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Flux measurements across a finger interface
at low values of the stability ratio

by Trevor J. McDougall[1,2] and John R. Taylor[1]

ABSTRACT

We present the results of laboratory experiments across a sharp finger interface using heat and salt as the properties which contribute to density. Values of the stability ratio R_ρ as low as 1.2 were achieved so the results approach the range of R_ρ which is of interest in the ocean. The buoyancy flux ratio, corrected for vertical heat conduction, R_f^* was found to depend on R_ρ, but at $R_\rho = 1.2$, R_f^* is still only 0.65 ± 0.1. Values of Stern's number

$$A = \frac{\beta F_S (1 - R_f)}{\nu(\alpha T_z - \beta S_z)}$$

were found to depend on the magnitude of the step in salinity across the interface as well as on R_ρ. Most of our experiments were performed with small contrasts in salinity between the layers and Stern's number was found to increase as this salinity difference decreased. On the basis of our measurements of A, we believe that pure vertical heat conduction will not be significant in the ocean.

1. Introduction

Many of the sites in the ocean where double-diffusive convection has been shown to be important (Joyce *et al.*, 1978) occur at frontal boundaries between water masses (Huppert and Turner, 1981). These regions are characterized by intrusions where the contrasts in density due to temperature and salinity are almost compensating. This

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1. Research School of Earth Sciences, Australian National University, GPO Box 4, Canberra City, A.C.T., 2601, Australia.
2. Present address: CSIRO, Division of Oceanography, GPO Box 1538, Hobart, Tasmania 7001, Australia.

balance is conveniently expressed by the parameter $R_\rho \equiv \bar{\alpha}\Delta T/\bar{\beta}\Delta S$ where $\bar{\alpha}\Delta T$ and $\bar{\beta}\Delta S$ are the contributions to density from the temperature and salinity differences. Laboratory measurements of the heat and salt fluxes across a finger interface have been made in the range $R_\rho > 1.6$ whereas the oceanographically relevant values of R_ρ are often much closer to 1. It is not clear that the laboratory flux measurements at higher R_ρ may be extrapolated confidently to lower values. The measurements reported in this paper attempt to redress this situation.

The quantity of most direct interest to oceanographers is the buoyancy flux ratio defined by $\bar{\alpha}F_T/\bar{\beta}F_S$, where F_T and F_S are the interfacial fluxes of temperature and salinity respectively. Since the characteristic feature of double-diffusive convection is the unequal vertical transport of salt and heat, the variation of R_f with R_ρ has important implications for the efficiency of double diffusion as a mechanism for cross-isopycnal transport in frontal intrusions. For instance, laboratory experiments show that for the diffusive mode of double-diffusive convection $R_f \rightarrow 1$ as $R_\rho \rightarrow 1$ (Turner, 1965; Crapper, 1975). Turner's (1967) measurements of R_f for fingers showed that it was constant in the range $2 < R_\rho < 10$ with a value of $0.56 \pm .02$. These experiments have been criticized because the interfacial fluxes were measured between periods of stirring by mechanically generated turbulence, resulting in an increase of the flux ratio due to sharpening of the interface. Linden (1973) performed conventional rundown experiments, using heat and sugar, and also found that the flux ratio was constant, although the value of 0.1 he quoted in a footnote to his paper was much lower than Turner's result. More recently Schmitt (1979) conducted a series of rundown experiments which included three determinations of the flux ratio for $R_\rho < 2$. These measurements gave an average value of $0.72 \pm .06$ for the range $1.5 < R_\rho < 2.0$. The buoyancy flux ratio value was not constant, but continued to decrease as R_ρ increased.

Our experiments were able to improve on these results mainly because of a unique tank which allowed the two fluid layers to be initially separated by a plastic barrier. This barrier was withdrawn horizontally to start the experiment, with little disturbance to the fluid interface. As well as allowing experiments to be started at low R_ρ the tank made it possible to use smaller temperature and salinity steps than had been used in the previous experiments.

2. Experimental procedure

The tank in which the experiments were performed is described in detail by McDougall (1981). The horizontal cross-section of the tank was 575 mm × 100 mm and the depth of each fluid layer was initially 225 mm. The essential feature of the tank which was necessary for the present experiments was the removal of the central polypropylene barrier at mid-depth. The procedure was to first prepare two solutions of

NaCl with the required salinities. The lower layer was put into the tank and the polypropylene sheet was slid into place. The upper layer was then placed in the tank above the polypropylene sheet. The temperatures of the layers were set *in situ* by bringing them to equilibrium with fluid from two baths at the desired temperatures circulating through a copper tube in each layer. Efficient heat transfer was ensured by mixing each layer with three rotating blades.

