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On the origins of mesospheric gravity waves

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[1] Using hourly data from a three-year simulation based on a gravity-wave resolving general circulation model, we have first inferred a global view of gravity wave sources and propagation affecting significantly the momentum balance in the mesosphere. The meridional cross section of momentum fluxes suggests that there are a few dominant propagation paths originating from the subtropics in summer and the middle to high latitudes in winter. These gravity waves are focused into the mesospheric jets in their respective seasons, acting effectively to decelerate the jets. The difference in the source latitudes likely contributes to the hemispheric asymmetries of the jets. The horizontal distribution of the momentum fluxes indicates that the dominant sources are steep mountains and tropospheric westerly jets in winter and vigorous monsoon convection in summer. The monsoon regions are the most important window to the middle atmosphere in summer because of the easterlies associated with the monsoon circulation.
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1. Introduction

[2] The wind around an altitude of 90 km in the upper mesosphere is always weak globally, indicating that the air at this level rotates at approximately the same speed as the solid earth. This is a remarkable characteristic because the wind in the mesosphere below exhibits a dominant annual variation, with a strong westerly jet in winter and easterly jet in summer, reflecting the latitudinal difference in absorption of ultra-violet solar radiation by the ozone layer. Theoretical work in the early 1980s suggested that gravity waves were a possible physical justification for the artificial drag used commonly in numerical models to simulate the realistic persistent weak wind layer in the upper mesosphere [*Lindzen*, 1981; *Matsuno*, 1982]. Accurate estimates of the momentum flux associated with gravity waves at middle latitudes provided by the Mesosphere-Stratosphere-Troposphere (MST) radars which were developed in the early 1980s supported this theoretical expectation [e.g., *Tsuda et al.*, 1990]. Since then, our knowledge of gravity waves has been greatly improved through high-resolution observations by radars, radiosondes and satellites, and gravity waves are now recognized as one of the essential components in the earth climate system [e.g., *Fritts and Alexander*, 2003].

[3] While some observations of gravity wave effects on the mesosphere are possible, a global picture of gravity wave sources is presently beyond our reach. This is partly because the mesosphere is quite far from the source level in the troposphere, and because the gravity waves inherently propagate in any direction. Current global climate models must usually include gravity wave parameterizations because gravity waves are usually sub-grid scale phenomena. But the gravity wave parameterizations still have a significant uncertainty in the formulations of the wave sources and take account of only vertical wave propagation. The purpose of this study is to elucidate relative importance of various sources of the gravity waves as a function of time and space, by examining their propagation to the mesosphere with a high-resolution global model. A comprehensive atmospheric general circulation model with resolved gravity waves that gives realistic results presumably has treated gravity waves correctly. Therefore, we can assume that the modelled effects are a good surrogate for observations of the actual atmosphere.

2. Gravity-Wave Resolving General Circulation Model

[4] We developed a high-resolution global spectral climate model to investigate seasonal and inter-annual variation of global characteristics of small-scale phenomena including gravity waves [*Watanabe et al.*, 2008]; this has the following advantages. First, our model covers quite a wide height range from the ground surface to the upper mesosphere. Second, our model resolution is T213 (triangular truncation at wavenumber 213 corresponding to about 60 km) in the horizontal and 300 m in the vertical, which is almost sufficient to simulate realistic propagation and momentum deposition of gravity waves. Third, no gravity wave parameterizations are included in our model, i.e., all gravity waves are internally generated. Fourth, the time integration was made over three model years in which a climatology with realistic seasonal variation was specified for the sea surface temperature and stratospheric ozone. Physical quantities were sampled every 1 hour.

