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Vertical resolution dependence of gravity wave momentum flux simulated by an atmospheric general circulation model

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Abstract

The dependence of the gravity wave spectra of energy and momentum flux on the horizontal resolution and time step of atmospheric general circulation models (AGCMs) has been thoroughly investigated in the past. In contrast, much less attention has been given to the dependence of these gravity wave parameters on models' vertical resolutions. The present study demonstrates the dependence of gravity wave momentum flux in the stratosphere and mesosphere on the model's vertical resolution, which is evaluated using an AGCM with a horizontal resolution of about 0.56°. We performed a series of sensitivity test simulations changing only the model's vertical resolution above a height of 8 km, and found that inertial gravity waves with short vertical wavelengths simulated at higher vertical resolutions likely play an important role in determining the gravity wave momentum flux in the stratosphere and mesosphere.

1 Introduction

Due to recent advancements in high-performance computing, simulations of the global atmosphere with sub-kilometer horizontal resolutions have been achieved, allowing deep individual convections to be resolved (Miyamoto et al., 2013; Satoh et al., 2014). Considering the global momentum budget in such ultra high-resolution atmospheric models, explicitly resolved gravity waves (GWs) undoubtedly play important roles (Alexander et al., 2010).

The dependence of the GW spectra of energy and momentum flux on the horizontal resolution and time step of atmospheric general circulation models (AGCMs) has been studied in great depth. Using comprehensive atmospheric general circulation models, Koshyk and Hamilton (2001) and Hamilton et al. (2008) demonstrated the dependence of the horizontal wavenumber spectra of GW energy on the horizontal resolution of the AGCM. Shutts and Vosper (2011) evaluated the dependence of GW energy on the horizontal resolution and time step of state-of-the-art numerical weather prediction models. These pioneering works have served as useful guidance to other modeling disciplines.

In contrast, much less attention has been given to the dependence of the GW parameters on the vertical resolution of the AGCM. At present, only a few AGCMs have achieved sub-kilometer vertical resolution covering throughout the middle atmosphere, which is believed to be crucial for accurately reproducing GW-related processes such as generation, propagation, dissipation, and mixing. Among such high-vertical-resolution AGCMs, the model developed for the KANTO project had the highest vertical resolution of 300 m, which was actually determined based on an expert judgment rather than a sensitivity test approach (Watanabe et al., 2008). The main purpose of the present study is to clarify the dependence of GW momentum flux on the vertical resolution of the model, with the aim of elucidating the optimum vertical resolution.

2 Model and experimental design

The model used in the present study was JAGUAR (Japanese Atmospheric General circulation model for Upper Atmosphere Research) (Watanabe and Miyahara, 2009). The vertical domain of this model extends from the Earth's surface to a height of about 150 km, although the present study focused on just the first 80 km. The horizontal resolution was set to 0.56°, which is the same as that used by Watanabe et al. (2008) and Watanabe and Miyahara (2009). This horizontal resolution allows the model to resolve GWs with horizontal wavelengths from 188 to 40 000 km. Considering the fact that the GWs observed in the mesosphere and lower thermosphere frequently include components with horizontal wavelengths in the order of 10 km, the present model did not cover the full range of GW spectra. Note, however, that a series of studies has suggested that the behaviors of explicitly resolved GWs and simulated large-scale thermal and wind structures qualitatively explain the observed phenomena (Watanabe et al., 2008, 2009; Tomikawa et al., 2008, 2012; Kawatani et al., 2010a, b; Miyazaki et al., 2010a, b; Sato et al., 2009, 2012).

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In the present study, we performed a series of sensitivity test simulations changing only the model's vertical resolution above 8 km. Vertical resolutions of dz = 200, 300, 400, 500, and 1000 m were used (Fig. A1). The vertical resolution below 8 km remained unchanged. (Changing the vertical resolution in the lower troposphere is known to have significant effects on the behaviors of physical parameterizations such as cumulus convection and boundary layer processes, but these are not addressed in the present study.) The vertical resolutions used in the KANTO project and the previous JAGUAR study were 300 and 500 m, respectively. The main focus in this study was GW momentum flux at northern summer mid-latitudes, where the short-term variability of planetary-scale and synoptic-scale waves is relatively small. This condition is important because it is preferable for GW source distribution (e.g., diabatic heating and jet-front systems) in the troposphere to be similar in each run, to a qualitative degree at the very least.