The sides of the tank were made of 12 mm thick perspex sheet and in order to reduce the conductive fluxes of heat between the room and the tank, the front and back faces of the tank were constructed as double perspex walls, with the sheets of perspex separated from each other by a 6 mm air gap. The side walls of the tank were insulated with 25 mm thick expanded polystyrene sheet.

After the layers had reached the desired temperatures, the pumps circulating water through the copper tubes were switched off, and then about a minute later the stirring propellers in both layers were also turned off. Approximately one minute later, when most of the turbulence in each layer had decayed, the experiment was begun by withdrawing the polypropylene sheet. This type of experiment is called a "run-down" experiment because in the absence of any external flux of heat or salt, the differences of temperature and salinity between the well-mixed layers decrease with time, although the density difference increases.

The temperature and salinity of both layers were measured as a function of time. The temperatures were measured using spatially averaging resistance thermometers consisting of 35 m of copper wire wound onto a perspex frame suspended at the mid-depth of each layer. Each thermometer formed one leg of a Wheatstone bridge. The out of balance voltage was calibrated directly as a function of temperature making it possible to measure the layer temperature to an accuracy of 0.002°C. Samples from each layer were withdrawn into syringes from ten very small holes (0.32 mm diameter) drilled into the length of two pieces of fine (2 mm outside diameter) stainless steel tube. These tubes were placed along the length of the tank in the middle of each layer. The samples were analyzed on a conductivity bridge (Beckman model RC-18A) and could be measured with a precision of better than 0.005‰.

The temperatures were logged continuously on the laboratory computer. The fluid samples were typically withdrawn slowly so that it took 50 seconds to fill the syringes. This had the advantage that a temporal average was obtained. During most of the experiments samples were taken once per minute and so there was just ten seconds between finishing the withdrawal of one sample and the beginning of the next.

3. Experimental results

Table 1 shows the values of the temperature difference ΔT and the salinity difference ΔS between the well-mixed layers at the beginning of each experiment. The

Table 1. Details of the experimental conditions. Columns 2, 3 and 4 are the initial salinity difference between the two layers, the corresponding initial temperature difference, and the initial stability ratio R_ρ, all evaluated at the beginning of each experiment. The last three columns are the salinity difference, the cabbeling parameter $\tilde{\delta}$ and the interface thickness, measured (or interpolated) at $R_\rho \approx 1.5$.

| | | | | $R_\rho = 1.5$ | | |
Exp.	$\Delta S(\%_0)$	$\Delta T(°C)$	R_ρ	$\Delta S(\%_0)$	$\tilde{\delta}$	Interface thickness (cm)
1210	1.035	3.04	1.086	0.54	.132	11.0
1810	1.442	4.03	1.015	0.63	.167	7.5
1410	1.508	4.27	1.039	0.68	.166	7.5
0811	2.071	5.74	1.059	1.02	.223	6.0
1111	3.469	12.15	1.116	1.97	.613	2.5
1211	2.034	9.01	1.364	1.75	.621	3.2

mean temperature of the layers was close to room temperature (in the range 20°C to 25°C) and the lower layer had an initial salinity of close to 0.5‰ in each experiment. The fourth column in the table shows the initial value of the density ratio R_ρ, defined by

$$R_\rho = 1 - \frac{\Delta\rho}{\rho_o \bar{\beta} \Delta S} \tag{1}$$

where $\Delta\rho$ is the density difference between the layers and $\rho_o\bar{\beta}\Delta S$ is the contribution to the density difference due to ΔS (Griffiths and Ruddick, 1980). This definition of R_ρ is more appropriate than the simple one $(\bar{\alpha}\Delta T/\bar{\beta}\Delta S)$ because it compensates for the nonlinearity of the equation of state so that $\Delta\rho \rightarrow 0$ as $R_\rho \rightarrow 1$. In practice the two definitions of R_ρ are quite similar except when the equation of state is significantly nonlinear such as in a cabbeling situation. The fifth column in Table 1 gives the salinity contrast between the layers at a constant value of $R_\rho = 1.5$. This salinity difference is more appropriate than the initial ΔS for ordering the strength of convective activity in our experiments and for comparing with the conditions in Schmitt's experiments. His salinity differences were typically double our largest ΔS. Even though our salinity steps are the smallest achieved so far in laboratory experiments, they are still between one and two orders of magnitude larger than typical values in the ocean.

