ADJUSTMENT PROCESSES IN HORIZONTAL CONVECTION

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Summary An overturning circulation is established in a fluid when differential heating is maintained along one horizontal boundary. We examine how thermally-equilibrated convection responds when the differential heating is suddenly perturbed. The subsequent flow and the re-equilibration timescale are relevant to understanding how the global overturning circulation in the oceans may respond to changes in surface buoyancy forcing, such as those due to global warming.

INTRODUCTION

'Horizontal convection' is the circulation induced by a gradient of temperature or heat flux along one horizontal boundary of a fluid [1]. Previous studies of horizontal convection have often been motivated by application to the global meridional overturning circulation (MOC) of the oceans, which is subject to surface forcing by wind-stress and by the variation of temperature or buoyancy flux with latitude. Horizontal convection can provide a useful model of an MOC in a limit where surface wind stresses do not enter the momentum budget of the flow [2]. The dynamics of horizontal convection is not clearly understood, but is important for providing insight into how the overturning circulation in the oceans, as well as in lakes and estuaries, might adjust in response to changing surface temperatures and freshwater inputs. Here we extend previous laboratory experiments with equilibrium flow [3] to investigate the transient flow response following a step-wise change in the thermal boundary conditions.

Most previous work on horizontal convection has focused on the flow in a box driven by steady thermal forcing for which the rate of heat supply varies monotonically with distance along the horizontal boundary, e.g. see [1,3]. The circulation fills the box. A convectively mixed layer is embedded within a stably stratified thermal boundary layer, which is adjacent to the forced boundary and which feeds a buoyant plume at the end of the box. In this equilibrium state the fluid entering the plume has just enough residual buoyancy to travel through the full-depth. Density stratification plays a role in the interior, leading to a horizontal outflow along the length of the box from the plume. The presence of a stratification in the thermally-equilibrated state suggests that vertical (down-gradient) diffusion of heat in the interior is essential.

EXPERIMENTS

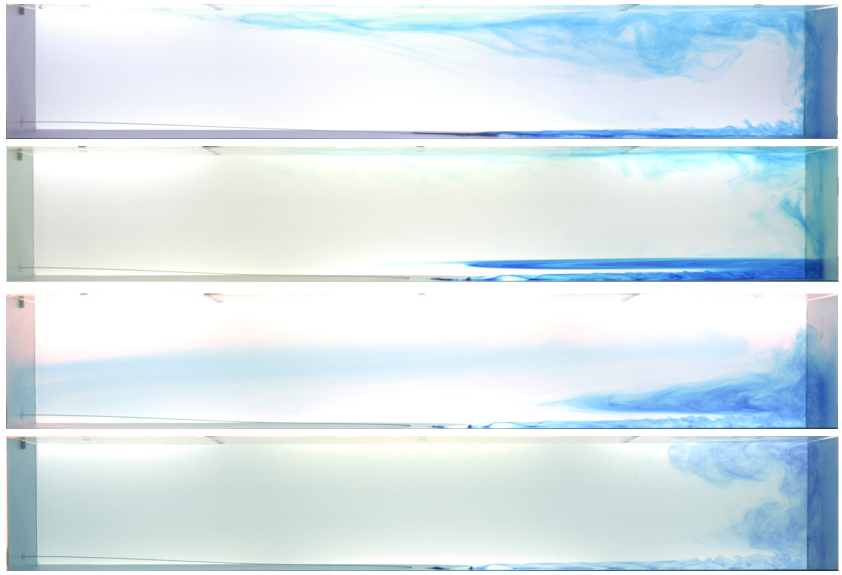
Experiments were carried out in a well-insulated and multiply-glazed box 1250 mm long, 305 mm wide and 200 mm deep that was filled with de-aired water. Differential heating was applied along the base of the box – heat was supplied to the working fluid over the right-hand half of the base and removed over the left-hand half of the base. Either a specified uniform flux or a specified uniform temperature was applied over the right-hand half, whereas the left-hand half was maintained at a specified uniform temperature. A detailed description of a similar experimental apparatus is given by Mullarney et al. [3].

The flow was allowed to equilibrate to the steady thermal forcing over a period of several days, thus setting the initial conditions in each experiment (figure 2a). Each adjustment experiment was started by a sudden step-wise perturbation of the thermal forcing. Several types of perturbations were examined, including increasing or decreasing the temperature applied to the left-hand half of the base and increasing or decreasing the temperature/heat flux applied to the right-hand half of the base. The perturbed circulation was visualized by introducing neutrally-buoyant food-dye into the flow at strategic locations. The side-wall insulation was removed from the box for only short periods to enable observation of the dye streams. A number of thermistors were used to monitor the temperature field in the box.

