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Sources of gravity waves in the polar middle atmosphere

Kaoru Sato

National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515

Abstract: Gravity waves are considered to be important for dynamics and chemistry in the polar middle atmosphere. However, there are only a limited number of studies of gravity waves in the polar region mostly because of difficulty of their observation. One of the significant issues on gravity waves is their source, because wave parameters such as wavelengths and phase velocities which are essential to evaluate the gravity wave effects on the large-scale field are highly dependent on the source. This paper describes dominant sources of gravity waves in the polar regions, namely topography, the polar-night jet, and tropical convection, by reviewing results from recent studies.

1. Introduction

Atmospheric gravity waves are small-scale waves with the restoring force of buoyancy. Lee waves visualized by clouds in satellite images are one example of typical gravity waves. The gravity waves had been studied for a long time mostly from their theoretical aspects. They had not been recognized as significant phenomena in meteorology until the early 1980's, because of their weak energy and small scales compared with synoptic-scale waves directly affecting daily weather. However, with the aid of recent developments in observation techniques such as MST (mesosphere, stratosphere and troposphere) radars (VHF/UHF Doppler radars), lidars and radiosondes as well as computer technology, many theoretical and observational studies of gravity waves have been made since the early 1980's. Gravity waves are now recognized as one of the essential phenomena to maintaining global circulation through their momentum transport, in particular in the middle atmosphere.

Even though gravity waves have weak energy in the source regions (mostly in the troposphere), their amplitudes of wind and temperature fluctuations become significantly large, as gravity waves propagate upward into the middle atmosphere because of the exponential decrease of atmospheric density. When gravity waves are dissipated by radiative relaxation, viscosity and/or local instability, a force is induced to accelerate the mean flow toward their phase velocity. According to recent studies, such a wave-induced force is essential to maintain the weak wind layers in the mid-latitude mesopause and in the mid-latitude lower stratosphere (a deceleration effect) and the zonal wind in the lower thermosphere blowing in the opposite direction to that in the mesosphere (an acceleration effect), and to drive the QBO (quasi-biennial oscillation) of zonal wind in the equatorial lower stratosphere, semi-annual oscillation in the equatorial upper stratosphere and mesosphere and recently discovered QBO in the lower thermosphere (an acceleration

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E-mail: kaoru@nipr.ac.jp

effect).

Gravity waves are also important in polar regions. They may control the strength of the polar-night jet in the stratosphere by their ability to transport momentum and keep the air inside the polar vortex warmer than expected by radiative balance (*e.g.*, Kanzawa, 1989). The meridional circulation in the middle atmosphere driven by the gravity wave force maintains lower temperature around the mesopause in the summer hemisphere than in the winter hemisphere, which is opposite to the meridional gradient expected from the radiative heating (*e.g.*, Hitchman *et al.*, 1989). This is a reason why noctilucent clouds around the mesopause are observed mostly in summer, and this is probably related to the existence of strong coherent echoes around the mesopause only in summer (polar mesospheric summer echo) detected by MST radars (*e.g.*, Röttger and La Hoz, 1990).

Another possible role is an effect on chemical processes. Temperature fluctuations associated with gravity waves can make local temperature sufficiently low to cause PSCs (polar stratospheric clouds), which are important to the heterogeneous reaction to destroy stratospheric ozone in spring (*e.g.*, Carslaw *et al.*, 1998). This effect is more important in the Arctic than in the Antarctic, because the mean temperature in the Arctic in spring is marginal to the PSC condensation, whereas that in the Antarctic is sufficiently low. This warmer temperature in the Arctic can be explained mostly by taking planetary-scale wave activity into account.

Nevertheless, only a limited number of studies of gravity waves have been made for the polar region so far, partly because the harsh environment of the Arctic and Antarctic regions makes ground-based observation difficult compared with low and middle latitudes. Only studies utilizing satellite data can treat gravity waves in the polar regions and the other latitude regions equally (*e.g.*, Wu and Waters, 1996a, b; Eckermann and Preusse, 1999). One of interesting issues on gravity waves in the polar regions is their source. There is little occurrence of vigorous convection which is an important source in the tropical region. Baroclinic wave activity is not so strong as in the middle latitude region. In this paper, possible sources of gravity waves in the polar regions are discussed by showing results of recent studies using observational data and a high-resolution climate model.

2. Topography

Gravity waves are generated by strong winds over mountains, because the air is lifted over the topography and becomes buoyant. According to recent observations by radars and aircraft, the topographically forced gravity waves are frequently observed in the Arctic (*e.g.*, Whiteway and Duck, 1996; Whiteway *et al.*, 1997).