The sixth column in Table 1 gives values of the "cabbeling parameter" $\tilde{\delta}$ at $R_\rho = 1.5$ (McDougall, 1981) which represents the importance of the nonlinearity of the equation of state. Since $\tilde{\delta} < 1$, double-diffusive convection will be much more important than the entrainment caused by the nonlinear equation of state.

The last column lists the interface thickness which was observed to remain virtually constant after the first four minutes of each experiment.

a. Data analysis. The rates of change of the salinity in both the upper and lower layers were used to determine the flux of salt F_S by the following formula,

$$\rho_\ell H_\ell \frac{dS_\ell}{dt} - \rho_u H_u \frac{dS_u}{dt} = 2F_S. \tag{2}$$

The subscripts u and ℓ refer to the upper and lower layers respectively, ρ is density, H is the height of a layer and S is salinity. The flux of salt is often expressed as $\beta^{-1}C(R_\rho)(\beta\Delta S)^{4/3}$, that is, as the product of a function of the stability ratio R_ρ and the $4/3$ power of the contribution of the salinity contrast ΔS to density ($\beta\Delta S$). In our data analysis we have used the fact that the salt flux varies as $(\beta\Delta S)^{4/3}$ to help in fitting a smooth curve to the salinity data versus time. If $C(R_\rho)$ were in fact a constant, then it is easy to show from the equation $-\beta\rho_u H_u \, dS_u/dt = C(\beta\Delta S)^{4/3}$ that $(S_u - S_m)^{-1/3}$ would be proportional to time, where $S_m = (S_u + S_\ell)/2$. The approach we adopted was to fit $(S_u - S_m)^{-1/3}$ and $(S_m - S_\ell)^{-1/3}$ against time by a cubic polynomial in time. When plotted with linear salinity and time axes, the fit to the data was more satisfactory than a polynomial fit to the unstretched salinity data. This can be seen in Figure 1 where fits are shown for the S_u data of the 1810 experiment using both methods. The salt flux F_S was obtained from (2) by differentiating the smooth curves of salinity versus time which were obtained by the above stretching procedure.

The buoyancy flux ratio, R_f, was found by fitting polynomials to both the T_u, S_u curve and the T_ℓ, S_ℓ curve. Examples of these data are shown for the 1810 experiment in Figure 2. The points marked $t = 0$ correspond to the layer properties immediately before the barrier was withdrawn and were not used in the fitting procedure. Toward the end of each experiment, the slopes dT_ℓ/dS_ℓ and dT_u/dS_u became significantly different and we have been unable to find a satisfactory explanation of this behavior. This problem was circumvented by ignoring the data from the last few samples when the slopes were different, and so we can be confident that the data we present are the result of double-diffusive convection and not some other process.

The buoyancy flux ratio for a two layer experiment is defined by (McDougall, 1981)

$$R_f = \frac{\rho_\ell \alpha_\ell H_\ell \dfrac{dT_\ell}{dt} - \rho_u \alpha_u H_u \dfrac{dT_u}{dt}}{\rho_\ell \beta_\ell H_\ell \dfrac{dS_\ell}{dt} - \rho_u \beta_u H_u \dfrac{dS_u}{dt}} \tag{3}$$

and we have used this expression to evaluate R_f with the temporal derivatives of temperature evaluated by taking the product of dS/dt and dT/dS.

