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Zonal flow scaling in rapidly-rotating compressible convection

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ABSTRACT

The surface winds of Jupiter and Saturn are primarily zonal. Each planet exhibits strong prograde equatorial flow flanked by multiple alternating zonal winds at higher latitudes. The depth to which these flows penetrate has long been debated and is still an unsolved problem. Previous rotating convection models that obtained multiple high latitude zonal jets comparable to those on the giant planets assumed an incompressible (Boussinesq) fluid, which is unrealistic for gas giant planets. Later models of compressible rotating convection obtained only few high latitude jets which were not amenable to scaling analysis.

Here we present 3-D numerical simulations of compressible convection in rapidly-rotating spherical shells. To explore the formation and scaling of high-latitude zonal jets, we consider models with a strong radial density variation and a range of Ekman numbers, while maintaining a zonal flow Rossby number characteristic of Saturn.

All of our simulations show a strong prograde equatorial jet outside the tangent cylinder. At low Ekman numbers several alternating jets form in each hemisphere inside the tangent cylinder. To analyze jet scaling of our numerical models and of Jupiter and Saturn, we extend Rhines scaling based on a topographic β-parameter, which was previously applied to an incompressible fluid in a spherical shell, to compressible fluids. The jet-widths predicted by this modified Rhines length are found to be in relatively good agreement with our numerical model results and with cloud tracking observations of Jupiter and Saturn.

1. Introduction

The surface flows of the gas giants Jupiter and Saturn are dominated by strong zonal motions (i.e. azimuthal flows). Zonal wind profiles at the surface are obtained by tracking cloud features with ground-based and space observations (e.g., Sanchez-Lavega et al., 2000; Porco et al., 2003, 2005; Vasavada and Showman, 2005).

As shown in Fig. 1, these zonal winds form a differential rotation profile with alternating eastward and westward flows. Both gas giants feature a strong prograde equatorial jet flanked by several weaker alternating secondary jets. Jupiter's central equatorial jet reaches a maximum velocity around 100–140 m/s and covers latitudes within ±15°. However the region of fast equatorial zonal flow extends to roughly ±25°, and features several strong prograde and retrograde jets that display marked equatorial asymmetry. The secondary undulating zonal winds at higher latitudes are weaker ($\sim$10–20 m/s) and narrower than the equatorial flow. Saturn's equatorial flow is stronger than that of Jupiter, wider, and more symmetrical, with a single equatorial jet extending roughly ±30° in latitude. It is flanked by several secondary jets in each hemisphere. These winds are significantly shifted towards the prograde direction when assuming the rotation period measured by Voyager (Desch and Kaiser, 1981). However, the suitability of this so-called System III rotation period, which is based on Saturn's kilometric radio (SKR) emissions, for characterizing the mean planetary rotation rate has been questioned. The current Cassini space mission has measured an apparent 6 min increase in the SKR rotation period since Voyager (e.g. Sánchez-Lavega, 2005). This simple change of 1% in the rotation rate can substantially modify the zonal wind speed (typically around 20% near the equator). Since such changes in the planetary rotation rate are unlikely (Heimpel and Aurnou, 2012), alternative rotation systems have been proposed. Here we adopt the System IIIw rotation period of Read et al. (2009), which is based on an analysis of potential vorticity. This System IIIw rotation period yields more symmetric zonal flows between the prograde and the retrograde directions (see Fig. 1). The amplitude of the equatorial flow then reduces from 450 m/s in the System III rotation period to 370 m/s in System IIIw.

Modeling of zonal wind dynamics can be categorized in two main approaches. In "shallow models", which are typically based on the hydrostatic approximation of fluid dynamics, the dynamics is confined to a very thin layer close to the cloud level (e.g. Vallis,

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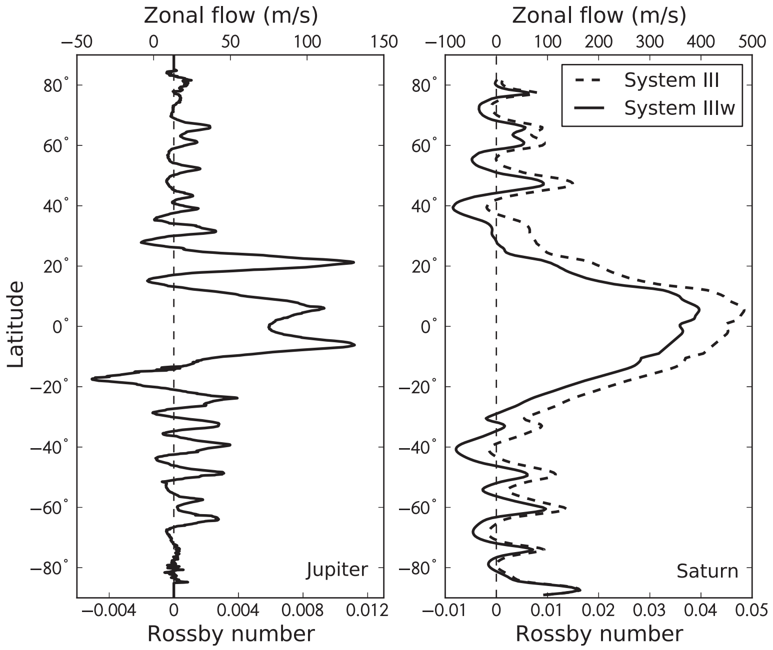

Fig. 1. Surface zonal flow profiles for Jupiter (left panel) and Saturn (right panel). Jupiter's zonal flow profiles come from Cassini's data by Porco et al. (2003) and Vasavada and Showman (2005). Saturn's profiles in the two rotations systems have been derived by Read et al. (2009). The conversion between zonal winds velocities in m/s and Rossby numbers is given by $u/\Omega r_o, r_o$ being the planetary radius at the 1 bar level.

