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

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For the purpose of acquiring insights into the physical processes characterizing dynamical structures of general circulations of the planetary atmospheres, 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). The result of the Mars simulation with several horizontal resolutions shows that resolution dependence of global mean dust mass flux at northern summer is different from that at northern autumn. Significant differences in resolution dependence are attributable to the difference in dust lifting in the regions with characteristic orographic features. This implies the importance of superposition of seasonally varying large scale circulation on the local orography-related circulation in the dust lifting in the model. On the one hand, to perform the high resolution simulations of the Venus atmosphere with realistic radiative forcing, an accurate radiative transfer model of the Venus atmosphere has been constructed. Sensitivity tests of the constructed new radiatiive transfer model show that the radiative equilibrium temperature profiles are highly sensitive to the line shape, which is one of the most ambiguous parts of the model. Further sensitivity tests will lead to determination of an appropriate line shape for Venus atmosphere and the simulations of the realistic superrotation with the realistic radiative forcing.

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.

In this study, circulations of those planetary atmospheres are simulated by using general circulation models with the common dynamical core of the AFES [1]. Appropriate physical processes are adopted for each planetary atmosphere. The aim is to understand the dynamical processes that characterize the structures of 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 to perform 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. It may be worth notifying that the amount and distribution of dust in the atmosphere affects the atmospheric circulation significantly. Hence the activities of small and medium scale disturbances should be consistently determined with the dust amount in the atmosphere. Until the last fiscal year, the dust lifting amount at northern autumn is investigated. In this fiscal year, in order to investigate the seasonal variation of dust lifting amounts, simulations of the Martian atmosphere at northern summer are performed with several resolutions.

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. In addition, the dust lifting parameterization [4] and the gravitational sedimentation are introduced. By the use of this GCM, the simulations in a condition of northern summer with the resolutions of T79L96, T159L96, and T319L96, which are equivalent to about 89, 44, and 22 km horizontal grid sizes, are performed.

2.3 Results

Figures 1 and 2 show examples of global vorticity distribution at the 3 hPa pressure level and the dust mass flux at northern summer with the T319L96 model, respectively. In the simulation performed in this study, a part of dust lifting events occur in the region with small scale vorticies shown in Fig. 1. This implies that the small scale disturbances would play a role in lifting dust in the model.

Figure 3 shows the resolution dependence of the global mean dust mass flux at northern summer and autumn. It is shown that the global mean dust mass flux increases with increasing horizontal resolution at northern autumn, while at northern summer, that does not change with horizontal resolution significantly. Figures 4 and 5 show the geographical distribution of resolution dependence of the dust mass flux at northern summer and autumn, respectively. At northern autumn, the dust mass flux increases with increasing resolution in some regions with characteristic orographic features, such as the Valles-Marineris around 300°E, 10°S. However, at northern summer, the dust mass flux is almost the same or slightly decreases with increasing horizontal resolution in those regions. This result implies that the

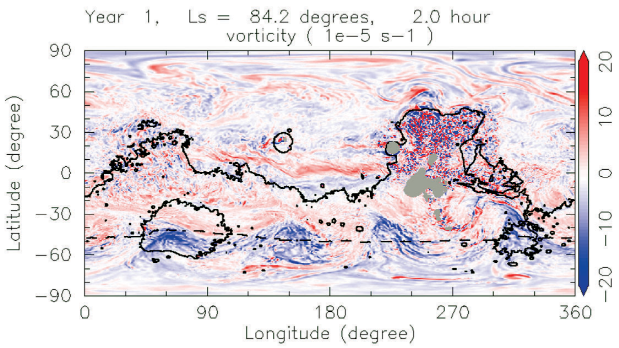

Fig. 1 Global distribution of vorticity at the 3 hPa pressure level at northern summer with the resolution of T319L96. Unit of vorticity is 10^{-5} s^{-1}. Also shown is the areoid (solid line) and low latitude polar cap edge (dashed line). Gray areas represent mountains at the 3 hPa pressure level.

