GEOPHYSICAL FLUID DYNAMICS

Geophysical Fluid Dynamics is the study of fluid flows and their roles in transporting heat, mass and momentum in the Earth’s hydrosphere, crust and deep interior. In the Research School of Earth Sciences, the research in this field is focussed on the exploration of physical processes of importance in three different areas: convection, mixing and circulation in the oceans; magmatic and volcanic processes; and the convection of the solid silicate mantle, with its implications for plate tectonics. The Geophysical Fluid Dynamics Group continues to emphasise the importance of dynamical modelling and a rigorous understanding of the underlying dynamical principles. Much of the research program is anchored strongly in experimental fluid dynamics and relies on laboratory facilities. A new purpose-built laboratory was occupied in 2000 and this year became fully operational (Figure 1). The research relies also on advanced computing facilities within the Research School and the Australian Partnership for Advanced Computing National Facility located at the University.

![Figure 1: Work in the recently opened Geophysical Fluid Dynamics laboratory, showing apparatus being used to study cooling and solidifying channel flows and the dynamics of basaltic lava channels.](image)

The research topics in Geophysical Fluid Dynamics this year include aspects of both the wind-driven upper ocean circulation and the buoyancy-driven thermohaline circulation of the oceans. Numerical modelling of circulation in a simple laboratory model driven by a surface wind stress continued, with the appointment of an Australian Postdoctoral Fellow, Dr A.E. Kiss, and an emphasis on the generalisation of an approximate mathematical formulation of the equations of motion suitable for numerical solution. A new PhD student, Ms J. Mullarney, joined the study of convective circulation driven by a horizontal gradient of surface heat flux and a freshwater (or salinity) input. The work has shown oscillatory behaviour for steady forcing, specifically for some values of the ratio of heat and freshwater buoyancy fluxes. Dr A.A. Bidokhti continued his nine month sabbatical leave from Tehran University and examined the structure of outflows from the Persian Gulf and Red Sea. He completed laboratory experiments with turbulent and double-diffusive (warm, salty) outflows, the results of which suggest that low-frequency internal gravity waves propagating downward in the water column may influence the observed vertical splitting of the outflows. Another visitor, Dr J.R. Taylor, spent five months in the Group on sabbatical leave from the University of New South Wales at the Australian Defence Force Academy, and carried out laboratory experiments modelling the formation and propagation of fronts in the atmospheric boundary layer resulting from differential surface
heating over plateaux or escarpments. The results have been used to interpret data for inland propagating fronts over the highlands of south-eastern Australia.

In the area of mantle dynamics, Dr G. Davies has continued his modelling of the stirring of chemical heterogeneities in the convecting mantle driven by internal heating and the subduction of lithospheric plates. The modelling has predicted mean isotopic ages of mid-ocean ridge basalts of two billion years, which is much older than previous modelling had suggested and consistent with measured ages. If subducted oceanic crust is given a small mass anomaly in the new models, there is consequently a small degree of buoyant settling of this material and the models predict the depletion of mid-ocean ridge basalts, relative to ocean island basalts, in incompatible trace elements. Novel experiments, in this case in the laboratory, have also been carried out, by Professor R.W. Griffiths and Dr R.C. Kerr, to understand rapid basaltic lava flows in channels. These experiments form part of collaborative work with volcanologist Professor K.V. Cashman from the University of Oregon, and involve measurement of flows of fluid down a long sloping channel while it is solidifying at its surface (Figure 1). This work is at an early stage, but has already indicated a criterion for formation of lava tubes rather than open lava channels. It also demonstrates the usefulness of fluid dynamics experiments as a tool with which to learn more about the processes that govern cooling, solidification and flow front advance in lava flows.

The staff of the Group was complemented this year by Mr C.J. Morgan, who joined us as a Senior Technical Officer. Mr M. Wells submitted his PhD thesis, received his doctorate, and took up a research position in fluid mechanics at Eindhoven University of Technology, The Netherlands. Two long term visitors Dr J.R. Taylor and Dr A.A. Bidokhti have been mentioned above and the Group continued to enjoy the presence of Emeritus Professor J.S. Turner. The staff, students and visitors all acknowledge the vital contributions of our technical and administrative support staff, R. Wylde-Browne, A.R. Beasley, C.J. Morgan and F.A. Chivas, to our research program. Collaboration continued with Australian Scientific Instruments, who received a further order for the ‘Geophysical Fluids Rotating Table’.

