DETAILED INNER STRUCTURE OF DOUBLE-DIFFUSIVE INTRUSIONS

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Abstract The inner structure of the double-diffusive intrusions emerge from a density-compensating thermohaline front is examined in numerical simulations and laboratory experiments. In the two-dimensional direct numerical simulations which can explicitly resolve finger and diffusive convections, a reversal of the slope of the intrusions is observed as the density differences for one component, Δ, which by definition is compensated by the other component, across the front, increases. The reversal is found to be caused by a number of qualitative changes in flow structure, which in turn is controlled by the activity of finger and diffusive convections and their vertical density transport in the intrusive layers. These results are also confirmed in the laboratory version of the experiments, which use two sugar and salt stratifications.

INTRODUCTION

When two oceanic water masses meet at a thermohaline front, where temperature and salinity have large gradient, a sequence of slightly sloped layers intruding into each other is seen to form[1]. The intrusions have attracted much attention as they drive lateral mixing in the oceans. The intrusive motion results from the double-diffusive convection[2, 3]. The two types of double diffusive convection, finger and diffusive convection, both appear at much smaller scale compared to that of the intrusion layers. Their collective transport of heat and salinity drives the larger scale intrusions, and that intrusions, in turn, maintain the local temperature and salinity gradient to drive small scale convections. Many questions including the mechanism that controls the slope and the lateral flux remain unsettled[4]. Analyses of numerical and laboratory experiments are presented here.

EXPERIMENTS

We have investigated the flow emerged from a density-compensating thermohaline front (fig. 1). The density differences for one component across the front, Δ, was used as the principal controlling parameter.

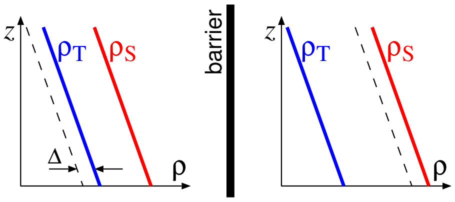

Figure 1. Initial stratifications in the fluids to the (a)left and (b)right of the barrier.

In the numerical experiments, variables are nondimensionalized based on an intrinsic length scale $(\kappa_T \nu \rho_0 / g \rho_{Tz})^{1/4}$, where κ_T is the diffusive coefficient for temperature, and ρ_{Tz} the basic vertical density gradient due to temperature stratification. Two-dimensional direct numerical simulations were conducted for various values of Δ. Initially the stratified fluids are at rest in both sides of the zero-thickness barrier which is to be broken at $t = 0$. Tiny random disturbances are added to initiate the convections.

In the laboratory experiments, we used salt and sugar for building up the density stratification, whose buoyancy period was set to 4.5 s.

RESULTS

Shortly after the barrier-breaking, small scale disturbances grow at the front. These disturbances merges to form a sequence of clearly defined layers. Each layer is sandwiched by sharp diffusive interfaces and is filled with finger convections which are very turbulent but almost homogeneous in the direction along the layers. Layers slowly grows horizontally without changing its thickness and finally fill up the whole calculation domain. The structure of the layer drastically changes around $\Delta \sim 200$ (see fig.2). When Δ is small, the layers has strong density interface with very active diffusive convection which transports most of the fluxes. When Δ is large, on the other hand, the finger convection dominates and the diffusive convection becomes passive or vanishes.

The transition from diffusive-dominated structure to finger-dominated takes place when the finger convections penetrate the diffusive interfaces and eventually reconnects the layers. In striking contrast to the structure around the central part of the layers, the structure of the noses of the intrusions are almost unchanged with Δ.

