Toward high resolution simulation for the atmosphere on Venus by AFES (Atmospheric GCM For the Earth Simulator)

Norihiko Sugimoto [1], Masahiro Takagi [2], Yoshihisa Matsuda [3], Yoshiyuki O. Takahashi [4],
Masaki Ishiwatari [5], and Yoshi-Yuki Hayashi [4]

[1] Research and Education Center for Natural Sciences, Department of Physics, Keio University
[2] Faculty of Science, Kyoto Sangyo University
[3] Department of Astronomy and Earth Science, Tokyo Gakugei University
[4] Department of Earth and Planetary Sciences, Kobe University,
[5] Department of Cosmosciences, Hokkaido University

1 Introduction

Super-rotation in the atmosphere on Venus is one of the most interesting topics in the planetary science. While Venus is similar to Earth in its radius, mass, and gravity acceleration, the atmosphere on Venus is quite different from that on Earth. Venus has a thick CO2 atmosphere, with surface pressure of 92 bar. Its surface temperature is about 730 K owing to the large greenhouse effect of massive CO2. In addition, there are optically thick clouds of sulfuric acid droplets, where solar heating is one of the energy sources to drive atmospheric circulation. While the solid part of Venus rotates at extremely slow rate with the period of 243 Earth days, the atmosphere at cloud-top level (about 70 km) rotates about 60 times faster in the same direction, which is called as “super-rotation”.

In order to elucidate the mechanism of super-rotation, several mechanisms, such as the Gierasch mechanism [1] through meridional circulation and the thermal tides mechanism [2] through wave mean flow interaction, have been proposed. Although simulations using Venus-like atmospheric general circulation model (GCM) [3,4] suggested that both mechanism can work to generate super-rotation, these simulations use only coarse resolutions and involve simple physical processes. Therefore, in the present study we modify AFES [5] (Atmospheric general circulation model For the Earth Simulator) to simulate the Venus atmospheric dynamics with realistic physical process and high resolution. AFES is highly optimized for the Earth simulator which is one of the world's largest vector super-computers provided by Japan Agency for Marine-Earth Science and Technology (JAMSTEC). Although our final goal is to understand the fundamental mechanism of the super-rotation, we have to check the numerical model before performing long time simulation. As a first step we investigate unstable modes initiated from the state of super-rotation by the nonlinear numerical simulation.

2 Experimental settings

A full nonlinear dynamical model for the atmosphere on Venus is constructed on the basis of AFES. The basic equations are primitive ones in sigma coordinates on the sphere. Values of physical parameters are chosen for Venus. Physical processes for the atmosphere on Earth have been replaced by the simplified version for the atmosphere on Venus. Experimental settings are basically based on the previous linear stability analysis [6]. The resolution is now T42L60 (medium), 128 and 64 grids are in the longitudinal and meridional direction, respectively. Vertical domain extends from the ground 0 to about 120 km with almost the constant grid spacing of 2 km. The model includes vertical and horizontal diffusions. Rayleigh friction (or sponge layer) is not used in the present model except at the lowest level, where the surface friction acts on horizontal winds. In addition, the dry convective adjustment scheme is used to restore the temperature lapse rate to the neutral one when an atmospheric layer becomes statically unstable. The specific heat is fixed to constant value.

The solar heating is excluded in the present study for simplicity, but scheme of the solar heating based on the previous works is also prepared. Vertical distribution of the specific heat at constant pressure can also be taken from the Venus international reference atmosphere (VIRA) data. The radiative forcing in the infrared region is simplified by Newtonian cooling. The coefficients are based on the previous study. The temperature field is relaxed to the prescribed zonally uniform but meridionally gradient field. It is also possible to take temperature profile from the VIRA data, for future improvement. We also develop scheme of realistic radiative forcing for future investigation.

The realistic but idealized static stability based on the observations is set. The lower atmosphere near the ground of Venus is weakly stable. In the cloud layer, there is a layer (from 55 to 60 km) with almost neutral stability due to the solar heating. Stable layer is at the bottom of the cloud layer, and the stability has a maximum value at around 45 km. The atmosphere above the cloud layer (from 70 km) is strongly stratified, as in the stratosphere on Earth. It is expected that unstable modes will appear in the cloud layer, because low static stability is preferred for the appearance of unstable barocilinic modes.