[5] Our preliminary analysis indicated that simulated large-scale dynamical structures were quite realistic and that gravity waves were essential for the momentum balance in the upper mesosphere [*Watanabe et al.*, 2008]. Using this model data, the tropopause and stratopause structure and the forcing of the QBO-like oscillation simulated spontaneously were examined by K. Miyazaki et al. (Transport and mixing in the extratropical tropopause region in a high vertical resolution GCM. Part I: Potential vorticity and heat budget analysis, submitted to *Journal of Atmospheric Sciences*,

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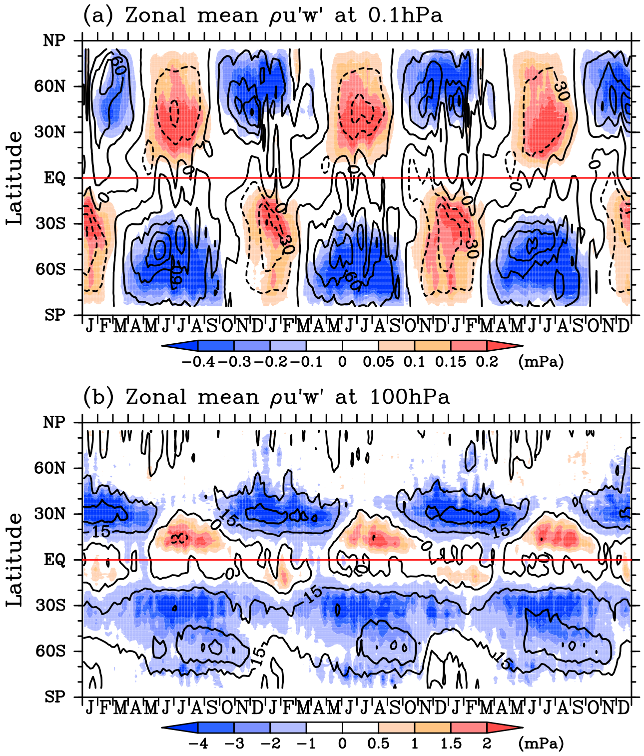

Figure 1. Time-latitude sections of momentum flux associated with gravity waves (colors) and zonal-mean westerly winds (contours; in m s^{-1}) (a) at 0.1 hPa in the upper mesosphere and (b) at 100 hPa in the lower stratosphere.

2009), *Tomikawa et al.* [2008], and Y. Kawatani et al. (The roles of equatorial trapped waves and internal inertia-gravity waves in driving the quasi-biennial oscillation. Part I: Zonal mean wave forcing, submitted to *Journal of Atmospheric Sciences*, 2009), respectively. Upper mesospheric four-day waves were analyzed by *Watanabe et al.* [2009]. The present study examined a global view of the sources and propagation of mesospheric gravity waves using the model data.

[6] Possible candidates for the sources of mesospheric gravity waves include high mountains, jet streams, cyclones, fronts and convection mainly in the troposphere. Among them, radiation of gravity waves through adjustment processes resulting from spontaneous imbalance of large-scale flows has recently received attention, though the details of this mechanism have not yet been explored theoretically [*O'Sullivan and Dunkerton*, 1995; *Zhang*, 2004; *Plougonven and Snyder*, 2007; *Sugimoto et al.*, 2008; *Sato and Yoshiki*, 2008]. Even such spontaneous emission of gravity waves is simulated explicitly in our model.

3. Characteristics of the Momentum Fluxes Associated With Gravity Waves

[7] The most important physical quantity for examining gravity wave propagation is the vertical flux of zonal momentum $\rho_0\overline{u'w'}$, where ρ_0 is the basic atmospheric density, u' and w' are eastward and upward wind fluctuations, respectively, and the overbar represents a time and/or spatial average. The momentum flux is a good diagnostic of gravity waves because it is conserved unless wave generation and/or dissipation occur [*Eliassen and Palm*, 1961]. Although recently-available high-resolution satellite observations capture a global image of gravity waves and provide useful information on the momentum flux in the stratosphere [*Ern et al.*, 2004; *Alexander et al.*, 2008], it is hard to examine the wave propagation because of the observational filter problem [*Alexander*, 1998].

