Development of a High-Resolution Climate Model for Model-Observation Integrating Studies from the Earth's Surface to the Lower Thermosphere

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The purpose of this project is to further develop a climate model for high-resolution simulations of the Earth's atmosphere from the surface to the lower thermosphere (we particularly focus on 0-100 km), and to investigate dynamics of the middle atmosphere by comparing the model's results to upcoming high-resolution observations which would be obtained by newly developed observation systems with balloons, radars, lidars, airglow imagers, and satellites. The main focus of this high-resolution study is on atmospheric gravity waves which have finer scales, i.e., horizontal wave length of O (10-100 km), than usual climate models resolve, and their characteristics and roles in the middle atmosphere have yet sufficiently understood. We are developing a gravity-wave-resolving high-resolution climate model which has horizontal resolutions of T213 and T639, corresponding to the minimal resolved horizontal wave lengths of 188 km and 62 km, respectively. The vertical resolution of the model is about 500 m. The model's spatial resolution is comparable to that of aforementioned observations, and T639 is enough to resolve large portion of gravity wave spectra which are observed in the middle atmosphere. This year we performed a single year pilot run of the T213 model to evaluate model's basic performance, and obtained simulation results which generally agree with observations. Results of an initial test run of the T639 model are briefly presented, too.

Keywords: High-resolution climate model, atmospheric internal gravity waves

1. Introduction

Long-term future climate change projections obtained by climate model simulations include large uncertainties arising from small-scale atmospheric gravity waves, i.e., horizontal wave length of O (10-100 km), which are not explicitly resolved by the climate models and instead approximately represented by using gravity wave parameterizations (Alexander et al. [1]). We have developed a high-resolution climate model, which explicitly resolves gravity waves, and investigated their characteristics and roles in the atmosphere (e.g., Watanabe et al. [2]). Those outcomes have been used to constrain gravity wave parameterizations to reduce their uncertainty (e.g., Watanabe [3]).

On the other hand, high-resolution observation systems, e.g., utilizing balloons, radars, lidars, airglow imagers, and satellites, have been newly developed. Some of those have global coverage, and others are focused into particular places. The Antarctic Syowa station is one of the latter, where newly developed systems of a MST radar (PANSY: Program of the Antarctic Syowa MST (Mesosphere/Stratosphere/Troposphere) / IS (Incoherent Scatter) Radar) and lidar start their operations. The radar has vertical resolution of O (100 m) and temporal resolution of O (1 min) and observes three dimensional wind fields, which will be compared to our model results in this project. The lidar observes temperatures with a little bit less vertical and temporal resolutions. By combination and integration of those high-resolution observations with model results, our understanding of atmospheric small-scale processes, e.g., gravity waves, will be greatly improved.

2. The high-resolution climate model

The high-resolution climate model is based on JAGUAR (Japanese Atmospheric General circulation model for Upper Atmosphere Research; Watanabe and Miyahara, [4]), which has been developed as a hybrid of the MIROC (Model for Interdisciplinary Research On Climate) -AGCM (K-1 model developers [5]) and Kyushu-GCM (Yoshikawa and Miyahara [6]). The model has a top boundary at about 150 km, whereas conventional climate models have their tops near 30-50 km (IPCC, 2007). Gravity waves are generally generated in the troposphere and propagate upward, and some of them propagate up to the mesosphere and lower thermosphere (MLT) region (z = 50-120 km) and dissipate there to affect background fields. In order to study such processes, we construct the high-top and high-resolution climate model. In addition to physical parameterizations used in conventional climate models, e.g., cumulus convection, boundary layer, large-scale precipitation, our model includes some more parameterizations required in the MLT region, e.g., radiation schemes based on non-local thermal equilibrium (important above 70 km), molecular viscosity, molecular thermal conductance, chemical heating, and ion drag (important above 100 km). A height dependent horizontal diffusion is introduced into the model's MLT to represent effects of background small-scale turbulences, whose strength is presumed to increase with increasing height from 60 km to 140 km.

The model has horizontal resolutions of T213 and T639, corresponding to the minimal resolved horizontal wave lengths of 188 km and 62 km, respectively. The vertical resolution of the model is about 500 m. These model's spatial resolutions are comparable to the aforementioned observations, and T639 is enough to resolve large portion of gravity wave spectra which are observed in the middle atmosphere (e.g., Alexander et al. [1]).