There are several operational radiosonde stations in the polar regions which provide wind and temperature data with sufficiently high resolution to examine gravity waves in the lower stratosphere (up to an altitude of about 30 km). Yoshiki and Sato (2000) analyzed wind and temperature fluctuations with small vertical scales in the Arctic and Antarctic using the operational radiosonde data over 10 years. In both polar regions, the amplitudes of disturbances are maximized in winter where the polar-night jet is situated. In the Antarctic, another maximum is seen in spring when the static stability becomes high in the lowermost stratosphere. This spring maximum of gravity wave intensity was

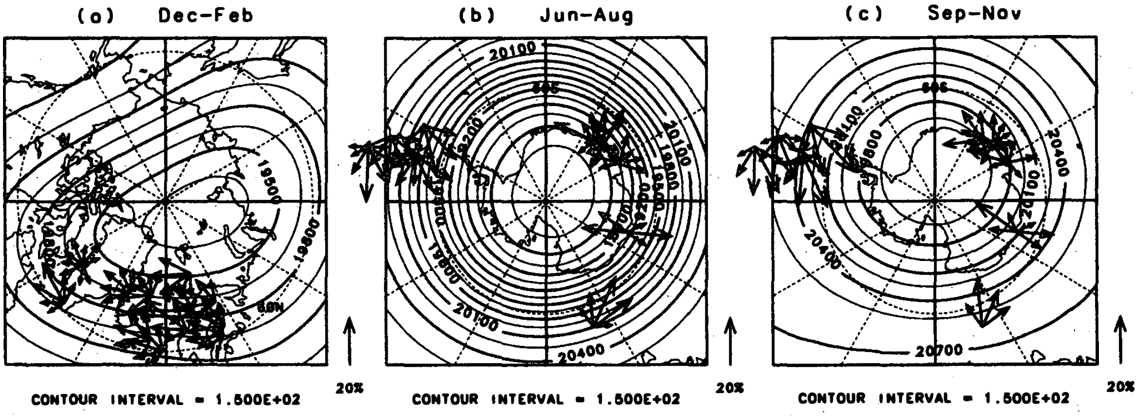

Fig. 1. Horizontal direction of gravity wave propagation relative to the mean wind in (a) the Arctic in winter, (b) the Antarctic in winter, and (c) the Antarctic in spring (Yoshiki and Sato, 2000). The length of an arrow shows the probability density at the direction at each station. The geopotential height (in m) at 50 hPa averaged over 10 years is also shown. The contour interval is 150 m.

also reported by Pfenninger *et al.* (1999) using radiosonde data at the South Pole.

An interesting feature shown by Yoshiki and Sato is the propagation direction of gravity waves. Figure 1 shows statistics of horizontal propagation direction of gravity waves in the Arctic in winter and in the Antarctic in winter and spring when gravity wave energy is large. Gravity waves in the Arctic propagate mostly westward relative to the mean wind, while there is no clear preference of propagation direction in the Antarctic. The ground-based phase velocities of gravity waves in the Arctic are around zero (not shown). These characteristics in the Arctic are consistent with topographically forced gravity waves.

It seems that the surface winds are sufficiently strong in winter to cause gravity waves both in the Arctic and Antarctic. However, contrary to the Arctic, the surface winds at Antarctic stations, most of which are located along the coast of the continent are westward. Thus, there is an altitude in the troposphere where the wind changes its direction and continues to the strong eastward wind in the stratosphere. This altitude corresponds to a critical level of topographically forced gravity waves where their vertical group velocity becomes zero. Therefore it is considered that most of gravity waves in the Antarctic winter stratosphere are not generated by topography.

3. Polar-night jet

Another possible source is the polar-night jet situated in the winter stratosphere, though few studies have been made from this view point. The polar-night jet is maintained by a strong meridional gradient of radiative heating by ozone in the stratosphere through the geostrophic or gradient wind balance. However, because of this tendency to balance winds and temperature, departure from the balance must propagate mostly as gravity waves somewhere from the jet stream. This kind of mechanism to generate gravity waves is known as the geostrophic (or spontaneous) adjustment.

It is well known that gravity waves with large energy are frequently observed near the eastward jet stream around the tropopause (about 10 km altitude) in the middle latitude region (*e.g.*, Kitamura and Hirota, 1989; Sato, 1994). Similar gravity waves appear in high-resolution global model simulations (*e.g.*, O'Sullivan and Dunkerton, 1995; Sato *et al.*, 1999). It is considered that these gravity waves are generated due to the geostrophic adjustment around the mid-latitude jet stream near the tropopause. It is quite natural to infer that a similar generation mechanism may exist around the polar-night jet.