[8] Small horizontal-scale fluctuations with total wavenumber n greater than 22 (horizontal wavelengths $\leq \sim$1800 km) were designated as gravity waves. A time-latitude section of $\rho_0\overline{u'w'}$ associated with the gravity waves is plotted in Figure 1a for the three model years at 0.1 hPa (a height of about 64 km) in the mesosphere. An annual cycle is clear, i.e., it is positive (negative) in summer (winter), which is consistent with radar observations at middle latitudes [*Tsuda et al.*, 1990]. The positive summer maxima are located at lower latitudes ($\sim$30°) than the negative winter maxima ($\sim$60°).

[9] Figure 1b shows the result for 100 hPa ($\sim$16 km) in the lower stratosphere, reflecting gravity wave source distributions in the troposphere. A similar annual cycle in the sign of $\rho_0\overline{u'w'}$ to the mesosphere is evident, which is also consistent with the MST radar observations [e.g., *Sato*, 1994]. However, the latitudes of the maxima are significantly lower than those in the mesosphere. Negative winter maxima are observed around 35° and positive summer maxima are located around 10° in both hemispheres. The significant difference in the maximum latitude suggests the latitudinal propagation of gravity waves which is ignored in most gravity wave parameterizations.

[10] In order to see the paths of gravity wave propagation from the lower stratosphere to the mesosphere, a meridional cross section of $\rho_0\overline{u'w'}$ as well as mean zonal wind was plotted in Figure 2a for July of the second year. The westerly jet in the winter (Northern) hemisphere is located around 60°S and 50 km, and the easterly jet in the summer (Southern) hemisphere exhibits a slanted structure above 50 km in the mesosphere. It is clear that the negative winter maximum around 35°S and the positive summer maximum around 10°N in the lower stratosphere are connected to the maxima in the mesosphere around 60°S and 30°N in their respective hemispheres. Similar paths were seen in the opposite season (i.e., January). It should also be added that there is another dominant path of gravity waves from 70°S in the lower stratosphere to 60°S in the mesosphere, although the corresponding path was not seen in the Northern Hemisphere winter.

[11] These characteristics of the momentum flux suggest that gravity waves penetrating from the lower atmosphere tend to be focused into the mesospheric jets in both seasons. Such focusing and vertical propagation of the waves determine the latitudinal distribution of the momentum flux convergence. Thus the focusing acts effectively to decelerate the mesospheric jets. It is also important to note that the hemispheric asymmetry of the mesospheric jets as observed in Figure 2a may partly be attributable to the difference in the source latitudes between the two seasons. For example, the gravity waves originating in the summer subtropical region propagate gradually to the higher latitudes, so that the mean wind deceleration occurs faster, namely, at lower altitudes at lower latitude regions. This

