AFESを用いた金星・火星大気の高解像度大循環シミュレーション

課題責任者
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大気大循環モデルAFES (AGCM (Atmospheric General Circulation Model) for the Earth Simulator)に基づく金星および火星大気の高解像度大気大循環シミュレーションならびに金星大気データ同化を実施している．本年度は第4世代の地球シミュレータへの移行作業として，コンパイル，テスト計算，結果のチェックを行うとともに，金星大気モデルの改良および数値実験，実観測のデータ同化で生成した金星大気客観解析データの力学解析，観測システムシミュレーション実験を行った．金星大気モデルの大気安定度と太陽加熱の分布を修正した結果，熱潮汐波の位相が改善し，金星探査機「あかつき」の近赤外カメラで観測されている熱潮汐波に近づき，雲層上端のケルビン波も再現された．また，これまでよりも現実的な模擬観測データを用いた観測システムシミュレーション実験を実施し，ケルビン波が再現されることを確認した．さらにケルビン波が，平均東西風分布における赤道上の高速域の高度を上昇させるがわかった．火星大気シミュレーションに関しては，流れ場の解析を継続中である．

キーワード：惑星大気，金星，火星，スーパーローテーション，ダストストーム

1. はじめに

地球型惑星の大気大循環は互いに大きく異なっている．金星や火星の大気の動態は惑星探査や数値計算によって様々に調べられてきたが，金星大気のスーパーローテーション，火星大気のダストの存在や全球ダストストームの発生といった，地球では見られない現象の発生機構は未だ理解されるには至っていない．このような大気大循環の特徴の違いがどのような力学によってもたらされているかを理解することは大気科学あるいは流体力学の最も興味深く重要な問題の1つである．本課題では，AFESの力学コアを共通基盤に地球型惑星個々の物理過程を導入し拡張してきたGCMを用い，地球と同じ力学的枠組みの下で，金星と火星の大気循環・擾乱を調査・記述し，大循環の多様性をもたらす力学的構造を理解することを目指す．

2. モデル

本課題で用いるモデルは，地球シミュレータ上で高速に実行できるように最適化されてきた大気大循環モデルAFES (AGCM (Atmospheric General Circulation Model) for the Earth Simulator)[1]を基に，金星大気と火星大気を計算するために，それらの条件に適当な放射過程，乱流過程，地面過程を導入したものであり，それぞれAFES-Venus，AFES-Marsと呼ぶ．これらのモデルは第3世代の地球シミュレータにおいて，120ノードでの実行実績（ベクトル化率と並列化効率の閾値を上回る）があり，金星，火星において惑星規模循環から，O(10 km)の水平スケールを持つ小規模擾乱までを同時に表現しながら，大気循環構造を計算することが可能である．

3. 結果

3.1. 金星大気実験

これまでに，金星大気大循環の大きな謎であるスーパーローテーションの解明を目指して数値実験と解析を行ってきた．過去の研究では，スーパーローテーションを駆動するために大気下層に非現実的に強い加熱強制を与え，低解像度モデルを用いて長時間積分する方法が主流であった．しかし我々は，現実的な強さの太陽加熱強制を用い，また，雲層下部付近の大気安定度の低い層(高度約55-60 km)の存在に注目して実験を行い，傾圧不安定波が運動量や熱の輸送に重要であることを指摘してきた[2, 3]．また，現実的な太陽加熱によって観測[4]と整合的な緯度分布をもつ雲層高度のスーパーローテーションが維持され，雲層高度で各緯度帯に特徴的な波が存在することを示した[5]．T42L60の中解像度による長時間積分実験では，鉛直渦粘性が小さければ，500地球年程度で，静止状態からスーパーローテーションが生成されることも示した[6]．さらに，暖かい極域と周極低温域の現実的な構造の再現[7]，欧州宇宙機関の金星探査機「Venus Express」による電波掩蔽観測の結果と整合的な

