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

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Medium and high resolution simulations of the Martian atmosphere have been performed by using a GCM (General Circulation Model) based on the AFES (Atmospheric GCM for the Earth Simulator), and an accurate radiative transfer model for the Venus atmosphere has been constructed to extend the model toward the calculations of the Venus atmosphere. Our aim is to have insights into the dynamical features of atmospheric small and medium scale disturbances in the Earth-like atmospheres and their roles in the general circulations. Confirmation of the results of Martian simulations obtained until last fiscal year is also an important task because a bug in estimation of surface fluxes was found in the model. The results of the simulation with horizontal grid size of about 44 km show that many kinds of atmospheric small and medium scale disturbances, such as, medium scale vortices in the lee of Alba Patera and small scale vortices in low latitudes, are represented. It is confirmed that these features are qualitatively similar to those reported until last year. The analysis of distribution function of surface stress suggests that the small scale disturbances in low latitude are important to generate large surface stress. Toward the high resolution simulations of the Venus atmosphere with realistic radiative forcing, an accurate radiative transfer model of the Venus atmosphere has been constructed. In order to construct the model, four absorption line profiles of CO_2 proposed by past studies were tested and the most promising line profile that leads to a reasonable temperature structure has been determined for a new radiation model. Incorporation of this model into the AFES will produce the first reliable general circulation simulation of Venus atmosphere.

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 are formed 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 the 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 the dynamical processes that characterize the structures of each planetary atmosphere by simulating circulations of those planetary atmospheres by using general circulation models with the common dynamical core of the AFES [1]. Appropriate physical processes are adopted for each planetary atmosphere. In our project so far, we have been mainly performing simulations under condition of Mars. In addition, the accurate radiation model of the Venus atmosphere has been constructed toward performing the simulations of the Venus atmosphere with realistic radiative forcing. In the followings, the particular targets of each simulation, the physical processes utilized, and the results obtained are described briefly.

2. Mars simulation

2.1 Targets of simulations

It is well known that a certain amount of dust is always suspended in the Martian atmosphere and the radiative effect of dust has important impact on the thermal budget of the Martian atmosphere. However, the physical mechanisms of dust lifting have not been well understood. It has been implied that the effects of wind fluctuations caused by small and medium scale disturbances would be important for the dust lifting processes. Until the last fiscal year, the features of disturbances and dust lifting amount at northern fall and summer were investigated. However, a bug in estimation of surface momentum and heat fluxes was found in the model. The disturbances near the surface may be strongly affected by the surface momentum and heat fluxes. In this fiscal year, after fixing the bug, the simulations are performed to confirm the features of atmospheric disturbances reported by the last year, and the distribution function of surface stress in the model is examined to have implications on effects of atmospheric disturbances on dust lifting.

2.2 Physical processes

The physical processes used for the Mars simulations are introduced from the Mars GCM [2, 3] which has been developed in our group so far. The implemented physical processes are the radiative, the turbulent mixing, and the surface processes. Before performing simulations, a bug found in estimation of surface process was fixed. By the use of this GCM, the simulations in northern fall condition are performed. Resolutions of simulations are T79L96 and T159L96, which are equivalent to about 89 and 44 km horizontal grid sizes. 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. But, the dust lifting parameterization [4] is included in the model, and the possibility of dust lifting can be diagnosed in the model.

2.3 Results

Figure 1 shows a snapshot of global distribution of relative vorticity at the 4 hPa pressure level at northern fall obtained from T159L96 simulation. In the simulation, many kinds of atmospheric disturbances can be observed. One of the most striking features is the baroclinic wave whose zonal wavenumber is 2-3. Associated with this wave, fronts are observed as elongated vorticity features. In addition to this large scale wave, small scale disturbances can also be observed. One of examples is medium scale vortices in the lee of Alba Patera around 255°E, 40°N. Analysis of circulation around Alba Patera suggests the interaction between mean wind and mountain and diurnally varying slope wind would cause this vortex generation. Small scale disturbances of another type are a lot of small scale vortices in low latitude. These vortices are generated in the afternoon and dissipated in the night. It is suggested that these would be an appearance of convective activity represented in the model. These results are qualitatively similar to those reported until last year although the calculation of surface flux is changed by fixing the bug.

The distribution functions of surface stress are analyzed to examine the effects of small and medium scale disturbances on dust lifting. Figure 2 shows the distribution functions of

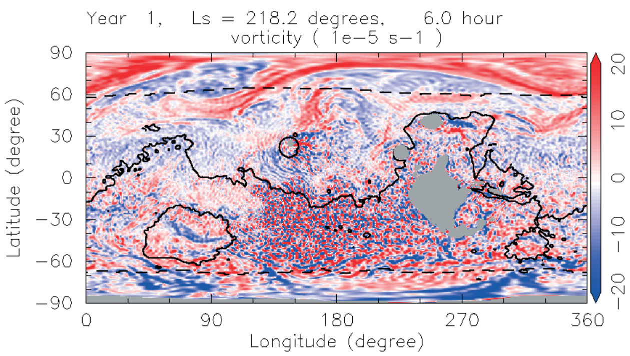

Fig. 1 Global distribution of vorticity at the 4 hPa pressure level at northern fall with the resolution of T159L96. Unit of vorticity is 10^{-5} s^{-1}. Also shown is the areoid (solid line) and low latitude polar cap edge (dashed line). Gray areas represent mountains at the 4 hPa pressure level.