Sato *et al.* (1999) examined global characteristics of gravity waves using a high-resolution global circulation model, because the model provides all physical quantities needed for the analysis and being uniformly distributed in space with equal accuracy, which is unlike most observation data. The reality of simulated gravity waves was confirmed by good coincidence in their phase structure and amplitudes with MST radar observations at a middle latitude. Meridional cross sections of wave energy, energy fluxes and momentum fluxes were shown, and frequency power spectra were displayed as a function of latitude. Most features seen in the figures were consistent with theoretical characteristics of gravity waves. One of interesting results obtained in this study was a dominance of downward propagation of wave energy around the polar-night jet in the winter hemisphere, suggesting the existence of gravity wave sources in the stratosphere. This is quite new because gravity wave sources have been considered to be mostly in the troposphere so far, such as, extratropical jets, fronts, cyclones, convection, and topography.

Sato and Takahashi (in preparation, 2000) extended this study to identify gravity wave sources by examining time variation of gravity wave phases in various cross sections. Figure 2 shows a snapshot of the polar stereo projection map of horizontal

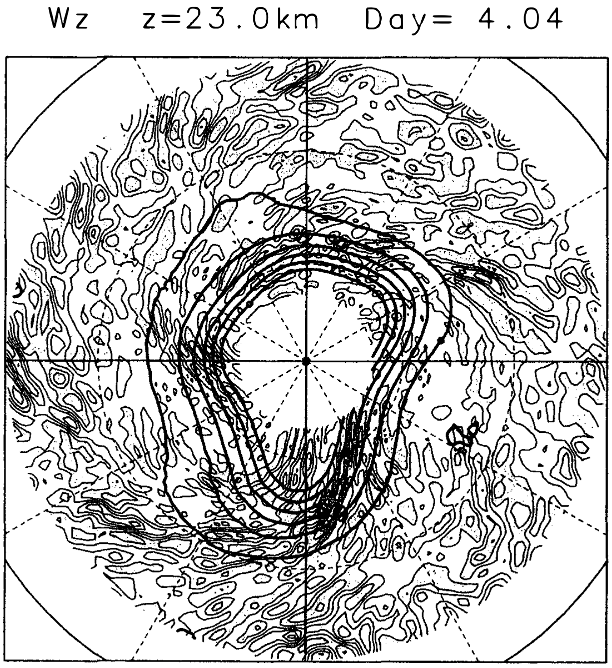

Fig. 2. A snapshot of polar stereo projection map of unfiltered horizontal divergence component (thin contours) at an altitude of 23 km. Darkly and lightly shaded regions indicates positive and negative values. Units are $2 \times 10^{-5} s^{-1}$. Thick contours show geopotential height at the same altitude. Contour intervals are 200 m. Displayed is a latitude region of 10–70°N.

wind divergence (thin contours with shading) at an altitude of 23 km in the lower stratosphere. Thick curves show contours of geopotential height, and dense contours indicate the location of the polar-night jet. Clear phase structure of gravity waves is seen around the polar-night jet in Fig. 2. However, gravity waves are not uniformly distributed around the jet stream. Large amplitudes are seen in the region with large curvature due to modification by planetary-scale waves. This fact suggests that these gravity waves are generated by the geostrophic adjustment around the polar-night jet. In fact, the local Rossby number, an index of departure from geostrophic wind balance is large in this region. The phase structure in the meridional cross-section of gravity waves around the polar-night jet shows downward energy propagation which is consistent with the results of wave energy fluxes (not shown).

By a statistical analysis of hodographs of small vertical-scale fluctuations, Yoshiki and Sato (2000) showed that the percentage of gravity waves with downward group velocity is relatively high in winter and spring in the Antarctic, while topographically-forced gravity waves with upward energy propagation are dominant in the Arctic. The result in the Antarctic is consistent with the scenario of gravity wave generation by the geostrophic adjustment around the polar-night jet.

4. Tropical convection

Another interesting result obtained using the high-resolution GCM by Sato *et al.* (1999) is that gravity waves propagate poleward and upward from the equatorial tropopause. Figure 3 shows a latitude-height section of vertical flux of meridional momentum ($\overline{v'w'}$) for fluctuations with periods shorter than 24h. For gravity waves propagating energy upward, positive (negative) $\overline{v'w'}$ values mean northward (southward) energy propagation. The direction of meridional energy propagation is opposite for gravity waves propagating energy downward.

