Simulations of Atmospheric General Circulations of Earth-like Planets by AFES

Project Representative

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High resolution simulations of the Martian atmosphere have been performed by using a General Circulation Model (GCM) based on AFES (Atmospheric GCM for the Earth Simulator). Also performed is a simulation of the Venus atmosphere by using AFES with simplified physical processes and with a resolution higher than previous studies. Our aim is to have insights into the dynamical features of small and medium scale disturbances in the Earth-like atmospheres and their roles in the general circulations. Mars simulations are performed by the use of quite high horizontal resolution which is almost the applicable limit of hydrostatic approximation. The results of the simulations in northern summer show a variety of small scale disturbances, which are qualitatively similar to those observed in a northern fall simulation. However, the resolution dependence of dust mass flux in northern summer shows a trend different from that in northern fall. This difference may be partly attributed to the seasonal difference in distance between the Mars and the sun, but further investigation is needed to understand it. As for the simulation of the Venus atmosphere, baroclinic modes grow at the cloud layer where static stability is low. The structures of unstable modes are similar to those obtained in the linear stability analysis, although they are modified by the time development of the basic state. Analysis of meridional transport of momentum and heat by these unstable modes suggest that those modes significantly contribute the general circulation of the Venus atmosphere. This must be a feature we should consider in the higher resolution numerical experiments.

Keywords: planetary atmospheres, superrotation, dust storm, Earth, Mars, Venus

1. Introduction

The structure of the general circulation differs significantly with each planetary atmosphere. For instance, the atmospheres of the slowly rotating Venus and Titan exemplify the superrotation, while the weak equatorial easterly and the strong mid-latitude westerly jets form in the Earth's troposphere. The global dust storm occurs in some years on Mars, but a similar storm does not exist in the Earth's atmosphere. Understanding physical mechanisms causing such a variety of structures of the general circulations of planetary atmospheres is one of the most interesting and important open questions of the atmospheric science and fluid dynamics.

The aim of this study is to understand dynamical processes that characterize the structure of each planetary atmosphere by performing simulations of those planetary atmospheres by using GCMs with a common dynamical core of AFES [1]. Appropriate physical processes are adopted for each planetary atmosphere. In our project so far, we have been mainly performing simulations under the condition of Mars. In addition, the accurate radiation model of the Venus atmosphere has been constructed for the simulations under the condition of Venus. In the followings, the particular targets of each simulation, the physical processes utilized, and the results obtained will be described briefly.

2. Mars simulation

2.1 Targets of simulations

Dust suspended in the Martian atmosphere plays an important role to maintain thermal and circulation structure of the Martian atmosphere through radiative process. However, the physical mechanisms of dust lifting are not understood fully. A previous study by using a Mars GCM [2] suggests that the effects of wind fluctuations caused by small and medium scale disturbances would be important for the dust lifting processes. However, the features of small and medium scale disturbances which may contribute to the dust lifting have not been clarified. Disturbances of these scales are not easy to be observed. In order to examine the disturbances in the Martian atmosphere and its effects on dust lifting, we have been performing medium and high resolution simulations of Martian atmosphere by using a Mars GCM. In this fiscal year, simulations are continued with the condition of northern summer, when a global scale dust storm is not observed on Mars, and examine the seasonal difference by comparing a result with that at northern fall, which was performed last fiscal year.

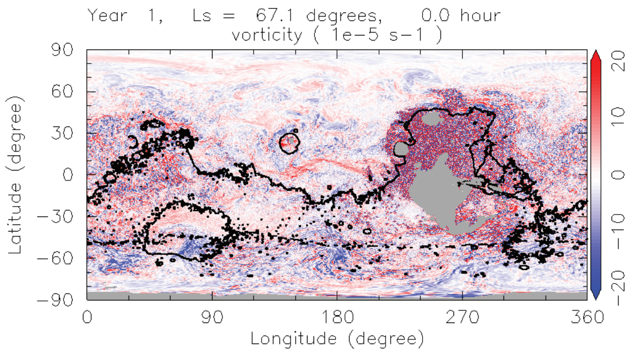

Fig. 1 Global distribution of vorticity at the 4 hPa pressure level at northern summer with the resolution of T639L96. Unit of vorticity is 10^{-5} s^{-1}. Also shown is the areoid (solid line) and low latitude polar cap edge (dashed line). Gray areas represent mountains at the 4 hPa pressure level.

