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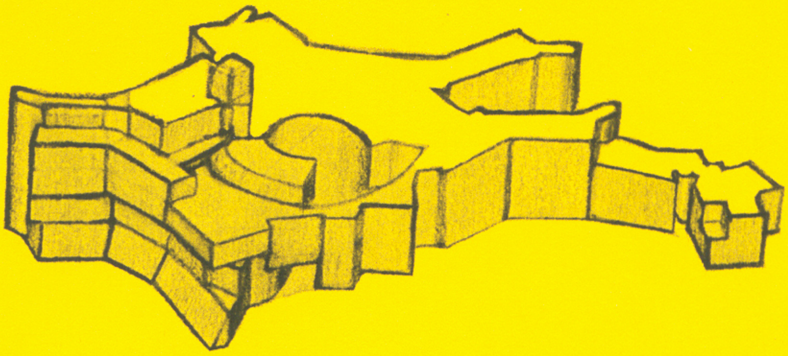

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Flow Patterns and Transitions in Rotating Convection

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Turbulent rotating convection frequently occurs in stars and planets. The process is so complex that its study often needs to resort to numerical simulations, especially since deep stratification is commonly involved. In an astrophysical context, the circulation is global, and ideally, the flows should be studied with a global model. In most instances, however, such is impractical due to the unaffordable demand on computing resources. Besides the long integration time required for thermal relaxation, the situation is worsened by the requirement of higher resolutions and shorter time steps in fast rotation situations. Therefore, some researchers adopt the convection-in-a-box approach [1, 2] which can only look at the idealized local behavior. A similar approach has long been used in geophysics; idealized atmospheric flows (predominantly two-dimensional) have been studied in localized f-planes and beta-planes. The results have been very useful in providing understanding for the basic flow processes.

Here, we report a rather special result from our numerical study of localized, deep, turbulent, rotating convection. The domain of each computation is a rectangular box termed 'f-box', *a la* f-plane. The angular velocity vector is held fixed in each case, but the flows are very much three-dimensional, and in particular the Coriolis force generated by the vertical velocity cannot be ignored.

Our main result can be summarized by a few sentences: Medium scale (width $\sim$ a few scale heights) coherent structures (flow patterns) are ubiquitous in rotating convection flows. The forms of the coherent structures depend on the Coriolis number ($\mathrm{Co} \equiv \mathrm{L}\Omega/\mathrm{V}$, reciprocal of the Rossby number) as well as the aspect ratio of the f-box. Pattern changes induce corresponding qualitative changes in the turbulence characteristics (e.g. moments of the fluctuating quantities). Therefore, coherent structures are crucial for the understanding of rotating convection. They are more fundamental than the concept of Reynolds stress. This conclusion is drawn from studying over one hundred cases of numerical experiments covering different input fluxes from the bottom, different latitudes (ϕ), different rotation rates (Ω), and different grid sizes. The corresponding locations of the boxes are from the equator to the North pole, and the range of Coriolis number is from 0 to 18.

The so-called coherent structures are essentially rolls tilted in different ways and thus presenting different impressions – either as convective rolls lying horizontally or slightly tilted, or as vortices with some possible tilts from the vertical.

When the rotation rate is low ($\mathrm{Co} < 1$), there is a *negative shear* in the mean zonal flow (eastward flow decreases with height) that has a linear vertical profile and spans the full depth of the convection zone (except at the pole, see [3]). It is basically a consequence of the conservation of angular momentum [4]. In the low latitudes ($< 45°$), vague features of east-west aligned rolls first appear; they can be understood as cloud streets [5] or in terms of preferential growth of linear modes [6]. The roll feature is most prominent at the equator.

When Co gets above 1, the alignment of the low-latitude rolls changes from east-west to north-south. Correspondingly the zonal-meridional component of the Reynolds stress changes from removing to feeding angular momentum towards the equator. The *negative shear* is compressed to shallower and shallower layers in the top region. The *local* value of Co remains low (V higher, L lower) there.

Remnant traces of east-west rolls can still be detected in this top region. In the lower region, the mean zonal flow tends to zero [3].

The alignment transition at the equator, however, occurs at a much higher Co (between 3 and 6). Before that the shear in the zonal flow stays negative and linear throughout the depth of the convection zone. Beyond a critical Co, it flips abruptly to a *positive linear shear*[7]. The positive shear is associated with the dominance of cyclonic rolls over anticyclonic rolls (all north-south aligned). For the same reason given in the previous paragraph, there is a shallow negative shear layer at the top of the convection zone. This process is important for explaining the occurrence of equatorial superrotation near the surface of the sun and the giant planets.

Coherent cyclonic structures in the form of vortices appear in the other latitudes around the same Co. The sizes of the vortices decrease towards the pole (as the value of the parameter $f = 2\Omega \sin\phi$ increases). These structures are accompanied by spotty horizontal distributions of thermal fields and possess very large horizontal velocities. Their presence induces a big drop in the coherence of the thermal variables with the vertical velocity. For example, the correlation coefficient between the temperature fluctuation and the vertical velocity drops from the general level of 0.75 to 0.15.

A further transition of flow pattern is found in non-equatorial regions when Co reaches about 12 - 18. Anticylonic vortices become the dominant feature. They are stronger and larger than the cyclonic vortices which still persist. This process may be important for the generation of the Great Red Spot and White Ovals in the Jovian atmosphere.

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