**Inclined turbulent fountains**

*R.C. Kerr and L.J. Bloomfield*

Inclined turbulent fountains are formed when a continuous jet of dense fluid is injected rapidly upwards into a less dense environment, or when a continuous jet of buoyant fluid is injected rapidly downwards into a denser environment. They arise in a number of important situations both in engineering and in nature, including: the forced heating or cooling of aircraft hangars, buildings or rooms; the disposal of brines, sewerage and industrial waste into the ocean; the improvement of water quality by forced mixing in reservoirs, small lakes and harbours; vehicle exhausts and accidental leaks of hazardous gases; the evolution of volcanic eruption columns; the replenishment of magma chambers in the Earth’s crust; and the exit snow from snowploughs.

Motivated by these diverse applications, we have explored the dynamics of turbulent fountains in a number of experimental and theoretical studies over the past six years. In particular, extensive investigations have been made of both axisymmetric and two-dimensional fountains in homogeneous environments, in stratified environments, and in environments with confining boundaries. In this latest study, we have examined experimentally the effect of the angle of inclination of the source on the behaviour of turbulent fountains in both homogeneous and stratified environments (Figure 2).

In a homogeneous environment, the initial fountain height was found to decrease monotonically as the inclination was increased, due primarily to the decreased vertical momentum of the source fluid. In contrast, the final fountain height was also affected by the

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turbulent interaction between the upflow and downflow, which decreased rapidly as the inclination was increased. As a result, the final height was found to increase, and then to decrease, as the inclination was increased. The maximum height of the fountain was found to occur at an angle of about 10 degrees, at which point the fountain was about 20% higher than the height of a vertical fountain.

In exploring the behaviour of inclined turbulent fountains in a stratified environment, we first examined the limiting case of zero buoyancy flux at the source. We found that the effect of inclination angle on both the fountain and the spreading heights is small, although there is some suggestion of a maximum in both heights at about 10 degrees. The small variation in this case was explained as being due to both the weak (1/4 power) dependence of the fountain height on the source momentum flux and the weak turbulent interaction between upflow and downflow. We then quantified the initial, final and spreading heights for a fountain inclined at 10 degrees, as a function of the strength of the stratification in the environment. In particular, we determined the stratification required for a maximum spreading height or a zero spreading height.

Figure 2: Photographs of turbulent axisymmetric fountains formed from a source inclined at 10 degrees to the vertical, in a homogeneous fluid (left), and in a stratified fluid, for the limiting case of zero buoyancy flux at the source (right).

Surface solidification in long channelized lava flows

R.W. Griffiths, R.C. Kerr and K.V. Cashman²

In a new project begun this year we are exploring the behaviour of basaltic lava flowing through large channels, with a view to predicting the distance that lava travels. Molten basaltic lava from large eruptions on volcanoes such as Hawaii is often channelled into rapidly-flowing rivers of melt. Channels are commonly 10—100 m wide and of the order of 10 km in length, with the flow being 2—10 m deep during its active period. Much longer channels, up to 750 km, were important in transporting lavas from large prehistoric flood basalt eruptions and spreading them over broad areas of the Earth. Lava tubes, channels that become fully encased in solidified lava, are also common. Tubes arise when the lava surface solidifies and forms a connected roof over the flow. The roof greatly reduces the rate of heat loss and hence enables

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the lava to flow much greater distances than would be possible if the roof were continuously
disrupted. The dynamics of solidifying channel flows thus influence the surfacing of much of
the Earth’s crust. These dynamics may be central to the interpretation of the geological evidence
and estimates of the rates and volumes of prehistoric eruptions. We therefore search for an
understanding of the relationships between eruption conditions, the form of lava flows and the
distances they spread. Similar questions arise in attempting to infer the geological histories of
Venus, Mars and the Moon from remote images of their surfaces.