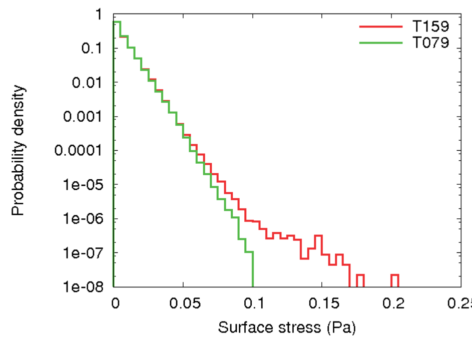

Fig. 2 Distribution functions of surface stress obtained from T159L96 resolution simulation (red), and T79L96 resolution simulation (green).

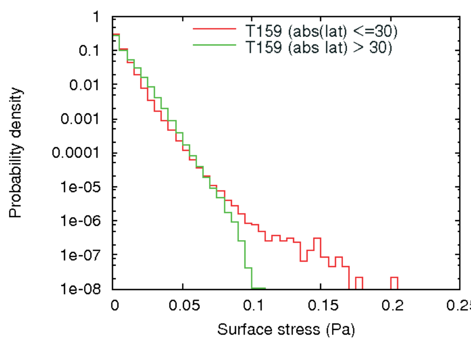

Fig. 3 Latitudinal dependence of distribution function from T159L96 simulation, equatorward of 30 degree latitude (red) and poleward of 30 degree latitude (green).

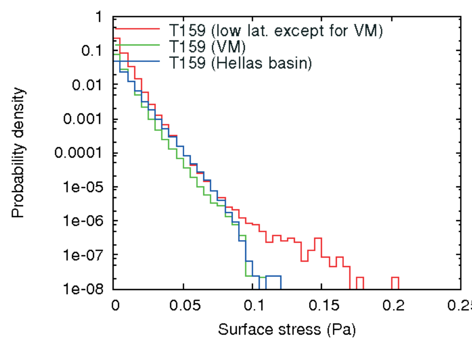

Fig. 4 Regional dependence of distribution function of surface stress at low latitude except for Valles-Marineris (VM) (red), VM (green), and Hellas basin (blue).

surface stress obtained from T159L96 and T79L96 resolution simulations. The distribution function from T159L96 simulation shows a large surface stress tail. The maximum surface stress in T159L96 simulation is about 1.5-2 times larger than that in T79L96 simulation. Diagnostics of possibility of dust lifting by dust lifting parameterization included in the model shows that the large surface stress shown in T159L96 simulation causes the dust lifting in the model.

In order to have implications for phenomena causing high surface stress, the latitudinal dependence of distribution function is examined. It is shown that the large surface stress tail is generated in low latitude region (Fig. 3). This simply implies the importance of disturbances in low latitude. At the same time, this also implies that the baroclinic waves and fronts in northern middle and high latitude do not play important roles in view of generating large surface stress.

Finally, the regional dependence of distribution function is examined by picking up two characteristic topography features, Hellas basin and Valles-Marineris (VM). However, it is shown that the large surface stress tail is not observed in distribution functions in these regions (Fig. 4). The analysis of circulation implies the importance of steep slope to generate atmospheric disturbances. But, disturbances in such regions do not have significant impact in view of generating large surface stress in our model and in our current resolution.

3. Venus simulation

3.1 Targets of simulations

Numerical simulations of the Venus atmospheric circulation have been actively made in recent years [5, 6, 7, 8, 9]. In most models used in these simulations, the radiative transfer process is represented by the Newtonian cooling. However, this approximation cannot be justified for the Venus atmosphere whose opacity is extremely large in the infrared region. In order to investigate the Venus atmospheric circulation, we must develop a radiative transfer model applicable to the Venus atmosphere and to the AFES.

3.2 A new radiative transfer model

The Venus atmosphere consists of the vast amount of carbon dioxide (CO_2), which leads to high pressure and high temperature in its lower atmosphere. In this situation, representation of the pressure broadening of CO_2 absorption lines is quite important for constructing an accurate radiative transfer model. The broadening of the absorption line is usually represented by the Lorentz profile. However, it is well known that the infrared absorption due to CO_2 is overestimated by the Lorentz profile, and several profiles have been proposed as a substitute for the Lorentz profile. In the present study, the following line profiles are used to obtain temperature profiles in the radiative and radiative-convective equilibrium states [10, 11, 12, 13]: Lorentz profile, profile by Tonkov et al. (1996), profile by Fukabori et al. (1986), and profile by Meadows and Crisp (1996). Collision induced absorption (CIA) is also taken into account [14]. It is assumed that the H_2O absorption line is represented by the Lorentz profile.