The T213 model is fully optimized for the Earth Simulator by the MIROC group with supports from the Earth Simulator Center. Although the T639 model could have a room of optimizations, scalability from T213 to T639 is relatively good, which is estimated based on theoretical expectations: an expected computational time becomes 27 times as long as the original one when we triple the horizontal resolution, and our model have achieved c.a. 32.

3. T213 pilot simulation

In order to investigate basic performance of T213 model to reproduce observed climatological wind and temperature fields, we performed a single year pilot simulation which starts from June of a certain model year and ends in next May. This is a free-running simulation that does not incorporate any observed fields into the model's atmosphere. Sea surface temperatures and sea-ice distribution are prescribed using observed climatology. Figure 1 compares the zonal mean temperature and the zonal mean zonal wind obtained with this simulation to the Met Office assimilation data (below 50 km) (Swinbank and O'Neill, [7]) and the 1986 Committee on Space Research (COSPAR) International Reference Atmosphere (CIRA) data (above 50 km) (Fleming et al. [8]). The model well reproduces observed wind and temperature distributions, especially below a 50 km level. It is challenging to reproduce winds and temperatures in the MLT region (50-100 km). The model qualitatively succeeds to reproduce them, but several biases are obvious. The model underestimates a temperature minimum near the Arctic summer mesopause (around 90 km) by 10-20 K. In the winter (southern) hemisphere, the model overestimates a temperature maximum above the Antarctic wintertime stratopause (around 60 km) by 10-20 K, and underestimates a temperature minimum around the mesopause (~100 km). These temperature biases are likely caused by biased distributions of vertical wind motions, which cause biases in dynamical heating. The first observation of