The initial state is an idealized super-rotation. The flow linearly increases with height from ground to 70 km. Its maximum is 100 m/s at 70 km at the equator and above there it is constant. Meridional distribution is solid body rotation. Temperature is in balance with the zonally uniform flow, namely, gradient wind balance. Meridional temperature difference from equator to pole is about 5 K at the top of cloud layer. Initiated from this idealized basic state of super-rotation, we perform nonlinear numerical simulation of AFES for a period of 5 Earth years. The leap frog method is used for the time integrations with an increment of 600 s. Computational modes are excluded by the Asselin filter.

3 Results

In the results of numerical simulation, super-rotation is gradually decreasing in the cloud layer (50 to 70 km) from mid-latitude to the pole owing to unstable modes of growing vortices. Figure 1 shows snapshot of horizontal cross section of vorticity disturbance at 54 km. Clearly vortices of wavenumber 3 and 4 grow at the mid latitude. These growing vortices decrease super-rotation where they evolve.

Figure 2 shows height – longitude cross sections of meridional flow (a) and temperature deviation (b) at the section of 40 ˚N where unstable modes grow. The phases of these disturbances are tilted from down-east to up-west. In addition, they are out of phase. Namely, cold air flows downward and southward, while warm air flows upward and northward. This is the typical structure of baroclinic instability. It is almost consistent with the results of previous linear stability analysis [6], although basic zonal flow changed in the time evolution of nonlinear simulation. Since stable layer exists below the cloud layer and atmospheric density is large in the lower layer, unstable modes do not vertically extend to the lower layer. We also estimate growth rate of these unstable modes by the time evolution of kinetic energy for each wavenumber. After around 240 days, there is a linear growth of energy disturbances for wavenumber 3 and 4. Its e-folding time is about 50 days, which is longer than the estimates of the previous study [6]. This is because of slowing down of super-rotation by 20 – 30 m/s.

We investigate momentum and heat transport of growing vortices. In the initial stage of baroclinic instability, zonal-mean zonal flow is accelerated by unstable modes using available potential energy. Thus, momentum flux converges to the latitudes where baroclinic modes develop. Heat flux is negative on the northern hemisphere, that is, heat is transported from equator to pole. However, after baroclinic vortices have developed, trains of cyclone and anticyclone vortex appear and they turn into barotropic vortices. While these vortices transport momentum to equatorial region where they develop, they transport heat pole ward.

In order to check the dependence of the results on the resolution we also perform simulation with T21L60 resolution, which has 64 and 32 grids for the longitudinal and latitudinal direction, respectively. Although we used the same condition except for the resolution (and therefore the horizontal diffusion), the flow field is quite different from that of T42L60. Only large scale vortices appear and there is no filament structure of vortex due to lack of the resolution. In addition, it takes more time for unstable mode to develop in T21L60 simulation than in T42L60 simulation. Although further analysis is needed to elucidate the dependence on the resolution, we have to use higher resolution than T21L60, as is done in the present study, in order to investigate these disturbances quantitatively.

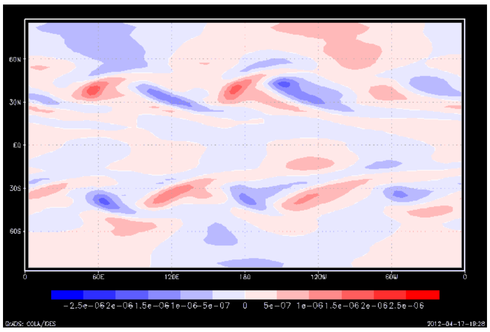

Fig. 1. Snapshot of horizontal cross section of vorticity disturbance at 54 km (300 days).

