Laboratory studies of interleaving

Corresponding author: Barry Ruddick,

Department of Oceanography,

Dalhousie University,

Halifax, N.S., B3H 4J1,

Canada.

email: barry.ruddick@dal.ca

Fax: (902) 494-2885

Draft, August, 2001, Revised, May, 2002

Submitted, Prog. Ocean.

Keywords:

Double-diffusion, salt fingers, ocean mixing, intrusions, layers, heated sidewall, melting iceblock, fine structure, fronts, thermohaline.

Abstract

This is a review of laboratory experiments on double-diffusive interleaving. Several configurations are discussed and compared, including thermohaline fronts, heated sidewalls, melting ice-blocks, point heat sources, and double-diffusive plumes, using both the heat-salt and sugar-salt systems to generate property anomalies. Two parallels emerge. The vertical scale of intrusions in most configurations is proportional to the "natural" scale given by the property anomaly divided by the density gradient. The speed of advance of intrusions into undisturbed water is proportional to the product of the buoyancy frequency and intrusion thickness, with a constant of proportionality of order 0.005, but which depends on the vertical gradient density ratio and on the experimental configuration.

We end with a long list of questions. Further progress will require new or more complex experimental configurations, more quantitative observations, and close comparisons with intrusion theories, both linear and finite-amplitude.

1. Introduction

When a laboratory tank is filled with a salinity gradient using water either warmer or cooler than room temperature, a regular sequence of layers is seen to form (Figure 1), first at the walls and then growing into the interior of the fluid (Turner and Stommel, 1964). This is one example of the many two-dimensional instabilities that arise due to double-diffusion. The pioneering work on this phenomenon is that of Thorpe, Hutt and Soulsby (1969, hereafter THS), a tour de force combining innovative experimental work and simplified but effective instability calculations. THS placed a stable salinity gradient confined between vertical walls and imposed a lateral perturbation by heating one sidewall by $\Delta T/2$, and cooling the other the same amount. A regular series of cellular motions formed and developed into a set of convecting layers, thus effecting a heat transfer from the heated wall to the cooled one.

In the initial stages, heat diffuses in from the sidewall and causes a buoyantly-driven vertical upflow, so that the basic state has a lateral temperature gradient compensated in density terms by a salinity gradient, and isopycnals are nearly horizontal. This basic state is unstable to convective rolls, which rapidly organize into inclined intrusive layers behind noses that propagate into the undisturbed interior. (Figure 2a). Each layer consists of upflow near the heated wall, fed by quasi-horizontal inflows and outflows. The layers appeared to be well-mixed convecting layers, with strongly sheared diffusive interfaces (WS below CF) separating the layers. The convecting layers end at the extending noses beyond which the fluid is stratified and the motion predominantly horizontal, apparently consisting of near-hydrostatic internal wave-like motions. THS also mention that layer merging sometimes occurs by penetration of thermally-driven upflow near the wall from one layer to the next. The merging of layers as they extend outwards can be seen in figures 1d-f. It can also be noticed that the noses propagate horizontally, so that layer slopes tend to decrease as the layers extend.

THS also performed a number of experiments that led to fully-developed layers extending from wall to wall (figure 2b). Direct measurement of the temperature and salinity structure showed convecting layers, well-mixed in S and stably stratified in T, separated by statically stable diffusive interfaces (figure 3). Based on later work by Turner (1978), described more fully in section 6, the sense of the interfacial slope can now be explained in terms of the diffusive interface fluxes: a fluid parcel rises along the heated end-wall and then flows outward underneath the diffusive interface. The diffusive interface flux causes the fluid parcel to lose heat, and also some salt, becoming more dense and sinking slightly as it moves to the right. When it reaches the cooled end-wall, the parcel is further cooled and sinks. The parcel then moves out towards the left at the bottom of the layer and gains heat and salt from the diffusive interface below it. Despite the detailed picture given by THS, a nonlinear model of the fully-developed layers does not exist; such a model would likely prove very useful.

The work by Thorpe et al (1969) spawned a variety of related investigations over the next decades: laboratory, theoretical and numerical work on similar configurations in the basic sciences and engineering heat transfer fields, as well as consideration of a large number of related geometries involving lateral inhomogeneities or heat sources. The seminal laboratory-based paper by Turner and Chen (1974) demonstrated a common thread connecting these experiments: when a lateral thermohaline inhomegeneity is imposed in the presence of a vertical stratification, a sequence of layers forms that tend to remove the lateral inhomogeneity. Therefore all of these configurations have some relationship to oceanic thermohaline intrusions, and so are briefly discussed, with attempts to bring out the parallels. The focus of this review article is on lateral thermohaline intrusions occuring near oceanic fronts. We begin with the heated sidewall experiments, since they are the easiest to set up in the laboratory in a reproducible manner, followed by the closely-related melting iceblock experiments. We then move on to experiments designed from the outset to simulate an oceanic thermohaline front, and then discuss other geometries.

2. Heated sidewall experiments

The experiments and the (surprisingly complete) instability theory of THS discovered and briefly described many of the phenomena that were studied in more detail by later authors. The findings from these studies fall roughly into two groups in terms of their relevance to oceanic intrusions. "Narrow slot" experiments (figure 2b), in which the lateral gradients and consequent layering extend from wall to wall, lend themselves to well-defined instability calculations, such as that by THS, and in their finite-amplitude state the convective motions transport heat from the warm wall to the cold. These studies have the most relevance to engineering (lateral heat transport) studies, and because the intrusions end at solid boundaries, may have less relevance to oceanic intrusions. "Wide tank" experiments, in which the layers form near one wall and extend into the interior behind propagating noses (figure 1a-f), are the most relevant to oceanic intrusions, whether frontal or created at a solid boundary (such as an iceberg or glacier). Because of the relevance to oceanic intrusions, our primary focus will be on the "wide tank" results.

THS noted, that the initial linear instability predicted cells with alternating sense of rotation, but the initial observations found that cells with upward velocity at the heated wall predominated; this was further studied by Hart (1971), and by Chen (1974). Hart (1973) performed nonlinear analysis of the growing instabilities, and further laboratory experiments with improved visualization techniques, and concluded that the linear motions with vortices of alternating sign did in fact occur, followed by transitions to larger wavelengths and mixing of the salinity gradient within the cells. Thangam, Zebib and Chen (1982) found in a nonlinear treatment that the cells with the "wrong" sense of vorticity were rapidly squeezed into the diffusive interfaces between the cells with a rotation sense supported by the sidewall forcing. A number of further experimental and numerical investigations, primarily with C.F. Chen as a co-author (summarized in Chen and Chen, 1997, see also Sabbah et al, 2001, Nekrasov et al, 1976, Levitskii et al, 1995), studied the finite-amplitude behaviour, including the migration and merging of layers (Tanny and Tsinober, 1988, 1989) and the consequences for lateral fluxes. A variety of instability sequences that relate to layer evolution in heated sidewall systems was studied theoretically by Kerr and Tang (1999), and in works cited therein. These may have parallels with the nonlinear evolution of oceanic intrusions, but are not discussed here.

Jeevaraj and Imberger (1991) performed experiments in which a constant sidewall temperature difference was applied to single (salt) and double (heat/salt) stratifications. They suggest that the motion in a single layer that extends from heated to cooled walls is similar to convection in a long box heated and cooled at opposite sides, and found favorable comparison of the observed velocity and temperature fields with a theory based on large horizontal Rayleigh number and low aspect ratio. The diffusive interface fluxes and tilt were ignored in this theory, which assumes linear horizontal temperature variation and uniform (in x) horizontal velocity (asymptotically valid for large length/layer depth). The theory of Jeevaraj and Imberger (1991) predicts the temperature structure of this state, but does not predict the horizontal variation of velocity observed by Ruddick and Turner (1979), Bormans (1992) and Ruddick, Phillips and Turner, (1999) in thermohaline fronts. This may be because the extending noses in thermohaline fronts were not present in the Jeeraraj and Imberger experiments. The scaling laws implied by Jeevaraj and

Imberger (1991) predicts the velocity within the layers to be limited by viscosity and to decrease inversely as the length of the intrusion.

