

# THE EFFECT OF ROTATION ON CONVECTIVE OVERSHOOT

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## **Abstract.**

In this note we discuss some preliminary results from our 3D numerical simulations of incompressible penetrative convection in the presence of rotation. Though these simulations pertain to a particular case of a deepening mixed layer with overshoot, we believe the results to have significance in the solar scenario. In particular, we conjecture that rotation has a constraining effect on convective overshoot.

**Key words:** convection, penetration, rotation, turbulence

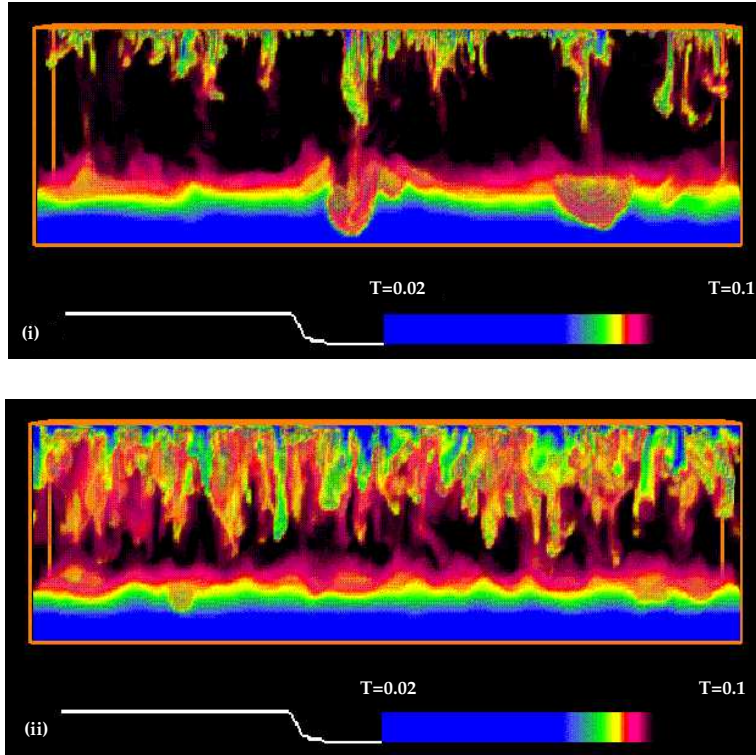
There are many examples in nature where regions of turbulent motions are bounded by regions of stably stratified fluid in which there is no local production of turbulence. These include the solar convection zone, superposed on the convectively stable radiative interior; the Earth's atmospheric convective boundary layer, which is capped by an inversion layer; and the mixed layer of the ocean, bounded from below by the thermocline. For these naturally occurring flows, turbulent motions at the interface between stable and unstable fluid may induce mixing through entrainment, with turbulent eddies (or convecting fluid elements) penetrating into the stable layer.

Despite its ubiquity, penetrative convection, and its role in the inherent organization on larger scales, is to-date elusive with regard to a comprehensive and quantitative understanding of the physical processes involved. Attempts to estimate (predict) the extent of overshoot beyond the base of the solar convection zone have been made by 1D models using mixing-length

like parameterizations (Schmitt *et al.* 1984, Zahn 1991) and through 2D numerical simulations (Hurlburt *et al.* 1994, Roxburgh & Simmons 1993). However given the increasing constraints and precision of solar structure currently being obtained through solar oscillation data provided by SOI on the SOHO spacecraft and GONG, such models and simulations are proving to be inadequate since they all somewhat over-estimate the extent of convective penetration. Helioseismic inferences currently have this bounded to a small fraction of a pressure-scale height (Basu *et al.* 1994).

Thus far, in all attempts to estimate the extent of solar convective overshoot many effects, such as magnetism, ionization and rotation, have been neglected. The primary reason being the simplification of an otherwise complicated phenomenon. Only now are such effects being considered, primarily due to the continual improvement of helioseismic inferences. In this note we wish to bring to the attention of the solar community some of our recent results on the constraining effect of rotation on convective penetration (Julien *et al.* 1996a). Though these results have been obtained for the case of penetrative convection particularly relevant to the time-dependent run-down scenario of a deepening ocean mixed layer, we believe them to be relevant to the statistically-steady configuration of the sun. We argue this to be the case because many of the key effects of rotation first observed in simulations of non-penetrative incompressible (Julien *et al.* 1996b) and subsequently compressible thermal convection (Brummell *et al.* 1996) are also observed here; *e.g.* enhanced lateral mixing due vortical thermal plume interactions and sustained unstable thermal stratification.