Due to the limited computational resources available for this study, we only performed a short-term deterministic forecast-type experiment starting from virtually the same initial condition as in the original (control) simulation. The original initial condition at 00:00 UT on 21 June was taken from a run using dz = 500 m, which had been spun-up for several years and well reproduced large-scale thermal and wind structures in the middle atmosphere. That initial condition was vertically interpolated into the dz = 200, 300, 400, and 1000 m runs, each of which was performed for the week of 21–27 June. The time step was set to 30 s in every run.

Metrological fields, e.g., winds, temperatures, and precipitations, were output every 30 min as 30 min averages, and GW components were extracted using a spherical high-pass filter with a cut-off horizontal wavelength of about 950 km, i.e., wavelengths 188–950 km were extracted (Watanabe et al., 2008). GW momentum flux is referred to as GWMF hereafter for simplicity. This paper focuses on the net vertical flux of eastward momentum associated with the GW components.

Both the chaotic behavior of the fluid system and the difference in the vertical resolution resulted in different evolutions of the synoptic motions and GW distributions.

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However, as will be shown later, the differences in the simulated GWMF in the middle atmosphere caused by the vertical resolution were significant. Since the simulated GW field requires only a few days for initial spin-up, i.e., to generate, propagate, and fill the stratosphere (Hamilton et al., 2008; Shutts and Vosper, 2011) the present work focused on the period of 24–26 June, during which the synoptic systems in all five runs held a morphological resemblance to each other.

3 Results

3.1 Strong dependence of GW momentum flux

Figure 1a compares vertical profiles of the GWMF for northern summer mid-latitude, which were simulated using the five different vertical resolutions. Positive values suggest the dominance of the GWs propagating upward and eastward against background easterly winds prevailing in the summertime stratosphere and mesosphere (e.g., Watanabe, 2008; Sato et al., 2009). It was quite surprising to find that the GWMF substantially decreases with increasing vertical resolution throughout the stratosphere and mesosphere. In other words, a coarse vertical resolution leads to a significant overestimation of the GWMF. This characteristic is opposite to that for horizontal resolution; a coarse horizontal resolution causes an underestimation of the GWMF, which results in a cold pole problem in the wintertime stratosphere (Hamilton et al., 1999). In these particular simulations, the dependence of the GWMF on the model's vertical resolution seems to start converging between dz = 300 and dz = 200 m. In the following sections, we discuss possible causes of this strong vertical resolution dependence.

3.2 Critical level filtering

Figure 1b shows similar vertical profiles to Fig. 1a but for the zonal mean zonal wind. The wind profiles are almost identical to each other below 30 hPa, which implies that critical level filtering of GWs propagating upward due to background large-scale flows in the troposphere and lower stratosphere does not explain the differences in the GWMF. The difference in the zonal mean zonal wind above the 30 hPa level rather reflects the difference in the GWMF, that is, the larger GWMF in the coarser vertical resolution runs generally gives larger GW forcing in the upper stratosphere and mesosphere, decelerating large-scale winds through wave-mean flow interactions.

3.3 Effects of particular GW events

It is necessary to determine whether the present vertical resolution dependence of the GWMF originates from particularly severe GW events. The upper panels of Fig. 2 compare longitude-height distributions of the net eastward GWMF for dz = 1000 and 200 m. It is revealed that the longitudinal distributions of large-scale zonal winds below the 30 hPa level are qualitatively similar to each other. Meanwhile, the GWMF in the dz = 1000 m run is generally larger than that in the dz = 200 m run. The GWMF is large not only near active source regions, (100–160° E and 60–150° W), but also near relatively calm regions (±45° from 0° E and near the date line).

The lower panels of Fig. 2 show the time evolution of the GWMF at the 30 hPa level, along with contours of strong precipitation. Strong GW events with large positive GWMF (e.g., 100–160° E) are repeatedly observed in the east of strong precipitation regions (e.g., 100–120° E), suggesting that the GWMF is likely associated with convectively generated high frequency GWs, which can penetrate westerly winds in the tropospheric subtropical jet (see the contours of the background zonal winds in the upper panels). Overall, it can be concluded that the vertical resolution dependence of the GWMF shown in Fig. 1 is not caused by any particular GW events, but is likely caused by systematic differences related to GW behaviors.

