The neglect of two-dimensional double-diffusive processes in studies of ocean circulation

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1 Introduction

Following the introduction to double-diffusive processes given by Ray Schmitt in the previous lecture, I will concentrate on a theme I have promoted for many years and in many places, including the 1996 GFD Summer Program. Double diffusion is no longer just an 'oceanographic curiosity' - layering and step-like distributions of T and S are now documented by many observations which have been explained in terms of these concepts. It has also long been accepted without question that both the stratification of the ocean and the thermohaline circulations within it are ultimately determined by the action of all the localized and distributed sources and sinks of heat and salt near the surface. The bottom water in the world's oceans is formed by the sources having the largest buoyancy flux, and the mean stratification adjusts to this influx, with the effects of upwelling being balanced by distributed downward fluxes from the surface. Sources having a smaller buoyancy flux (or more mixing) cannot penetrate to the bottom of this density gradient set up by the major sources of bottom water, but instead spread out as mid-depth intrusions.

Even a superficial look at the T-S properties of ocean water masses and smaller scale intrusions shows, however, that these are distinguished not by their density differences alone but also by (often compensating) temperature and salinity differences i.e. they are inherently double-diffusive. Yet there have been relatively few D-D studies in two-dimensional geometries, compared with those of one-dimensional transports through interfaces. In this seminar I have attempted to fill this gap by discussing a series of two-dimensional laboratory experiments, (using many of my own slides and movies) and relating them to particular observations in the ocean.

Earlier two-dimensional laboratory experiments Several of the experiments to be described first were carried out many years ago, but they have a fresh relevance in the present context. An inflow of concentrated sugar solution released into a tank of homogeneous salt solution of the same density immediately separates, because of differential molecular diffusion, to form strong upward and downward convecting plumes, which spread out along the top and bottom boundaries - very different from a laminar plume of salt flowing into salt solution of almost the same density. This illustrates several counter-intuitive features of double-diffusive processes. Many phenomena occur when the system is hydrostatically stable or neutrally stratified, and the vertical density difference actually increases (rather than decreasing as it does with mechanical mixing); and the rates of convective transport can be large, even though the ultimate cause is molecular diffusion.

Line sources of fluid released continuously into a density gradient also behave quite differently depending on their composition relative to the environment [1]. A dyed source of salt solution released into a salinity gradient just spreads as a single intrusion at its own density level. However when a sugar source having the same density and flowrate is injected into the same salinity gradient there is strong vertical convection near the source (due to the same double-diffusive separation process observed in a homogeneous environment), but the vertical spread is now limited by the stratification. Several intrusions spread out at levels above and below the source; since these contain an excess of sugar, diffusive interfaces form above them and salt fingers below, and there is a slight upward tilt to the layers as they extend, implying that the net density flux due to fingers is larger than at diffusive interfaces.

Horizontal property gradients When the side-wall boundary conditions do not match those in the interior of a fluid containing several diffusing properties, instabilities can develop without the injection of any fluid from a source. The heating of a salinity gradient through a vertical side boundary produces a series of equally-spaced extending layers. Similar effects are seen when one wall of a tank consists of a solid block of a soluble salt, and this dissolves into a gradient formed using another salt with a different molecular diffusivity. Turner and Chen [2] investigated the equivalent process in a sugar-salt system by setting up a stable density gradient composed of smooth opposing gradients of salt and sugar solutions, with a maximum of salt at the top and of sugar at the bottom. With vertical side walls the system was stable since the surfaces of constant concentration were normal to the boundaries and the no-flux condition was satisfied. When a sloping boundary was inserted, however, diffusion distorted these surfaces and upset the hydrostatic equilibrium, producing counterflows parallel to the slope and intrusions propagating into the interior. Huppert and Turner [3] have studied the melting of ice into a salinity gradient, a case where both temperature and salinity are unmatched to the interior properties. Colder, fresher intrusions extended into the ambient fluid along the whole depth of the vertical ice wall; no fresh water at all reached the surface, showing that this is not a practical way to 'harvest' fresh water from icebergs.

Fronts Conditions at oceanic fronts have been modelled using a geometry which removed the solid wall present in the above experiments. Ruddick and Turner [4] set up identical vertical density gradients on either side of a vertical barrier, using salt solution on one side and sugar on the other . When the barrier was removed the large horizontal salt and sugar gradients drove a series of inclined intrusions across the front, consisting of layers of fingers separated by diffusive interfaces, with velocity and scale both proportional to the horizontal gradients at the depth of the layer. Recent work [5] has led to a greatly improved understanding of this phenomenon, using the concept of continuous hydrostatic adjustment. Intrusions driven by temperature and salinity differences showing the same features as this salt-sugar analogue system (including a systematic tilt) have been observed in the ocean. Note a remarkable general implication of these (and other oceanic measurements). Not only can differential molecular diffusion across interfaces affect the convective motions on the layer scale (tens of metres in the vertical) but it can also, by driving intrusions across fronts, influence the large-scale mixing between oceanic water masses.

