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Disappearance of surface banded structure produced by thermal convection in rapidly rotating thin spherical shells

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Surface flows of Jupiter and Saturn are characterized by the broad prograde zonal jets around the equator and the narrow alternating zonal jets in mid- and high-latitudes. It is not yet clear whether those surface jets are the result of fluid motions in the "shallow" weather layer, or they are produced by convective motions in the "deep" region. "Shallow" models consider atmospheric motions driven by the solar differential heating and the intrinsic heat flow from the deeper region under the assumption of hydrostatic balance in the vertical direction as a result of the thin atmospheric layer compared with the radius of the planet. These models can produce narrow alternating jets in mid- and high-latitudes, while the equatorial jets are not necessarily prograde. On the other hand, "deep" models, which describe thermal convection in rapidly rotating spherical shells whose thickness is comparable to the radius of the planet, can produce equatorial prograde flows easily, while it seems to be difficult to generate alternating jets in mid- and high-latitudes.

Heimpel and Aurnou (2007)[1](hereafter, HA2007) proposed thin spherical shell models and show 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. However, they assume eight-fold symmetry in the longitudinal direction and calculate fluid motion only in the one-eighth sector of the whole spherical shell. Such artificial limitation of the computational domain may influence on the structure of the global flow field. For example, zonal flows may not develop efficiently due to the sufficient upward cascade of two-dimensional turbulence, or stability of mean zonal flows may change with the domain size in the longitudinal direction. Further, since time integration of their numerical experiment is so short as 1600 rotation period (0.024 viscous diffusion time), their result may not reach statistically steady state. Therefore, in the present study, we perform long time numerical experiment of thermal convection in the whole thin spherical shell domain, where the experimental setup is same as that of HA2007.

We consider Boussinesq fluid in a spherical shell rotating with constant angular velocity. The non-dimensionalized governing equations consist of equations of continuity, motion, and temperature. The non-dimensional parameters appearing in the governing equations, the Prandtl number, the Ekman number, the modified Rayleigh number, and the radius ratio, are fixed to 0.1, $3\text{x}10^{-6}$, 0.05, and 0.85, respectively. The initial condition of the velocity field is state of rest and that of the temperature field is conductive state with random temperature perturbations. After time integration for 7500 rotation period, An equatorial prograde surface zonal jet and alternating banded zonal jets emerge, which seem to be consistent with the result of HA2007. However, extending time integration further, mid- and high- latitudinal regions are entirely accelerated eastward, zonal banded structures disappear, and finally one broad eastward zonal jet appears in mid- and high- latitudes of each hemisphere around 12800 rotation period. Formation of these broad zonal jets is attributed to the angular momentum transport in the radially outward direction by topographic Rossby waves, which are excited by thermal convection inside the tangent cylinder. Note that further time integration is necessary to obtain statistically steady state since kinetic energy still increases in the final state of the present calculation.

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Reference : [1] Heimpel, M., Aurnou, J. (2007) Icarus, 187, 540–557.,

Keywords: atmospheres of the gas giant planets, banded structure, equatorial prograde jet, Rossby waves, Jupiter, Saturn