3.4 Effects of thin GWs

Sato et al. (1999) reported existence of a spectral peak of GWs near the inertial frequency in the global lower stratosphere of a high-resolution (about 1° horizontal res-

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olution) aqua-planet AGCM experiment, which was later confirmed by observational evidence. Such GWs have the lowest inertial frequency among vertically propagating GWs and generally have short vertical wavelengths (e.g., less than 2–3 km). Therefore, a coarse vertical resolution systematically reduces their number. Here, there is the apparent contradiction that the GWMF *decreases* in runs with higher vertical resolutions, in which thin GWs can be resolved.

Figure 3 shows close-up views of instantaneous longitude-height GW distributions (horizontal wind divergence components). In the dz = 200 m run, thin GWs (λ_z = 1–3 km) which are likely emitted by convective heating at around 140° E propagate upward and westward against the tropospheric westerly jet. Qualitatively, these low-frequency GWs generated within the sub-tropical jet reach their own critical levels near the zero-wind contours below a 50 hPa level, and do not directly affect the GWMF observed above the 30 hPa level.

As expected, the thin GWs (λ_z = 1–3 km) in the lower stratosphere are absent in the dz = 1000 m run. Instead, GWs with λ_z > 4–5 km are dominant everywhere, and the amplitude of the GWs seen above the 30 hPa level is obviously larger than those in the dz = 200 m run. These circumstances may imply the existence of suppression effects of the thin GWs in the dz = 200 m run, which effectively suppress the high-frequency GWs with longer vertical wavelengths.

4 Discussions

Through GMDD (Geoscientific Model Development Discussions), which provides a platform for open discussions, we welcome any suggestions and/or corroborative studies on the most plausible mechanisms through which the thin GWs in the lower stratosphere of northern summer mid-latitude systematically suppress the amplitude of the high-frequency GWs observed above (Fig. 4).

An alternative possibility is that the origin of this phenomenon is a source issue; different vertical resolutions above 8 km (Fig. A1) may affect the generation of high-

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frequency GWs. Any comments following this line of thought would also be greatly appreciated.

5 Concluding remarks

In order to investigate the vertical resolution dependence of the GWMF in a comprehensive AGCM which explicitly resolves a portion of the GW spectra ($\lambda_h > 188$ km), a series of sensitivity test simulations was performed changing only the model's vertical resolution (dz = 200, 300, 400, 500, and 1000 m). The simulated GWMF in the stratosphere and mesosphere of northern summertime mid-latitude showed a strong dependence on the model's vertical resolution. The GWMF was systematically overestimated with decreasing vertical resolution; it was confirmed that this overestimation did not stem from any particular GW events. The existence of low-frequency thin (λ_z = 1–3 km) GWs in the lower stratosphere likely causes the vertical resolution dependence of the GWMF. Further discussions and investigations are required to obtain plausible mechanisms that explain the causality of the present finding.

Author contributions. S. Watanabe developed the model code. S. Watanabe and K. Sato designed the experiments, and S. Watanabe carried them out. S. Watanabe prepared the manuscript with contributions from all co-authors.