Chereskin and Linden (1986) studied the effects of rotation at rate f/2 on the intrusions produced by sidewall heating. Coriolis effects were seen to cause an along-front (azimuthal, since their geometry was circular) component of both velocity and of wavenumber, and a systematic increase of the vertical scale by a factor of 2 as f/N was increased from 0.1 to 1, with little effect for f/N<0.1 , which is a typical maximum oceanic value. The initially axisymmetric intrusions were observed to be unstable to non-axisymmetric motions with length scale related to the deformation radius based on the natural vertical scale. An extension of the stability analysis of Thorpe et al (1969) found that rotation suppressed the onset of convective motions to a higher critical Rayleigh number, and this was interpreted as accounting for the observed increase in layer scale. Although the initial rate of extension away from the wall was similar to the non-rotating case, rotation inhibited growth after the intrusions reached the midpoint of the stratified domain. This is the only experimental work (that I have located) on the effects of rotation on intrusions.

Vertical layer scale

A theoretical analysis by THS considered the instability within a relatively narrow slot whose walls are separated a distance d and inclined from the horizontal at an angle γ. They assumed a prescribed vertical gradient of both T and S, and uniform horizontal temperature gradient that was compensated in density terms by a horizontal gradient of S. The appropriate scaling for such a setup is based on d, the wall separation distance. THS defined a vertical Rayleigh number involving vertical S and T gradients, the vertical separation between walls, and the slope angle, plus a horizontal Rayleigh number involving the lateral temperature and salinity gradients. Assuming modes that satisfied approximate boundary conditions, THS found there was a critical horizontal Rayleigh number below which no instabilities occurred, and above which cellular motions occurred with vertical scale and slope that compared well with observations. THS found that in both theory and experiment, the dimensionless layer thickness h/d asymptotically approached a nearly constant value with a weak (-1/6 power) dependence on (large) vertical Rayleigh number. They argued that, due to the connection between horizontal and vertical Rayleigh numbers in their experiments, this thickness approached the value

$$H = g\alpha\Delta T / N^2, \qquad (1.)$$

where $N^2 = -\frac{g}{\rho}\frac{\partial\rho}{\partial z}$ is the undisturbed vertical density gradient. The quantity H, called the "natural scale" by Turner (1973), is roughly the height that a fluid parcel heated an amount ΔT can rise in the stratification. Therefore, for the "narrow slot" configuration, the vertical scale of layers approaches the natural scale, and becomes only weakly dependent on slot width.

For the "wide tank" configuration, the layer scale should not depend on tank width, and the natural scale is a likely candidate for the length scale. Defining a Rayleigh number based on the natural length scale (Huppert and Turner, 1980):

$$Ra = \frac{g\alpha\Delta T H^3}{\nu\kappa_T} = \frac{(g\alpha\Delta T)^4}{\nu\kappa_T N^6}, \qquad (2.)$$

Dimensional reasoning suggests that h/H is a function of Ra, of the density ratio $R_\rho \equiv \frac{-\alpha T_z}{\beta S_z}$ (which is zero for a pure salinity stratification), and of the diffusivity ratios ν/κ_T and κ_T/κ_S.

The vertical scale of the resulting intrusions is discussed in some detail by Huppert and Turner (1980). They note that Chen, Briggs and Wirtz (1971) found h/H=0.81±0.1 for a Rayleigh number (based on H) ranging from 14000 to 54000, and this was broadly supported by numerical calculations in Wirtz et al (1972) and Chen (1974). Huppert and Turner (1980) examined a wider range of Rayleigh number for both heated and cooled sidewalls, and found h/H= 0.62±0.05 for $Ra>5\times10^5$. Chereskin and Linden (1986) later found h/H=0.53±0.03 for $Ra>10^7$ and f/N<0.1 Thus it appears that the heated sidewall layer scale is a weakly decreasing function of Rayleigh number, even for very large Ra, a result reminiscent of the findings of THS. Tanny and Tsinober (1989), applied a temperature difference that increased with time in a prescribed fashion to a constant value, and observed the formation and somewhat chaotic merging of layers. They found that layers formed initially at a scale governed by molecular diffusion:

$$h \approx 25\left(\frac{\upsilon\kappa_S}{N^2}\right)^{1/4}, \qquad (3.)$$

and then increased towards the "natural" scale as the Rayleigh number was increased (note that they define a Rayleigh number a factor κ_T/κ_S larger than (2)) . The scale (3) arises in a variety of contexts, and is associated with convective-diffusive instabilities in which no external scale is imposed, so that the inherent scale is governed by the diffusion distance in a buoyancy period, $\sqrt{\kappa_T/N}$, and diffusion ratios such as Prandtl or Schmidt numbers (c.f. Kelley, 1984).

Imposed lateral heat flux

Narusawa and Suzukawa (1981) discussed the onset of instability when a constant heat flux (as opposed to constant temperature difference) is applied to the wall of a salinity stratified fluid. Suzukawa and Narusawa (1982) described the growth rate of the convection cells in terms of their thicknesses and propagation velocities, and quantified the vertical and lateral temperature distributions within the cells. This transient state of growing intrusive noses invites comparisons with the vertical scale and speed of advance of thermohaline frontal intrusions; however, frontal intrusions have a constant T/S difference across the front, not a constant imposed heat flux. Shirtcliffe (unpublished, pers. comm., 1978) performed experiments with a constant applied temperature difference from which observations of layer scale and advance speed could be inferred.

Schladow et al, (1992), and McDonald and Koseff (1994) describe the structure of intrusions formed under the application of a constant heat flux applied at one endwall, noting overturns and weak salt fingers within the cells. They found the velocity and temperature distribution of these propagating intrusions compared favorably with that predicted by Jeevaraj and Imberger (1991) when an assumed higher eddy viscosity and diffusivity due to convective overturns was allowed for. Schladow et al conducted experiments for various gradient density ratios (defined such that diffusive gradients have R_ρ <1) and heat fluxes, denoted by a lateral stability parameter $R_l = g\alpha q/N^2\kappa_T$. The behaviour fell into three classes:

Class I: Flow generated under relatively high vertical and lateral stability (low R_l and R_ρ), with small vertical scale and propagation speed.

Class II: Moderate vertical and lateral stability. In this class, intrusions stop propagating after the sidewall heating is turned off. Salinity in the intrusive layers is well-mixed, and temperature is stably stratified.

Class III: Low gravitational and lateral stability (high R_l and R_ρ). The thickness and propagation speed of these intrusions is the largest, and temperature and salinity is well-mixed in the intrusive layers. In this case, as found by Turner and Chen (1974), intrusions continued to propagate after the heat source was removed.

3. Melting iceblock experiments

Huppert and Turner (1978, 1980) and Huppert and Josberger (1980) showed in a series of laboratory experiments that melting ice in salt-stratified water produces a regular sequence of intrusive layers (figure 4), and found that their thickness is proportional to the temperature difference between the ice and the environment, and inversely proportional to the ambient density gradient -- the "natural scale" of eq. 1. They showed that the layers formed had the same slope and structure, and nearly the same vertical scale, as layers formed at a cooled sidewall, suggesting that the motions are primarily driven by molecular diffusion of heat into a cold and fresh boundary layer adjacent to the ice. In the laboratory experiments, and in the field, such intrusions appear to be driven laterally by diffusive interface fluxes, and rise upwards from the cold surface as they spread outwards. However, in the case of a cooled sidewall the lateral salt flux is zero at the wall, while in the case of melting ice the freshwater flux and the (negative) heat flux are linked by the latent heat of melting.

Laboratory experiments with melting ice-blocks in unstratified salty water have shown a cold, fresh convecting, doubly-diffusive boundary layer adjacent to the ice surface, with complicated physics and opposing buoyancy effects due to the combined action of freshwater and latent heat of cooling (Josberger and Martin, 1981). Similar boundary layers occur in the stratified experiments above, and likely in the field, and may be involved in the formation and driving of intrusions. Next to the ice face there is a thin layer of melt-water flowing upwards (if the ambient salinity were below about 16 psu this would not occur.), and outside of this is a thicker turbulent downflow. Double-diffusion between these layers, and turbulent entrainment, cause the density of the fluid in these layers to change, and give rise to the intrusive motions noted above. The melt water is thus entrained into the intrusive motions, where it spreads laterally rather than rising to the surface. This causes difficulty in retrieving fresh water from melting icebergs towed to low latitudes to provide drinking water.