OVERVIEW OF RESULTS AND CONCLUSIONS

It is important to note that when the flow is at thermal equilibrium, there is no net input of buoyancy to the box, i.e. the rate at which heat is input at the forced boundary is equal to the rate at which heat is removed through the remainder of that boundary (and which is equal to the heat 'throughput' in the flow). Accordingly the flow response following a sudden

Figure 1. Enhanced full-depth convective circulation (side view looking horizontally through the flow) at $t \approx 6$ min after a sudden increase in heat input. Blue dye injected for $t > 0$ displaces red dye injected for $t < 0$. Cooling and heating are applied over the left- and right-hand halves of the base, respectively. The initial thermally-equilibrated circulation is visualized in figure 2a.



(a)

(b)

(c)

(d)

Figure 2. Dye visualization sequence showing the adjustment of convective circulation following a sudden decrease in heat input at time $t = 0$: (a) the thermally-equilibrated full-depth overturning for $t < 0$; (b) convective 'shut-down' at $t \approx 7\,\text{min}$; (c) gradually deepening partial-depth overturning cell and the occasional oscillatory penetration of the overlying stratification by the buoyant plume at $t \approx 20\,\text{hr}$; (d) partial-depth circulation and increasing oscillations of the buoyant plume through the box depth at $t \approx 25$ hr, prior to the re-establishment of the full-depth overturning similar to that shown in (a).

perturbation to the thermal forcing may be summarized qualitatively in two categories. Firstly, when the perturbation leads to a temporary net input of destabilizing buoyancy to the box (e.g. net heating at the base), the excess buoyancy at any time is accommodated in a stronger plume, which drives a stronger circulation occupying the full depth of the box (figure 1). Initially vertical advection in the box interior is important for balancing the increased buoyancy transport in the plume, as in the filling box [4]. Flow evolves to a new thermally-equilibrated state as the bulk density of water in the box adjusts towards that of the plume such that the transports of buoyancy by the plume and by vertical diffusion in the interior come into balance. Secondly, when the perturbation leads to a temporary net input of stabilizing buoyancy to the box (e.g. net cooling at the base) a relatively complicated evolution of the flow follows. The buoyancy deficit leads temporarily to a weaker plume that cannot penetrate through the full depth of the box. Instead the plume outflow enters the box interior forming a partial-depth convecting circulation (figure 2b). The partial-depth convecting layer deepens only very gradually (figure 2c), eventually occupying the full depth of the box. The experimental observations suggest that the transition between partial and full-depth convection involves oscillatory penetrations of the plume through the full depth (figure 2d).

Using temperature time-series measured in the experiments (not shown here), we found that the adjustment reached 99% completion on a timescale of O(20) hrs in all runs with the first type of perturbation, and required approximately twice as long in all runs with the second type of perturbation. Adjustment was consistently faster in the first case because the buoyancy anomaly is advected through the full depth by the plume at all times. However, despite a rapid shut down of the circulation in the second case, the adjustment timescale is shorter than if molecular diffusion through the box depth was responsible for bringing the plume buoyancy transport back into balance with that in the interior. This re-equilibration mechanism is currently the subject of ongoing investigation.

Our laboratory observations are consistent with a rapid shut down of the global overturning circulation of the oceans following decreased surface cooling or increased surface freshwater fluxes at high latitudes, which are anticipated consequences of global warming. Further, our scaling analysis (not included in this paper) suggests that thermally-equilibrated horizontal convection would be re-established in a box with the same average depth and volume as the global oceans on a timescale of the order of 5000 years. It is nevertheless speculative to extrapolate this timescale to the MOC for a number of reasons. The surface forcing is coupled to the flow and likely to evolve, and we expect bottom topography in the oceans to play an important role.

References

[1] Hughes G.O., Griffiths R.W.: Horizontal Convection. *Annu. Rev. Fluid Mech.* **40**:185–208, 2008.

[2] Hughes G.O., Griffiths, R.W.: A simple convective model of the global overturning circulation, including effects of entrainment into sinking regions. *Ocean Model.* **12**:46–79, 2006.

[3] Mullarney, J.C., Griffiths, R.W., Hughes G.O.: Convection driven by differential heating at a horizontal boundary. *J. Fluid Mech.* **516**:181–209, 2004.

[4] Baines, W.D., Turner, J.S.: Turbulent buoyant convection from a source in a confined region. *J. Fluid Mech.* **37**:51–80, 1969.