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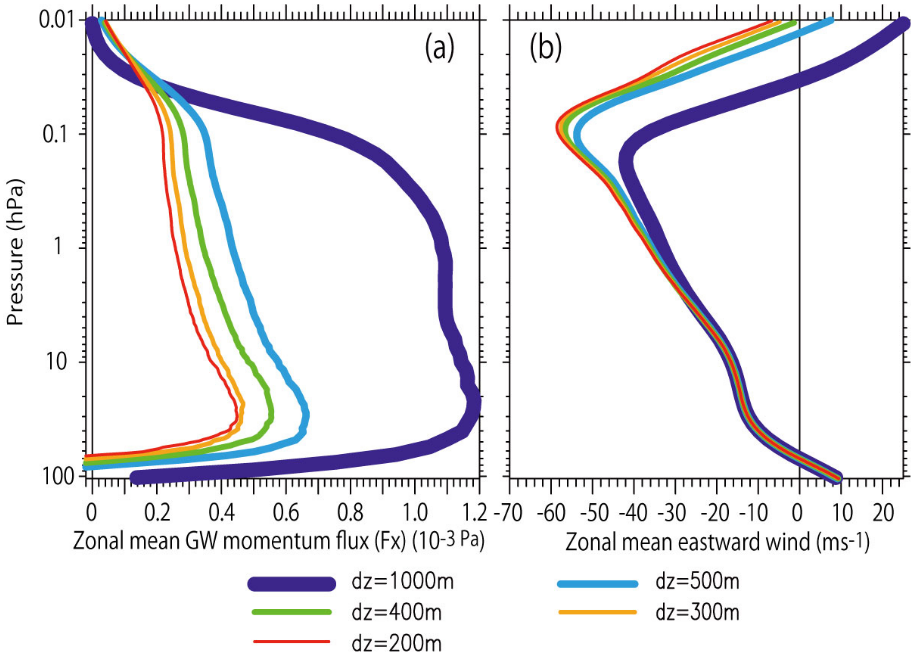

Figure 1. (a) Vertical profiles of the zonal mean net upward flux of the eastward momentum associated with the gravity wave component (λ_h = 188–950 km) for each vertical resolution. **(b)** Similar to **(a)** but for the zonal mean eastward winds. Averages over 35–40° N from 00:00 UT 23 June to 00:00 UT 27 June are shown.

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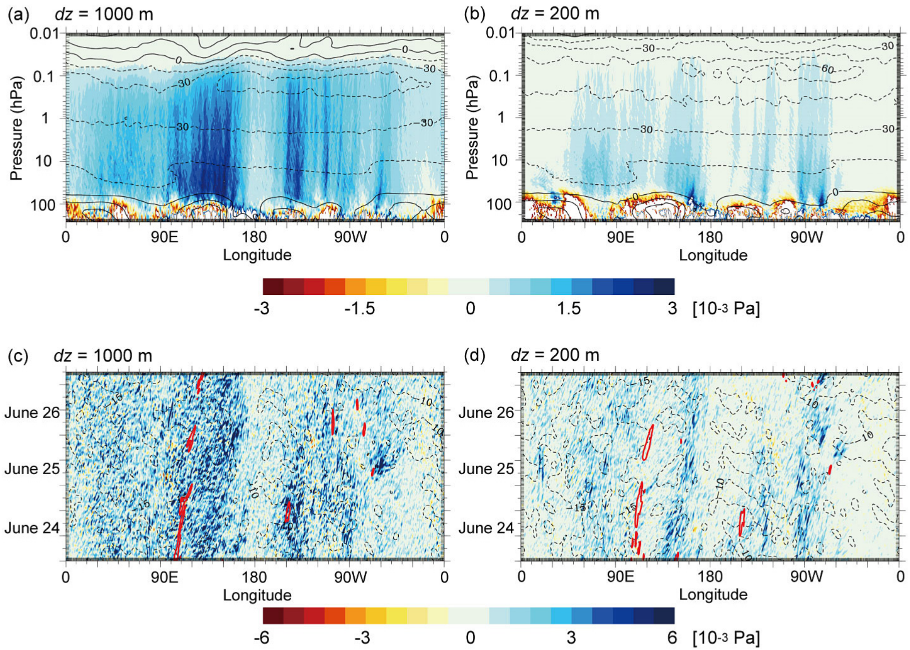

Figure 2. Upper panels: longitude-height distribution of net upward flux of the eastward momentum associated with the gravity wave component (λ_h = 188–950 km) in the dz = 1000 m run **(a)** and dz = 200 m run **(b)**. The contours show low-pass filtered (> 1000 km) eastward winds with an interval of 15 m s^{-1}. Averages over 35–40° N from 00:00 UT 24 June to 00:00 UT 27 June are shown. Lower panels: Hovmöller diagrams of the eastward gravity wave momentum flux (color) and the background large-scale eastward winds (black contours with an interval of 5 m s^{-1}) at 30 hPa. Red contours show precipitation rate of 2 mm h^{-1}.