4. Thermohaline front experiments

Ruddick and Turner (1979) performed laboratory experiments in which a sharp thermohaline frontal zone was produced by withdrawing a dam separating two stratifications with similar densities but with salt (called "T" to mimic cool fresh water) on one side and sugar (called "S") on the other (figure 5a). This set of initial conditions simulated a sharp oceanic thermohaline front, with equal densities on each side but cross-frontal sugar-salt difference increasing linearly with depth. The equal density and lack of rotation and vertical or horizontal shear prevents direct comparison with ocean fronts possessing baroclinic and barotropic shear. Additionally, the initial narrowness of the front may also be an issue.

In all the experiments reported in Ruddick and Turner (1979), a sequence of intrusive motions formed at the front, consisting of alternating diffusive interfaces and finger regions, with counterflowing velocities and slope consistent with fluid parcel density changes dominated by sugar fingers (Figure 6). These intrusions spread from the frontal zone into undisturbed fluid behind "noses". The horizontal velocity in the intrusions exceeded the nose velocity, indicating significant recirculation. The thickness of each intrusion was proportional to the cross-frontal salinity contrast. Ruddick and Turner (1979) set out a mechanistic argument for the redistribution of heat and salt by intrusive advection followed by salt finger rundown (figure 7), and considered the potential energies involved. They deduced bounds for the vertical intrusion scales that were supported (to within a factor of two) by the laboratory observations, and consistent with a variety of published ocean observations. The resulting estimate for the intrusion scale *h* is:

$$h = \frac{3}{2}\frac{(1-\gamma_f)g\beta\Delta S}{N^2} = \frac{3}{2}\frac{(1-\gamma_f)g\alpha\Delta T}{N^2} \qquad (4.)$$

where N is the large-scale buoyancy frequency, $\beta\Delta S$ is the density contrast due to the cross-frontal salinity change, measured along isopycnals (and therefore equal to $\alpha\Delta T$, the density contrast due to the cross-frontal temperature change in these non-baroclinic experiments), *g* the gravitational acceleration, and $\gamma_f \cong 0.9$ the sugar finger flux ratio (see Turner and Veronis, 2000 for a summary of flux ratio values). This form is again similar to the "natural scale" (Turner 1973) found by Thorpe et al. (1969), Chen et al. (1971) and others for heated sidewall in a salt stratification, and Huppert and Turner (1980) for melting ice in salt stratified water, to be discussed in following sections.

Ruddick, Phillips and Turner (1999) present a detailed analysis of the laboratory experiments initially described by Ruddick and Turner (1979), and conclude that the lateral fluxes can be deduced from observations of the "nose" velocity, *c*, of the intrusions, which was found to be independent of time and reasonably well-fit by the scaling relation:

$$c = (0.005 \pm 0.0025)\, Nh \qquad (5.)$$

The relationship (5) corresponds to a small, but nearly constant Froude number; c/Nh = O(1) would suggest a balance between fluid inertia and buoyancy effects, as is found in gravity currents. The fact that c/Nh is very small may mean that the buoyancy terms are very small (i.e., that the lateral density differences are much smaller than the hydrostatic density change over an intrusion depth), or alternatively that the buoyancy terms are balanced by frictional effects. We cannot tell at this time which is true, and our nearly complete ignorance of vertical fluxes of momentum in double-diffusive systems makes it difficult to deal with these dynamical issues.

Ruddick et al (1999) develop a kinematic theory based on the heat and salt conservation equations, and the hypothesis of "continuous hydrostatic adjustment": the motion is sufficiently slow that the density field is close to hydrostatic equilibrium with the ambient density on either side. This hypothesis is supported by the smallness of c/Nh, discussed above. This theory successfully predicts the lateral structure and incorporates the intrusive noses. The relationship (5.) for the nose velocity is derived although the numerical value of the coefficient was not predicted. Their solution suggests that a more general similarity form solution may be feasible. Detailed vertical profiles in Ruddick et al (1999) show that the diffusive interfaces were much thicker than would be expected in a two-layer system (interface bounded by convecting regions above and below), lending support to their assumption that in these experiments, the finger fluxes dominated the diffusive fluxes. Our knowledge of oceanic vertical fluxes in intrusions is insufficient to make such an assumption for oceanic intrusions. Indeed, extrapolation of the experimental findings to the much larger oceanic scales is not easy to argue with confidence.

Holyer, Jones, Priestley and Williams, 1987 performed experiments in which the initial stratification was doubly stable, with a T-S contrast constant with depth and equal "doubly stable" gradient density ratio $R_\rho \equiv \frac{-\alpha T_z}{\beta S_z}$ on either side (Figure 5b). The parameters were chosen with a generally very small cross-frontal contrast, so that the vertical scale predicted by eq. (4.) was small, typically 4 mm, and always less than 17 mm. The resulting intrusions took hours to form, compared with O(10 min) for Ruddick and Turner (1979), and all sloped in a manner consistent with density changes driven by diffusive interfacial fluxes, the opposite of that shown in figure 6. Fingering was observed by Holyer et al, but was classified as "weak". The resulting intrusion scales were larger than predicted by (4.) by a factor of 3-5, possibly because the vertical fluxes were initiallly due to molecular diffusion.

Bormans (1992) extended the experiments of Ruddick and Turner (1979) with a "hybrid" fill technique (Figure 5c,d). She used a pure salt stratification on the left ($R_\rho = -\infty$) and on the right R_ρ ranged from -1 (doubly stable) to +0.8 (diffusive). The right-hand value was tabulated by Bormans and is used in summary figures within this paper. The cross-frontal T-S contrast increased linearly with depth and the observations from a single central intrusion were tabulated and analyzed. The intrusions all exceeded 2 cm, and were observed to slope in the finger-dominated sense. The intrusion scale agreed with that of Ruddick and Turner (1979) at $R_\rho = -1$ and was otherwise about 30% smaller than predicted by (4.) Bormans found the intrusion nose speed to be consistent with (5), noting an increase (and consequent increase in lateral salt flux) for R_ρ >0.65, due to the extra energy source present in the unstable salt stratification.

In a later section, we will compare the observations and predictions of intrusion scale and speed from these and other laboratory experiments.

5. Sloping sidewall experiments

Building on the qualitative experiment shown in Turner and Chen (1974), Linden and Weber (1977) performed a definitive series of experiments in which a sloping sidewall boundary was imposed on a double-diffusive stratification. The no-normal-flux boundary conditions for the salt and sugar components caused along-slope flows that became unstable, creating intrusive layers. The vertical scale of the layers was found to depend strongly on the gradient density ratio of the stratification (larger layers for density ratio closer to 1), and only weakly on the slope of the sidewall.

For the case of diffusive sense stratification, Linden and Weber solved the governing advective-diffusive boundary layer equations and showed that the boundary layer had no steady solution compatible with the boundary conditions on T and S. They were able to relate the imposed lateral flux due to the tilted boundary to an effective imposed "temperature" difference, and thence to the critical Rayleigh number and fastest-growing vertical wavelength found in heated sidewall experiments. It was noted in section 2 that this led to layers asymptotically proportional to the "natural scale", eq. 1.

Linden and Weber (1977) performed detailed analyses of their experimental observations, and pointed out several features that parallel intrusions in other configurations:

1. The vertical scale of the layers could be related to the "natural" scale of eq. 1 in terms of the lateral diffusive flux imposed by the sloping wall.
2. Each layer consisted of a relatively sharp diffusive interface and a broader, quite weak, fingering region. As noted by Ruddick et al (1999), the fact that the fingers occur in a gradient region makes it difficult to quantify finger fluxes. The layers sloped in a manner consistent with driving by the diffusive interfaces.
3. Each layer grows laterally behind a "nose" that propagates into stratified fluid at a steady speed. The nose speed was found to obey the relationship $c=FNh$, where the coefficient F is of order 0.005 (the value in eq. 5, noted for thermohaline intrusions in Ruddick et al 1999), and a strong function of gradient density ratio. Bormans (1992) found similar behaviour in frontal intrusions.
4. The horizontal velocity in the layers exceeded the velocity of the noses by a factor between 2 and 5, implying an interior recirculation within each layer. Ruddick et al (1999) found a similar recirculation with a factor of 3.7.

