# Turbulent Horizontal Convection and the Global Thermohaline Circulation of the Oceans

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A very simple conceptual model for the meridional overturning component of the ocean circulation is the convective flow driven by a horizontal surface temperature gradient. The meridional overturning circulation (also referred to as the global thermohaline circulation) carries warm subtropical surface waters to high latitudes, where it cools and sinks. In the present pattern of circulation the dense cold (and sufficiently saline) water sinks in confined regions at high latitudes to form `Deep' and `Bottom' waters. There must be a slow, possibly basin-wide, upwelling to the surface to match the poleward mass flux, with the loop closed by an inferred zonal average return flow toward the equator at depths below the thermocline. The density structure and heat transport must depend on the rate of vertical diffusion of heat. In the oceans the diffusion is attributed internal, turbulent mixing processes, which act to increase the potential energy of the water column. The resulting heat flux carried by the overturning circulation has a significant role in the climate system, and changes in this circulation have been implicated as a cause of climate variability on decadal to millennial timescales. However, there is uncertainty in the source of the energy for internal mixing, and a discrepancy between predicted and measured rates of mixing. There is also controversy as to whether the meridional heat flux (*i.e.* buoyancy) is a significant forcing for the oceans. Some have concluded that the heat flux is simply incidental to a flow forced by surface wind stress and in which the density structure is maintained by mixing energised by winds and tides. We address these issues by examining circulation forced purely by thermal buoyancy.

Our laboratory and numerical experiments show that convective circulation driven by differential heating at a horizontal boundary can be vigorous and turbulent. The circulation in a long box forced at the base (by heating one half and cooling the other half, with all other boundaries insulated) includes a stable boundary layer against the forcing boundary. Water in this layer (the thermocline) flows from the region of stabilising buoyancy flux towards the region of destabilising flux, and feeds into a vertical plume at the end of the box. The plume `sinks' to the opposite boundary. We have achieved large Rayleigh numbers with a small basin aspect ratio, such that the plume and its outflow are turbulent. The destabilising boundary flux also produces small-scale three-dimensional convection in a mixed layer within the stably stratified thermocline, and this mixed layer deepens toward the end of the box. The mixing penetrates through the depth of the thermocline only at the end of the box. Hence the deepest mixing and the bulk `sinking' are coincident.

In the non-rotating case, the mean flow in the plume supplies a turbulent return flow that fills 1/3 of the depth of the box. Thus we conclude that a temperature difference imposed along a horizontal surface (such as the ocean surface) can drive a vigorous and turbulent flow throughout the basin. In the rotating case, the small-scale convection in the turbulent mixed layer is unaffected by rotation, but the `sinking' occurs in localized, unsteady chimney structures. The geostrophic return flow is approximately independent of depth above the thermocline and tends to take the form of eddies that carry water, heat and tracer across high-gradient frontal zones between large gyres that fill the width of the basin.

We correctly predict the measured mass transport and density structure in the experiments from a simple model in which vertical advection and diffusion of density in the interior are balanced to give a steady state. In this model we impose a zero net buoyancy flux at the forcing boundary and allow for a depth-dependence of the interior vertical velocity (owing to entrainment of water into the `sinking' region). The vertical velocity is therefore larger further from the forcing boundary. For simplicity, and in line with previous ocean models, we also assume a uniform vertical diffusion coefficient. The model is related to the "filling-box" model for a container that is filled with density stratification by a turbulent plume. Applying the same model to the meridional overturning circulation of the global ocean, we find that the volume flux of Antarctic Bottom Water and the measured globally-averaged density profile through the ocean depth can both be maintained by the estimated surface heat fluxes, if we assume the vertical diffusivity equal to that measured in the open oceans (order $10^{-5}$ m$^2$/s). We conclude that the much larger diffusivity inferred by Munk (1966) and the larger external energy input to interior mixing predicted by Munk & Wunsch (1998) are not required if downwelling regions and sloping bottom currents entrain surrounding waters. The overturning circulation can, in principle, be driven by the surface heat fluxes alone, and we suggest that energy arguments purporting to imply that the heat flux is passive and coincidental are may not be correct. However, additional energy inputs to internal mixing from tides and winds will enhance the uptake of buoyancy at the surface and may increase the overturning mass flux.