The physical processes that govern the formation of channels and the continued flow
through them are complex, and involve the interaction of fluid and solid mechanics. Even small
amounts of solidification on the surface will influence the rate of cooling of the flow. Rapid
crust formation tends to insulate the flow and strongly affect the morphology of the flow front,
as in the case of Hawaiian pahoehoe flows (Figure 3). In the first stage of a new study of
channel flows, and in collaboration with volcanologist Professor K.V. Cashman of the
University of Oregon, we are using laboratory fluid dynamics experiments with a material that
serves as analog to lava. In the experiments polyethylene glycol wax flows under cold water
down a 3m-long, sloping channel. Our flows are laminar, having Reynolds numbers of 0.2—
70 based on flow depth and centre-line speed. For a constant source volume flux we have found
two steady state regimes, depending on the flow velocity and the temperatures of the wax and the
water relative to the freezing temperature of the wax.

![Figure 3: Professor Griffiths examining the rheology of freshly exposed melt in a Hawaiian pahoehoe flow.](image)

For sufficiently high flow speeds and temperatures a solidified surface crust develops in
the centre of the laboratory channel at some distance from the source (Figure 4) and is carried
downstream. This crust remains separated from the walls by shear regions in which solid phase
is continually forming but fragmented into small pieces by the shear, before being carried down
into the interior of the flow by convection currents. At lower flow speeds and temperatures
solidification creates a stationary roof and flow continues through an insulated tube beneath
(Figure 4). Our initial results indicate that the condition for tubes is $U_0t_s/W < 0.75 \pm 0.2$, where
$U_0$ is the surface speed without cooling at the centre-line, $t_s$ is the predicted time for onset of
solidification in an idealised initial-value problem and $W$ is the channel width. Time-dependent
behaviour occurred under conditions near the transition from open channel to tube flow. We
also found that small non-uniformities in the channel that increase flow speed can promote open
channel flow, while large irregularities in the channel width tend to cause the formation of tubed
flow.
Oscillations in models of the ocean thermohaline circulation

R.W. Griffiths and J.C. Mularney

A new laboratory model designed to help us understand the processes that control the strength and patterns of large-scale overturning circulation in the oceans has begun to yield results. The experiment follows up a much earlier recognition that thermohaline circulation of the oceans is forced by the meridional gradient of surface heat flux, and modified by surface water fluxes. Our experiments involve a long channel that is heated and cooled non-uniformly along its base, thus turning the ocean upside down. The heat flux gradient forces a large-scale convective circulation which includes a stable thermal boundary layer, similar to the upper ocean thermocline, and deep convection strongly confined to a small region at one end of the tank. We introduce a small flux of more dense salt solution at one bottom corner in order to model the input of buoyancy by relatively fresh water at the surface of the ocean at high latitudes.

Figure 4: Overhead photographs showing the two apparently steady state regimes of surface solidification in a channel flow cooled from above. The upper photograph shows a mobile central crust with lateral shear zones when $U_{\theta t}/W = 2.2$. The lower photograph shows tube flow when $U_{\theta t}/W = 0.43$. Solid wax is white, liquid PEG is transparent and the base of the tank is painted black. Flow is from left to right. The photographs correspond to distances from the entrance sluice gate of 0.5m to 1.1m and 0.2m to 0.8m, respectively.

Figure 5: An example of temperature records from the laboratory experiment with thermal and salinity buoyancy fluxes in a ratio that leads to oscillatory behaviour. Three records shown are from thermistors fixed 1cm above the base in the bottom boundary layer of the flow and (1) within the warm, salty bottom layer near the salt input, (2) at the centre of the heated base, (3) at the centre of the cool base. Record (4) is from the flow near the top of the tank.
Using prototype apparatus we have begun to map out in parameter space a number of different flow regimes. We have also shown that an unstable convectively mixed layer, not unlike the surface mixed layer of the ocean at high latitudes, forms above the heated portion of the boundary. The salinity flux leads to another mixed layer and a stable interface (or halocline) within the thermal boundary layer. There are conditions under which the circulation is essentially steady, conditions under which the halocline periodically breaks away (Figure 5) and conditions under which oscillations give way to a stable salty layer that floods the entire base. The latter case leaves a strongly layered ‘ocean’ with little transport between the forcing surface and the bulk of the water depth. The temperature evolution has been monitored (Figure 5), and we have developed a means of observing and measuring, using ‘synthetic schlieren’, the (two-dimensional) distribution of refractive index gradient, hence density, throughout the entire tank.