Several experiments, notably involving C.F. Chen as a co-author (e.g., Chen et al, 1971, 1976, Levitskii et al, 1996), have been performed on a heated/cooled sidewall system in which the sidewalls were sloping. These studies have engineering applications but do not appear to have direct relevance to oceanic intrusions, and so are not discussed here. See Chen and Chen (1997) for a summary.

6. Two-dimensional Intrusions associated with double-diffusive sources

Turner (1978) produced intrusions by releasing a line source of fluid with anomalous T-S properties flowing in at the same density level of a stratified tank (for example, a source of sugar into a salinity gradient, or vice-versa). Vigorous mixing and vertical convection near the source preceded the lateral spread of the mixed fluid via intrusions. This was the first clear demonstration of the alternating diffusive interface and finger structure that drove the propagating noses of each intrusion. Dye visualization showed that the plume water enters the intrusions and spreads with them, diluted by environment water so as to spread horizontally and vertically over a much larger region than a non-double-diffusive source. When a source of sugar was introduced into a salt gradient, the intrusions sloped upwards as they spread, consistent with the density changes due to dominance by the finger fluxes. Conversely, when a source of salt was introduced into a sugar gradient, the intrusions sloped downwards in a manner again consistent with dominance by the finger interfaces. This was the first clear demonstration of the link between intrusion slope and density changes due to diapycnal double-diffusive mixing. Although the experiments in Turner (1978) were qualitative, many key concepts about intrusive dynamics emerged here, and a number of experimental configurations were demonstrated for the first time in this landmark paper.

Nagasaka, Nagashima and Yoshida (1995) performed several experiments repeating the configuration of Turner (1978), quantifying the number of intrusions, the vertical layer scale and the propagation speed of the intrusions. They found that the *total* thickness of all the intrusions formed was proportional to the scale (eq. 1) found by Ruddick and Turner (1979), but a factor of about 4 larger. The thickness, h_i, of individual intrusions was found to depend on the number of intrusions that split from the turbulent plume, and this in turn was found to increase systematically with the property anomaly, $\beta\Delta S$, of the plume. Thus, for small $\beta\Delta S$, a single intrusion was formed, with thickness about 4 times that given by (1), and for larger $\beta\Delta S$, up to 6 intrusions were formed, each with thickness a factor of 6 smaller. Results were similar for a source of sugar in a salt gradient, and vice-versa.

The propagation speed of the intrusions depended on whether or not splitting occurred. For the case in which a single intrusion occurred (no splitting), the intrusion speed appeared to be about $0.007Nh_i$. When the turbulent plume split into multiple intrusions, the propagation speed appeared to be about $0.0035Nh_I$, a factor of 2 slower.

Turner (1998) described a laboratory model of an inverse estuary, driven by heating and evaporation over a shallow "shelf" region. The resulting salt fingers drove surface outflow and dense, salty inflow that accumulated at the shoreward end of the shelf, then flowed as an entraining gravity current down the slope into the deep portion of the tank. The "filling box" nature of this gravity current (see Turner, 1973 for a review of the filling box) produced a stratification in the deep part of the tank. The T-S anomaly of the gravity current caused it to mix into the stratified interior via a series of thermohaline intrusions. The experiment thus combined salt fingers, diffusive regions, convectively driven recirculations, gravity currents, entrainment, filling box dynamics, and thermohaline intrusions, a very complicated situation with only one person (J.S. Turner) knowledgable about all of its aspects . Furthermore, the circulation on the shelf was found to be unsteady, with the dense, saline and warm shelf-bottom waters occasionally becoming dense enough to break off the shelf and flow to the tank bottom. The processes noted appear to occur in more than one location on the Australian NW shelf, and probably occur in other strongly evaporative locations. A key aspect may be the fact that salt fingers flux salt downwards but trap the heat near the surface, and this greatly enhances the density of the shelf-bottom waters that are produced. This configuration could also be regarded as a model of many of the processes occurring to deep inflows associated with large-scale thermohaline circulation.

Turner and Veronis (2000) attempted to simplify aspects of Turner's (1998) experiment, by releasing a saline plume at one end, and a sugar plume at the other of a long tank, and allowing a quasi-steady state to be achieved via an overflow mechanism. Each plume exhibited turbulent upflows and downflows due to double-diffusion driven by its thermohaline anomaly. The "filling box" nature of the plumes created vertical stratification, and the lateral T-S differences produced by the plumes caused thermohaline intrusions to form. The experiments achieved a quasi-steady state, with lateral and vertical variations of T, S, and density, and continuing irregular intrusive flows.

7. Experiments Involving point, line, or cylindrical heat sources

In what are probably the most beautifully visualized intrusion experiments to date, Tsinober et al (1983) applied a point source of heating within a salinity gradient. The rising plume from the heat source entrains fluid from several depths and produces thermohaline anomalies above the plume. Fluorescent dye visualization techniques showed a systematic shearing in conjunction with tilted diffusive interfaces, similar to heated sidewall intrusive structures (figure 7). Furthermore, the existence of complicated three-dimensional vortical motions invisible to shadowgraph techniques was illustrated with dye and particle tracking, and dye techniques showed the entrainment of fluid from the central plume into the intrusive layers. The observed layer thickness was found to be proportional to the natural scale when a temperature difference was defined in terms of the input heat flux and the basic stratification. Because of the radial spread of the layers, intrusion advance speed was not a constant (as was found for rectilinear fronts, heated sidewall, and melting iceblock intrusions), but was found to decrease with time such that *layer area* increased linearly with time. See also related experiments by Belyaev and Chashechkin, 1989, Kistovich and Chashechkin, 1987, Chashechkin and Tupitsyn, 1979, Tupitsyn and Chashechkin, 1981, and Chashechkin and Belyaev, 1982.

Chashechkin and Popov (1979), and Popov and Chashechkin (1980) studied convection and layering produced by a cylindrical heat source in a stratified fluid. This work has engineering applications, but does not address the oceanographic issues focussed on here, and will not be discussed here.

8. Contrasts and comparisons

The laboratory experiments reported above are relevant to frontal thermohaline intrusions because they demonstrate a well-measured state in which lateral advection is balanced by vertical double-diffusive fluxes. In the transient state of the heated sidewall, sloping sidewall, melting iceblock , point heat source, or plume-created layers, before the intrusions fill the width of the tank, (Figure 1a) the intrusive region outside the vicinity of the heated endwall (or it's equivalent) is analogous to one half of a frontal thermohaline intrusive system. The analogous features are:

- alternating diffusive interfaces and convecting or fingering regions
- advection/diffusion balance across the layers
- noses that extend into stratified fluid
- heat flux through the boundary extends into the intrusive region.

A key difference is that thermohaline intrusions appear to slope in the "finger-dominated" sense unless the overall stratification is strongly diffusive (Ruddick, 1992), while the other geometries slope in the opposite, diffusively dominated, manner, even though they exhibit weak fingers.

Table 1 lists the types of laboratory experiments reviewed above, comments on their relevance to oceanic phenomena, and attempts to pull together the known results regarding intrusion thickness and propagation speed. The vertical scale in most geometries was found to be proportional to the "natural scale", or could at least be related to the imposed flux. This suggests a question: can experiments involving constant-source heated sidewall, point-heat source, and sloping sidewall be related to an "equivalent temperature anomaly", such that the intrusion scale can be related to the natural scale?

