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Understanding the formation of super-rotation under zonally symmetric forcing on slowly rotating planet

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Abstract

A novel two-dimensional model in which dynamical instabilities are parameterized was developed and used to elucidate the dynamics of the formation and maintenance of the atmospheric super-rotation on Venus. This approach bridges a gap between idealized theoretical studies and three-dimensional modelling with which clear-cut diagnosis is not necessarily feasible. It is shown that, under realistic zonally symmetric thermal forcing, the instabilities act passively like eddy diffusivity to adjust the zonal flow toward the gradient wind balance, creating realistic super-rotation. Such thermal control explains a latest observational finding on the super-rotation and albedo variability.

1. Introduction

Venus is known for its fast, super-rotating atmosphere (so called, the four-day circulation) formed on the slowly rotating solid planet at the period of 243 days. Zonal flow around the rotation axis, such as the super-rotation, efficiently transports heat to the nightside hemisphere. However, it is well known that the super-rotation cannot emerge unless the angular momentum (AM) around the rotation axis is transported by zonally-asymmetric flows such as waves and turbulence, since, without them, the AM is conserved along meridional circulation [1]. Titan is also known to have super-rotating atmosphere on its slowly rotating solid-body part, although the angular speed contrast is smaller.

Recently, a number of Venus atmosphere GCM have been reproducing the super-rotation. However, its formation mechanism is still unclear, which is partly be due to the difficulty in analysis of three-dimensional models as well as the problem of the models' dynamical cores to violate conservation laws [2].

Idealized theoretical models can illustrate the dynamics of the formation and maintenance of super-rotation. However, simplification such as the use of the Boussinesq approximation and constant eddy viscosity/diffusivity coefficients makes it difficult to apply them to planets having thick atmosphere like Venus.

Here, I present the results of a series of numerical experiments conducted by using a novel two-dimensional model and propose how they are understood.

2. Model

The model used is based on the transformed Eulerian mean (TEM) equations. It enables us to parameterize the effects of zonally asymmetric flows such as waves and disturbances arising from dynamical instabilities as the divergence of the Elisassen-Palm (EP) flux and/or diabatic heating. The actual parameterized processes are convective, symmetric (including inertial), and barotropic/baroclinic instabilities. By supposing the gradient-wind balance, the meridional circulation is obtained by solving an elliptic equation. The model has no eddy viscosity or diffusivity with prescribed coefficient.

The model is non-dimensionalized but is run with settings to mimic the external parameters and thermal forcing in the Venus atmosphere. The radiative forcing was expressed as Newtonian cooling with realistic time scales that vary exponentially with the log-pressure height. The Newtonian cooling background has a vertical structure crudely mimicking the temperature structure of Venus and also has a meridional structure to mimic the net radiative forcing [3], although the magnitude was significantly reduced. The radiative forcing is slowly increased from zero to secure computational solvability. Surface friction is expressed as a simple linear relaxation, often called the Rayleigh friction. When the surface friction is turned off, the model conserves the total AM nearly perfectly because of its AM conserving numerical scheme and parameterizations.

3. Results

The control run was initialized as the resting atmosphere, which rotates at the same angular velocity

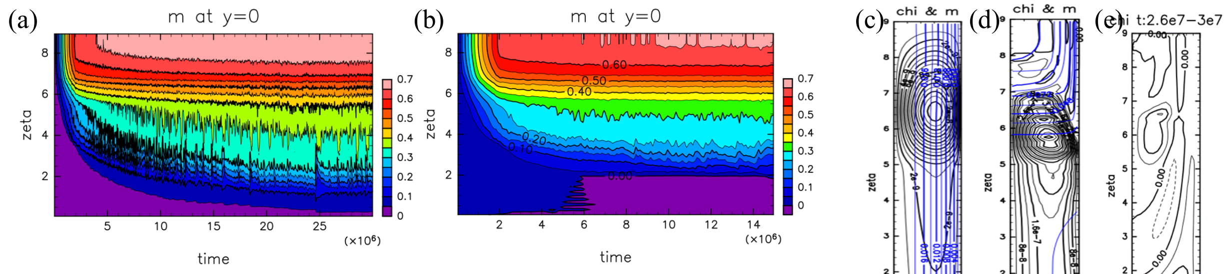

Figure 1: (a) The time evolution of the AM at the equator in the control run. All quantities are non-dimensionalized. The dimensional scale of the altitude and time coverage are ~0—80 km and ~0—5×10^4 years, and the AM value of 0.7 corresponds to ~70 m/s. (b) as in (a) but for the run in which surface friction is turned off over a shorter period. (c) Meridional mass stream function (black contours) and AM (blue contours) at *t* ~ 4 years in the control run. The abscissa is sin(latitude) over a hemisphere. (d) As in (c) but for *t* ~ 400 years. (e) Meridional mass stream function over the last ~6000 years.

as the planet's surface. Super-rotation gradually emerged to reach a statistically steady state at around 4×10^4 Earth years (Fig. 1a). The angular velocity at the equator reached more than 30 times as large as the planetary rotation near the model top corresponding to ~80 km. The emergence of the AM greater than the planetary one at the equator was realized by the AM transport due to the EP flux divergence associated with the symmetric and baroclinic/barotropic instabilities; it is shown that the both instabilities are important. It is noteworthy that the simulated zonal flow exhibits internal variability on various time scales.

In the early stage, the meridional circulation is deep and have a single thermally-direct cell (Fig. 1c), but the vertical redistribution of AM occurs mainly within the upper part of atmosphere. This is the reason why the initial development of the super-rotation is similar even when the surface friction is turned off (Fig. 1b). As the super-rotation develops, the top of the direct circulation is lowered (Fig. 1c). In the final state, the meridional circulation is separated (Fig. 1e). In the run in which surface friction is turned off (Fig. 1b), the lower atmosphere rotates oppositely to the planetary rotation; because of the exponential density stratification, the total AM is kept with this slow retrograde flow at low level.

4. Discussion

The resultant zonal winds are close to the thermal wind balance with respect to the gradient wind corresponding to the Newtonian cooling background. A number of additional experiments indicate that the AM transport by dynamical instabilities act to adjust the AM distribution in response to the thermal forcing. In other words, AM transport occurs passively, and the super-rotation strength is controlled thermally.

This view explains a latest observational finding mainly from Venus Express and Akatsuki, that the albedo of Venus is correlated with the strength of the super-rotation [4]. The albedo variation changes net radiative heating and thereby affects the super-rotation strength through the change of the gradient wind toward which AM redistribution occurs.

There is a drawback in the Newtonian cooling approach; if the flow is adjusted perfectly, no meridional circulation occurs under it, while heat transport does not vanish on the actual Venus. Also, this study did not treat the effect of the zonal asymmetry in solar heating, which should be taken into account to obtain comprehensive understanding.

References

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