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Surface zonal flows induced 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.

Recently, Heimpel and Aurnou (2007) 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 insufficient upward cascade of two-dimensional turbulence, or stability of mean zonal flows may change with the domain size in the longitudinal direction. In the present study, we perform numerical simulations of thermal convection in the whole thin spherical shell domain while coarse spatial resolution and slow rotation rate compared to Heimpel and Aurnou (2007) are used due to the limit of computational resources.

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, 10^{-4}, 0.05, and 0.75, 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 35000 rotation period, kinetic energy is saturated and statistically steady state seems to establish. Obtained velocity field satisfies Taylor-Proudman theorem; it is almost uniform in the direction of the rotation axis. An equatorial prograde surface zonal jet emerges in the region outside the tangent cylinder. In the inside of the tangent cylinder, the surface zonal flows are retrograde, but eastward spike features appear near the tangent cylinder in low latitudes. Correspondingly, coherent small scale convective motions exist in these latitudinal zones. It is expected that these convective motions excite topographic Rossby waves which remove westward angular momentum from these zones, producing eastward spike features. This mechanism may explain the origin of the strong thin jet at about 25 degrees north observed on the surface of Jupiter.

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

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