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8.1 Vertical scale

In figure 9a we attempt to compare the observed layer thicknesses of the three thermohaline front experiments, which used the sugar-salt analogue to heat-salt. Note from the experimental descriptions (figure 5) that there are subtle differences in the definition of the density ratio. The scales from Ruddick and Turner (1979) and Bormans (1992) agree, and agree with the energy scale argument of Ruddick and Turner (1979). The scales observed by Holyer et al (1987) are considerably larger than the Ruddick and Turner (1979) scale (lower dashed line), and approach the scales predicted by the Ruddick and Turner (1979) energy argument under the assumption that diffusive fluxes dominate (upper dashed line). This difference is consistent with the observation that the intrusions in Holyer et al have diffusive-sense slope, weak fingers, took hours to form, and had parameter values that favored a very small vertical scale. We conclude that the small scale in Holyer et al (1987) allowed molecular diffusion to dominate over finger fluxes, a situation unlikely to apply to large-scale oceanic intrusions. The intrusions formed from double-diffusive plumes described by Nagasaka et al (1995) are of similar magnitude (the sum of layer thicknesses is about 4 times the Ruddick-Turner scale), but their thickness is not plotted here due to the complex dependence on layer splitting.

Figure 9b has a number of vertical brackets showing the range of (H-normalized) layer scales observed in the heated sidewall and melting iceblock experiments. These experiments use the heat/salt system, with $\gamma_f \approx 0.6$ and $\gamma_d \approx 0.15$, (Turner, 1973). The energy arguments of Ruddick and Turner (1979) transferred to the heat-salt system would predict h/H to be 1.25 if diffusive fluxes dominate, and h/H=0.6 if finger fluxes dominate. It is puzzling that the intrusions slope in the diffusive-dominated sense, yet the observed intrusion scales are much closer to the finger-dominated value of 0.6.

8.2 Nose Propagation Speed

In both the thermohaline front experiments and the sloping sidewall experiments, the propagation speed of the noses was found to be proportional to *Nh*, with the constant of proportionality (a Froude number) approximately 0.005, and a function of density ratio. Figure 10 shows the normalized nose velocity versus density ratio from both types of experiments. The thermohaline front experiments show a constant Froude number of the order of 0.005, and increasing by about a factor of 2 for density ratio larger than about 0.65. The layers sloped in the finger-dominated sense, even under these conditions. The sloping sidewall experiments were driven by lateral diffusive fluxes from the sloping wall, and even though weak fingers occured, the layers sloped in the diffusive-dominated sense. Layers formed only for gradient density ratio larger than 0.7, and their propagation speed increased rapidly in the range 0.89 - 0.96. Although the precise dependence on density ratio is very different, the propagation speed and overall variation with density ratio are similar to frontal intrusions.

The intrusions formed from a double-diffusive plume studied by Nagasaka et al (1995) had a propagation speed proportional to Nh (with h being the thickness of individual intrusions). The Froude number was of order 0.0075, and was smaller in the case of intrusions that split. Propagating nose structures occurred in other geometries: heated sidewall, point source, melting iceblock. It is a reasonable but untested hypothesis that the intrusion nose velocity in these experiments scales in a similar manner: nose velocity proportional to *Nh*, independent of intrusion length.

9. Summary

Intrusions have a very similar structure in all the experiments described here: alternating sloping finger and diffusive interfaces, advective-diffusive balance leading to lateral fluxes, and intrusions extending behind propagating noses. Most intrusions were found to have vertical scales proportional to the "natural scale" of eq. 3, and nose extension velocity of order 0.005Nh, and a weak function of gradient density ratio.

10. Unresolved questions

1. A major problem with laboratory intrusions (and possibly oceanic ones) is that the fingers often dominate the fluxes, and fill the region between diffusive interfaces. The finger fluxes are therefore very difficult to predict, being based on salinity gradient, and perhaps limited or affected by the intrusive shear. Without predictions, or even measurements, of finger fluxes in a continuous gradient system, we cannot easily model or understand the effects of fingers in driving thermohaline intrusions.

2. Ruddick et al (1999) found the diffusive interfaces were thicker than expected for a diffusive interface bounded by convecting layers. Bormans (1992) noted a "double structure" to the interfaces. These factors make it difficult to quantify the diffusive fluxes within intrusions because they indicate strong lateral non-uniformity of property gradients.

3. The model of Jeevaraj and Imberger (1991) ignores diffusive interfaces, has no fingers in interior, no noses, and no slope, yet seems to predict some intrusion properties. Can this solution be compared with that of Ruddick et al (1999)? Can an improved, fully dynamical theory be developed?

4. The fact that such similar scaling of propagation speed occurs for two intrusive systems, one driven by salt finger fluxes and the other by diffusive interfacial fluxes, suggests that a universal theory predicting intrusion propagation should be feasible. Key aspects are likely to involve the balance between advection and vertical double-diffusive fluxes (both finger and diffusive), entrainment of "new" undisturbed fluid near the noses, and the internal wave dynamics of the disturbances beyond the propagating noses. Other aspects that may or may not be essential are the recirculation within the intrusions, and the details of flow near the noses. Phillips and Huppert are currently applying the theoretical approach of Ruddick et al (1999) to the heated end-wall configuration (J.S. Turner, pers. comm. , 2001).

5. Can heated sidewall with constant heat flux experiments, point heat source experiments, and sloping sidewall experiments have an "equivalent temperature anomaly" defined, such that the intrusion scale can be related to the natural scale of eq. 3?

6. What is the effect of the tank endwalls on intrusions? They seem to propagate at constant speed until the noses reach the endwalls, but this has not been investigated in detail.

7. What is the effect of finite frontal width? No experimental studies have been published.

8. What is the effect of rotation and baroclinic shear on intrusions? Laboratory studies have only been performed for circular geometry heated sidewall.

9. Can frontal intrusions result in the formation of a thermohaline staircase?

10. How can sugar/salt experimental results be extrapolated to the oceanically relevant heat/salt system?

11. In the presence of lateral shear, intrusions can be expected to transport momentum as well as heat and salt. How strong or important are such transports?

12. In the experiments of Thorpe et al (1969), the system reached a finite-amplitude, quasi-steady state (Figures 2b,3) that was well-measured and described. A finite-amplitude analytic theory that allows for double-diffusive fluxes and convective motions (combining aspects of Ruddick et al, 1999, for frontal intrusions and Jeevaraj and Imberger, 1991 for low-aspect ratio convection) could be useful, but does not to our knowledge exist. Phillips and Huppert (pers. comm, 2002) are working on such a model.

13. Is there a scaling law, perhaps similar to (5) for the nose velocity in heated sidewall intrusions? It may be sufficient to collect and collate observational data from existing experiments to answer this question.

Acknowledgements

I am grateful to Dan Kelley and Jiro Yoshida for very helpful comments on an earlier draft, and to Stewart Turner and an anonymous referee for their valuable and helpful suggestions. Stewart Turner, Josef Tanny, and Arcady Tsinober graciously consented to the reproduction of figures from their experiments. My research is supported by the Canadian Natural Sciences and Engineering Research Council.

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Config-uration	Sugar/ salt?	Vertical scale, h (H = natural scale)	Nose propagation speed	Comments
Thermo-haline front	Yes	$$h = \frac{3}{2}\left(1-\gamma_f\right)H$$ (Eq. 1)	$c \approx FNh$ $F = F\left(R_\rho\right) \approx .005$	Needs laboratory study of "non-sharp" front, Coriolis effects. Finger dominated unless h is very small.
Heated sidewall	No	h/H= 0.62±0.05 (Huppert and Turner 1980), h/H=0.53±0.03 (Chereskin and Linden, 1985)	Interior velocity, $$u \approx .008\frac{g\alpha\Delta Th^3}{\nu L}$$ Jeevaraj and Imberger (1991). L = intrusion length	Precise and easy to set up, Coriolis effects studied. Diffusive- dominated, weak or no fingers. Relevant to Arctic.
Sloping sidewall	Yes	h related to lateral flux from wall, and thence to heated sidewall.	$c \approx FNh$ $F = F\left(R_\rho\right) \approx .005$	Very systematic behaviour, and amenable to theoretical study. Diffusively-dominated; weak or non-existent fingers.
Melting iceblock	No	h/H=0.66±0.06 (Huppert and Turner, 1980)		Directly relevant to icebergs. Diffusive-dominated.
Point heat source	No	h related to input heat flux	c decreases with time, as intrusions extend radially.	Precise and easy to set up. Relevant to geothermal plumes. Diffusive-dominated.
Anomalous Plumes or gravity currents	Both			Relevant to dense inflows and geothermal plumes. Direct study of double-diffusive plumes needed.