Sloping layers produced by 'diagonal' gradients Two other previous experiments will be discussed in more detail, since they provide a direct laboratory analogue of the extensive series of layers documented in the C-SALT observations, and summarized by Schmitt [6]. That study revealed very strong temperature and salinity steps in the main thermocline over an area of 1 million sq km, separating well-mixed layers 5-30m thick. The vertical T and S

gradients were in the finger sense, and indeed sheared fingers were observed in the interfaces. The layers had strong horizontal coherence and persisted over several years; they were warmer, saltier and denser in the north, and cooler fresher and lighter in the south. They had a systematic slope, and the property gradients can be interpreted in terms of a constant lateral density ratio $T_x/S_x = 0.85$. Thus we have called the overall gradients 'diagonal', in the sense that they have both vertical and horizontal components.

Schmitt compared this system to tilted sheared layers described in the exploratory paper by Turner and Chen [2] already citeerred to. While a long tank was being filled from the top with vertical gradients of sugar and salt in the finger sense (salt stable, sugar unstable), shearing motions were observed which sometimes broke down to form well-mixed layers. Usually the filling took place using the 'double-bucket' technique and three floats extending over the whole of the surface to make the distributions as uniform horizontally as possible. But when only a single float was used at one end of the tank, horizontal as well as vertical gradients were set up and these generated the strongest shears.

A subsequent experiment carried out during the 1974 GFD Summer Program, and documented with a movie, is even more directly related to the C-SALT observations. The experimental tank was constructed with three compartments, separated by horizontal barriers which extended along most of the length but leaving small gaps, with removable covers, on the right of the upper and on the left of the lower barrier. In a typical run the bottom compartment was filled with salt solution, the centre with crossed gradients of sugar and salt in the finger sense, and the top with sugar solution. When the covers were removed to allow communication between the three compartments, diagonal gradients of salt and sugar were set up. These rapidly produced strong shearing motions in the central fingering region, leading to breakdown and the establishment of inclined well-mixed layers. Several variations on this experiment were also studied, including starting with three or four layers in the central chamber rather than a continuous gradient, and with stratification in both the finger and diffusive senses.

2 Heating and evaporation on a shelf

We turn now to some more recent laboratory experiments designed to model smaller scale oceanic processes, the circulation on a shelf or in an estuary.

In this case the heat-salt system was used directly; of particular interest was the 'inverse estuary' in which horizontal temperature, salinity and density anomalies are set up by heating and evaporation at the shallow end. The experiments [7] were all carried out in a tank 1.8 m long, 80 mm wide and 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 500 mm long plane with a slope of 1:30, placed so that the minimum depth over the shelf was about 10 mm, with a curved transition region leading to a slope of 450 inclination. 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 held device to keep the depth (and thus the mean salinity) constant. There was no mechanical mixing on the shelf, and the motions were two-dimensional.

Typically, steady counter-flows developed near the surface less than 30 min after the heating was begun, and these were observed using dye streaks. There was a warm, salty outflow from the shelf and below this a return flow, with strong salt-finger convection between these layers. These fingers deposited denser fluid on the slope and this produced a flow down the slope and out along the bottom, leading in time to a strong stratification of T and S (in the 'diffusive' sense) and intrusions at various levels. This was quantified using thermistor profiles and direct density measurements on samples withdrawn at various depths. A second mechanism of 'bottom water' formation was also apparent in several runs, namely the direct flow of hot very salty water off the shelf and down the slope. This could be initiated more predictably by turning off the heater lamps.

A direct comparison with the ocean has been made using unpublished CTD data from the Australian NW Shelf, kindly supplied by Dr Peter Holloway, of the Australian Defence Force Academy. Five salinity profiles obtained at various positions across the shelf and down the slope in depths ranging from 162m to 1382m, show features which can only be interpreted in terms of the processes described above. The temperature gradient was strongly stable at each station, with the highest T at the surface and superimposed fluctuations and reversals of gradient associated with saline intrusions. There was a clear well-mixed salty (and hot) surface layer in each profile, and at 162m depth also a salinity maximum near the bottom, consistent with the deposition of salt by salt fingers. Further offshore, in a depth of 302m, a thicker intrusion had developed, leaving the slope some distance above the bottom. Its salinity was greater than the surface value at this position, so it must have formed higher up the shelf. The profiles in deeper water, extending a further 50km off shore, showed a thickening of this outflowing layer, extending away from the slope at a depth of about 200m.

3 Horizontally separated buoyancy sources in a long tank

Another oceanographic phenomenon will be described first, to provide a further specific motivation for the laboratory experiments to be described next. Observations in the Arctic Ocean since 1990 have shown that a major and continuing warming has taken place, due to the influx of anomalously warm waters from the Atlantic. The transition is occuring via persistent multiple intrusions, 40-60 m thick, extending laterally in a coherent manner through the Atlantic water and upper deep waters of the Arctic. The distributions of T and S can support both diffusive and finger convection, and it seems highly probable that the layers are self-organizing and self-propelled by double-diffusive transports.