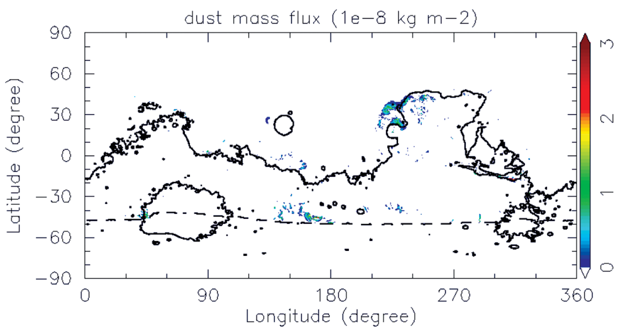

Fig. 2 Same as Fig. 1, but for dust mass flux diagnosed in the model. Unit of dust mass flux is 10^{-8} kg m^{-2}.

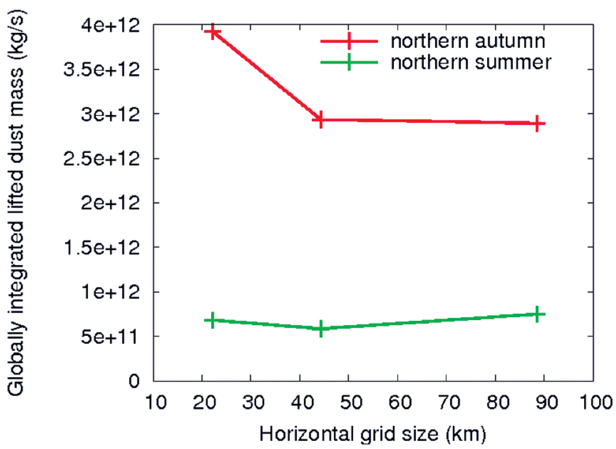

Fig. 3 Resolution dependence of global mean dust mass flux at northern summer and autumn.

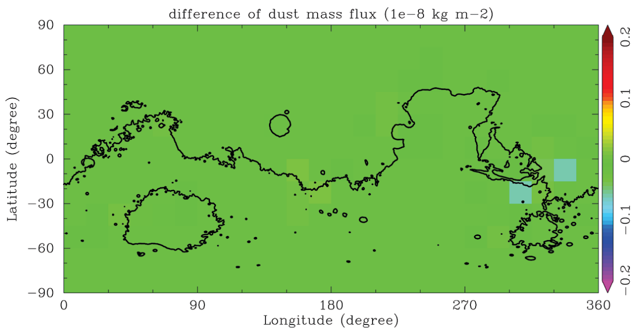

Fig. 4 Difference of dust mass flux between T319L96 and T79L96 simulations at northern summer.

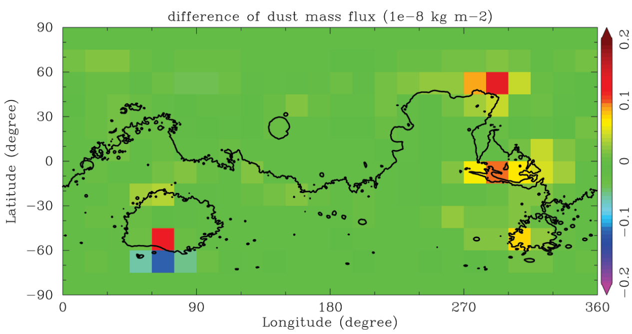

Fig. 5 Same as Fig. 4, bur for northern autumn.

effects of superposition of seasonally varying large scale circulation and small scale disturbances would be important in dust lifting in such regions.

3. Venus simulation

3.1 Targets of simulations

The Venus atmospheric superrotation is one of the most prominent phenomena in the field of planetary meteorology. The existence of fast prograde zonal winds extending from the ground to 70–80 km altitudes over almost all latitudes is quite different from general circulations of the Earth or Mars atmospheres. Although many studies have been made so far, the generation mechanism of the Venus atmospheric superrotation remains a mystery. Recently, several studies succeeded in reproducing fast prograde zonal winds whose structures look like those of the Venus atmospheric superrotation [5, 6]. However, it should be noted that unrealistically strong solar heating is assumed in those studies, and that the fast prograde zonal winds do not appear with realistic solar heating based on observations.