The thickness of the finger interface was measured at intervals during the experiment by vertically traversing a thermistor through this region. This thickness increased very rapidly at the beginning of the experiment and then remained virtually
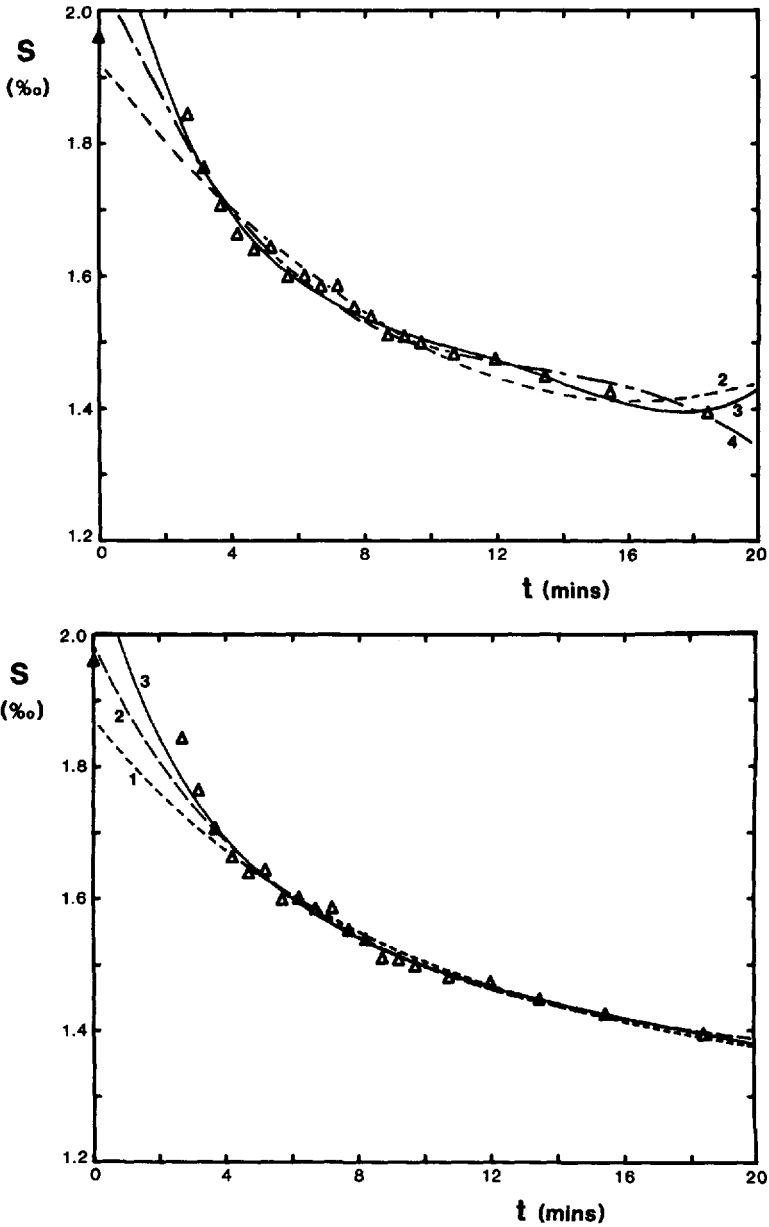
Figure 1. (a) Polynomial fits (quadratic, cubic and quartic) to the upper layer salinity data as a function of time for experiment 1810. (b) Polynomial fits to the same data as Figure 1(a), but with stretching of salinity according to the $4/3$ power law (linear, quadratic and cubic fits).
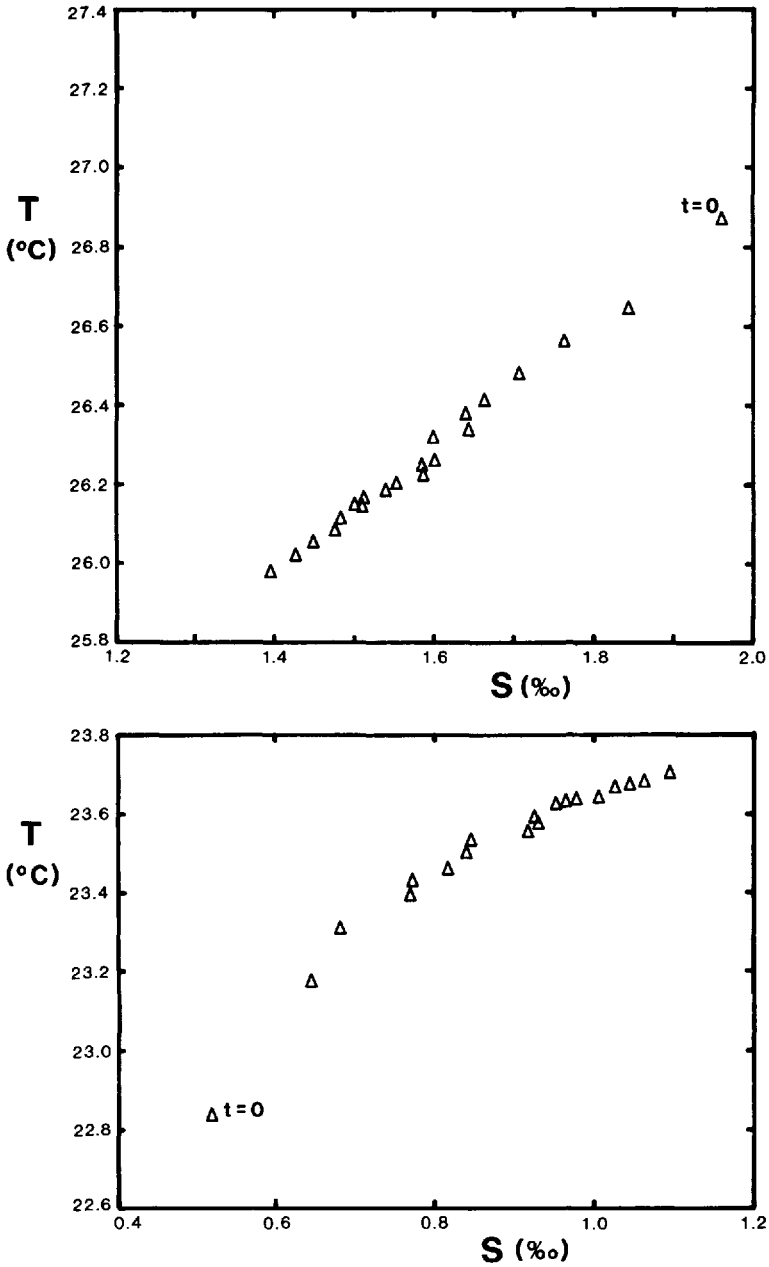