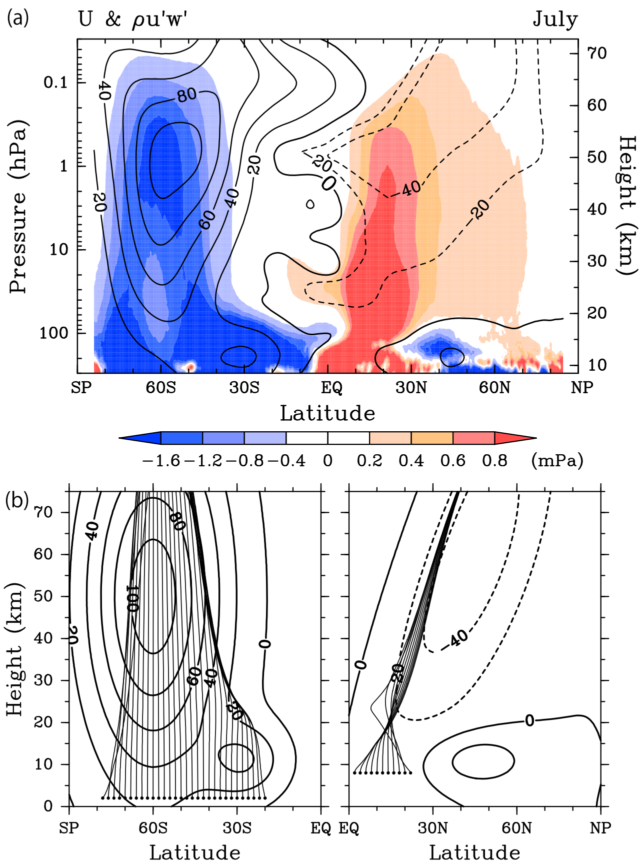

Figure 2. (a) A meridional cross section of momentum flux associated with gravity waves (colors) and zonal-mean westerly winds (contours; in m s^{-1}) in July. (b) Rays of gravity waves (thin curves) in the idealized background westerly winds (thick contours in m s^{-1}).

propagation feature may be significant in contributing to the easterly jet structure leaning toward higher latitudes.

4. Meridional Propagation of Gravity Waves

[12] The wave focusing into the mesospheric jet can be explained theoretically by the modification of the wavenumber vector by the background fields. A ray-tracing theory indicates that the time rate of change of the meridional wavenumber l along the ray is proportional to the meridional gradient of the background westerly wind U and the zonal wavenumber k:

$$\frac{dl}{dt} = -k\frac{\partial U}{\partial y}, \tag{1}$$

where we assume a sinusoidal wave structure proportional to $\exp(kx + ly + mz - \omega t)$, t is time, x, y and z are the longitudinal, latitudinal and vertical coordinates, and ω is the frequency relative to the ground [*Jones*, 1969]. For simplicity, the static stability is assumed to be constant latitudinally. Linear theory shows that the direction of the horizontal wavenumber vector (k, l) is equal to that of horizontal group velocity relative to the mean wind for gravity waves propagating energy upward. Because the mean meridional wind is generally weak, it is considered that the sign of l is equal to that of the meridional group velocity relative to the ground. Linear theory also indicates that gravity waves with negative k have negative $\rho_0\overline{u'w'}$. Thus, (1) means that the gravity waves having negative $\rho_0\overline{u'w'}$ tend to have negative (positive) l to the north (south) of the westerly jet. This is consistent with a general feature that the gravity waves with negative $\rho_0\overline{u'w'}$ generated in the lower atmosphere are focused into the mesospheric westerly jet in winter. Such wave focusing into the westerly jet was discussed by *Dunkerton* [1984], and the importance of wavenumber modification by *Preusse et al.* [2002]. The focusing of gravity waves with positive $\rho_0\overline{u'w'}$ into the easterly jet in summer is also understood with this mechanism.

[13] To confirm the wave focusing into the jet, a simple ray tracing calculation was made for an idealized background condition and simple initial wave parameters, so as to make its essence clear. A steady zonally-uniform westerly wind field that mimics the simulated (i.e., real) one in Figure 2a was given as the background field (thick contours in Figure 2b). The initial wave parameters given are purely westward (eastward) wavenumber vectors in the winter (summer) hemisphere as is consistent with the sign of simulated $\rho_0\overline{u'w'}$, a typical horizontal wavelength of 500 km, and a phase speed of zero relative to the ground. The gravity wave launch level was 2 km for the winter hemisphere and 8 km for the summer hemisphere, because the dominant wave sources are high mountains in winter and strong convection in summer, as shown later. Thin curves in Figure 2b show the results of the ray tracing. The wave focusing into the jet is clear and consistent with the momentum flux distribution (Figure 2a). A slight change of given initial wavelengths modifies the ray paths to some degrees but not by much.