2006; Liu and Schneider, 2011). In this approach, zonal winds are maintained by turbulent motions coming from several possible physical forcings that occur at the stably-stratified cloud level (e.g. latent heat release or solar radiation). These shallow models reproduce several features observed on Jupiter and Saturn and notably the alternating direction of the zonal winds (Williams, 1978; Cho and Polvani, 1996). While earlier models yielded a retrograde equatorial jet for both gas giants, prograde equatorial flow has been obtained in more recent models via the inclusion of additional forcing mechanisms, such as water vapor condensation (Lian and Showman, 2010) or enhanced radiative damping (e.g. Liu and Schneider, 2011).

In an alternative approach, zonal winds may be driven by deep-seated convection. This is supported by the latitudinal thermal emission profiles of Jupiter and Saturn, which are relatively flat, implying that deep-seated, outward directed heat flow exceeds absorbed solar heat for both planets (Ingersoll, 1976; Pirraglia, 1984). Although deep convection must drive the dynamos that produce the global magnetic fields of Jupiter and Saturn, it is thought that fast zonal flows would be strongly attenuated at depth by the magnetic braking resulting from the strong increase in the electrical conductivity (Guillot et al., 2004; French et al., 2012). Based on an estimate of the associated Ohmic dissipation, Liu et al. (2008) concluded that the zonal flows must therefore be confined to a relatively thin layer (i.e. $0.96R_J$ and $0.85R_S$). This magnetic exclusion of fast zonal flow to an outer region has been demonstrated in recent dynamo models that include radially variable electrical conductivity (Heimpel and Gómez Pérez, 2011; Duarte et al., 2013).

The deep convection hypothesis has been tested by 3-D numerical models of turbulent convection in rapidly-rotating spherical shells (e.g. Christensen, 2001; Heimpel et al., 2005). Rapid rotation causes convection to develop as axially-oriented quasi-geostrophic columns (Busse, 1970). This columnar flow gives rise to Reynolds stresses, a statistical correlation between the convective flow components that feeds energy into zonal flows (e.g. Busse, 1994). The usual prograde tilt of the convective columns goes along with a positive flux of angular momentum away from the rotation axis that yields an eastward equatorial flow (e.g. Zhang, 1992). While such models can easily reproduce the correct direction and amplitude of the equatorial jets observed on Jupiter and Saturn, they usually fail to produce multiple high-latitude jets (Christensen, 2002). Numerical models in relatively deep layers and moderately small Ekman numbers (i.e. aspect ratio $r_i/r_o = 0.6$ and $E = 10^{-4} - 10^{-5}$) typically produce only a pair of jets in each hemisphere (Christensen, 2001; Jones and Kuzanyan, 2009; Gastine and Wicht, 2012).

Reaching quasi-geostrophic turbulence in a 3-D model of rotating convection is indeed numerically very demanding. These numerical difficulties can be significantly reduced by using the quasi-geostrophic approximation which includes the effects of the curvature of the spherical shell (i.e. the topographic β-effect) while solving the flow only in the 2-D equatorial plane (Aubert et al., 2003; Schaeffer and Cardin, 2005). For instance, the two-dimensional annulus model of rotating convection considered by Jones et al. (2003), Rotvig and Jones (2006) and Teed et al. (2012) allows very low Ekman numbers to be reached. Multiple alternating zonal flows have been found and the typical width of each jet scales with the Rhines length (e.g. Rhines, 1975; Danilov and Gurarie, 2002; Read et al., 2004; Sukoriansky et al., 2007). Independently of these models, the 3-D simulations of Heimpel et al. (2005) and Heimpel and Aurnou (2007) were computed with lower Ekman numbers and larger aspect ratio ($r_i/r_o \geqslant 0.85$) than previous numerical models (e.g. Christensen, 2001). These simulations show clear evidence of multiple jets inside the tangent cylinder. While these simulations produce fewer bands than observed in the quasi-geostrophic simulations, at least in part due to the unavoidable computational limitations, the width of each zonal band follows the Rhines scaling (Heimpel and Aurnou, 2007, hereafter HA07).

Most of the previous models have employed the Boussinesq approximation where compressibility effects are simply ignored. In giant planets, however, the density increases by more than 1000 in the molecular envelope (Guillot, 1999; French et al., 2012) and the applicability of the topographic Rhines scaling is therefore questionable (Evonuk, 2008). More recent anelastic models that