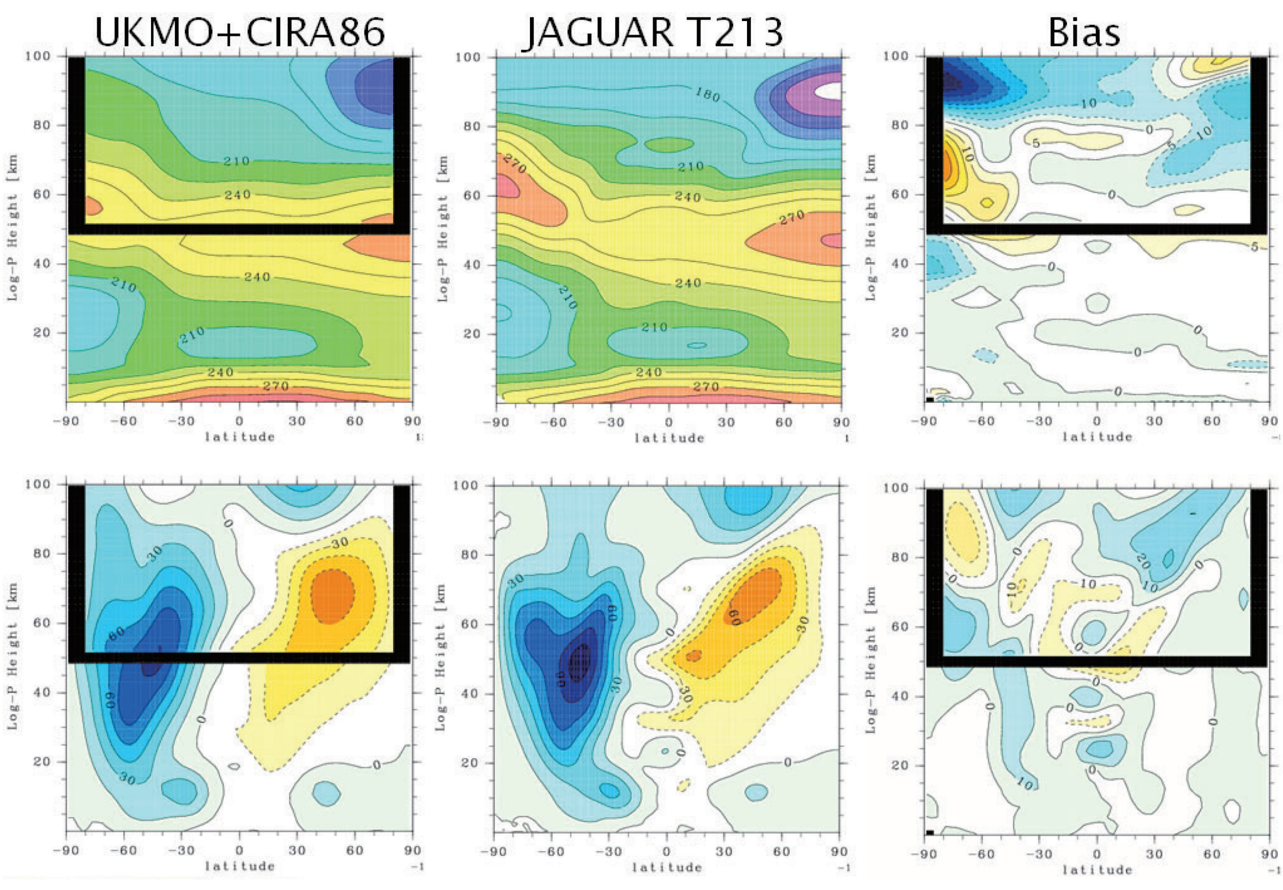

Fig.1 The zonal mean zonal wind and the zonal mean temperature in July.

vertical winds over the Antarctic MLT region will be done by the PANSY radar, and it would be very useful to further evaluate the model's result. It would be also important to investigate sensitivity of model's performance to changing the horizontal resolution, which would also be tackled in this project.

Figure 2 shows seasonal evolution of zonal and meridional winds over the Syowa station simulated with the T213 model. Strong westerly winds are predominant in wintertime lower mesosphere (60-70 km), above which the westerly winds rapidly decrease with increasing altitude (70-75 km) and weak westerly winds exist in the upper mesosphere and lower thermosphere (75-100 km). The meridional winds are generally weaker than the zonal winds, and poleward flows are dominant around 75 km, where the strong reduction of westerly winds occurs. This reduction of westerly winds with altitude is caused by dissipation of gravity waves in the model (e.g., Watanabe et al. [2]), and will be further investigated in this project. In summer, easterly winds exist in an altitude range of 60-90 km, above which they reverse to westerly winds. Strong equatorward flows exist between the easterly and westerly winds. This vertical inversion of zonal winds must also be explained by effects of gravity waves, which will be elucidated in this project using model's three dimensional data. Overall, the seasonal evolution of horizontal winds is qualitatively similar to that obtained by MF radar observations at the Syowa station (e.g., Tsutsumi et al. [9]), which is encouraging for us to develop the finer T639 model and further investigate dynamics in the MLT region by combining the model's result with observations.

4. T639 initial run

Since we ran the T639 model for the first time, we had to obtain an initial condition by interpolating the T213 model's data. This section describes rather a technical issue to prepare initial conditions used in the finer T639 resolution. A simple linear interpolation was used to convert T213 grid data into the T639 grid. On the other hand, the surface topography in the T639 model is (independently) generated from surface elevation dataset and is generally finer and steeper than that for T213. Hence, an imbalance occurs between the interpolated surface pressure and wind fields and the finer surface elevation in the T639 model. This imbalance causes an initial shock in the model fields; rapid adjustment processes occur and spurious dispersive gravity waves are emitted from near the surface, which three-dimensionally propagate far away from their source regions, continuously reaching the MLT region. These spurious gravity waves generally have huge amplitudes, small horizontal wavelengths and large vertical group velocities, and easily reach the MLT region and violate temperature and wind structures there. Therefore we have to reduce their amplitude by introducing unusually strong scale-selecting damping of wave motions until the initial shocks calm down. This damping, of course, damps gravity waves originally existing in the T213 model's fields, too, which means that T639 model's wind and temperature fields just after the damping retain only very small information of the T213 wave fields. After several initial trials, we have found that about 3 days are needed with the enhanced damping to obtain a proper initial condition that does not contain suspicious large amplitude small-scale waves. Figure 3 demonstrates such spin-up processes in terms of time evolution