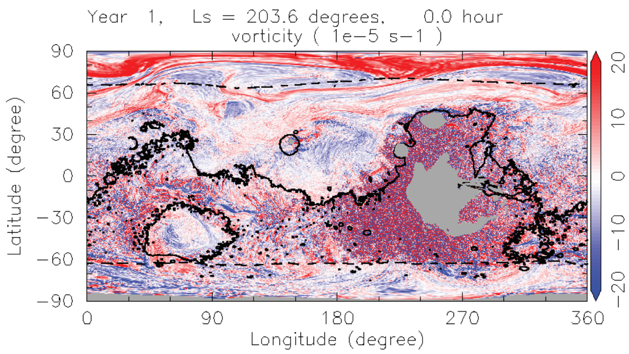

Fig. 2 Same as Fig. 1, but for northern fall.

2.2 Model and experimental settings

Mars simulations are performed with the physical processes introduced from the Mars GCM [3, 4] which has been developed in our group, and the values of physical constants appropriate for the Mars. The implemented physical processes are radiative, turbulent mixing, and surface processes. By the use of this GCM, the simulations in northern summer condition are performed. Resolutions of simulations are T79L96, T159L96, T319L96, and T639L96, which are equivalent to about 89, 44, 22, and 11 km horizontal grid sizes, respectively. The horizontal resolution of T639 is almost the applicable limit of hydrostatic approximation. In the simulation performed in this fiscal year, the atmospheric dust distribution is prescribed, and the dust is uniformly distributed in horizontal direction with an amount corresponding to visible optical depth of 0.2. Nevertheless, the dust lifting parameterization [5] is included in the model to diagnose the possible amount of dust lifting. As for the surface condition, the observed spatial variations of orography, surface albedo, and surface thermal inertia are prescribed. As a sensitivity test, the simulations with flat surface, uniform albedo and thermal inertia, are also performed to examine intrinsic effects of horizontal resolution on disturbance generation and dust lifting without such variations.

2.3 Results

Figure 1 shows a snapshot of global distribution of relative vorticity at the 4 hPa pressure level at northern summer from T639L96 simulation. In the simulation, a variety of atmospheric disturbances can be observed, such as baroclinic waves in the southern middle and high latitudes, medium scale vortices, some of which are associated with mountains, small scale streaks, and small scale vortices in the low latitude. Here, the small scale vortices in low latitude are focused. Comparing the vorticity distribution at northern summer with that at northern fall (Fig. 2),

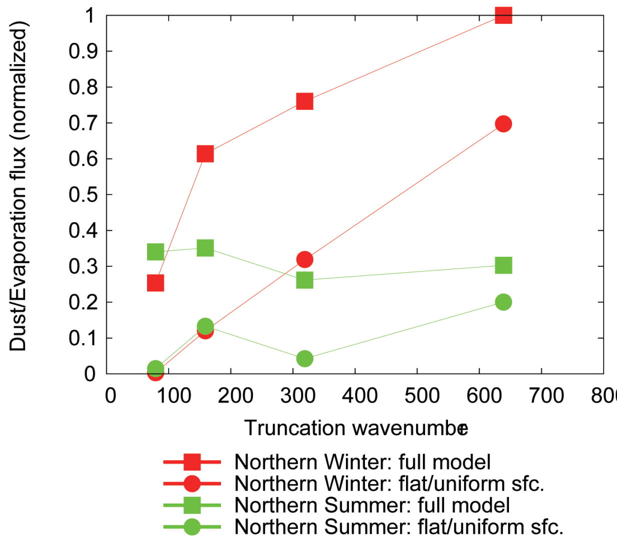

Fig. 3 Resolution dependence of normalized globally integrated dust mass flux. Squares indicate normal simulation, while circles indicate simulations without surface variations.

it is found that the similar small scale vorticies are observed in both seasons. As is the case at northern fall, the horizontal size of those small scale vortices at northern summer do not seem to converge up to the highest resolution performed in our study. It is considered that these small scale vortices are representation of vertical convection in the model. The latitude where the vortices are observed is different because of the different seasonal condition. The area where the small scale vortices are observed may be slightly smaller than that at northern summer. This may reflect the facts that the distance between the Mars and the sun is larger at northern summer than that at northern fall, and that the elevation of northern hemisphere is lower than that of southern hemisphere.

