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 global atmosphere and the aqua-planet atmosphere which is an abstraction of the Earth's atmosphere have been performed by using GCMs (General Circulation Model) based on the AFES (Atmospheric GCM for the Earth Simulator) as a common dynamical core. In addition, we have developed a physical process module for simulating the Venus atmosphere and performed a preliminary calculation. The results of the Mars simulation with the horizontal resolution of T319 demonstrate a clear frontal structure associated with baroclinic waves, and a number of small and medium scale disturbances including medium scale vortices generated in the vicinity of high mountains. As for the aqua-planet simulation, calculations are performed with and without cumulus parameterization. The results of both cases indicate spontaneous appearance of hierarchical structures in the activities of equatorial precipitation. Analysis of these structures implies that Kelvin wave-CISK (Conditional Instability of the Second Kind) would play a role in organizing precipitation activities. A result of preliminary Venus simulation confirms the importance of thermal tides in maintaining the superrotation. This result is consistent with the results of the previous studies obtained by using linear models.

Keywords: planetary atmospheres, equatorial disturbances, superrotation, dust storm, Earth, Mars, Venus, Aqua-planet

1. Introduction

The common characteristics of the atmospheres of the terrestrial planets and satellites, such as Venus, Mars, and Titan, are the small vertical scale of the atmosphere compared to the radius of the planet or the satellite, and the existence of solid surface that clearly defines the lower boundary of the atmosphere. These characteristics would naturally evoke an expectation that the features of the general circulation of these atmospheres would be described within the same dynamical framework as that of the Earth's atmosphere. Nevertheless, the general circulations of these atmospheres show various features, such as the superrotation in the atmospheres of slowly rotating Venus and Titan, and the global dust storm in the atmosphere of Mars as compared to the moist atmosphere of the Earth.

In this study, the general circulation of each planetary atmosphere is simulated by using the same dynamical core of the AFES [1] and the physical processes appropriate for each planetary atmosphere with the aim of understanding the dynamical processes that characterize the structures of each planetary atmosphere, and locating the atmospheric circulation state of each planet as one realization on a broad parameter space. For these purposes, we have been performing simulations under conditions of Mars, aqua-planet, i.e., a virtual Earth whose surface is covered by the ocean, and Venus. 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

One of the most important open questions of Martian atmosphere is to figure out the features of small and medium scale disturbances, which cannot be observed easily, and possible relationships between those features and occurrence and maintenance of dust storms. It has been implied that the effects of wind fluctuations caused by small and medium scale disturbances must be important on the dust lifting processes. However, the actual features of those disturbances and their effects on dust lifting and transport have not been well investigated yet. 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. In this study, in order to address those questions, we perform high resolution simulations of the Martian atmosphere, in which small and medium scale disturbances can consistently coexist under the simulated amount of dust.

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 process and the gravitational sedimentation are introduced. By the use of this GCM, a simulation in a condition of northern fall with the resolution of T319L96, which is equivalent to about 22 km horizontal grid size, is performed.

2.3 Results

Figure 1 shows an example of global vorticity distribution at the 4 hPa pressure level in northern fall. A number of small and medium scale disturbances are observed in Figure 1. In the northern high latitude region, a baroclinic disturbance with zonal wavenumber two appears. Associated with this wave, fronts are observed clearly as a narrow tail-like structure of vorticity.

In the lees of several high mountains in the northern hemisphere, medium scale vortices appear. One of the typical regions is the Alba Patera (250˚E, 40˚N). Figure 2 shows composite distributions of vorticity there. In the lees of the Alba Patera, the vortex pairs are generated periodically with a period of one Martian day. It seems that the mean wind and the diurnally varying circulation around the Alba Patera cause these periodic vortex generation.

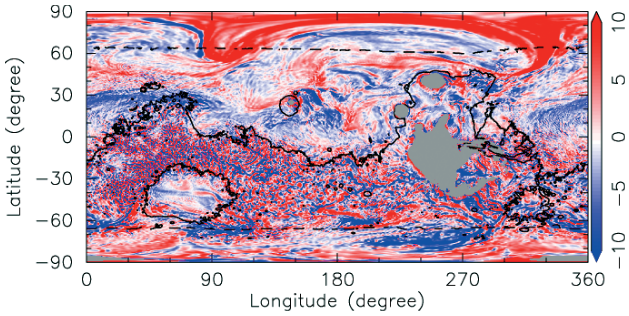

Fig. 1 Global distribution of vorticity at the 4 hPa pressure level in the northern fall. Unit of vorticity is $10^{-5}s^{-1}$. Also shown is the areoid (solid line) and low latitude polar cap edge (dashed line). Gray areas represent mountains at the 4 hPa pressure level.