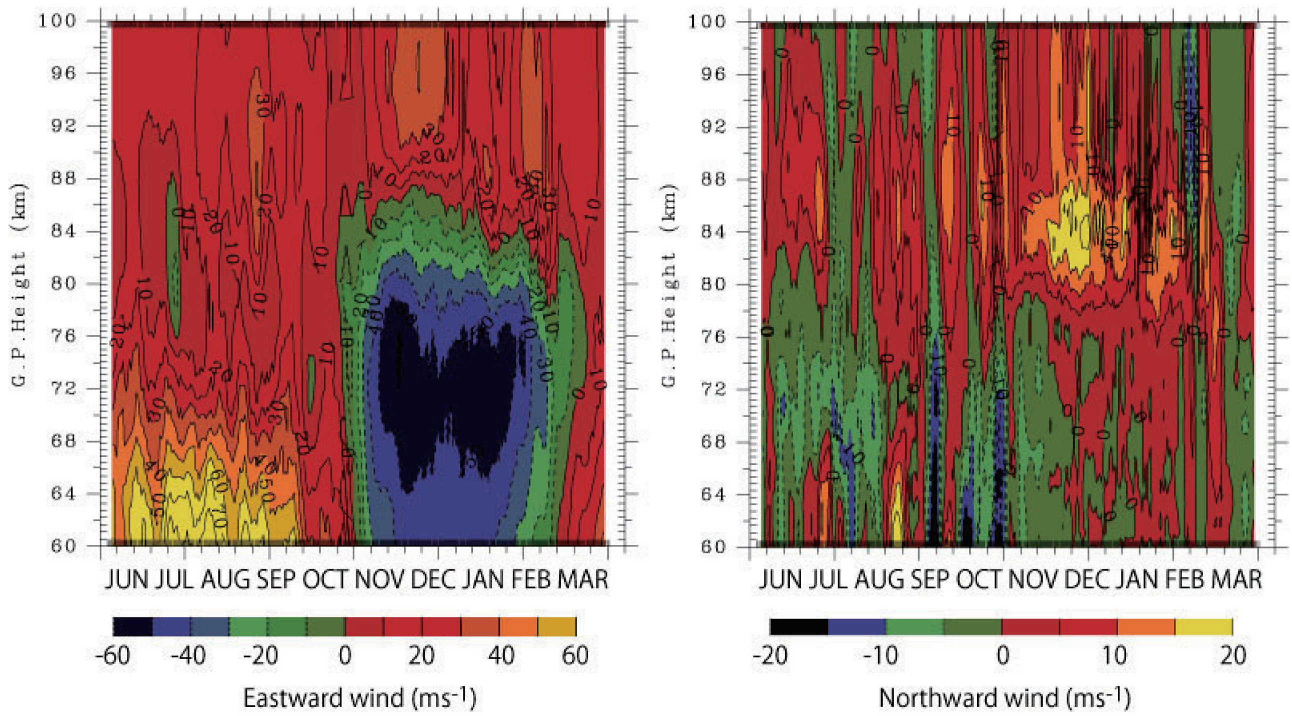

Fig. 2 Time evolution of horizontal wind profiles over the Syowa station simulated with the T213 model.