In order to assess the effects of small and medium scale disturbances on dust lifting, the resolution dependence of globally integrated dust mass flux diagnosed in the model is examined. Figure 3 shows the resolution dependence of globally integrated dust mass flux. The dust mass fluxes at northern fall and those in the flat/uniform surface experiments are also shown. The globally integrated dust mass fluxes at northern summer do not increase with increasing resolution significantly. This trend is not the same as that at northern fall. This implies that the strength of small scale disturbances represented in our model at northern summer would not be the same as that at northern fall. However, the physical mechanisms of this seasonal difference have not been interpreted yet. Further investigation is needed to understand seasonality of dust lifting.

3. Venus simulation

3.1 Targets of simulations

The mechanism of the super-rotation is one of the most interesting topics in the planetary science. Several mechanisms, such as the Gierasch mechanism [6] through meridional circulation and the thermal tides mechanisms [7] through wave mean flow interaction, have been proposed to explain this special phenomenon. In the results of previous numerical simulations using Venus-like GCMs, both mechanisms can work to generate super-rotation [8, 9]. However, since these models have coarse resolutions and simple physical processes, it is unclear whether the previous results can hold in case of high resolution realistic numerical simulations. In addition, as is usually done in the context of geophysical fluid dynamics on Earth, parameter studies, such as resolution, horizontal and vertical eddy viscosity, topography, heating rate, and radiative process, are also needed to obtain the comprehensive understandings of the atmosphere of Venus.

In the present study, we develop a GCM for Venus by modifying AFES to achieve high resolution numerical simulation for the atmosphere of Venus. 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 with high resolution. Therefore, as a first step, we investigate structure of unstable modes initiated from an initial condition of super-rotating flow and a realistic static stability. In addition, momentum and heat transport achieved by the unstable modes are also addressed in this study.

3.2 Model and experimental settings

Venus simulations are performed with simplified physical processes and physical constants appropriate for the Venus. Experimental settings are basically based on the previous linear stability analysis [10]. Physical processes included in the model are vertical eddy diffusion with a constant diffusion coefficient of 0.015 m^2/s, a dry convective adjustment, the Newtonian cooling, and the Rayleigh friction at the lowest level to represent the surface friction. Unlike the many previous studies, Rayleigh friction is not imposed in the upper layers. In addition, the model includes 8th order horizontal diffusions (∇^8) with e-folding time for the maximum wavenumber of about 0.8 days. The Newtonian cooling coefficients are based on the observation [11]. The equilibrium temperature distribution toward which the temperature is relaxed by the Newtonian cooling is an initial value written below.

A basic state used in a dynamical core is partly based on an observed static stability distribution [12]. The lower atmosphere close to the ground is weakly stable. In the cloud layer, there is an almost neutral layer (from 55 to 60 km) due to the solar heating. At the bottom of the cloud layer it is stable, and static stability has a maximum at around 45 km. Above the cloud layer (above 70 km), it is strongly stratified. It is expected that unstable modes will appear in the cloud layer.

The resolution used in a simulation is T42L60, which has 128 and 64 grids in the longitudinal and latitudinal direction, respectively. Vertical domain extends from the ground to about 120 km with almost the constant grid spacing of 2 km.

The initial condition is an idealized solid body super-rotating flow. The flow linearly increases with height from ground to 70 km, which is suggested by the observation [13]. Its maximum is 100 m/s at 70 km at the equator, and above there the velocity is constant. Temperature is in balance with the zonally symmetric flow, namely, gradient wind balance. 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 model is integrated for 5 Earth years.

3.3 Results

In the results of numerical simulation, super-rotation gradually decreases in the cloud layer (50 - 70 km). It is the unstable modes of growing vortices that decrease super-rotation in the later stage. Figure 4 shows snapshots of horizontal cross section of vorticity disturbance and zonal mean horizontal flow at 54 km for two different times. Clearly, vortical structure of wavenumber 3 and 4 grow at the mid latitude. They have significant amplitude at the later time. These growing vortices decrease super-rotating flow where they evolve.