Table 1. Summary of the geometries of laboratory experiments relating to intrusions, with comments on their oceanic relevance, vertical scale, and propagation speed

Figures

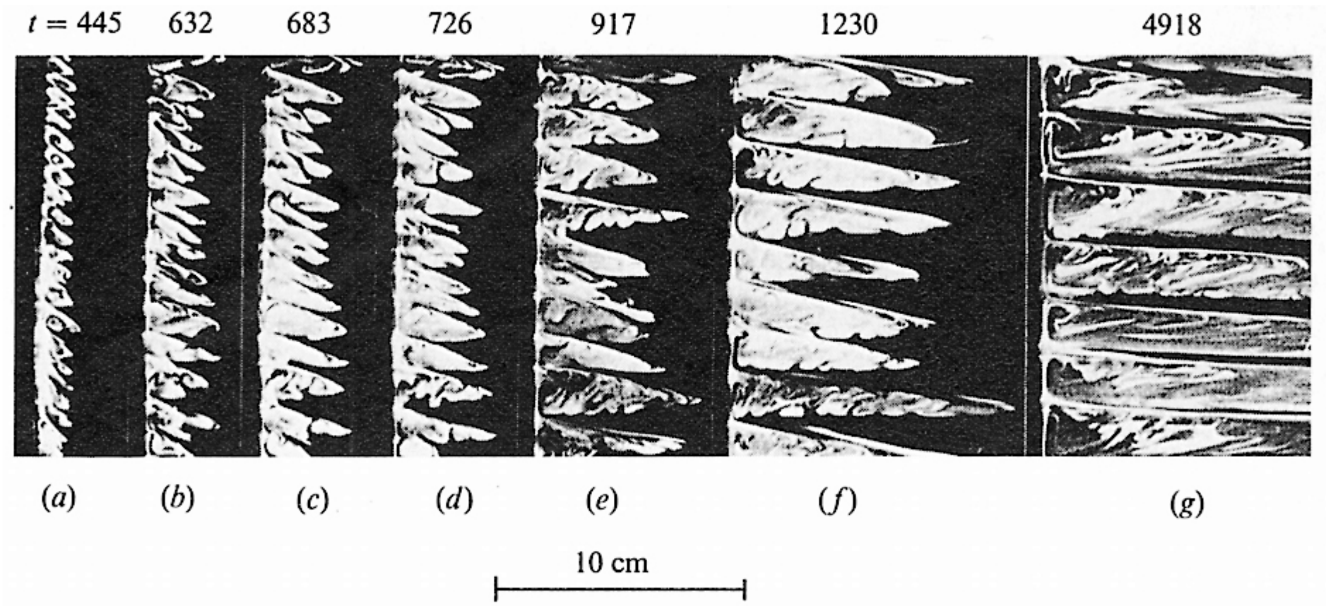

Figure 1. (Reproduced by permission of Cambridge University Press, from Tanny and Tsinober, 1988, figure 1.) The formation and development of layers in a linear salt gradient heated from the side. (a) Initial layers. (b-f) layer merging. (g) final layers (fragment).

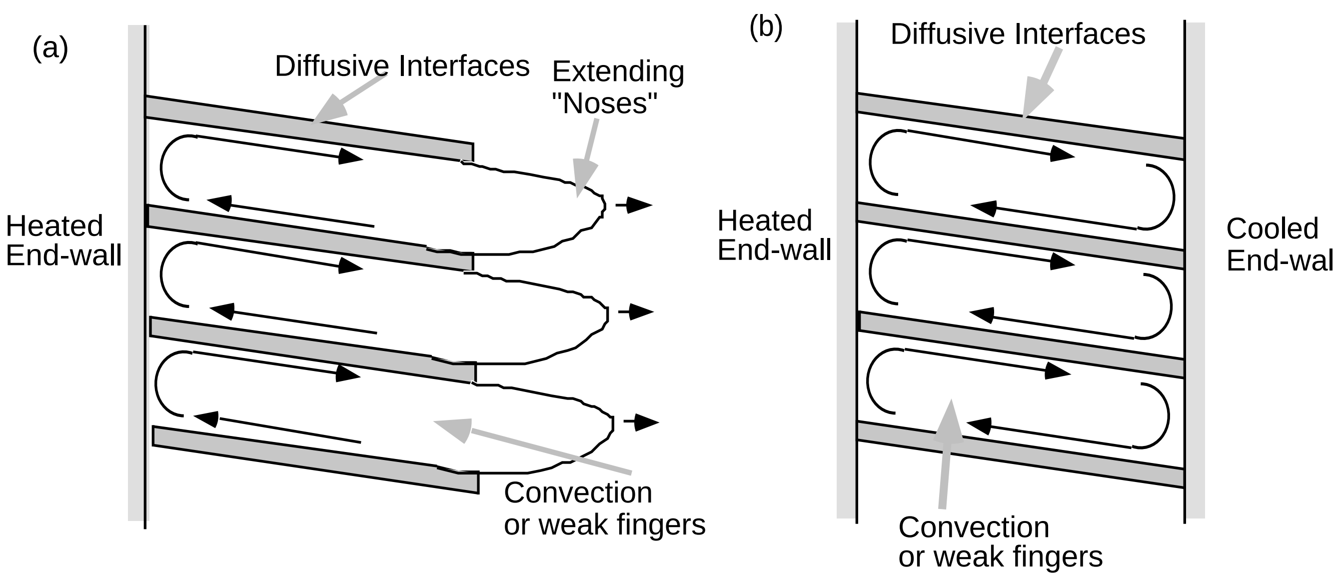

Figure 2. Geometry and features of the heated sidewall experiments of Thorpe et al,(1969), in the (a) initial stages, and (b) quasi-steady later stages of the experiments, when layers have extended across the width of the tank. Layers tend to migrate and merge in this later stage.

Figure 3. (Reproduced by permission of Cambridge University Press, from Tanny and Tsinober, 1988, figure 17.) The heated sidewall experiment at a later stage, using flourescent dye traces to show the stable shear flow at the interfaces (nearly horizontal straight lines) and the unstable shear flow within the layers (inclined convoluted lines).

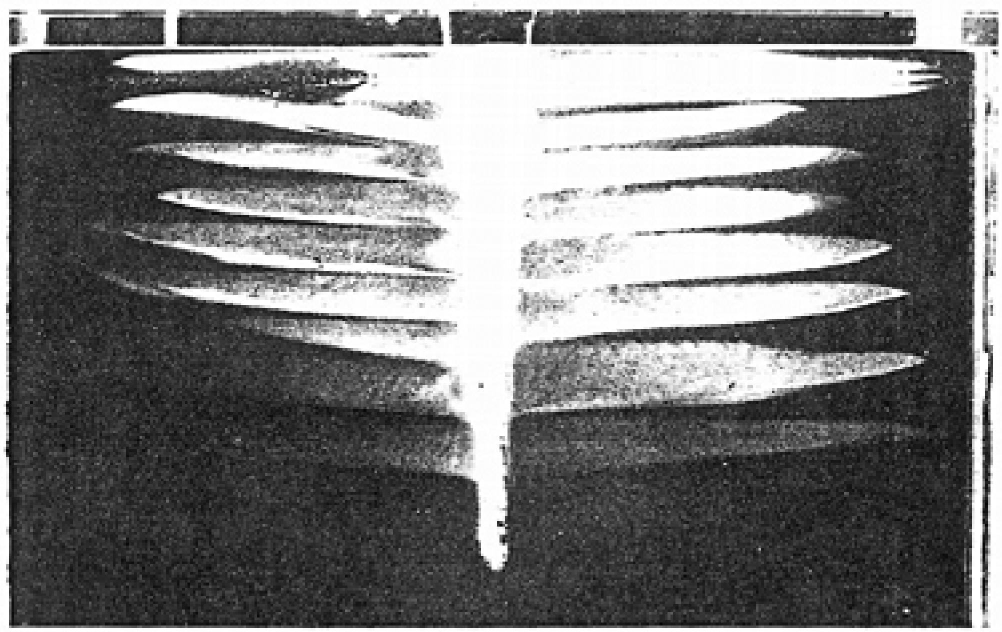

Figure 4. (Reproduced by permission of Cambridge University Press, from Huppert and Turner, 1980, figure 8.) The formation and development of layers in a linear salt gradient against a melting vertical ice wall. Fluorescein dye was frozen into the ice surface prior to insertion, and shows that melt water has been entrained into the thermohaline layers.