**Modelling thermally driven circulations in the atmosphere**

*J.R. Taylor*

Similar differential heating and cooling phenomena to those that drive the ocean thermohaline circulation are also important at much smaller scales in the atmosphere. They result in local winds such as sea breezes and plateau winds. The Canberra summertime easterly is a local example of this type of flow. However, in contrast to the ocean, the daily cycle of heating and cooling at the Earth’s surface and the resulting change from stable to unstable conditions in the boundary layer result in complex unsteady circulation systems. Buoyancy, inertial forces and turbulent friction all play important roles at different stages. Particularly interesting is the formation and acceleration of an inland-propagating afternoon wind surge.

An unsteady differential heating experiment has been set up in the GFD laboratory to model frontal development in a diurnally forced plateau circulation system. The main dynamical regimes of the flow can be adequately delineated by simple scaling arguments. However, measurements of the velocity field from particle imaging velocimetry and the temperature field from rapid thermistor traverses give a more detailed picture of the frontal development process. The laboratory results will help in the interpretation of atmospheric observations and the design of future field experiments.

**Damping of internal gravity waves**

*G.O. Hughes*

In stratified environments such as the atmosphere and oceans, internal gravity waves are commonly generated when the density field is disturbed from equilibrium. These waves transport both energy and momentum vertically, and are an important means of coupling the motion at different levels in a stratified flow.

In most geophysical flows the internal gravity wave field is subject to damping by the stresses arising from background turbulence. To help understand the evolution of such wave fields I have used laboratory experiments in which the damping is due to viscosity. Sufficiently strong damping is observed to both attenuate the wave amplitude with distance from the wave source and to modify the intrinsic frequency/wavelength of wave motion. Measurements of the wave field (Figure 6) have been compared with existing inviscid theory and with a theory developed last year that incorporates damping due to viscosity. The experimentally observed wave field is much better predicted by the theory that incorporates viscous damping. Damping has been found to be particularly important for internal waves with low excitation frequencies — up to at least $O(10^{-2})$ of the maximum frequency — over a wide range of experimental conditions.

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Figure 6: Comparison of theoretical predictions and experimental measurements for strongly damped internal gravity wave fields. The dimensionless vertical phase velocity $w_a'$ of a wave mode is plotted as a function of dimensionless vertical wavelength $\lambda/H$: —— inviscid theory; + and O, experimental measurements for two different levels of damping; ········· and ———, damped theory corresponding, respectively, to the two levels of damping.

Internal waves as a source of finestructure at ocean fronts

A.A. Bidokhti$^4$ and R.W. Griffiths

Laboratory experiments carried out during the year have shown that vertically travelling internal gravity wave modes excited by outflows from marginal seas can produce counter-flowing shear layers that may split up the outflows into a series of counter-flowing interleaving layers. Turbulent plumes of relatively dense waters commonly flow out of marginal seas such as the Mediterranean Sea, Persian Gulf and Red Sea, and tumble down the sloping bottom until they reach a depth at which they become neutrally buoyant. There the water intrudes into the surrounding ocean, forming a large mass having anomalous temperature and salinity. These intrusions are found to be rich in finestructure, with temperature and salinity gradients broken into many uniform layers and sharp interfaces. Similar finestructure is common at temperature-salinity fronts (regions of large horizontal temperature and salinity gradient but with little or no density gradient) in the open ocean where two water masses meet.

The fine-scale layering has commonly been attributed to the action of thermohaline convection, which draws on the vertical gradients of both temperature and salinity and produces density ‘staircases’. Our new experiments with plume outflows into a density-stratified tank of salty water show that a series of counter-flowing horizontal layers can be formed even in the absence of thermohaline convection. These layers are forced by excitation of a preferred internal wave mode. This mode propagates downward while being advected upward from the depth of the outflow and its phase is therefore nearly stationary in the water column. In other experiments using two turbulent dense plumes at opposite ends of a large channel, we have formed a density front near the centre of the channel and again observed the generation of strong counter-flowing horizontal shear layers. These layers cause interleaving of the water from each side of the front, and are qualitatively similar to the interleaving layers found in the oceans. When the two plumes have differing temperatures and salinities, the front separates two distinct

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water types and the interleaving layers are modified slightly by thermohaline convection. However, their vertical scale is not altered by the convection. We propose that low-frequency internal wave modes in the oceans excited by a variety of sources may be responsible for establishing the scale of interleaving layers in ocean fronts and plume outflows.