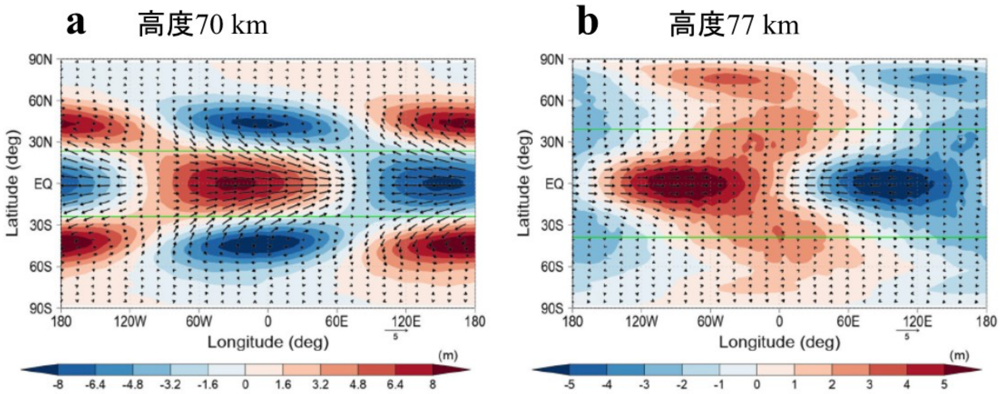

図1. 3.3日波の水平構造（合成図）. ジオポテンシャル高度（m, 色）と水平風（m/s, 矢印）の擾乱成分（東西平均からのずれ）. 対数シグマ高度（a）70 km, （b）77 km. 緑線は東西平均風速が波の位相速度と同じになるクリティカル緯度を示す.

極域の温度の時間変動と鉛直構造の再現[8]にも成功した. 金星大気の波動に関しては, 熱潮汐波の3次元構造を解析[9]し, 赤道域の温度場の電波掩蔽観測との比較も行った[10]. 水平格子間隔約 79 km, 鉛直 120 層(T159L120)の高解像度の数値実験では, 日本の金星探査機「あかつき」の2μmカメラ「IR2」による観測で得られた下部雲層の惑星規模筋状構造を再現することに成功し, その物理的解釈を与えた[11]. 世界最高解像度(T639L260)の数値実験においては, 熱潮汐波からの自発的な重力波放射の存在を明らかにした[12]. 雲の表現に関しては, 簡略化した雲物理過程を導入[13]し, 雲層下部の赤道域ではケルビン波に伴う周期的な雲の変動を再現することができた[14].

これらの成果, 特に, 観測と AFES-Venus による計算結果との整合性から, 世界初となる金星大気データ同化システムの構築も進め[15], Venus Express の「Venus Monitoring Camera」で観測された雲層上端の風速（雲追跡風）を同化した結果, 熱潮汐波の位相構造が改善され, 全球の風速場が大きく修正された[16]. また, あかつきの紫外線カメラ「UVI」画像の雲追跡で得られた風速データを同化し, 客観解析データの作成を行ってきた[17]. 観測システムシミュレーション実験（OSSE）も試行し, 固定点での衛星間電波掩蔽観測の同化実験[18]を拡張して, 実軌道[19]を考慮した観測可能性の検討を進め[20], データ同化によってケルビン波を表現しうる観測条件を調べてきた[21].

今年度はまず, 第4世代の地球シミュレータへの移行作業として, AFES のコンパイル, テスト計算, 結果のチェック等を行った. 次に, AFES-Venus で再現された, これまでの電波掩蔽観測[22]と整合的な下層大気の温度構造の成因を調査した. さらに, AFES-Venus の大気安定度と太陽加熱の分布を改良し, その数値実験結果の解析を行った. データ同化に関しては, 実観測の同化結果の解析を継続し, いくつかの観測システムシミュレーション実験も実施した. 以下に主要な成果を示す.