In this project, we are trying to simulate the Venus atmospheric superrotation by assuming the realistic solar heating. The results obtained so far show that nonlinear interactions among the mean zonal flow, the mean meridional circulation, and the thermal tides have to be examined. It is obvious that the Newtonian cooling is unsuitable to simulate atmospheric motions in the lower Venus atmosphere. Therefore, we are going to construct a new radiative transfer model which is able to represent the radiation field in the Venus atmosphere, and integrate it into our Venus GCM which has been constructed in this project.

3.2 New radiative transfer model

A new radiative transfer model has been constructed based on the correlated k-distribution (CKD) method. In order to apply this model to the Venus atmosphere, it is very important to calculate the absorption coefficients of CO_2 and H_2O precisely in a wide range of wavenumber at vertical levels from the ground up to above 80 km. It should be noted, however, that the line shapes of the infrared absorption due to CO_2 and H_2O have not been well-established for this purpose.

3.3 Results

Several line shapes of the CO_2 absorption have been proposed [7, 8, 9]. Figures 6 and 7 show dependences of the absorption coefficients on wavenumber obtained at 0.1, 1.0 and 10.0 bars by using the Lorentz profile and that proposed by Pollack et al. [7], respectively. Vertical temperature profiles in the radiative equilibrium state obtained for these absorption coefficients are shown in Figs. 8 and 9. The results clearly show that the atmosphere becomes too opaque (transparent) for the infrared region in the case of the Lorentz (Pollack et al.) profile.

We are going to make further comparison for other profiles proposed by Fukabori et al. [8] and Meadows and Crisp [9], which will lead to a definite distribution of the CO_2 absorption coefficient suitable for the Venus atmosphere. We also intend to integrate it into our Venus GCM to make it possible to simulate the atmospheric superrotation realistically.

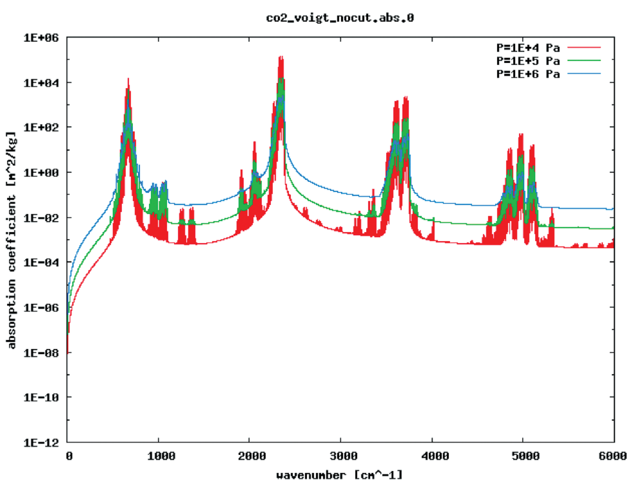

Fig. 6 Dependences of the absorption coefficients on wavenumber obtained by using the Lorentz profile. Red, green, and blue lines indicate absorption coefficients at 0.1, 1.0 and 10.0 bars, respectively.

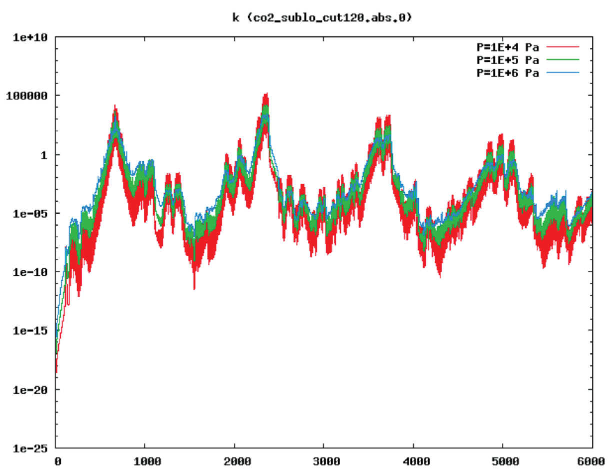

Fig. 7 Same as Fig. 6, but by using the Pollack et al. profile.

