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Long-time asymptotic states of the forced two-dimensional barotropic incompressible flow on a rotating sphere

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The nature of mathematical models used in Geoscience is often not clear. This study investigates the long-time asymptotic states of the two-dimensional barotropic incompressible flow on a rotating sphere, which is one of the basic models for planetary atmospheres. When the system has no external sources of turbulence, its long-time asymptotic state is known to accompany westward circumpolar jets (Yoden and Yamada (1993), Takehiro, Hayashi, and Yamada (2007)), and the scaling laws for this state are already given in Takehiro, Hayashi, and Yamada (2007). On the other hand, the long-time asymptotic state of the system with external sources of turbulence has not been made clear yet. When the sources of turbulence are given as the Markovian random forcing, Nozawa and Yoden (1997) pointed out that its long-time asymptotic state has a multiple zonal-band structure or a structure with westward circumpolar jets. However, their numerical time integration does not seem to be long enough.

This study reexamines the long-time asymptotic state of the system with a small-scale, Markovian random forcing. Numerical simulations with different rotating rates of the sphere and different wavenumbers of the forcing were performed from zero initial condition. At an early stage of the integration, in line with the findings of Nozawa and Yoden (1997), a multiple zonal-band structure or a structure with westward circumpolar jets emerged. However, in the course of time development, multiple zonal-band structures appeared in all runs. The multiple zonal-band structures then entered quasi-steady states showing little energy increase with nearly steady spectral component distribution of the flow, followed by a sudden merger/disappearance of the jets, accompanying an energy increase. At the final stage of the time integration (around 100 to 500 times of the integrated time of Nozawa and Yoden (1997)), a zonal-band structure with only a few (2 or 3) jets was realized in each run.

Each of the long-time asymptotic states observed in the numerical experiments has the Rhines wavenumber larger than the representative total wavenumber of the flow (2 or 3). Huang et al. (2001) has argued that the inverse energy cascade goes below the Rhines wavenumber when the forcing is white noise, and not when it is a Markovian random forcing. In our case of Markovian random forcing, however, the inverse energy cascade does not stop around the Rhines wavenumber but goes down finally to lower wavenumbers. This suggests that, concerning long-time asymptotic states, a forced two-dimensional barotropic incompressible flow on a rotating sphere is not a proper model for the dynamics of the planetary atmosphere with multiple zonal-band structure such as the one seen on the Jupiter. The turbulence behind the zonal jets is essential for the mergers/disappearances of jets, as a laminar zonal jet with a meridional scale larger than the Rhines scale is linearly stable.