaviour for the two flow rates, especially as the density ratio becomes very large or very small, but a measurable counter buoyancy flux of the input fluid persists in both cases, and for both large and small input rates.

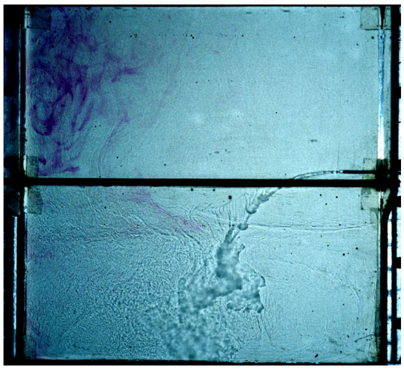

Figure 8. Shadowgraph of the structure produced after 16min by a dense plume of sugar solution flowing into salt solution at 20ml/min.

Conclusions

Previous laboratory experiments [3] on the stratification and motions produced by double diffusion, using separated sources of sugar and salt in a long tank, pointed to the need to understand in more detail the convection and upward and downward transports due to each source separately. Observations and measurements have been presented for sugar plumes feeding into a homogeneous tank of salt solution, and salt into sugar solution, over a range of density ratios between the input and tank fluids. Experiments have been carried out using two flow rates, though detailed results have been given here only for the runs at the lower rate, 5ml/min, and with density ratios closest to unity.

Because of the different rates of diffusion of salt and sugar into and out of a plume moving through an environment of the other property, there is a substantial difference between the proportions of the two properties transported up or down, and these have been measured directly. At a density ratio close to 1 a salt plume produces equal upward and downward transports, whereas at this same density ratio a sugar plume leads to a much larger downward flux. Equal upward and downward transports of sugar occur only when the plume is substantially lighter than the tank fluid. This difference does explain the behaviour described in [3] and shown in figure 5.

Using measurements of density and a second property, optical rotation for the sugar inputs and conductivity for the salt inputs, and inverting using the procedure developed in [2], the change in the distribution of the tank component has also been calculated. This too shows a systematic difference between the sugar and salt plumes. An increase in the input fluid concentration in a given layer is associated with a larger flux of water, and hence a more negative change in the concentration of the tank solute, and vice versa.

The results of these experiments, using salt and sugar as analogues for heat and salt, are of course not directly applicable to the ocean. They do show, however, how important double-diffusive effects can be, even with a much smaller diffusivity ratio. They also suggest that the behaviour of hot salty or cold fresh intrusions may be very different and not just antisymmetric as is commonly supposed.

Acknowledgments

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