① 下層大気の温度構造の成因の解析

Venus Express とあかつきの電波掩蔽観測では, 低安定度層が高緯度域で高度 45 km 程度まで深く広がることが報告されている[22]. AFES-Venus でも同様な構造が再現されており, その成因調査を行った. その結果, 大気大循環と波動による赤道向き熱輸送が, 極域の高度 45 km 付近の低安定度化に重要であることがわかった[23].

② 改良版の AFES-Venus によるケルビン波の再現

これまでの AFES-Venus では, 観測で示唆されている, 雲層上端の赤道ケルビン波がうまく再現できていなかった. そこで, 最近の観測とより整合的な大気安定度と太陽加熱を導入した数値実験を行ったところ, 雲層上端のケルビン波の再現に成功した（図 1b）. 詳しい解析の結果, このケルビン波は雲層下部のロスビー・ケルビン結合不安定（図 1a）により励起されることが分かった[24].

③ 改良版の AFES-Venus の熱潮汐波の解析

これまでの AFES-Venus の熱潮汐波の位相は, あかつき中間赤外カメラで観測される位相とずれていた. そこで, 上記②の実験結果について長周期擾乱を解析し, 熱潮汐波の位相が改善されていることが確認できた. また, スーパーローテーション（平均東西風速場）は, 基本場の大気安定度分布に強く依存することも確認された[25].

④ 実観測データ同化の解析と OSSE の実施

昨年度に実施した, あかつきの UVI 画像から雲追跡法で導出された水平風速を同化した世界初の金星客観解析データにおける熱潮汐波の構造を解析した[17]他, 周極低温域やケルビン波の解析も行った. また OSSE では, 水平風速同化によるケルビン波の再現[21]の発展として, 同化領域をより現実の観測に近づけた実験を行い, ケルビン波が再現可能なこと（図 2）を示した. さらに, ケルビン波は, 赤道域の高度 70 km の東西風を減速させ, その上空の高度 80 km 程度までを加速させることがわかっ

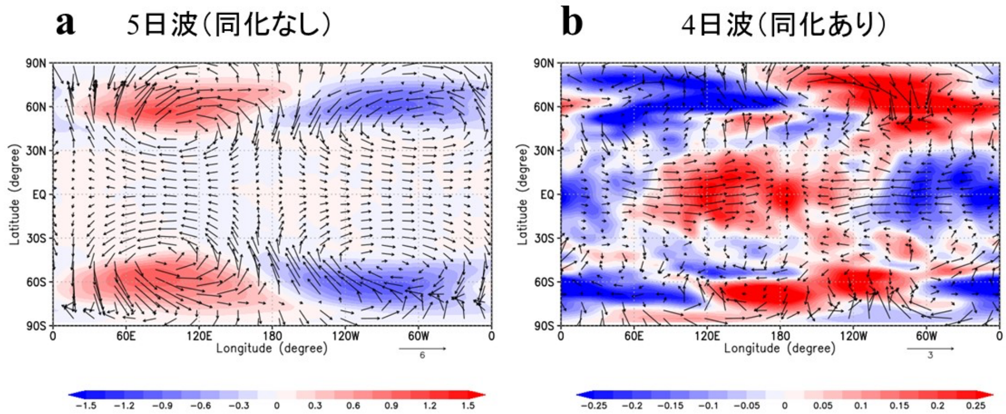

図 2. 対数シグマ高度 70 km の温度（K, 色）と水平風（m/s, 矢印）の擾乱成分（東西平均からのずれ）. (a) 5 日波（同化なし）, (b) 4 日波（同化あり）の合成図.

た[26].

