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# Zonal flow formations in two-dimensional Rossby wave turbulence on a rotating sphere

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Plenty of studies on fluid dynamics in nonrotating systems have been carried out in relation to fluid phenomena in daily life. The fluid dynamics in rotating systems is also attracting much interest in relation, for instance, to observations in geoscience and of environmental problems. One of the features which have attracted people's interest in rotating systems may be the appearance and the robustness of zonal structures. The zonal flow structure is observed in numerical experiments as well as on many giant planets. The atmosphere on a surface or in an outer shell of a planet is believed to be in a turbulent state induced by, for example, a heat convection caused by an inner heating system or a heat injection from the sun. On many giant planets, a large-scale zonal-band structure is commonly observed and is maintained for a very long time, where the structure is almost always maintained. The emergence of the multiple zonal-band structure, a structure with alternating eastward and westward jets, is interesting not only because it may have emerged from and maintained in a perturbed small-scale flow filed, but also because it possesses a strong anisotropic structure.

One of the mainstream studies on the origin of the multiple zonal-band structure started with Busse [1], who argued that the structure is a surface manifestation of three-dimensional circulations deep inside of a planet. Although appealing, this theory is difficult to prove, especially because of the lack of the knowledge of the interior of a planet, and because of the lack of computational power. Nevertheless, much three-dimensional research including heavy numerical calculations has been done. Now Busse's idea [1] possesses strong support in a wide area of geoscience these days. However, it is difficult to extract the essence of the physics in the complex mathematical models. Therefor in this talk, we consider a two-dimensional incompressible flow on a rotating sphere governed by the two-dimensional Navier-Stokes equation (barotropic model); one of the simplest mathematical models for planetary atmospheres.

Although the barotropic model is highly simplified and does not contain many physical processes that may be actively functioning in real atmospheres, the flow field shows rich and interesting phenomena, including a spontaneous formation of large-scale zonal flows. With random and uniform forcing, a multiple zonal-band structure emerges in the course of time development. The multiple zonal-band structure then experiences intermittent mergers and disappearances of zonal jets. Finally, a structure with only wo or three large-scale zonal jets is realised as an asymptotic state [2]. The formation of large-scale zonal flows is also seen in a freely decaying case where we consider no forcing and numerically vanishing viscosity. The multiple zonal-band structure does not appear in this case, but westward circumpolar jets still appear.

The flow dynamics in the barotropic model is governed by nonlinear interactions of Rossby waves. It is dominated by three-wave resonant interactions of Rossby waves especially when the rotation rate of the sphere is high enough [5]. Our numerical experiments found that, that energy is accumulated in zonal Rossby modes that can get involved in three-wave resonant nonlinear interactions [6]. By investigating the energy transfer by nonlinear interactions, we found that the energy accumulation is caused by nonresonant nonlinear interaction. This was also confirmed through an investigation of energy transfers between two modes defined by utilizing the principle of detailed balance [7]. These results suggest that even in a system with a high rotation rate of the sphere, where resonant interactions are dominant, nonresonant interactions are playing an important role to form large-scale zonal flows, and that somehow only resonant zonal modes get energy and realise the zonal flows symmetric about the equator.

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