Figure 5 shows height – longitude cross sections of meridional flow disturbance (a) and temperature disturbance (b) at 40ºN where unstable modes grow. The phases of these disturbances are tilted from down-east to up-west. In addition, they are out of phase. That is, while cold air flows downward and southward, warm air flows upward and northward. This

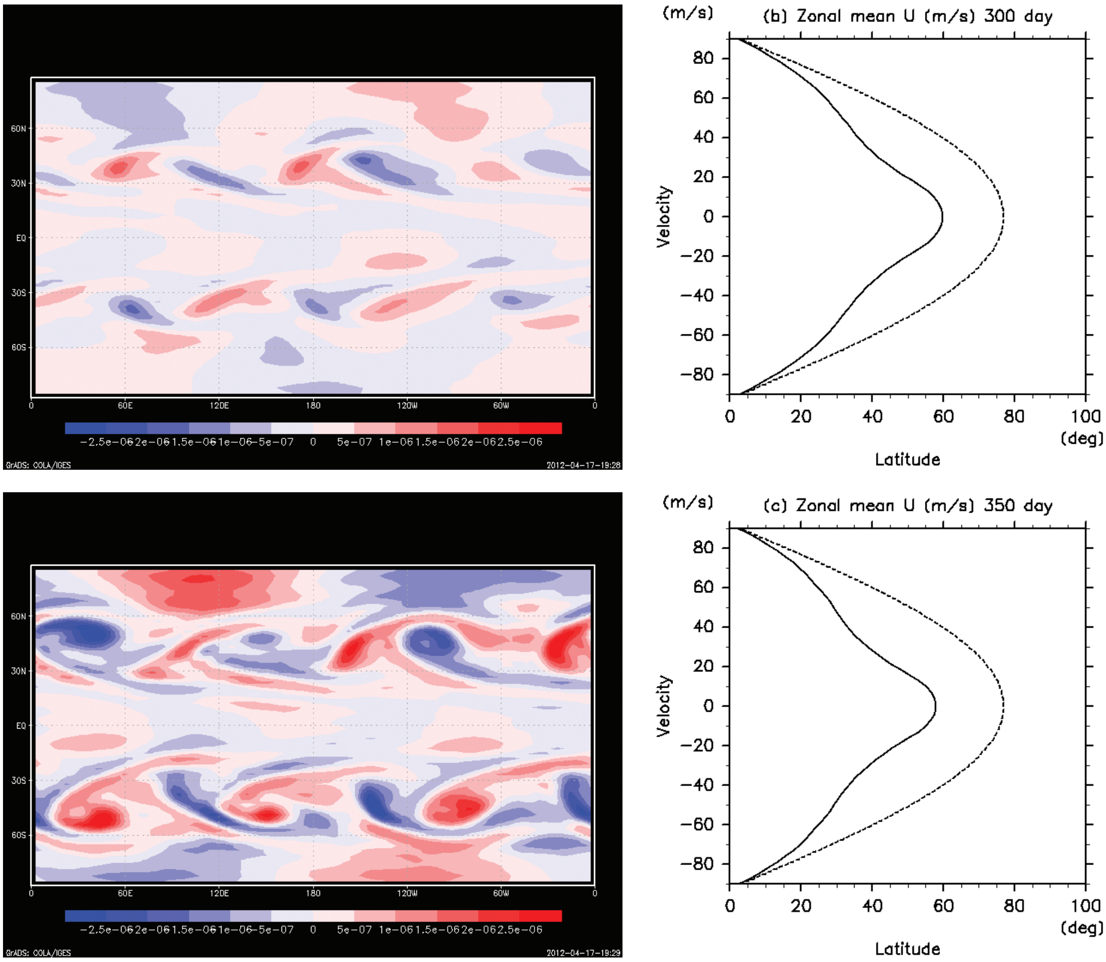

Fig. 4 Snapshots of horizontal cross section of vorticity disturbance (left) and latitudinal profile of zonal mean horizontal flow (right) at 54 km; (top) 300 days and (bottom) 350 days.