**Dynamics of ocean circulation driven by surface wind stress**

*A.E. Kiss*

At mid-latitudes the large-scale mean horizontal circulation of the upper ocean is dominated by recirculations (“gyres”) which are driven by the surface wind stress and span the width of ocean basins. The gyre circulation consists of a broad, slow flow in most of the basin (towards the equator in subtropical gyres). This flow is returned by a narrow, rapid boundary current at the western side of the basin and which separates from the coast as an unstable meandering jet. The Gulf Stream in the northern Atlantic is the best-known western boundary current, but similar currents are found in all ocean basins, and the local example in the southwest Pacific is the East Australia Current. The western boundary currents (WBCs) of subtropical gyres form an important part of the global climate system by carrying a large amount of heat from subtropical to subpolar latitudes. The flow in WBC separation regions is highly energetic, and strongly variable on timescales of a few years to a few decades; this variability is thought to be an important factor in climate fluctuations.

In June I commenced an ARC Postdoctoral Fellowship to investigate the dynamics of WBC variability through the application of simplified laboratory and numerical models which capture the essential physical processes controlling the wind-driven circulation. This research builds on my PhD work to explore the modes of instability and their dependence on parameters such as the strength of the wind forcing. Steady wind forcing has been employed in the initial stage to map out the stability boundaries in parameter space, prior to an investigation of the influence of time-dependent forcing. This study also explores the effects of steeply sloping topography such as continental slopes, which form the lateral boundaries of ocean basins. Such large relative depth variations preclude the use of standard quasigeostrophic equations to describe the flow. I developed a modified formulation during my PhD, which permits large depth variations but retains the simplicity and most of the conservation properties of the usual quasigeostrophic equations. The scope of applicability of this formulation has been investigated in greater detail this year in preparation for its use in further modelling.

**Plume zonation**

*C. Mériaux*

Basalts from hotspot ocean islands, such as the Hawaiian and Galápagos Islands, are widely attributed to melting of mantle plumes, which likely ascend from the core-mantle boundary layer. While it has long been recognized that lavas in these islands have different compositions, different geochemical domains across the hotspot tracks have now been identified and found to be persistent along the hotspot track. Complex processes related to partial melting and melt migration can produce some geochemical variability, but they do not explain all of the observations. Thus, many geochemists believe that the variability within oceanic islands basalts also reflects a source characteristic.

A series of laboratory experiments has been undertaken to assess whether a distribution of “heterogeneities” entrained in a plume conduit sheared by plate motion will maintain its identity. For transport in a vertical conduit, we expect simple stretching and thinning of heterogeneities. When horizontal shearing motion is superimposed on the buoyancy-driven vertical motion, the conduit is carried horizontally, becoming bent over. This leads to a complex recirculation in the conduit and entrainment of surrounding fluid. Thus “heterogeneities” at the source can be stirred, possibly to the extent that heterogeneities observed at the surface might no
more reflect their distribution at the source. The amount of stirring depends on the buoyancy flux of the plume and the imposed shear, which together determine the angle of tilt of the conduit. In the experiments, a slowly rotating lid drives horizontal motion in a cylindrical tank of glycerol 60 cm in diameter and 24 cm deep. A hot plume is generated by an electrically heated pad 10 cm in diameter on the tank base. Two small tubes filled with dyed glycerol were set at diametrically opposite positions on the heated pad relative to the plume origin and perpendicular to the shear direction. The flow can be characterised by a Rayleigh number and a ratio of the lid velocity divided by the ascent velocity.

Figure 7: View from the top of a steady tilted plume conduit in a shear flow. Two streams of dyed glycerol are entrained into the plume within the heated bottom boundary layer (Rayleigh number $1.4 \times 10^{10}$ and velocity ratio 0.4).

We find that tracers from opposite sides of the source region are gently stirred within the tilted conduit, but remain separated on opposite sides of the vertical plane through the axis of the conduit. Near the surface lateral spreading of the conduit further separates the two streams (Figure 7). For Rayleigh numbers larger than $10^{10}$ and velocity ratios less than 0.6 the extent of wrapping of dye tracers within the conduit by the time the tracers reach the surface is insignificant. Three-dimensional numerical modelling of the problem is currently being tested using the software package ‘FLUENT’.