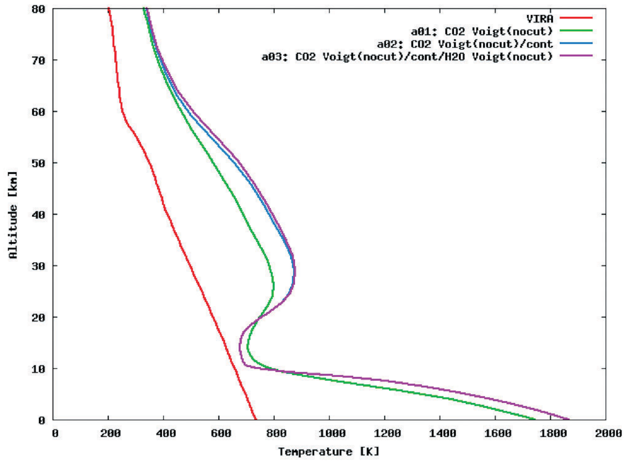

Fig. 8 Vertical temperature profiles in the radiative equilibrium state obtained by using the Lorentz profile. Red line shows the observed temperature profile by VIRA (Venus International Reference Atmosphere). Green, blue, and purple lines show the radiative equilibrium temperature considering the absorption of CO_2 permitted transtion only, CO_2 permitted transtion and continuum, and CO_2 permitted transtion, continuum, and H_2O, respectively.

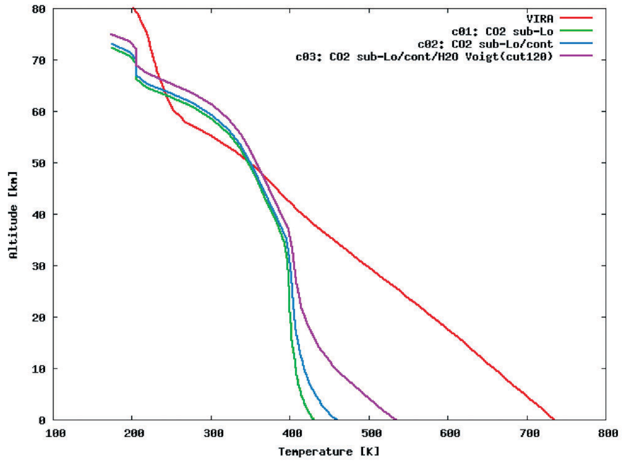

Fig. 9 Same as Fig. 8, but by using the profile of Pollack et al.

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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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様々な惑星大気循環の力学的構造を特徴付ける物理過程を理解するために、大気大循環モデルAFES（AGCM (Atmospheric General Circulation Model) for the Earth Simulator）を力学コアとするGCMを開発し、これ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。複数の水平解像度で火星大気循環の計算を行ったところ、北半球の夏におけるモデル内で巻き上げられるダストの量の解像度依存性は、北半球の秋におけるそれとは異なっていることが示された。この解像度依存性における重要な差違は、特徴的な地形の領域におけるダスト巻上げ量の差に起因している。このことは、モデル内におけるダスト巻上げ過程において、季節変化する大規模循環と局所的な地形に関係した循環との重ね合わせが重要であることを示唆する。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の構築を行った。構築した放射モデルを用いた感度実験を実施したところ、得られる放射平衡温度分布は用いた吸収線型に対して非常に敏感であることが示された。吸収線型の選択は、金星大気放射モデルの最も不確定な部分の一つである。今後さらに感度実験を行うことで金星大気に適した線型を決定し、完成した放射モデルを用いて現実的な放射強制の下での金星大気大循環実験を行いたいと考えている。

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