A radiative transfer model constructed in the present study is based in the correlated k-distribution method. A wavenumber region of 0-6000 cm^{-1} is taken into account, and divided into 30 channels. It is assumed that the H_2SO_4 cloud is optically "grey" and its optical thickness is 10. An atmospheric layer of 0-80 km is divided into 50 layers in the following calculations. A vertical profile of the solar heating is based on the observations [15]. Vertical convection is represented by the vertical eddy viscosity based on the mixing length theory. Radiative and radiative-convective equilibrium temperature profiles are obtained for the following conditions:

- Case 1: CO_2 only (CIA is excluded)
- Case 2: Case 1 + CIA
- Case 3: Case 2 + H_2O

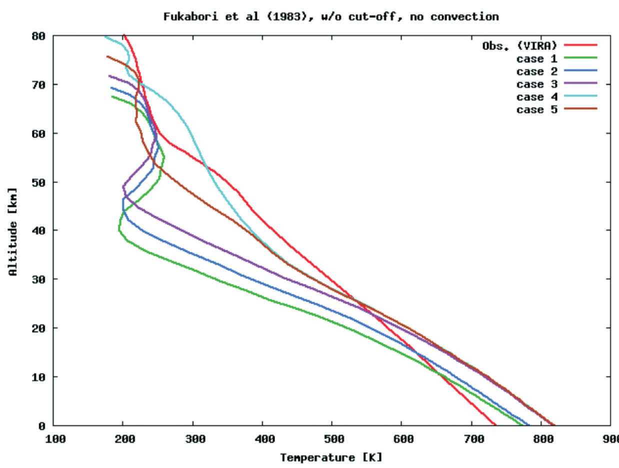

Fig. 5 Radiative equilibrium temperature profiles obtained for the cases 1-5 by using the Fukabori line profile. The red line shows the observed temperature profile.

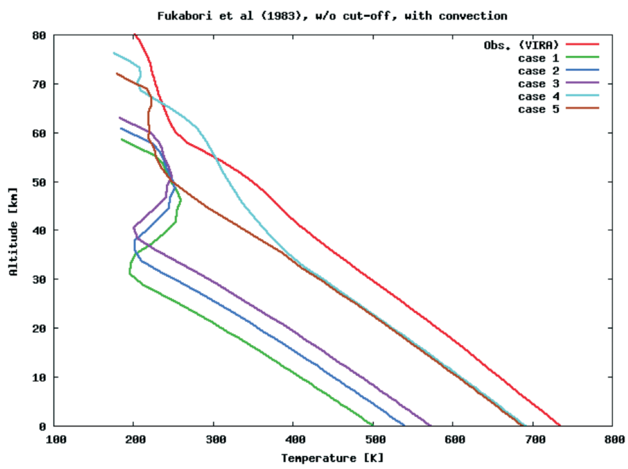

Fig. 6 The same as Fig. 5, but for the radiative-convective equilibrium.

- Case 4: Case 3 + H_2SO_4 cloud (constant k ρ)
- Case 5: Case 3 + H_2SO_4 cloud (constant k).

In this report, results obtained by the Fukabori profile are shown in Figs. 5 and 6. These results and others (not shown here) can be summarized as follows:

- Temperature profiles close to the observed one can be obtained by using the line profiles of Fukabori et al. [12] and Meadows and Crisp [13].
- Realistic radiative transfer model for the Venus atmosphere may be constructed by these line profiles.
- In the radiative equilibrium states, the temperature profiles are super-adiabatic from the surface to 10-80 km (the top level depends on the CO_2 line profiles). The temperature at the surface is much higher than the observed one.
- In the radiative-convective equilibrium states, a convective layer is formed from the surface to 30-50 km. The temperature at the surface strongly depends on the temperature at the cloud bottom.

See Takagi et al. [16] for more details of the new radiative transfer model.

In order to simulate the Venus atmospheric circulation and investigate the generation mechanism of the atmospheric superrotation, we are going to carry out numerical simulations with the AFES combined with the new radiative transfer model.

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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、火星大気の中高解像度大気大循環シミュレーションを実施した。また、金星大気計算への拡張を目指して、高精度の金星大気放射モデルを構築した。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。また、昨年度に地表面におけるフラックスの計算においてバグが発見されたため、昨年度までの火星大気シミュレーションの結果を確認することも今年度の重要な目的である。水平格子点間隔約 44 km の解像度での火星大気シミュレーションを行った結果、アルバ・パテラ領域の風下での中規模渦や低緯度での小規模渦群といった様々な大気擾乱が表現された。これらの特徴は、昨年度までに見られていたものと定性的に同様であることが確認された。計算結果を用いて地表面応力の分布関数について解析を行ったところ、低緯度で生じる小規模擾乱が大きな値の地表面応力を生成する上で重要であることが示唆された。また、現実的な加熱強制を与えた金星大気の高解像度大気大循環シミュレーションの実施に向けて、高精度の放射モデルを構築した。モデル構築においては、先行研究で提案された 4 つの CO_2 吸収線型をテストし、理にかなった温度構造の得られる吸収線型を決定した。この放射モデルを AFES に導入して計算を行うことにより、初めての信頼に足る金星大気の大気大循環実験を行いたい。

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