Figure 2. Salinity versus temperature data for experiment 1810 (a) upper layer (b) lower layer. The points marked $t = 0$ are the S, T points before the barrier was removed.
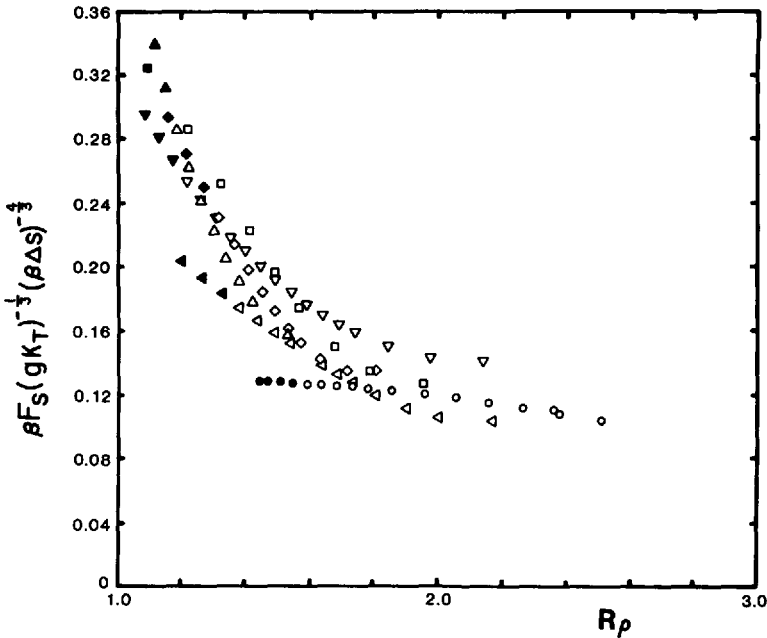
Figure 3. The normalized salt flux, $\beta F_S (g\kappa_T)^{-1/3} (\beta\Delta S)^{-4/3}$, versus R_ρ. The filled data points are those calculated from measurements taken before the interface reached a quasi-steady state. The symbols apply to the following experiments and the numbers in brackets are the salinities at $R_\rho = 1.5$ (from Table 1). □ 1210 (0.54‰), ▽ 1810 (0.63‰), △ 1410 (0.68‰), ◇ 0811 (1.02‰), ◁ 1111 (1.97‰), ○ 1211 (1.75‰).