5. Origins of Gravity Waves Propagating Into the Mesosphere

[14] Next, so as to see the dominant source regions of gravity waves, the horizontal distribution of $\rho_0\overline{u'w'}$ at 100 hPa in the lower stratosphere is examined. Figure 3 shows the

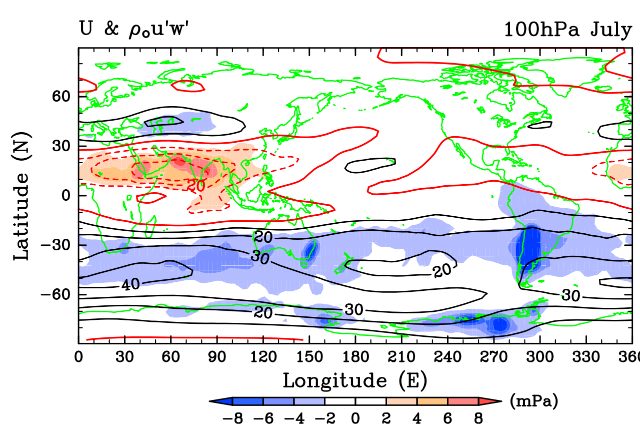

Figure 3. A horizontal map of momentum flux associated with gravity waves (colors) at 100 hPa in the lower stratosphere. Red solid, red dashed, and black dashed contours indicate zero, easterly, and westerly winds (in m s^{-1}), respectively.

result for July. It is clear that the distribution of $\rho_0\overline{u'w'}$ is not zonally uniform. In the Southern (winter) Hemisphere, large negative values are observed at 100 hPa over high mountains such as the Andes at mid-latitudes and the Antarctic peninsula at high latitudes. Thus, these are likely due to topographically-forced gravity waves. In addition to these isolated peaks, zonally-elongated negative $\rho_0\overline{u'w'}$ regions are present in middle to high latitudes in the Southern Hemisphere. These are likely due to gravity waves spontaneously emitted from strong westerly jets and fronts [*O'Sullivan and Dunkerton*, 1995; *Kawatani et al.*, 2004; *Zhang*, 2004; *Plougonven and Snyder*, 2007; *Tateno and Sato*, 2008].

[15] In the Northern (summer) Hemisphere, positive $\rho_0\overline{u'w'}$ values are dominant in the Indian and African summer monsoon regions. Thus, these are likely due to gravity waves generated by strong convection in the monsoon regions. It is important that the mean wind in this region is easterly in the lower stratosphere associated with the monsoon circulation, because it allows the eastward-propagating gravity waves to penetrate into the middle atmosphere.

[16] Similar features are observed in January (not shown). Dominant sources are the Rocky Mountains, mountains in East Asia, and strong westerly jets in middle latitudes of the Northern Hemisphere. Gravity waves in high latitudes of the Northern Hemisphere are weak for lack of steep topography. Strong positive $\rho_0\overline{u'w'}$ is observed in the subtropical summer monsoon regions in the Southern Hemisphere.

6. Summary and Concluding Remarks

[17] Using a high-resolution general circulation model, we examined the dominant sources and propagation of the mesospheric gravity waves that affect significantly the momentum balance in the mesosphere. There were a few dominant propagation paths to the mesosphere originating in the subtropics in summer and in the middle to high latitudes in winter in the lower stratosphere. These dominant gravity waves were focused into the mesospheric jets, which was attributable to the wavenumber modification by the jets themselves. The seasonal dependence of the source latitudes likely plays an important role in accounting for the hemispheric asymmetry of the mesospheric jets. The features of momentum fluxes in the lower stratosphere indicated that the dominant gravity wave sources are steep mountains and strong upper-tropospheric westerly jets in winter and vigorous subtropical monsoon convection in summer. The monsoon regions were the most important source region in summer because of the easterlies in the lower stratosphere.

[18] These results indicate that the latitudinal propagation of gravity waves is important in determining the dynamical structure of the mesosphere, although it has been ignored in most gravity wave parameterization schemes. An improvement of the gravity wave parameterizations by including relevant wave propagation and sources likely would lead to more accurate, detailed and longer-term prediction of the weather and climate.

[19] Although high-resolution global models are powerful to examine gravity waves in many aspects as discussed in this paper, the reality must be confirmed by observations with similar or higher resolutions. In particular, our observational knowledge in the polar regions is limited. Combination of high-resolution models and observations with MST radars and satellites will be promising for precise understanding of the global and detailed momentum balance.

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