Most of the experiments in this series were carried out in a tank 750mm long and 75mm wide, filled to a depth of 150mm. Sources of fluid with different densities and/or compositions were supplied near the two ends, and flowed in at different depths in the several experiments, at constant rates controlled by a peristaltic pump. The depth was kept fixed using a constant head overflow pipe at the centreline, with its inlet also at different depths. A 'control' experiment was conducted, with homogeneous salt solution in the tank, S.G. 1.11, and two sources of salt solution, one lighter (S.G. 1.10) and one denser (S.G. 1.12) than the tank fluid, flowing in at the same rate (5.3 ml/min) near the surface at the two ends; the overflow was also near the surface, in the centre. As the stratification evolved, the fluid at the bottom became steadily denser, while that at the top at first became lighter, citelecting the density of the lighter input, and then denser again, eventually reaching the mean density of the two inputs. Note also that the density range in the tank never went outside that of the two inputs in this experiment. In a non double-diffusive system, with ordinary turbulent mixing, there is no mechanism for it to do so.

These results clearly cannot explain the Arctic observations described above. However when one salt source (S.G. 1.104 , fed in at the bottom) and one sugar source (S.G. 1.100 , fed in at the top at the other end of the tank), were injected into a tank containing a 50:50 mixture the behaviour was very different from the salt/salt case. The density of the bottom fluid increased steadily and rapidly became greater than that of the input, and at first the top became lighter for the same reason. As the withdrawal of fluid (from the top in this case) became more significant the overflow density again approached the mean density of the inputs, but the final vertical density difference was much larger than the original small difference between them. Dye streaks revealed vigorous double-diffusive intrusive motions, with the level of the outflows changing in time in response to the evolving density structure.

An instructive series of runs was conducted under nominally identical conditions, but making different measurements in each run. The tank fluid was salt solution S.G. 1.11. The inputs and withdrawal were all near the top, with the salt input being a denser turbulent plume S.G. 1.12, and the sugar at the other end laminar and lighter, S.G. 1.10. The time history of intrusions and plumes was monitored using photos and video recordings of dye streaks. Initially the salt outflow along the bottom behaved as it would in a non D-D 'filling box', while there was vigorous convection near the sugar input. A sugar-rich intrusion moved across the top of the outflowing salt (the bottom water) and in fact this is a good analogue of the Mediterranean outflow, with fingers forming below it. Polarimeter records (of the total sugar in a light beam shone through the tank) showed fluctuations with a 45-60 min timescale, corresponding to the passage of fronts, confirming the observations made using dye streaks. Samples were withdrawn at discrete times and various positions and depths and their citeractive index measured. These values were inverted using the Ruddick and Shirtcliffe results [**?**] to give the separate salt and sugar contributions to the density, and they showed that the vertical differences over the bottom half of the tank evolved from the initial finger sense to the diffusive sense after several days, with excursions due to the passage of fronts.

Three closely related experiments were monitored over many days using the analysis of withdrawn samples. These all started with the tank fluid and the input salt and sugar solution having the same density (S.G. 1.10), and both inputs and withdrawal at mid-depth. The only difference was that in the three experiments the tank fluid was pure salt, pure sugar or a 50:50 mixture, respectively. The most remarkable result is that although the detailed behaviour and rate of evolution was very different, specially in the early stages when the sources produced a different local double-diffusive behaviour, all three runs evolved to the same asymptotic state. The top to bottom density difference increased steadily over time, reaching an asymptotic maximum after about 100 hours of approximately 0.05 g cm^{-3} (and remember that there were no density differences at the start). In about 20 hours a clear two-layer structure had developed, with a sharp interface at mid-depth and weak gradients above and below this. Strong shears and intrusive motions persisted, however, even when the mean density was no longer evolving. In the 'final' state the overall salt distribution was unstable, with a slightly higher value in the top layer, while the sugar was strongly stable. The sugar concentration in the top layer was lower than the two salt concentrations, and in the bottom layer it was larger than either salt concentration. The energy to drive the continuing intrusions must be provided in some way by the unstable salinity distribution.

The 'final' distributions in all three experiments in fact corresponded quite closely to the 'rundown' state of a two-layer diffusive system, with a flux ratio of 0.475 if the asymptotic state is interpreted as resulting from the one-dimensional transport through an interface between a layer of salt solution placed above a layer of sugar solution of the same density and depth. It could not be achieved by rundown across a finger interface, which leads to a much smaller density change. Clearly the approach to this condition of minimum potential energy has been reached via much more complicated intrusive processes, and is different in the three cases. Local vertical convection near each of the sources must also play an important role, and the detailed interpretation of the evolution requires further work and thought.

4 Conclusions

All of the laboratory experiments discussed above, when they are compared with the corresponding ocean observations which motivated the studies, show that double diffusion plays a vital role in interpreting the data. Density differences alone are not enough, nor are one-dimensional D-D transports; the intrusive motions observed must be driven by horizontal gradients of T and S. I hope that sea-going oceanographers will become more aware of these novel phenomena, and look for regions where further examples may be found and interpreted in terms of two-dimensional double-diffusive processes.

References

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