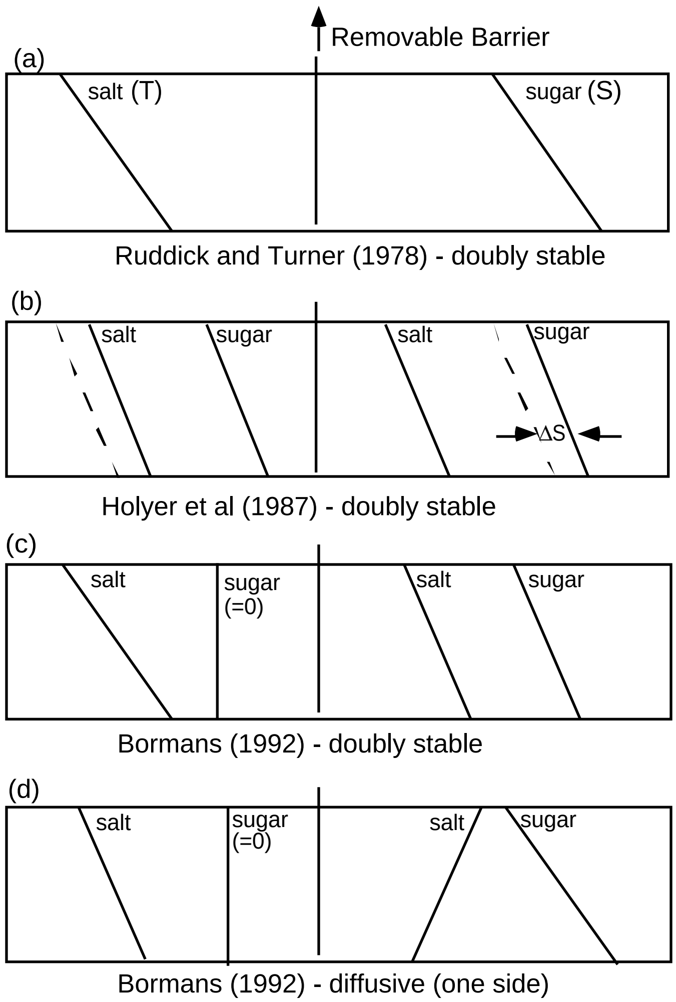

Figure 5. Laboratory setup for thermohaline intrusion experiments, showing the long tank separated into two halves by a removable vertical barrier. Each side is filled at the same time by two separate double-bucket fill systems. The types of gradients on each side are shown for (a) Ruddick and Turner, 1978, (b) Holyer et al, 1987, (c) Bormans, 1991, doubly stable and (d) Bormans, 1991, diffusive

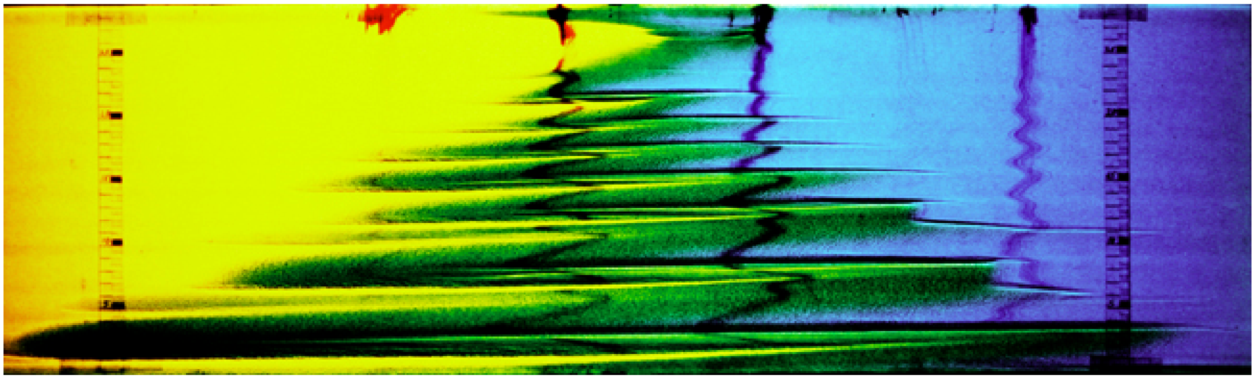

Figure 6. Color shadowgraph from the experiments of Ruddick et al (1999) using sugar and salt stratification to model a thermohaline front. The salty water on the left mimics

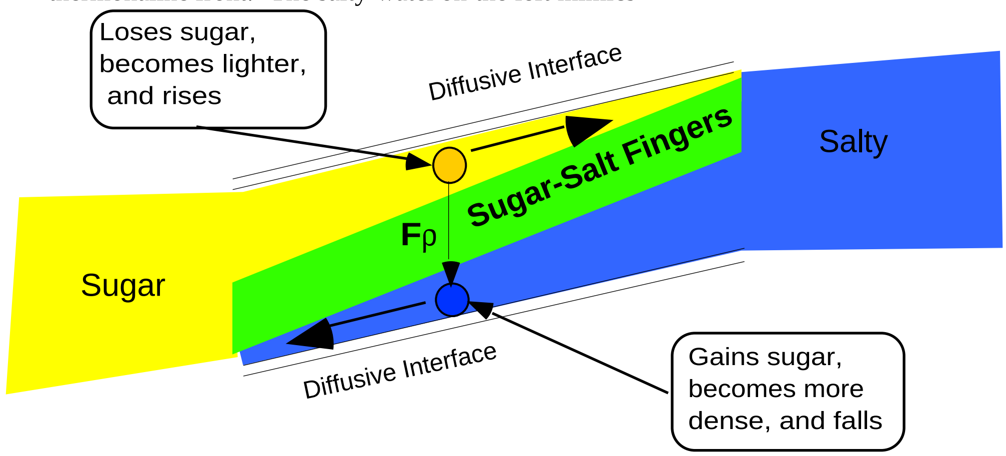

Figure 7. Schematic sideview of sugar-finger driven thermohaline intrusions, showing the counterflows (thick arrows), finger and diffusive regions, and slopes induced by the finger density flux F_ρ. If the diffusive interface density fluxes (not shown) were to dominate, the slopes would be reversed (Turner, 1978).

(a)

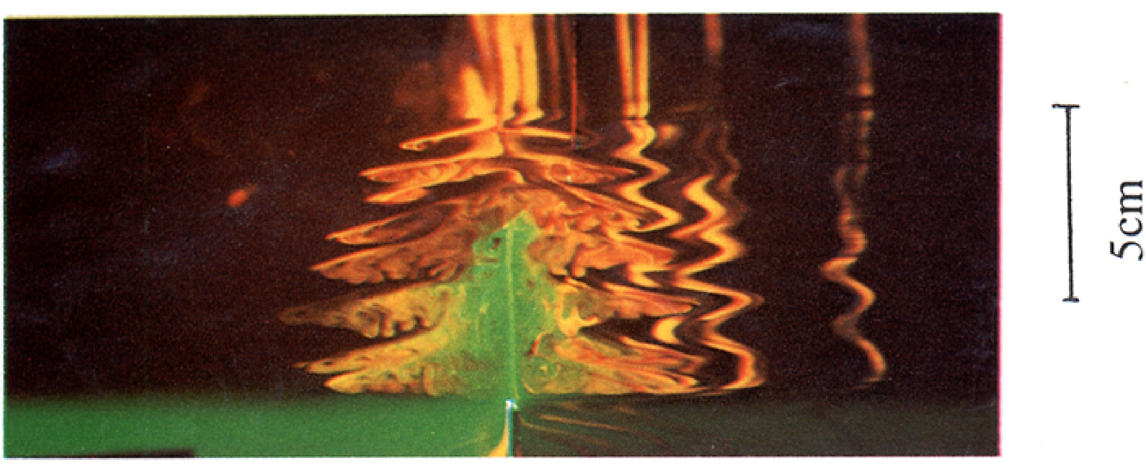

Figure 8. (Reproduced by permission of Cambridge University Press, from Tsinober et al, 1983.) The layers formed from a point source of heat in a stable salt stratification, visualized with fluorescent dyes.