constant. The first temperature profile, taken approximately 45 seconds after the start of each experiment showed a very sharp interfacial region which was at most 1 cm thick. The second temperature profile was usually taken about 4 minutes after the start of the experiment and the interface had typically reached 75% of its eventual thickness at this stage. We do not regard the data taken in the initial 4 minutes of each experiment as indicative of an interface in a quasi-steady state and these early data points are distinguished in the presentation of the results and are not included at all in our final graph, Figure 6.

b. Results. Figure 3 shows the salt flux F_S, multiplied by β to give dimensions of velocity and divided by $(gK_T)^{1/3} (\beta\Delta S)^{4/3}$. This is the same form of presentation as used by Schmitt (1979). His data spanned the range of R_ρ from 1.6 to 10.0 whereas we have concentrated on the range $1.2 \leqslant R_\rho \leqslant 2.2$ Our value for βF_S is 30% higher than Schmitt's at $R_\rho = 2.0$. There is an indication of a possible reason for this discrepancy in the data of Figure 3 in that there is a trend for the experiments with higher values of ΔS (at $R_\rho = 1.5$) to exhibit a smaller salt flux βF_S. The vertical range of the data in Figure 3 is partly due to experimental scatter and partly due to this trend with ΔS.
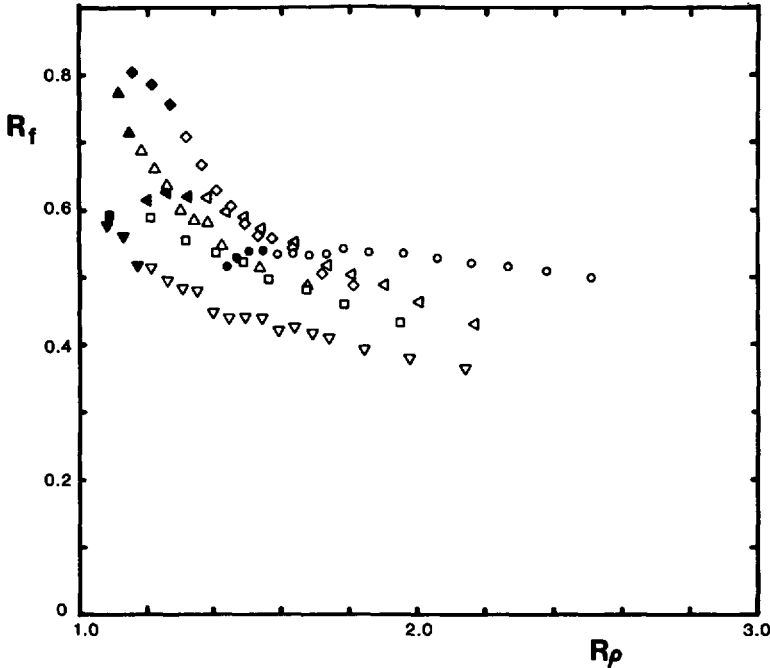
Figure 4. The buoyancy flux ratio, R_f, versus R_ρ. Symbols are the same as for Figure 3.

Schmitt's experiments were performed with values of ΔS at $R_\rho \approx 1.5$ of about twice our largest value. However, the differences in the mean magnitude of βF_S in the two sets of experiments is too large to be explained by this slight trend with ΔS in our data. The existence of such a trend in $C(R_\rho)$ with ΔS calls into question the validity of the $\frac{4}{3}$ flux law, but the vertical range of the data in Figure 3 could be regarded as equivalent to a power law of $\frac{4}{3} \div \frac{1}{10} = 1.23$. We do not regard this as a serious rebuttal to the $\frac{4}{3}$ power law as there remains the question of how much of our scatter is experimental in nature and how much is due to an underlying trend with ΔS. The Rayleigh number (using the measured interface thickness as the length scale) was not less than 10^7 in our experiments and so there appears to be no doubt about the applicability of high Rayleigh number theories. Another possible objection to our procedure is the sharp starting condition, but since we waited until the interface had reached 75% of its equilibrium thickness before using the data, we do not believe this to be a problem.

Our results for the buoyancy flux ratio R_f are shown in Figure 4. Once again there is a trend (although not a monotonic trend) in the data with the value of ΔS for the experiments, this time with small values of ΔS leading to small values of R_f. At $R_\rho = 2$, our data for R_f are 35% smaller than Schmitt's. This is also in the same direction as could be expected from the differences in ΔS between the respective experiments, although it is not possible to say whether the differences between our data and

Schmitt's can be explained by this trend. Perhaps the most important feature of our results is that values of R_f were measured at very low values of R_ρ. At $R_\rho = 1.2$ for example our data indicate that $R_f = 0.65 \pm 0.1$. In the application of double-diffusive concepts to the ocean, the buoyancy flux ratio due to fingers is often taken to be 0.7, but since there have not been any reliable measurements at $R_\rho < 1.6$, the value of R_f at lower values of R_ρ has always been open to question. Now we can be confident that R_f does not approach 1.0 too rapidly for $R_\rho > 1.2$. These results for R_f have used the total measured flux of heat across the finger interface. Both Turner (1967) and Schmitt (1979) subtracted the heat flux caused by purely vertical conduction from their values of the measured heat flux. We discuss this procedure in detail in section 4.