以上の成果は，本課題で実施している AFES-Venus による数値実験によって，あかつきや地上望遠鏡による観測結果の理論的・力学的解釈をいっそう進めていることを示している．さらに，この AFES-Venus にデータ同化技術を活用することであかつき観測を活用した金星大気客観解析データの生成し，その力学解析も進めている．また，OSSE を実施することで次期金星探査計画の検討に貢献している．

3.2. 火星大気実験

これまでに，中小規模擾乱が火星大気中に浮遊するダストの重要な供給過程であることを念頭に置き，擾乱の特徴を調べるための数値実験と解析を行ってきた．数値実験は，水平格子点間隔が約 11 km の解像度（T639）までの複数の解像度で実施し，特に高解像度計算の中で低緯度に現れる多数の小規模渦に注目し，その成因を解析してきた．今年度は，昨年度に引き続き，山岳，渓谷，アルベド濃淡など，地表面の不均一性が風応力に与える影響について調べた．その結果，山岳波・斜面風など地表面の不均一性によって駆動される局地風と，傾圧不安定波や大気潮汐に伴う大規模風，さらには対流性の小規模渦の間の複雑な重畳関係の存在が示唆された．また，状況により風応力のモデル解像度依存性が異なっていることが確認されたため，今後さらに詳細を調べる予定である．

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High Resolution General Circulation Simulation of Venus and Mars Atmosphere using AFES

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High-resolution simulations of the Venus and the Mars atmospheres have been performed using general circulation models (GCMs) based on AFES (Atmospheric GCM for the Earth Simulator). In this fiscal year, we first compiled the model codes for the fourth generation Earth Simulator and checked the results of test calculations. Then, in simulations of the Venus atmosphere, we modified the profiles of the static stability and the solar heating to improve the representations for the Kelvin waves and the thermal tides which were observed by the Longwave Infrared Camera onboard Akatsuki. We also performed observation system simulation experiments (OSSEs) with more realistic observational situations and showed that Kelvin waves can be reproduced by the assimilating cloud-tracked horizontal winds which are to be obtained in such realistic observations. In simulations of the Mars atmosphere, detailed analyses of velocity distributions around small-scale vortices were continued.

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

1. Introduction

The structure of the general circulation differs significantly in each of the atmospheres of terrestrial planets. Understanding physical mechanisms causing such a variety of features in the general circulations of those atmospheres is one of the most interesting and important open questions of atmospheric science and fluid dynamics. This study aims to understand dynamical processes that characterize the structure of each planetary atmosphere by performing simulations using general circulation models (GCMs) with a common dynamical core of AFES (Atmospheric GCM for the Earth Simulator) [1].

2. Results

2.1. Venus simulation

In the previous years, we have achieved the following results with the AFES-Venus, the Venus version of AFES. The model atmosphere reaches a quasi-equilibrium superrotational state by time-integration from an initial state of a given idealized solid-body superrotation. The obtained meridional distribution of the zonal flow agrees fairly well with the observed superrotation [2]. In addition, we succeeded in obtaining a superrotational state from a motionless initial state after time-integration over 500 Earth years in a long-term experiment with a medium-resolution (T42L60) [3]. A key for producing superrotation is to set the vertical eddy viscosity coefficient sufficiently small. Planetary-scale waves are produced at each latitude in the cloud layer, and features of these waves are consistent with those observed [4]. The cold collar and vertical structure of the polar vortex are well reproduced [5, 6]. Three-dimensional structures of thermal tides produced in GCM are also investigated [7] and compared with observation data by Akatsuki's radio occultation measurements (RO) [8]. The high-resolution simulations with T159L120, equivalent to a horizontal grid size of about 79 km with 120 vertical layers, reproduced planetary-scale streak structures consistent with the morphology in the lower clouds observed in a night-side image of Venus taken by Akatsuki's 2-μm Camera (IR2) [9]. Last year, we have performed numerical experiments of T639L260, which is the world's highest resolution for Venus atmospheric simulations, and found spontaneous small-scale gravity wave radiation from thermal tides [10]. We also implemented a simplified cloud physical process [11] and reproduced periodic cloud fluctuations associated with Kelvin waves in the equatorial region, which are similar to those observed by IR2 [12].