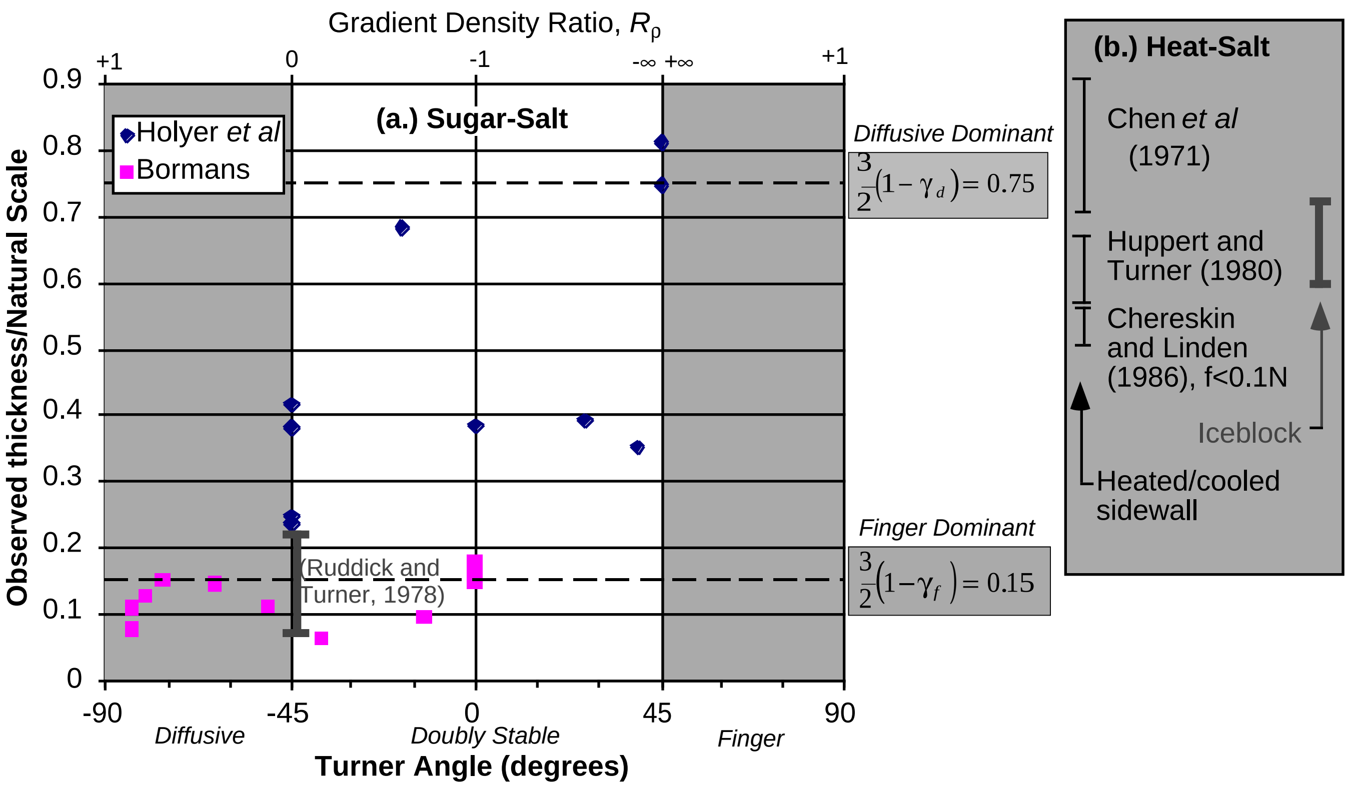

Figure 9. (a.) Observed layer scale, h, normalized by natural scale H (eq. 1) from the sugar-salt front experiments of Ruddick and Turner (1979), Holyer et al (1987), and Bormans (1992). The x-axis is the Turner angle (Ruddick, 1983), a convenient condensation of density ratio, which has key values indicated at the top of the plot. Note that there are subtle differences in the manner in which density ratio is defined (see figure 5); that from the sugar side of the experiments of Bormans, and of Ruddick and Turner is graphed, while the density ratio is equal on both sides of the experiments of Holyer et al. Lower dashed line and gray error bars: Eq. (4) from energy arguments and observations of Ruddick and Turner (1979), which assume the finger flux $\gamma_f = 0.9$ is dominant. Upper dashed line: as for lower line, but assuming the diffusive interface fluxes are dominant, with a flux ratio of $\gamma_d = 0.5$ (Turner and Veronis, 2000). (b.) Observed layer scale normalized by natural scale from a variety of heat-salt intrusive layering experiments.

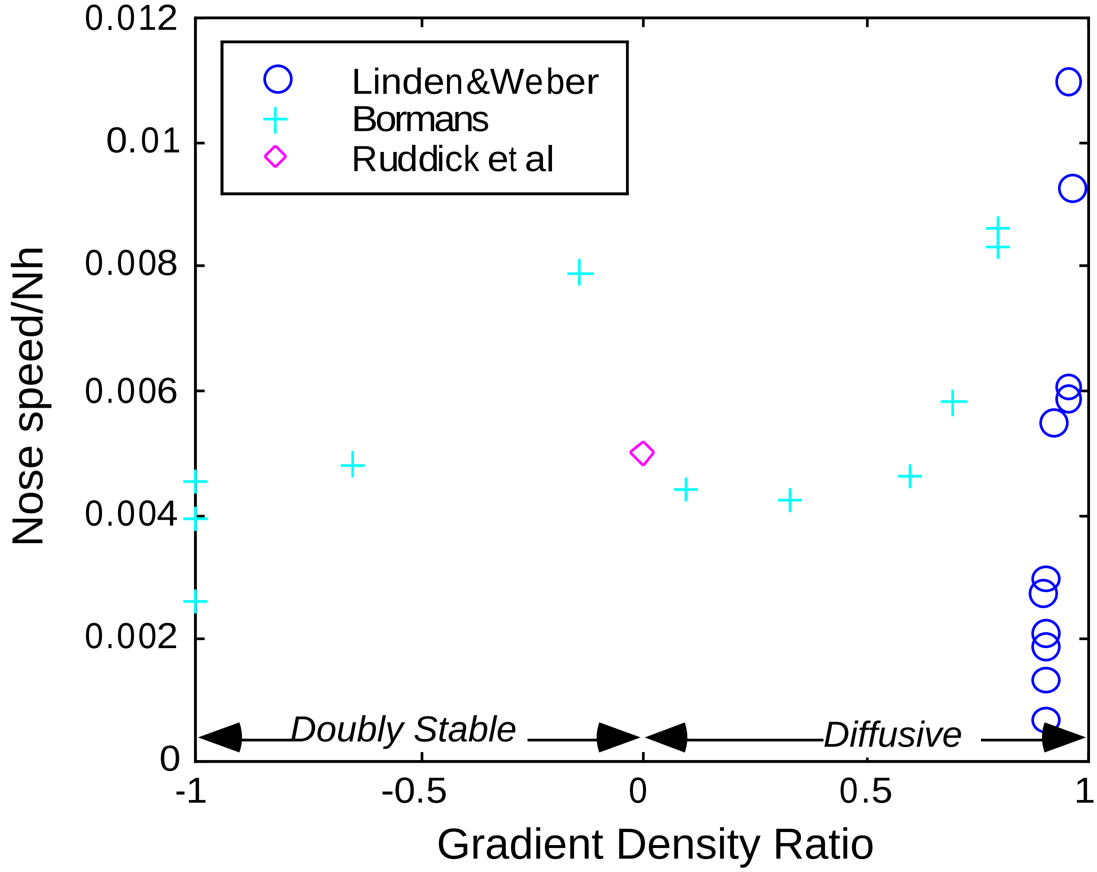

Figure 10. Normalized nose propagation velocity (Froude number) from the thermohaline front experiments of Ruddick et al (1999), Bormans (1992), and the sloping sidewall experiments of Linden and Weber (1977). Density ratio is that for the sugar side of the tank in the experiments of Bormans and of Ruddick et al, and for the tank interior in the experiments of Linden and Weber.