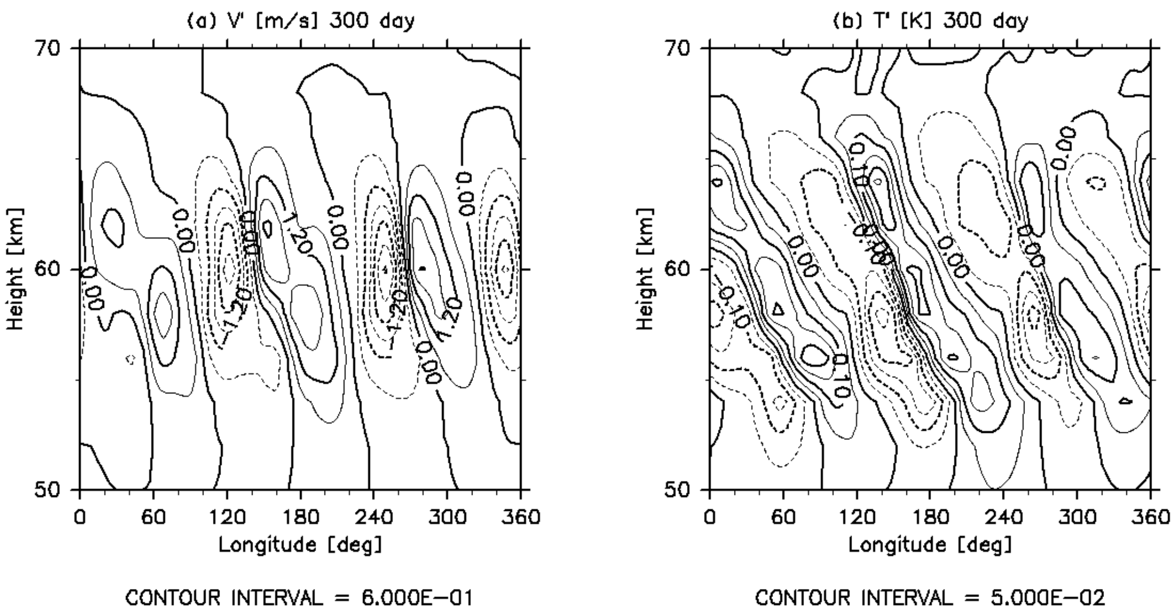

Fig. 5 Height – longitude cross sections at 40 degrees north of meridional flow disturbance (a) and temperature disturbance (b) at 300 days.

is the typical structure of baroclinic instability. It is almost consistent with the results of previous linear stability analysis, although basic zonal flow changed in the time evolution of nonlinear simulation. Since stable layer exists below the cloud layer and density in the lower layer is large, unstable mode does not extend to the lower layer. We investigate momentum and heat transport by growing vortices. It is found that zonal flow is accelerated by unstable modes using available potential energy in the initial stage of baroclinic instability. Thus, momentum flux converges to the position where baroclinic modes develop, and heat flux is poleward in the northern hemisphere.

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.

So far, there are no observations of baroclinic instability on Venus, though they are considered to be important [14]. This study suggests they could exist in the cloud layer where super-rotating flow is fast and meridional temperature gradient is large, and could be important on maintaining general circulation on Venus through momentum and heat transportation.

Finally, this study treated only an initial growth of baroclinic instability. For future work, we hope 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 [15]. Long time numerical simulation initiated from super-rotation 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.

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AFES を用いた地球型惑星の大気大循環シミュレーション

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大気大循環モデル AFES（AGCM (Atmospheric General Circulation Model) for the Earth Simulator）に基づく GCM を用いて、火星大気の高解像度大気大循環シミュレーションを実施した。加えて、これまでに開発してきた高精度の金星大気放射モデルを用いた高解像度シミュレーションの下準備として、簡単な物理過程を用いた中解像度での大気大循環シミュレーションを実施した。我々の研究の目的は、地球型惑星大気における中小規模擾乱の力学的特徴と、その大気大循環への影響を調べることである。火星大気シミュレーションは、おおよそ静水圧近似が成り立つ限界付近の非常に高い解像度で実施した。北半球の夏の時期におけるシミュレーションの結果は、北半球の秋の時期のシミュレーションと定性的に同様な様々な小規模擾乱を示す。しかし、北半球の夏の時期における、ダスト巻き上げフラックスの解像度依存性は、北半球の秋の季節とは異なることが示された。この違いは、部分的には、火星－太陽間距離の季節変化が原因であると考えられるが、その理解のためにはさらに調査が必要である。金星大気シミュレーションに関しては、安定度の小さい雲領域における傾圧不安定モードの成長が示された。これらの傾圧不安定モードの構造は、時間発展していく基本場の影響も受けているようであるが、基本的には線形安定性解析で示されていたものであると考えられる。これらの傾圧不安定モードによる運動量と熱の南北輸送を解析した結果、金星大気大循環において重要な寄与をなしていると評価された。高解像度計算において着目されるべき特徴であると予想される。

キーワード : 惑星大気, スーパーローテーション, ダストストーム , 地球, 火星 , 金星