Stern (1969) and Holyer (1981) have developed a theory for the breakdown of infinitely long fingers by internal gravity waves, a process that has become known as "collective instability." This theory predicts that "Stern's number" A, defined by

$$A = \frac{\beta F_S (1 - R_f)}{\nu(\alpha T_z - \beta S_z)} \qquad (4)$$

is constant. Holyer's detailed theory suggests a value of $\frac{1}{3}$ for A. Schmitt (1979) measured this number (his Fig. 5 is of $A/(1 - R_f)$) and found values of A close to 0.4 at $R_\rho \approx 2$. We evaluated A using the temperature gradient T_z estimated from thermistor traverses through the interface and by assuming that S_z was small since $\kappa_S \ll \kappa_T$. Figure 5 shows the results for A plotted against R_ρ. The most striking feature of these results is the large values of A obtained in the four experiments which had low values of ΔS. This result has important implications for the problem of the contribution to the interfacial heat flux by vertical conduction and this will be discussed in the next section. These large values of A imply that the "collective instability" (which has been investigated theoretically only for infinitely long fingers) is not the limiting phenomenon at a finger interface which is confined between two well-mixed layers.

4. Discussion

Underlying all previous investigations of heat-salt fingers has been the assumption that while the vertical *conduction* of heat across an interface may be significant in the laboratory, it is negligible in oceanic situations. For this reason both Turner (1967) and Schmitt (1979) estimated the conductive heat transfer across their finger interfaces and subtracted this from the measured total heat flux to obtain the "heat flux which can be attributed to salt-fingering" alone. Here we show that the vertical conductive heat flux divided by the total heat flux across a finger interface is a function only of Stern's number A and so the subtraction of the conduction heat flux from laboratory data is only justified if values of Stern's number in the ocean are high.

Consider a field of salt-fingers in which we express the velocity components $(u, v, w,)$ and the temperature T as the sum of a horizontally averaged component which is a
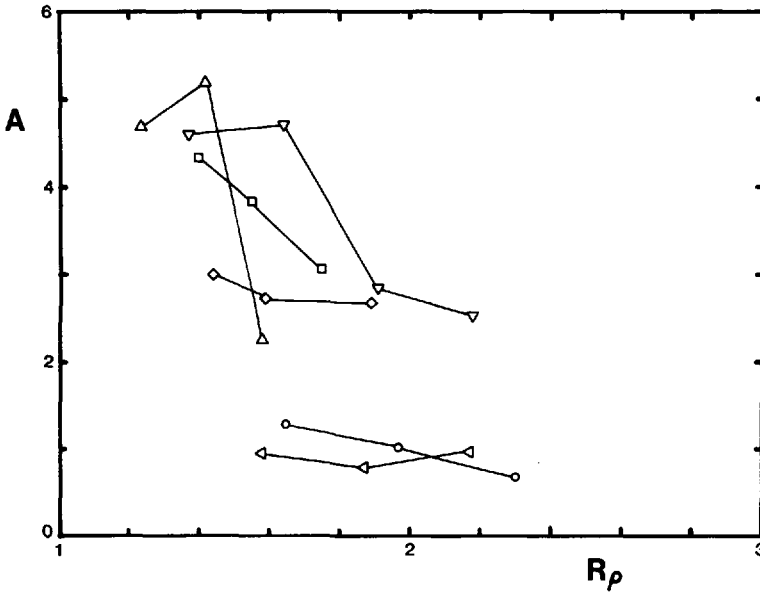
Figure 5. Calculated values of Stern's number, A, versus R_ρ. Symbols are the same as for Figure 3.

function only of the vertical coordinate z, and a part which has a horizontal average of zero and is a function of x, y and z. We have then

$$T(x, y, z) = \overline{T}(z) + T'(x, y, z); \qquad \overline{T'} = 0 \qquad (5)$$

and the horizontal average of each of the velocity components is zero. Assuming Boussinesq, nondivergent ($\nabla \cdot \boldsymbol{u} = 0$) flow, the equation of conservation of T is

$$T_t + \nabla \cdot (T\boldsymbol{u}) = \kappa_T \nabla^2 T. \qquad (6)$$

We now assume that the flow is steady and we take the horizontal average of (6) across many fingers, giving

$$(\overline{wT'})_z = \kappa_T \overline{T}_{zz} \qquad (7)$$

or

$$\overline{wT'} - \kappa_T \overline{T}_z = \text{constant} = \text{Total vertical heat flux.} \qquad (8)$$

Eq. (8) shows that there are two contributions to the heat flux across a finger interface, (i) a convective heat flux of magnitude $(-\overline{wT'})$ and (ii) a conductive flux $\kappa_T \overline{T}_z$. Huppert and Manins (1973) have shown that for infinitely long fingers (i.e., T' is not a function of z) the dominant balance in (6) is between $w\overline{T}_z$ and $\kappa_T (T'_{xx} + T'_{yy})$. This implies that the *horizontal* heat conduction between the rising and falling fingers

produces the mean *vertical* temperature gradient $\overline{T}_z$ down which *vertical heat conduction* takes place.