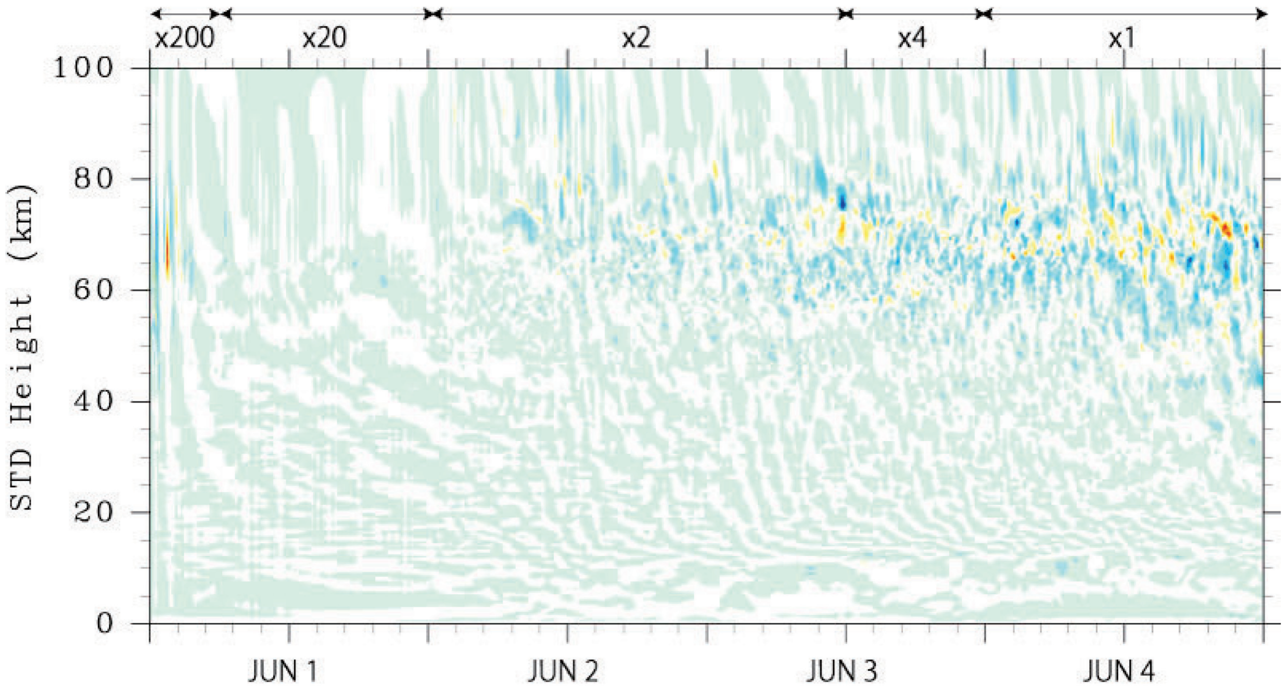

Fig. 3 Time evolution of horizontal divergence profile over the Antarctic Syowa station simulated with the T639 model. The numbers with arrows on the top of the figure show the strength of the scale-selective damping relative to its standard value. After appearance of the initial shocks in the first 6 hours, the damping is reduced so that wave motions relevant to the T639 horizontal resolution gradually spin-up. Around 12:00 universal time on the third day, a rapid amplification of suspicious gravity waves arising from the initial adjustment processes terminated the model's integration, which occurred in different grid points. Therefore the strength of damping was doubled for 12 hours, and then the model stared running successfully.

of horizontal wind divergence profiles, which approximately show gravity wave phase patterns, over the Antarctic Syowa station.

5. Summary

The motivation and goal of the present project are described, that is, to improve our understanding of atmospheric small-scale processes, e.g., gravity waves, the state-of-art high-resolution climate model and high-resolution observation (including the PANSY radar at the Antarctic Syowa station) are going to be combined and integrated. The model we are going to develop and use in this project resolves wave motions with 62 km in horizontal and 1 km in vertical at the minimum scale, which can be closely compare to the upcoming high-resolution observations.

The single year pilot simulation using the lower (~188 km) horizontal resolution model shows generally encouraging results, which qualitatively agree with observations in terms of the monthly averaged zonal mean zonal winds and temperatures and the temporal evolution of horizontal wind profiles at the Antarctic Syowa station. To further improve model's results, the usefulness of upcoming observation data set is undoubtful.

The spin-up processes of the higher-horizontal resolution model are also briefly presented, which may be informative for initialization of any forecast / assimilation experiments which we are planning to perform later in this project. Overall, the initial goals we expected in the first year of this project have successfully been achieved.

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高解像度気候モデルの開発
－地表から下部熱圏大気のモデル・観測統合研究に向けて

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本研究の目的は、地球大気の地表から下部熱圏（0-100km）までの高解像度シミュレーションを行うことができる気候モデルを開発・発展させるとともに、そのモデルのシミュレーション結果と、最新の高解像度の観測を比較することによって中層大気の力学過程を詳細に調べることである。（観測データは気球、大気レーダー、ライダー、大気光イメージャおよび衛星測器のものを用いる。）

我々の高解像度研究の主要な対象は、通常の気候モデルでは解像することができず、いまだ中層大気中におけるそれらの性質や役割の理解が十分でない小規模の大気内部重力波である。このため、我々は重力波を直接解像できるような高解像度気候モデルを開発している。モデルの水平解像度は T213 と T639 の 2 バージョンがあり、それぞれの解像できる最小水平波長はおよそ 188km と 62km に相当する。モデルの鉛直解像度は 500m であり、水平解像度とともに、上述の観測データと 1 対 1 比較できるほどの解像度を持っている。

本年はモデルの基本的な性能を評価するために、T213 モデルで 1 年間の試行実験を行い、観測データとの比較を行った。モデルの結果は観測された温度や風の場を概ね良く再現することが確認できた。また、T639 モデルを用いたスピンアップ実験の結果も簡単に報告する。

キーワード : 高解像度気候モデル , 大気内部重力波