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Compressibility effects on driving zonal flow in gas giants

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1. Introduction

The banded structures at the surfaces of Jupiter and Saturn are associated with prograde and retrograde zonal flows [11]. Two competing type of models tried to explain their origin. "Shallow models", relying on global circulation codes, assume that zonal flows are restricted to a very thin layer close to the surface. These models are able to reproduce the alternating easterly and westerly jets but fail to reproduce the observed direction of the most prominent equatorial jet [1]. On the contrary, "deep models" are based on the assumption that the jets extend deeply below the surface. These models rely on numerical simulations that solve the global dynamics of rapidly rotating spherical shells. Direction, amplitude and number of jets were reproduced in a convincing way by such numerical simulations, provided thin shells are assumed and convection is strongly driven [6]. In these models, strong zonal jets are maintained by Reynolds stresses created by spiralling convection.

The Boussinesq approximation, widely used in this kind of simulations, assumes that the background density and temperature are constant [2]. Nevertheless, in the molecular envelope of Jupiter, the density increases by about two orders of magnitude [4, 5]. Therefore, the anelastic approximation provides a more realistic framework to simulate stratified fluids as it allows compressibility effects, while filtering out fast acoustic waves [9].

Recent anelastic simulations suggest that compressibility effects may cause interesting differences [8, 10]. In fact, the density stratification adds a new vorticity source that possibly help to generate Reynolds stresses that drive the jets [3]. Differences between compressible and Boussinesq convection are addressed here. We focus first on the differences in the convective patterns when stratification is increased. We then present a parametric study of the density stratification on the generation of zonal flows. A scaling law is obtained and a universal asymptotic regime is reached provided mass-weighted quantities are considered.

2. The model

Thermal convection of an anelastic fluid in a spherical shell rotating with a constant frequency Ω is considered. The background state of the shell is a polytropic and perfect gas, meaning that $\rho = T^m$, where m is the polytropic index, ρ and T density and temperature, respectively. We also assume a $1/r^2$ gravity that corresponds to a centrally condensed planet.

3. Results

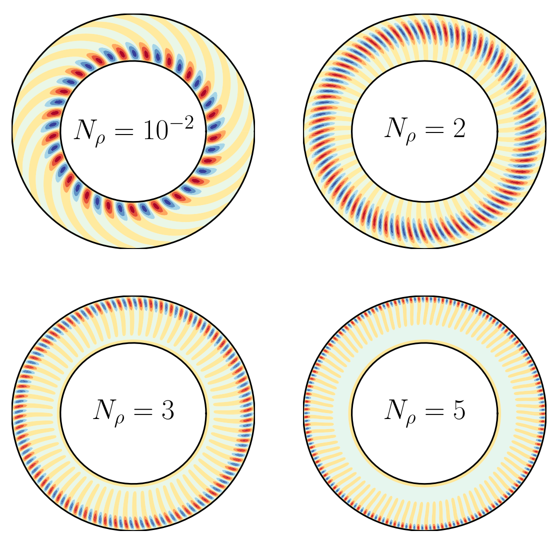

Figure 1: Radial component of the velocity v_r in the equatorial plane for different density stratifications ($N_\rho \equiv \ln \rho_{\text{bot}}/\rho_{\text{top}}$), red positive, blue negative.

Figure 1 displays the convective patterns close to the onset of convection for different density stratifications. The flow tends to move outward when the stratification increases, from convection close to the inner boundary in the nearly Boussinesq case ($N_\rho = 0.01$) to convection concentrated in a very thin region close to the outer boundary for strongly stratified case ($N_\rho = 5$). This outward shift of the onset of convection can be explained by the local value of the Rayleigh number: when the density stratification increases, the entropy gradient becomes steeper close to the surface and leads to a local increase of the Rayleigh number. We also note that compressible convective patterns show smaller scale structures than the Boussinesq case.

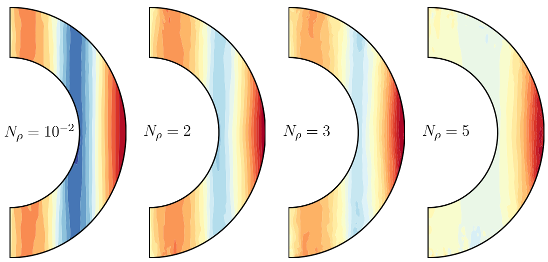

Figure 2: Mean zonal velocity v_ϕ for different density stratifications, red prograde, blue retrograde.

Kinetic energy is transferred by Reynolds stresses from convective motions into large scale zonal flows. A strong prograde equatorial jet is a common feature of the simulations displayed in Fig. 2. The latitudinal extent of this band is also found to be independent of the density stratification. Inside the tangent cylinder, the scale and the orientation of the jets are also very similar between Boussinesq and anelastic simulations, provided the convection is strongly driven (i.e. the Rayleigh number is large enough [7]). This result may explain why Boussinesq simulations are already very successful in reproducing the number of jets observed in Jupiter [6].

To determine how density stratification affects zonal flows, we have performed a parametric study. For each simulation, the time-averaged mean velocity is plotted against a modified Rayleigh number that accounts for the density stratification (Fig. 3). An asymptotic scaling law is reached, provided the Rayleigh number is large enough. The obtained mass-weighted velocities are found to be independent of the density stratification.

Conclusion

Both Figs. 2 and 3 thus show that the density stratification is not changing significantly the amplitude, the extent and the scales of the zonal jets compared to the Boussinesq simulations. It means that the additional

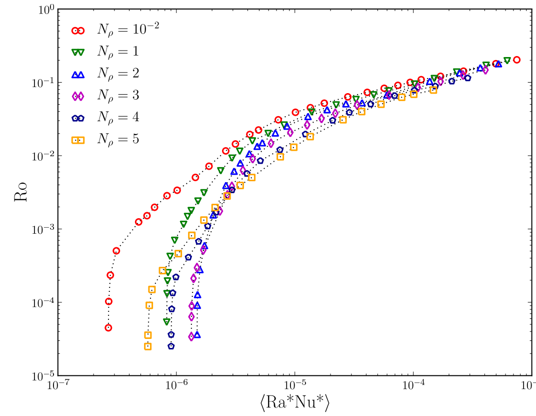

Figure 3: Time-averaged mean velocity plotted against the mass-weighted flux-based Rayleigh number. Velocities are expressed as Rossby numbers, defined as the ratio of v over Ωd.

vorticity source provided by compressibility [3] does not drastically influence the generation of zonal flows.

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