Based on these results in a good agreement with observations, we have been constructing the first Venus atmosphere data assimilation system [13]. It is found that the phase of thermal tides was improved and the zonal mean zonal wind is significantly modified globally by assimilating the cloud-tracked horizontal winds at the cloud top obtained from ultra-violet images taken by the Venus Monitoring Camera onboard Venus Express [14]. We also assimilated horizontal winds derived from Akatsuki's Ultraviolet Imager (UVI) observations with the cloud tracking techniques and produced an objective-analysis data set of the Venus atmosphere for the first time [15]. Observation system simulation experiments (OSSEs) have been performed, for planning a next Venus mission utilizing RO among orbiting small satellites, with a fixed temperature-observation point in the polar region [16] and with observations from 2 or 3 satellites in realistic orbits [17, 18]. By using OSSEs, we also investigated observational conditions to produce Kelvin waves by assimilating horizontal winds [19].

In this fiscal year, transition work to the fourth generation Earth Simulator were conducted: compiling model codes and checking results of test calculations. Then, we explored the simulated lower atmospheric thermal structure, which is consistent with that observed by RO [20]. We also modified the basic profiles of static stability and solar heating in AFES-Venus and performed numerical experiments. In addition, further OSSEs were performed. The main results are as follows.

1) Temperature structure of the lower atmosphere.

Recent RO observations suggested the low-static-stability layer in the high-latitudes is deeper than that in the low-latitudes [20]. This feature is reproduced in AFES-Venus. We have analyzed the numerical results and found that, in high-latitudes, equatorward thermal transport by circulation and waves are important to create the deeper low-static-stability layer [21].

2) Kelvin waves in the improved AFES-Venus.

The equatorial Kelvin waves which have been observationally suggested were not reproduced in the simulations by AFES-Venus so far. We performed numerical experiments with the improved version of AFES-Venus, in which the profiles of static stability and solar heating are modified to be consistent with recent observations, and succeeded in reproducing the Kelvin waves. Our analysis showed that the Kelvin waves are excited by the Rossby-Kelvin coupling instability in lower cloud layer [22].

3) Thermal tides in the improved AFES-Venus.

The phase of thermal tides reproduced by AFES-Venus so far was not consistent with that observed by Akatsuki's Longwave Infrared Camera (LIR). We analyzed thermal tides in the improved version of AFES-Venus and found that the phase of thermal tides is much better than previous simulations. Additionally, we found that the superrotation depends strongly on the profile of the static stability [23].

4) Analyses of the objective-analysis data set and OSSEs.

Using the first objective-analysis data set produced last year, we analyzed the thermal tides [16], cold collar, and Kelvin waves. For OSSEs [19], we proceeded to perform more realistic cases: 24-hourly dayside satellite observations in an equatorial orbit. We showed that the Kelvin waves can be reproduced by assimilating horizontal winds with a realistic time-interval and spatial range. Furthermore, we found that the Kelvin waves shift the peak altitude of the superrotation higher above the equator [24].

The above results show that the Venus simulations performed in this project are quite helpful for theoretical interpretation of the Akatsuki and ground-based observations. The Akatsuki's observational data is also assimilated to AFES-Venus to produce the objective-analysis data set, which is also useful for dynamical analyses of the Venus atmosphere. In addition, our OSSEs are contributing to planning the next Venus mission.

2.2. Mars simulation

We performed high-resolution (T639L96) simulations of the Martian atmosphere to reveal the features of small- and medium-scale disturbances in the Martian atmosphere and their effects on dust lifting. The resolution is equivalent to a horizontal grid size of about 11 km with 96 vertical layers (dz ~ 1km). The numerical results suggest that there is a complex relation among local winds caused by such as the topography and surface albedo, large-scale winds caused by such as baroclinic instability and thermal tides, and small-scale convective vortices. In addition, we found that the model-resolution dependence of the wind stress differs by situations. We are going to explore the details of those.

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