In figure 1, we illustrate two examples of our penetrative convection solutions, with and without rotation. Shown here are vertical sections of the instantaneous temperature field. Convection is driven by a homogeneous surface buoyancy forcing into a stably stratified fluid. Hence, as mentioned above these solutions represent a time-dependent deepening mixed-layer with overshoot. However these visualizations reveal striking differences in the plume structure in the non-rotating (i) and rotating flows (ii). Without rotation, a few strong plumes extend into the mixed layer. On encountering the stably stratified region below, the plumes penetrate deep into this region. Fluid is entrained into the mixed layer through vigorous upwelling around the plumes, providing evidence for the transport of fluid from the stably stratified region below. At high rotation, the cell size (defined as the average spacing between plumes) is considerably reduced (bearing close correlation to that predicted by linear theory), leading to a larger number of weaker plumes. In this case, all thermal plumes are cyclonic due to the conservation of angular momentum during their development. Interaction between such cyclonic structures result in a strong stirring and lateral mixing of temperature, diluting the buoyancy anomaly in the plumes (Julien,



*Figure 1.* Vertical section of the instantaneous temperature field shown for two penetrative convection solutions with (i) Rossby number  $Ro = \infty$ , (ii)  $Ro = 0.21$ . Convection is driven by a homogeneous surface buoyancy forcing into a stably stratified fluid. Only the upper half of the simulation volume is displayed, showing convective plumes initiated at the upper surface, a turbulent convective layer, and the interface with the stable layer below. Smaller  $Ro$  results in a larger number of plumes, but less entrainment at the interface with the stable layer.

*et al.* 1996a,b,c). Furthermore, the plumes which reach the bottom of the mixed layer are small and weak with their horizontal dimensions increasing little with depth, unlike the non-rotating case. Thus upwelling around the plumes is also significantly diminished. The vertical transport of buoyancy is therefore reduced indicating an equivalent reduction in transport of fluid from the stably stratified region below.

We therefore expect the principle differences introduced by rotation in penetrative convection to be a reduction in the magnitude of the negative buoyancy flux and in the width of the penetration zone. All indicate a less efficient transport of properties in the vertical. We suggest that this reduction in vertical transport can be explained by increased lateral mixing due to the vortex-vortex interactions observed at high rotation. This is in fact evidenced by the differences in the instantaneous kinetic energy budgets for the rotating and non-rotating case (figure 2). Whereas the buoyant production term  $\sigma Ra \langle wT' \rangle$  is approximately unchanged in the upper part of the mixed layer, at high rotation the dissipation of kinetic energy

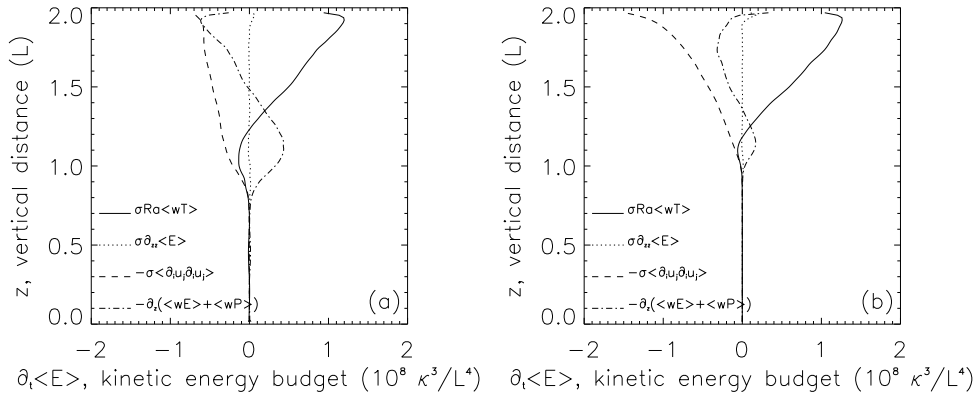


Figure 2. Horizontal averaged instantaneous kinetic energy budgets at  $t = 0.012L^2/\kappa$ . (a)  $f = 0$ ; (b)  $f = 2500L^2/\kappa$ .

$-\sigma < (\partial u_i / \partial x_j)^2 >$  is larger due to lateral mixing, and the transport of kinetic energy  $-(\partial/\partial z)(\langle wE \rangle + \langle wP \rangle)$  out of the upper part of the mixed layer is correspondingly smaller. Since the integral of the transport term over the vertical must be zero, this results in less transport of kinetic energy into the lower part of the mixed layer and, hence, less negative buoyancy flux in the penetration zone. Plumes therefore have less energy available for entrainment in the penetration zone. Note the reduction in the width of the penetration zone (figure 2).

In conclusion, we note that the existence of significant downwelling plumes that are rotationally influenced remains an open question for helioseismology.

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