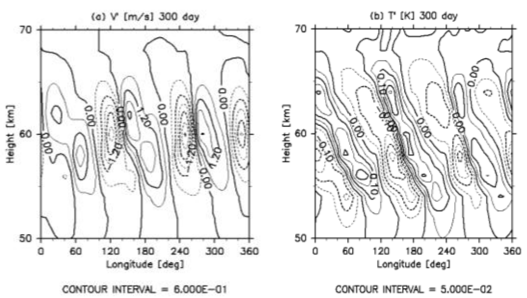

Fig. 2. Height – longitude cross sections at 40 degrees north of meridional flow disturbance (a) and temperature disturbance (b) at 300 days.

4 Summary and discussion

We investigated unstable modes growing in the idealized super-rotation using AFES with medium resolution. Baroclinic instability occurred at the mid latitude in the cloud layer where super-rotation is fast and meridional temperature gradient is large. They transported momentum from equator and pole to the region where they evolved, and accelerated super-rotation using available potential energy. After baroclinic vortices developed to finite amplitude, they turned into vortices of barotropic type. They transported significant momentum from pole to equator while they transport heat from equator to pole. Since basic zonal flow was changed in the time evolution of nonlinear simulation, the results of the linear stability analysis [6] could not apply to all stages of the evolution. Especially, vortices of barotropic type appeared at the later stage, which was not anticipated in the linear stability analysis.

So far, there are no observations of baroclinic instability on Venus, though this instability is considered to have very important roles. This study suggests barocilinic modes could exist in the cloud layer with small static stability. The condition of baroclinic instability will be satisfied by the solar heating. It is also expected that baroclinic modes have a significant impact on the general circulation on Venus through momentum and heat transportation.

Finally, this study treated only an initial growth of baroclinic instability. For future work, we plan to include realistic solar heating in the model to maintain meridional temperature gradient. It is expected that the solar heating will keep strong super-rotation in the cloud layer. As is frequently discussed on Gierasch mechanism, several unstable modes are candidates to transport momentum from pole to equator [7]. Long time numerical simulation initiated from super-rotation [8] would be one of the promising ways to investigate roles of disturbances, including baroclinic modes, on super-rotation. Further study with high resolution simulations and realistic radiative process will reveal generation and maintenance mechanism of super-rotation on Venus.

Acknowledgements

This study was conducted under the joint research project of the Earth Simulator Center with title "Simulations of Atmospheric General Circulations of Earth-like Planets by AFES".

References

[1] Gierasch, P. J., Meridional circulation and maintenance of the Venus atmospheric rotation, J. Atmos. Sci., 32, 1038-1044, 1975

[2] Fels S. B. and Lindzen R. S., The interaction of thermally excited gravity waves with mean flows, Geo. Fluid Dyn., 5, 149-191, 1974

[3] Yamamoto, M. and Takahashi, M., The fully developed superrotation simulated by a general circulation model of a Venus-like atmosphere, J. Atmos. Sci., 60, 561-574, 2003

[4] Takagi, M. and Matsuda, Y., Effects of thermal tides on the Venus atmospheric superrotation, J. Geophys. Res., 11, D09112, doi:10.1029/2006JD007901, 2007

[5] Ohfuchi, W., Nakamura, H., Yoshioka, M. K., Enomoto, T., Takaya, K., Peng, X., Yamane, S., Nishimura, T., Kurihara, Y., and Ninomiya, K., 10-km Mesh Meso-scale Resolving Simulations of the Global Atmosphere on the Earth Simulator, -Preliminary Outcomes of AFES-, Journal of the Earth Simulator, 1, 8-34, 2004

[6] Takagi, M. and Matsuda, Y., A study on the stability of a baroclinic flow in cyclostrophic balance on the sphere, Geophysical Research letters, 33, L14807, doi:10.1029/2006GL026200, 2006

[7] Iga, S. and Matsuda, Y., Shear instability in a shallow water model with implications for the Venus atmosphere, J. Atmos. Sci., 62, 2514-2527, 2005

[8] Kido, A. and Wakata, Y., Multiple equilibrium states appearing in a Venus-like atmospheric general circulation model, J. Meteor. Soc. Japan, 86 (6) , 969-979, 2008