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Baroclinic instability in the Venus atmosphere simulated by general circulation model

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Abstract

Baroclinic instability in the super-rotation of Venus is investigated by a newly developed atmospheric general circulation model for Venus. An idealized superrotation, i.e. solid-body rotating flow with a weak stable layer, is set as an initial basic state. In the time evolution, baroclinic modes appear in the cloud layer with small static stability and large vertical shear of the basic zonal flow. Meridional transport of momentum and heat by these unstable modes is discussed. It is also examined how the baroclinic instability depends on the basic state, i.e. the meridional profile of zonal flow and the vertical profile of static stability.

1. Introduction

On Earth, baroclinic instability plays very important role on the general circulation through meridional transport of momentum and heat. Baroclinic instability is also important in the Martian atmosphere. In the present study, we focus on baroclinic instability in the Venus atmosphere, which is not observed yet but expected to exist according to the several previous linear stability researches [2, 3].

To investigate baroclinic instability, we construct a new General Circulation Model (GCM) based on AFES (Atmospheric GCM for the Earth Simulator) for realistic high-resolution simulations of the Venus atmosphere. Since traditional GCM studies for Venus need long spin up time to generate superrotation, their models tend to be low resolution with strong solar heating and large static stability. Instead, our model includes realistic static stability, but initial super rotating flow is assumed. After we study fundamental features of baroclinic instability appearing in the solid-body rotating flow, we extend our study to cases including the mid-latitude jets.

2. Model

AFES simulations are performed with simplified physical processes and physical constants appropriate for Venus. Detail experimental settings are summarized in [1]. The resolution used in the present study is T42L60 (a triangular truncation at wavenumber 42 with 60 layers). The vertical domain extends from the ground to about 120 km with almost the constant grid spacing of 2 km. Simulations with T159L120 are also performed in our project.

The physical processes adopted in the model are vertical eddy diffusion with a constant diffusion coefficient of 0.15 m2/s, a dry convective adjustment, the Newtonian cooling, and the Rayleigh friction at the lowest level to represent the surface friction. In the upper region above about 80 km, a sponge layer is assumed; the friction increasing with altitude gradually acts to damp the zonal wave component only. In addition, the model includes a 4th-order horizontal diffusion with an e-folding time for the maximum wavenumber of about 0.1 days. The Newtonian cooling coefficients are based on the previous study (Fig.1, (a)). The vertical temperature profile of the initial condition is constructed based on the observed vertical distribution of static stability. We also prepare several distributions (Fig. 1, (b)).

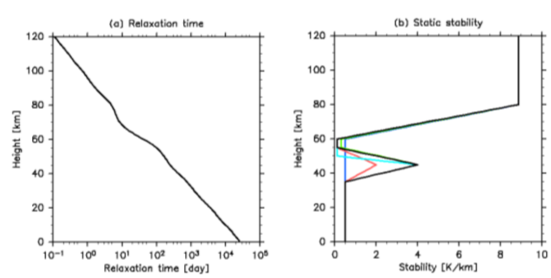

Figure 1: Vertical profiles of relaxation time of Newtonian cooling (a) and the static stability (b).

The equilibrium temperature distribution toward which the temperature is relaxed by the Newtonian cooling is an initial value written below. In the present study, we exclude solar heating for simplicity. However we also prepare the realistic solar heating, i.e. a zonally averaged solar heating distribution and a diurnally varying solar heating distribution.

The initial condition for wind velocity is zonally symmetric, solid-body superrotating flow (Fig.2, (a)). The temperature field is determined by the gradient wind balance (Fig.2, (b)). Meridional temperature gradient from equator to pole is about 5 K on a sigma surface at the top of cloud layer. Initiated from this initial condition, the time integration is performed for four Earth years. We also prepare a relatively realistic profile of zonally uniform zonal flow with mid-latitude jets near the cloud levels.

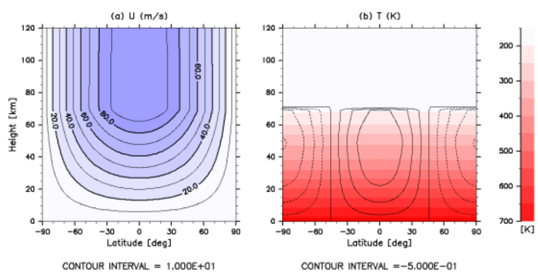

Figure 2: Latitude - height cross sections of zonally-uniform zonal flow (a) and temperature (b) used for initial basic state for the control experiment.

3. Results

Fig. 3 shows snapshot of vorticity disturbance in horizontal cross section at 54 km and 30 days. Vortices with wave numbers 5 and 6 appear in the mid-latitudes. The vertical structure shows characteristics of baroclinic instability (not shown).

Fig. 4 shows momentum and temperature flux. In the initial stage, baroclinic modes use available potential energy to develop. They accelerate where they grow up. However, this acceleration does not hold in the later stage (not shown). It is expected that solar heating will maintain meridional temperature gradient to produce baroclinic modes continuously.

Finally, it is verified that baroclinic instability does not appear for the case of larger static stability (not shown). We summarize detail results in [1].

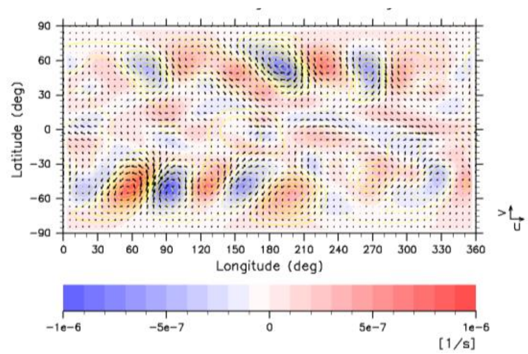

Figure 3: Snapshot of vorticity disturbance in horizontal cross section at 54 km and 30 days.

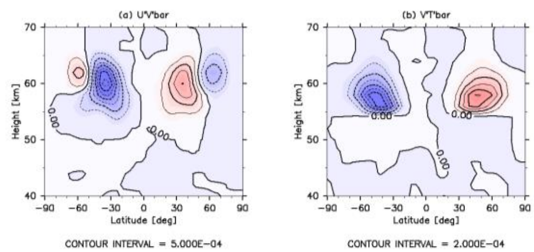

Figure 4: Latitude – height cross sections of momentum (a) and heat flux (b) averaged over 30 days from 31 days.

4. Summary and Conclusions

We investigate baroclinic instability in the superrotation of Venus by a newly developed GCM. Baroclinic modes develop in the cloud layer with small static stability and large vertical shear of the basic zonal flow. It is verified that meridional transport of momentum and heat by these unstable modes is important. Baroclinic modes crucially depend on the vertical profile of static stability.

References

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