In Figure 1, a number of small vortices are observed in the broad low latitudinal region around 20˚E–150˚E, 30˚S–0˚S. These small scale vortices are generated and dissipated periodically with a period of one Martian day, and the small scale vortices are generated in the afternoon hours. The vortices may be generated in relation to local thermal convection represented in the model.

Figure 3 shows distributions of dust mass flux and dust optical depth scaled to the 6.1 hPa pressure level obtained at the same time as the vorticity field plotted in Figure 1. In Figure 3a, it is shown that dust is lifted in the frontal region observed in Figure 1. The lifted dust is advected along the front and results in a dust storm as shown in Figure 3b. Dust storms of this shape are frequently observed by spacecraft and are referred to as “flushing dust storms” or a “frontal dust storms” [4]. Our result confirms that the strong wind in the frontal regions is one of the major mechanisms of dust lifting event.

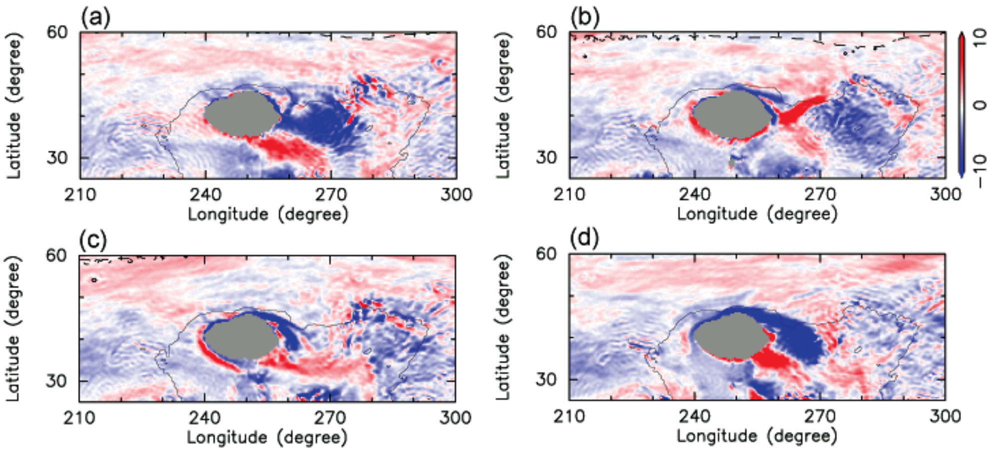

Fig. 2 Composite distributions of vorticity for 15 days at the 4.1 hPa pressure level around the Alba Patera in the northern fall. Panels (a)–(d) show vorticity distributions at the local solar time of 0, 6, 12, and 18 hours at 255˚E, respectively. Others are the same as those of Figure 1.

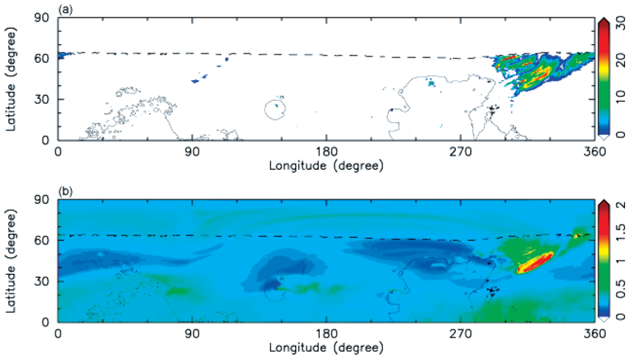

Fig. 3 Dust mass flux on the ground [10^{-8} kg m^{-2}] (a), and dust optical depth normalized to the 6.1 hPa pressure level (b) of the northern hemisphere at the same time as that for Figure 1. Others are the same as those of Figure 1.

3. Aqua-planet simulations

3.1 Targets of simulations

It has been recognized that there appears a hierarchical structure in the precipitation activities over the equatorial region [5]. It has been also recognized that the hierarchical structure of precipitation activities has not been well represented in GCMs; precipitation activities obtained by GCMs strongly depend on resolutions, numerical schemes, and implementations of physical processes such as radiation and cumulus parameterization [6]. Since the horizontal scale of the actual clouds in the real atmosphere is far small compared to the grid intervals of GCMs, moist convection in the model is forced to occur in the minimum grid scale. There is a possibility that precipitation patterns change drastically with varying model resolution because of incompleteness of cumulus parameterization schemes. In this study, we investigate the model representation of organized way of precipitation activities and their hierarchical appearances in a high resolution aqua planet GCM.