The ratio of the conductive heat flux to the total (convective plus conductive) heat flux, γ, can be written in terms of Stern's number A as

$$\gamma \equiv \frac{\kappa_T \overline{T}_z}{F_T} = \frac{\left(\dfrac{1}{R_f} - 1\right)}{\sigma A} \tag{9}$$

where σ is the Prandtl number (ν/κ_T) and we have assumed $\overline{S}_z$ to be negligible. The buoyancy flux ratio, R_f^*, defined using only the convective heat flux $(-\overline{wT'})$ is

$$R_f^* = R_f(1 - \gamma) = R_f - \frac{(1 - R_f)}{\sigma A}. \tag{10}$$

The Prandtl number is 7 at room temperature and so for $A = \frac{1}{3}$ (Holyer, 1981) the correction to R_f in (10) is approximately 0.15. However, if A is large, the conductive correction is small. Thus the assumption made by previous researchers that heat conduction through the fingers is negligible in the ocean is only true if A is large. Our results for Stern's number, A, shown in Figure 5 suggest that this may be true, especially for low values of ΔS, the interfacial salinity difference. Perhaps the discrepancy between these large values of A and the value of $\frac{1}{3}$ predicted by the collective instability theory is due to the fact that the fingers in the interfacial region are not infinitely long, nor is the density gradient in the interfacial region constant as is assumed in the collective instability theory.

Figure 6 shows R_f^*, the flux ratio corrected for heat conduction across the interface. This adjustment makes a significant change to the data of experiments 1111 and 1211 at the larger R_ρ points, and reduces the scatter between the results of the different experiments. It is this corrected value of the flux ratio which we believe should be used to determine fluxes due to salt fingering in the ocean.

5. Conclusions

We have presented the results of laboratory experiments on finger double-diffusive convection that have been conducted at lower stability ratio, R_ρ, and lower salinity differences, ΔS, than have been reported previously. These experiments were made possible by using a novel experimental tank. Our main results are as follows:

1. The ratio of the vertical transports of heat and salt (in density units), R_f^*, remains significantly less than 1 even for R_ρ as low as 1.2.

2. The nondimensional salt flux across the interface continues to increase as $R_\rho \to 1$ and is 0.26 at $R_\rho = 1.2$.

3. Those of our experiments which had a small salinity step across the interface had large values of Stern's number A (up to a value of 5).
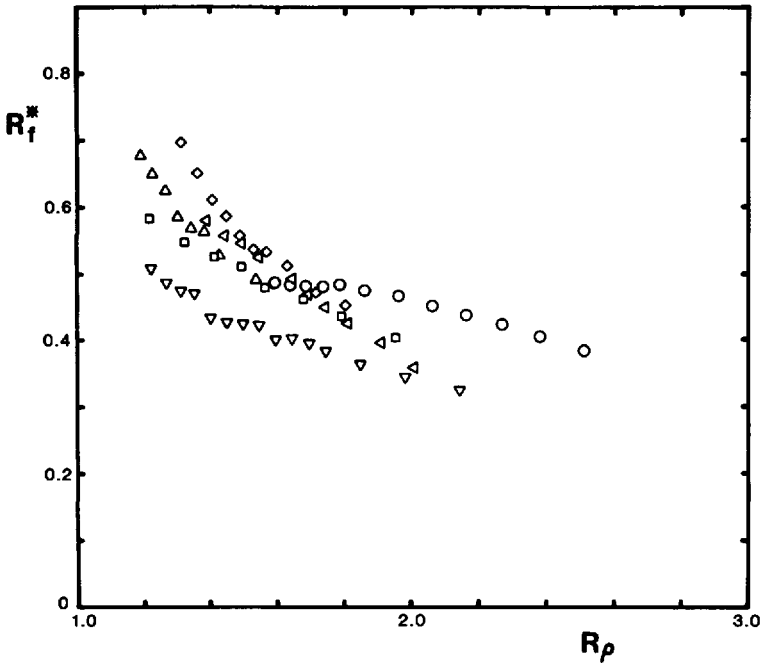
Figure 6. The buoyancy flux ratio R_f^* corrected for vertical heat conduction through the interface versus R_ρ. Symbols are as for Figure 3.

4. We have shown that the correction to the buoyancy flux ratio R_f^* for the purely conductive heat flux across the interface depends only on Stern's number A. On the basis of our measurements of A, we believe that pure heat conduction will not be significant in the ocean.

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