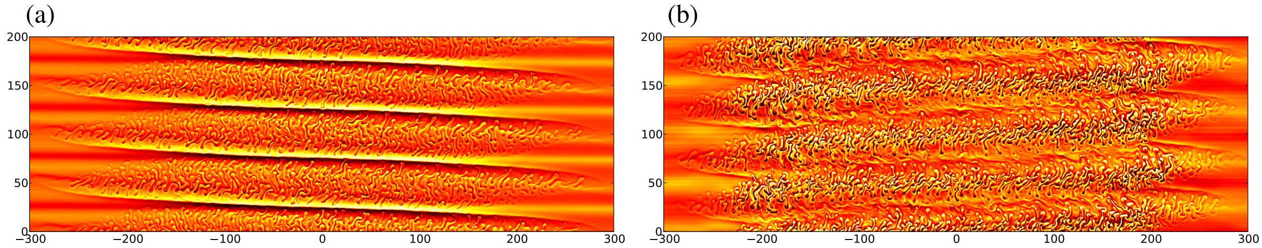

Figure 2. Snapshots of density fields in numerical experiments for (a) $\Delta = 150$, (b) $\Delta = 400$. Density deviations from horizontal averages are plotted. Only the central half of the whole calculation domain is shown.

These characteristics observed in the numerical experiments was confirmed in the laboratory experiments (fig. 3), in spite of the fact that salt and sugar which have different diffusivity ratio from numerical simulations was used.

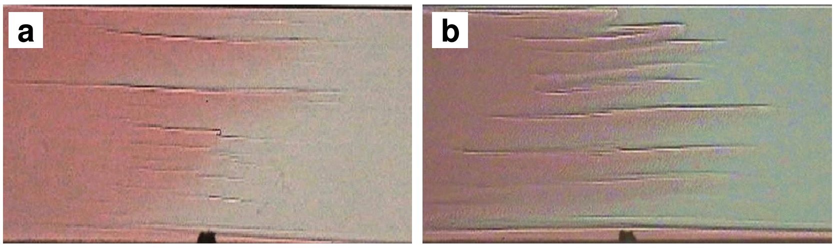

Figure 3. Shadowgraphs of intrusive layers in the laboratory experiments. (a) $\Delta = 0.01$ g cm^{-3}, 60 min after the removal of the barrier, (b) $\Delta = 0.03$ g cm^{-3}, 10 min. Only the central part of the tank is shown.

The flow structures for small and large Δ is schematically presented in figure 4. The change in the structure is not merely a horizontal reversal of the slope as it has been thought[5], but qualitative changes in many aspects particularly in the small scale convections. The results suggest that the estimation of lateral fluxes in oceans can be improved by taking the change in the flow structure into consideration.

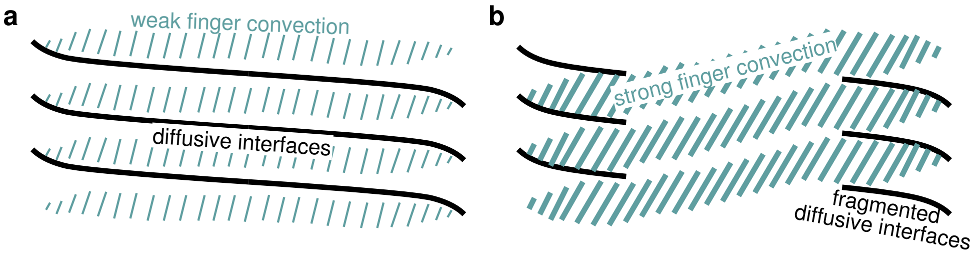

Figure 4. Schematic representation of the two different modes of interleaving: (a) diffusive-dominated interleaving when cross-frontal density difference is small, and (b) finger-dominated interleaving when cross-frontal density difference is large.

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References

[1] B. Ruddick, O. M. Phillips, and J. S. Turner. A laboratory and quantitative model of finite-amplitude intrusions. *Dyn. Atmos. Ocean.*, **30**:71–99, 1999.
[2] J. S. Turner. Double-diffusive intrusions into a density gradient. *J. Geoph. Res.*, **83**:2887-2901, 1978.
[3] H. Niino. A linear theory of double-diffusive horizontal intrusions in a temperature-salinity front. *J. Fluid Mech.*, **171**:71–100, 1986.
[4] B. Ruddick., and K. Richards. Oceanic thermohaline intrusions: observations. *Prog. Oceanogr.*, **16**:499–527, 2003.
[5] B. Ruddick. Laboratory studies of interleaving. *Prog. Oceanogr.*, **16**:529–547, 2003.