3.2 Physical processes

The physical processes used for the aqua-planet simulations are those of AFES [1]. As for cumulus parameterization, two cases are considered; a case with no cumulus parameterization scheme (case nc) and a case with Emanuel scheme [7] (case eml) as a cumulus parameterization scheme. The SST (sea surface temperature) distribution is that proposed by Neale and Hoskins [8]; SST is given fixed and is hemispherically symmetric and zonally uniform. Model resolution is T159L48.

3.3 Results

Figure 4 shows temporal variations of equatorial precipitation. In case nc (Fig. 4a), a hierarchical structure of precipitation activities emerges clearly. Eastward propagating structures are composed of westward propagating grid-scale structures. Wavenumber-frequency spectrum analysis and composite analysis suggest that the eastward propagating features are composed of a Kelvin wave-CISK like structure and the westward propagating structures are composed of vertical convections advected by background wind. In case eml (Fig. 4b), there also appears a hierarchical structure of precipitation activities, although it is not so clear as that of case nc. It can be considered that eastward propagating structures and westward propagating structures are separately represented in our experiments. It should be noted that dependence of the representation of precipitation activities on parameterization scheme have not been well revealed yet. Sensitivity experiments are necessary, where model parameters and/or implementation of parameterization schemes are changed.

4. Venus simulation

4.1 Targets of simulations

The atmospheric superrotation of Venus is one of the most remarkable phenomena in the planetary atmospheres. Although many studies have been performed so far, the mechanism generating the superrotation is not still well understood. Recently, Takagi and Matsuda [9, 10] examined thermal tides in the Venus atmosphere in detail by using a linear model based on the observed zonal flows. They showed clearly that the thermal semidiurnal tide excited in the cloud layer propagates downward to the ground and

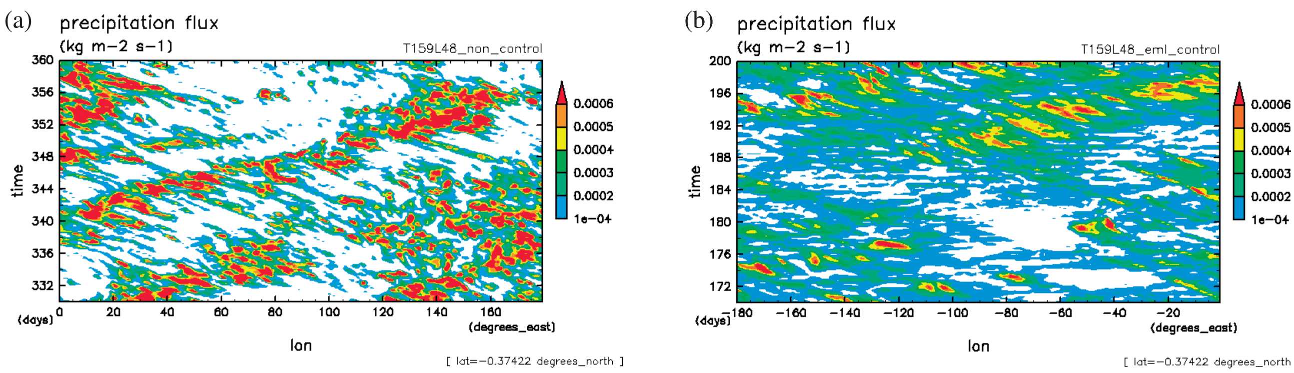

Fig. 4 Temporal variation of equatorial precipitation [kg m^{-2} s^{-1}]. Longitudinal area from 0 degree to 180 degree is shown. (a) case nc, (b) case eml.

accelerates the atmosphere in the direction opposite to the Venus rotation at altitudes of 0–10 km. It was argued from this result that the surface friction acts on this counter flow and consequently the net momentum is supplied from the solid part of Venus to the atmosphere to maintain the superrotation.

In this study, by extending the works of Takagi and Matsuda [9, 10], we investigate whether the atmospheric superrotation of Venus can be generated by the nonlinear effect of the thermal tides by integrating a full nonlinear dynamical model in spherical geometry.