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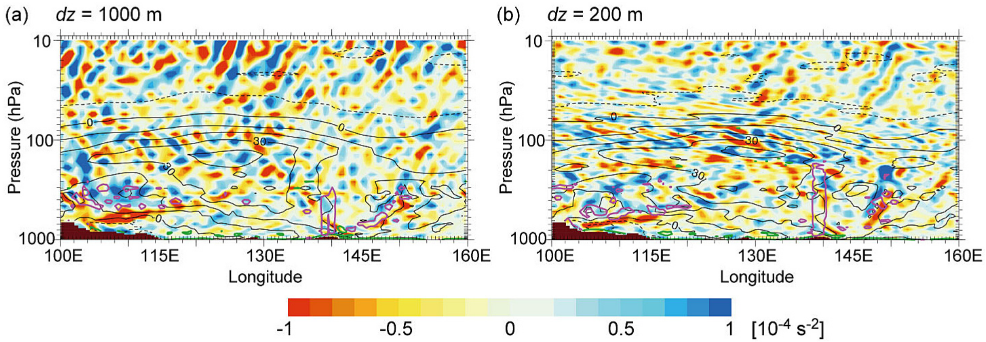

Figure 3. Instantaneous longitude-height distribution of the unfiltered divergence component of the horizontal winds (color), the low-pass filtered (> 1000 km) eastward winds (black contours with an interval of 15 $m s^{-1}$) and the moist diabatic heating rate of 0.1 $K h^{-1}$ (purple contours) at 37.5° N, 00:00 UT 24 June. Note that the longitudinal coverage is different from Fig. 2.

Figure 4. Schematic illustration of the suppression effects of thin (blue) gravity waves on the generation and propagation of higher-frequency (red) gravity waves.

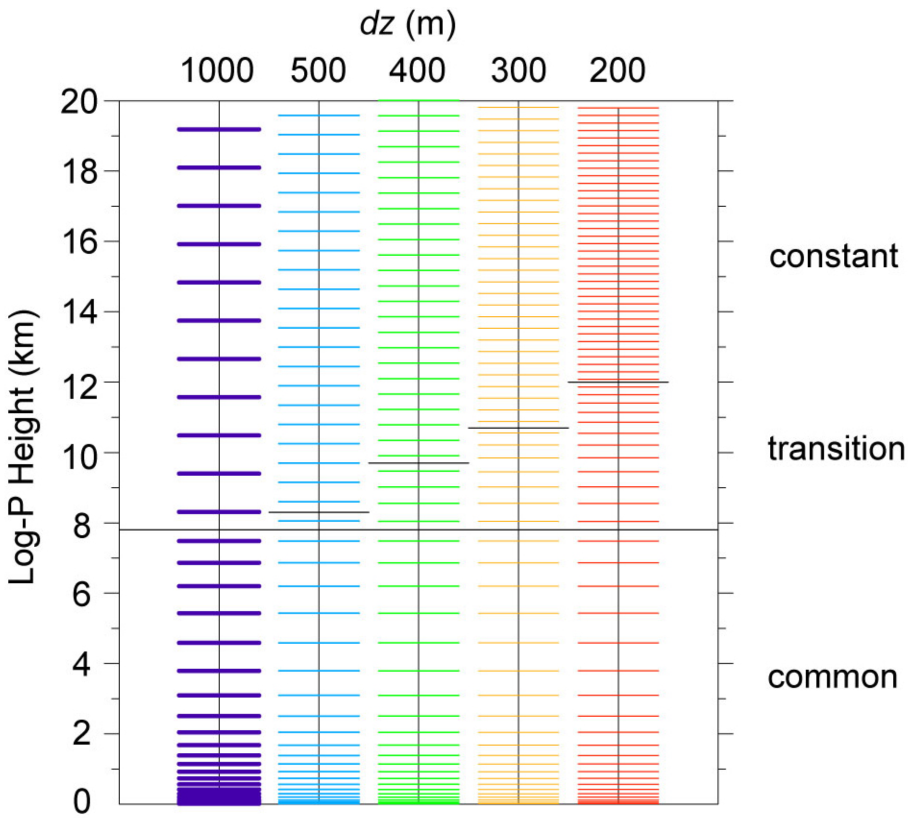

Figure A1. Standard vertical layer distribution for each vertical resolution. Note that a hybrid sigma-pressure coordinate system was actually used in the model, and a scale height of 7 km was used to calculate the log-pressure standard levels shown in this figure.

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