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Zonal Banded Jets Generated by Thermal Convection in Rapidly Rotating Spherical Shells

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Banded structures and alternating zonal jets observed in the surface atmospheres of Jupiter and Saturn have attracted many researchers in planetary atmospheric sciences, however, satisfactory physical explanations and understandings are not yet obtained. One of the model categories explaining the surface patterns of the gas giant plants is so called ``deep" models, which describe thermal convection in rapidly rotating spherical shells whose thickness is comparable to the radius of the planet. The models proposed in the earlier studies could produce equatorial prograde flows easily, while it seemed to be difficult to generate alternating jets in mid- and high-latitudes. Heimpel and Aurnou[1] tried to solve this difficulty by considering a thinner spherical shell model than that used in the previous studies performed so far, while their shell thickness was not yet thin enough to neglect the latitudinal component of the planetary rotation. They showed that the equatorial prograde zonal jets and alternating zonal jets in mid- and high-latitudes can be produced simultaneously when the Rayleigh number is sufficiently large and convection becomes active even inside the tangent cylinder. Several successive studies with the anelastic system have been performed to explain the banded structure of the gas giants[2,3]. However, in these studies, longitudinal symmetry was assumed and the computational domains were not the whole but the sectorial regions of the spherical shells. Moreover, they introduced hyper viscosity in order to save the numerical resources and compensate for the model resolution. Such artificial dissipation process might influence on the structure of the global flow field, however, the effects of hyper viscosity have not been examined so far. Therefore, in the present study, we perform numerical simulations of thermal convection in the whole thin spherical shell domain for various strength of hyper viscosity.

We consider Boussinesq fluid in a spherical shell rotating with a constant angular velocity Ω. The non-dimensionalized governing equations consist of equations of continuity, motion, and temperature[2]. The non-dimensional parameters appearing in the governing equations are the Prandtl number, $P_r = \nu/\kappa = 0.1$, the Ekman number, $E_k = \nu/\Omega D^2 = 3 \times 10^{-6}$, the modified Rayleigh number, $R_a = \alpha g_o \Delta T/\Omega^2 D = 0.05$, where ν, D, κ, α, r_o, g_o, and ΔT are the kinematic viscosity, the shell thickness, the thermal diffusivity, the outer radius of the shell, the thermal expansion coefficient, the acceleration of gravity at the outer boundary, and the temperature difference between the boundaries, respectively. The spherical shell geometry is defined by the radius ratio, $r_i/r_o = 0.85$ or 0.9, where r_i is the inner radius of the shell. Computational domain is full spherical shells without any assumption for longitudinal symmetry, while we also perform additional numerical experiments with longitudinally eight-fold symmetric domain for comparison. The thermal boundary condition is fixed temperature. Free-slip condition is adopted at the top boundary, while no-slip condition is applied at the bottom boundary. The initial condition of the velocity field is state of rest and that of the temperature field is the steady state solution of the heat conduction equation with random temperature perturbations. Following Heimpel and Aurnou[1], we introduce the hyper visocosity as:

$$\nu = \nu_0 \ (l \le l_0),\ \nu_o[1+\varepsilon(l-l_0)^2] \ (l > l_0),$$

where l is the total horizontal wavenumber. We varies l_0 as 170, 85, and 42, and ε as $10^{-4}, 10^{-2}, 1$, respectively. The results of the experiments with full spherical shell geometry show that a single strong and broad jet appears around the equator for all cases. When the hyper viscosity is weak enough, there emerge alternating zonal jets in mid- and high-latitudes in both hemispheres and generates zonal banded structures at around 10^4 non-dimensional time (about 1600 rotation period). However, these banded structure disappear and only one prograde jet exists in high-latitudes of each hemisphere by the time of 10^5 non-dimensional time (about 16000 rotation period). The prograde jet is sharp when $\varepsilon = 10^{-4}$, while it become blunt and weak when ε is increased. In contrast, when the hyper viscosity is strong enough, the amplitude of the zonal jets in mid- and high-latitudes is small, and it is difficult to observe any banded structure. These characteristics for zonal flows can be found in the results with eight-fold longitudinal symmetry experiments although disappearance speed of the banded structures is slightly slow compared with that for full geometry experiments.

References

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