Equatorial Super-rotation on Gas Giants Driven by Internal Convection

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I. Abstract

Jupiter and Saturn’s atmospheres are dominated by multiple zonal jets with strong superrotation around the equator. We have modified the MIT general circulation model to be suitable for giant planets. The model’s geometry is a full 3D sphere down to an inner core (unlike the traditional spherical shell). It is non-hydrostatic, anelastic, uses an equation of state suitable for hydrogen-helium mixtures (SCVH), and is driven by internal heat. In the parameter regime suitable for Jupiter and Saturn the system in steady state is to first order geostrophic and hydrostatic. Since the aspect ratio is not small this includes all four Coriolis terms, and the numerical results show that the vertical Coriolis contribution is significant in the balance between pressure and buoyancy. The basic steady state balance before correction by the convection drive is given by

\[ \frac{\partial}{\partial t} \mathbf{u} = -\mathbf{f} \times \mathbf{u} + \nabla p + \mathbf{g} \frac{\rho^*}{\rho_0^*} \mathbf{e}_z + \mathbf{F}_h \]

This implies that thermal wind balance on the sphere will have the form

\[ 2 \mathbf{f} \times \nabla \rho = \frac{\rho^*}{\rho_0^*} \mathbf{e}_z + \nabla p + \mathbf{g} \rho^* \]

The 3D fields are presented with three slices through the sphere. Figure 3. The top panels are slices through the meridional plane (radius latitudes), the middle three are in the equatorial plane (radius-longitude), and the bottom three are on the surface (latitude-longitude) of a 90° sector in longitude. The left panels are the zonal velocity field, the middle ones are the potential temperature anomaly and the right ones are the 2D streamfunction (vorticity) field. Since the Rossby number is small and the system is convective the vorticity tends to align with the direction of the axis of rotation (V). Due to the mean density gradients (V) the zonal velocities are stronger near the upper levels. The zonal velocities have strong superrotation at low latitudes, and a counter west retrograde flow in the interior. Large poleward vortex columnar eddies are embedded in this shear (see the bottom figures). The potential temperature anomaly at the poles due to the alignment of the convective plumes with rotation axis. A closer look at the analyzed data shows that the poleward transfer of heat is mainly due to the poleward heat transfer. The mechanism is supported by positive vorticity transported along the momentum columns.

IV. The Effect of the Mean Density Gradient: Anelastic vs. Boussinesq

One of the key questions on the giant planet’s atmospheres is what is the baroclinic structure of the zonal winds. To date most models (c.f. Hampp et al., 1995) used the Boussinesq approximation, but clearly the mean density variation plays an important role in setting this vertical velocity structure. Here we use an anelastic model to account for this effect. In Fig. 4 we compare a Boussinesq to an anelastic run; both are driven large columnar eddies have positive vorticity resulting in superrotation around the equator.

\[ \frac{\nabla \rho}{\rho} = \frac{\rho^*}{\rho_0^*} \mathbf{e}_z + \frac{\nabla p + \mathbf{g} \rho^*}{\rho} \]

The derivatives are calculated from the SCVH polynomial equation of state with respect to pressure, and the primed variables are the anomaly at every grid cell. This variation in the density gradient and pressure determines the vertical motion, which is the main driver of the zonal and meridional flow patterns.

V. Effect of Rotation

The system is convective and therefore plumes are driven by buoyancy across the center of gravity. However since the Rossby number is small the convective motion tends to align with the direction of the axis of rotation. The ratio between the magnitude of the buoyancy frequency and the rotation frequency scales are aligned by Taylor’s frozen column approximation which only vary in the rotation frequency. The fast rotation has convective motion aligned with the rotation axis while the slow one has a more homogeneous distribution of plumes. Both runs are well inside the turbulent regime (Rayleigh number is ~100 times critical), and after the initial spin up have reached a statistically steady state with sporadic emergence of plumes.

VI. Anelastic Momentum Columns & Super-rotating Equatorial Flow

Large scale eddies form on the equatorial plane. All eddies have positive vorticity (in respect to the direction on the rotation axis) and are embedded in the mean vertical shear flow. In Fig. 6 we plot slices in the radius- longitude plane (the plane on a certain latitude – from the center of the planet outward). The slices in the equatorial plane are spaced by 10° in latitude. The higher the latitude the further away from the center of the planet the large eddies are, such that the eddies are all aligned parallel to the axis of rotation. These columnar structures result from the rotation, but unlike Taylor columns they are in a state close to having the momentum constant along the axis of rotation rather than the velocity itself.

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The leading order momentum balances are set by the radial eddy fluxes and the radial viscous fluxes.

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VII. Summary

- In a rapidly rotating system the character of convective turbulence is strongly affected by the ratio of the magnitude of the buoyancy frequency to the rotation frequency (see part V).
- In an anelastic system columns develop along the direction parallel to the axis of rotation, but unlike Taylor columns they are closer to having the zonal momentum constant along the axis of rotation rather than the velocity itself. (see part VI).

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