4.2 Physical processes

The physical processes used for the Venus simulation includes a prescribed realistic distribution of the solar heating based on the works of Tomasko et al. [11] and Crisp [12]. The infrared radiative process is simplified by the Newtonian cooling [13]. The Rayleigh friction is not used except in the lowest layer to mimic the surface friction. The values of physical parameters are adopted from those of the Venus atmosphere. The initial state of numerical integration is the state at rest. In order to isolate specific effects of the thermal tides on the generation and maintenance of the Venus atmospheric superrotation, only the solar heating without mean zonal component is used for time integration.

4.3 Results

Figure 5 shows the meridional-height distribution of the mean zonal flow obtained at 25 Earth years. It is observed that a weak superrotation (about 12 m/s) is formed at around the altitudes of 50–60 km. Vertical profiles of the mean zonal flow at several latitudes are shown in Figure 6. It is found that the critical level forms at the altitudes of 90–100 km. These results are consistent with those obtained by the linear model of Takagi and Matsuda [9,10].

It is confirmed that the thermal tides may generate the atmospheric superrotation. Further experiments with higher resolutions and long time-integration are now being schedules.

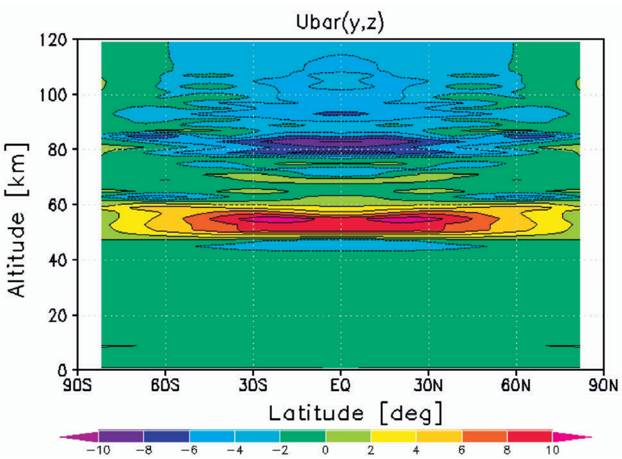

Fig. 5 Meridional-height distribution of the mean zonal flow obtained by time-integration from the rest state. The integration time is 25 Earth years. The contour interval is 2 m/s.

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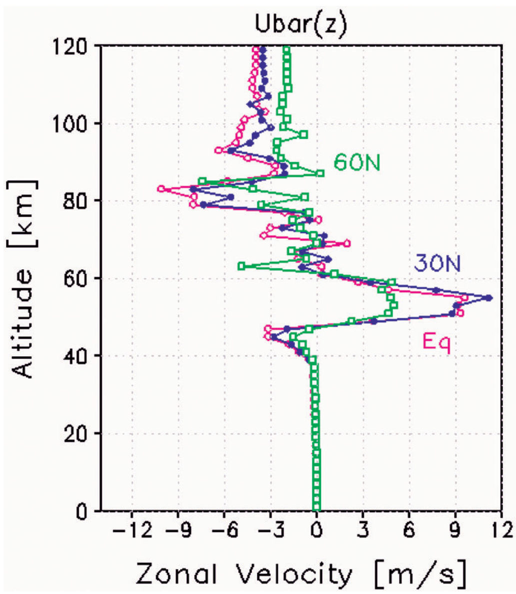

Fig. 6 Vertical profiles of the mean zonal flow at Equator, 30N and 60N.

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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)を共通の力学コアとするGCMを開発し、これを用いて、火星、水惑星の高解像度大気大循環シミュレーションを実施した。また、同じ力学コアを用いて金星大気の計算を行うための物理過程モジュールを開発し、予備実験を実施した。T319の解像度のモデルを用いて行った火星大気循環の計算では、温帯低気圧に伴う前線構造が明瞭に表現され、また、山岳周辺で生じた中規模渦など多数の中小規模擾乱の存在が明らかにされた。特に前線に伴う大気擾乱は、大気へのダスト供給に大きく寄与していることが示唆された。水惑星大気循環の計算は、積雲パラメタリゼーションを用いた場合と用いない場合の2種類のモデルを用いて行った。T159の解像度を用いた計算では、2種類のどちらの場合にも赤道域における降水活動に階層的な構造が見られ、その構造解析の結果、ケルビン波に伴うwave-CISK (Conditional Instability of the Second Kind) が対流構造の組織化をもたらしていることが示唆された。金星大気循環の予備実験の結果は、線形モデルの結果に基づいてこれまでに提唱してきたメカニズムと整合的であり、金星大気スーパーローテーションを維持する上で熱潮汐波の重要性が確認された。

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