Stirring of chemical tracers by mantle convection

G.F. Davies

Work on this project has progressed well since a preliminary report last year. Stirring of tracers simulating a basaltic component has been studied in models (Figure 8) that feature stiff surface plates and subducting lithosphere, migrating subduction zones and a higher-viscosity lower mantle. An important innovation has been to take account of the likelihood that the mantle was turning over faster in the past, because radioactive heat sources were stronger. This was done by running the models for the equivalent of 18 Ga at present rates, and re-scaling the tracer ages. Chemical differentiation associated with melting was simulated by partitioning tracers into an oceanic crust as they entered a melting zone defined by a prescribed depth of first melting. The melting depth decreased with time, to take account of mantle cooling.

The most striking result of these computations is that the mean age of simulated mid-ocean ridge basalts (MORBs) is routinely greater than 2 Ga. This contrasts with previously published
models, which have yielded ages much less than the apparent ages of lead isotope heterogeneties, which are approximately 1.8 Ga. Since there are several reasons why the new exploratory models might have over-estimated the ages, the models open the way to matching the observations and remove the need for *ad hoc* layering to explain the isotopic ages.

Assigning a positive mass anomaly to the tracers, to represent excess density of subducted oceanic crust, causes depletion of the tracer concentration in the upper-most mantle and a modest accumulation of tracers at the base of the mantle. These effects can explain the depletion of MORB, relative to ocean island basalts (OIBs), in incompatible trace elements.

![Figure 8](image)

*Figure 8*: The pattern of tracers after stirring in a model of the mantle for the age of the earth. (a) The tracers, plotted as black dots, with tracer-depleted zones representing melt residue. The tracers are plotted over a background shaded according to viscosity, darker representing higher viscosity. Tracers that have passed through the lowermost 20km of the mantle are plotted as white dots, and are evident as columns rising from the base. (b) Temperature (grey scale) and streamlines at the same time as (a). There are two plates, left and right, approaching and subducting under a notional continental plate in the centre. Subducted lithosphere has high viscosity because it is colder, and it buckles as it enters the lower mantle, whose viscosity is ten times greater than the upper mantle.

In these models, OIB is assumed to be produced by plumes that rise from the base of the mantle, so that each plume samples the lowermost mantle. The mean age of the OIB sample increases as the mass anomaly of tracers increases. With zero mass anomaly, the mean OIB age is less than the MORB age, and a modest but plausible mass anomaly yields a mean age comparable to the MORB mean age. The reconciliation of geophysical and geochemical observations of the mantle has been puzzling and controversial, and these results show that models that include reasonably realistic plates, a moderately-high-viscosity lower-mantle and the faster overturn of the mantle in the past show great promise.
Double-diffusive plumes in a homogeneous environment

J.S. Turner

In experiments described in last year’s report Turner and Veronis used horizontally separated point sources of salt and sugar to study the structures and motions generated by compensating horizontal and vertical gradients of T and S in the ocean. This system, with the more rapidly diffusing salt used as the analogue for heat (T) and sugar as the analogue for salt (S) has proved to be a very effective method of studying double-diffusive processes. It was shown that, starting with equal densities of the homogeneous tank fluid and both the input solutions, the asymptotic state (after about 100 hours) was the same when the experimental tank contained either homogeneous salt or sugar solution initially. In both cases large vertical density and property differences developed, with a weakly unstable salt and a very stable sugar distribution (corresponding to cold fresher water over hot salty water in the ocean, the ‘diffusive’ state). The early behaviour in the two cases was different, however, and the current work seeks to explain this and its effect on the overall evolution.

The new experiments demonstrate that this difference arises because the individual input plumes are not completely equivalent (or even antisymmetric). Salt diffuses rapidly out of a saline plume in a tank of sugar solution 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. With equal densities these two transports of salt in a sugar environment are nearly equal, while for a sugar source in a salt tank there is a larger flux of sugar downwards; the fluxes only become equal when the input is much lighter. This bias towards the production of diffusive vertical property distributions near one source, combined with continuing horizontal interleaving motions that allow communication between the two sources, is consistent with the asymptotic state observed in the previous two-dimensional experiments.