It is seen in Fig. 3 that in the low and middle latitude stratosphere where upward energy propagation is dominant, large negative (positive) values are observed in the southern (northern) hemisphere. Moreover, the latitudinal expanse of large $\overline{v'w'}$ increases with altitude. The $\overline{v'w'}$ contours of $\pm 2 \times 10^{-3}\mathrm{m}^2\mathrm{s}^{-2}$ reach the mid-latitude of ϕ 50° at an altitude of $z = 27$ km. This V-shaped distribution suggests that short-period gravity waves are generated in the equatorial region and propagate poleward in both hemispheres.

In fact, the V-shaped curve of large momentum fluxes can be explained by gravity wave theory. Figure 4 shows ray paths obtained by integrating their group velocities of meridionally propagating gravity waves passing through an altitude of 15 km and a latitude of 20 degrees which is roughly corresponding to the higher latitude end of the tropical tropopause. Numerals on the rays denote wave periods in hour. It is seen from this figure that longer-period gravity waves from the equatorial region should be observed at lower altitudes. An important point is that the gravity waves cannot propagate beyond the latitude at which the intrinsic wave frequency equals the inertial frequency and group velocities become zero. The boundary of this unreachable region traced by a dashed curve in Fig. 4 does not change even if gravity waves propagating zonally as well as meridionally and passing at lower latitudes are also taken into account. The boundary of

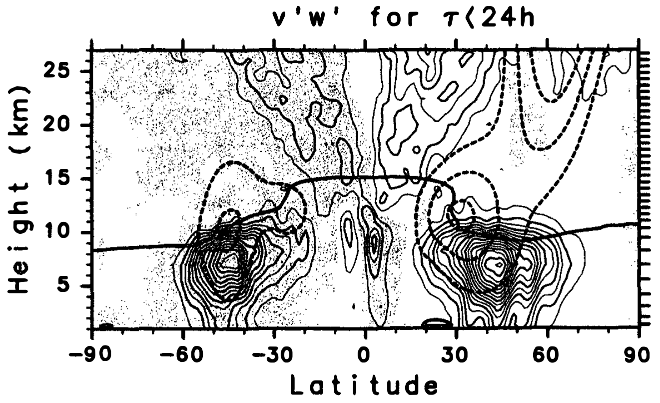

Fig. 3. A latitude-height section of vertical fluxes of meridional momentum ($\overline{v'w'}$) for gravity waves with periods shorter than 24 h (Sato et al., 1999). Contour intervals are 0.002 m^2s^{-2}. Negative regions are shaded.

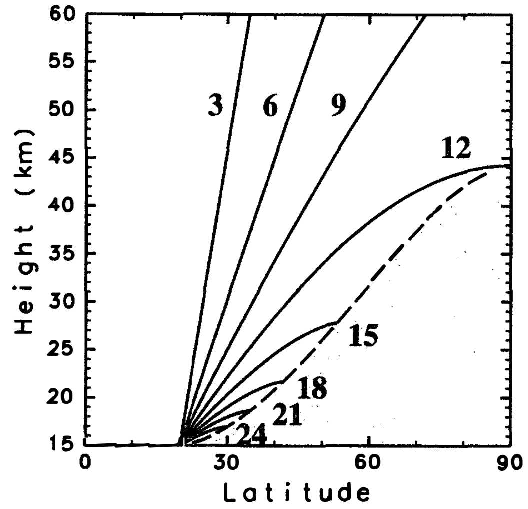

Fig. 4. Rays of poleward propagating inertia-gravity waves which pass through ϕ 20° at a height of 15 km. Numbers near each ray denote the wave period in hours. Shaded is the region which the inertia-gravity waves cannot reach.

this V-shaped region seen in Fig. 3 is almost in accord with the boundary of unreachable region. For example, both boundaries are located at z~21 km for $|\phi| = 40°$ and z~26 km for $|\phi| = 50°$.

It is interesting in Fig. 4 that the boundary curve reaches the pole at z~44 km. This means that gravity waves originated from tropical convection can be observed in the polar region above the 44 km altitude. Therefore, one of important sources of gravity waves in the polar region may be vigorous convection in the tropical region.

5. Summary

Gravity waves are considered to play an important role in the dynamics and chemistry of the polar middle atmosphere, although only a limited number of studies have been made, compared with studies for the other latitudinal regions. This is mostly due to the difficulty of observation in the severe environment of polar regions. In this paper, we discussed possible and important sources of gravity waves in the polar regions, namely topography, the polar-night jet, and tropical convection sequentially by reviewing results from recent studies.

It is worth noting here that there are several other possible sources although they may not be important for global-scale circulation in the middle atmosphere because of their weak energy. Secondary generation of gravity waves is possible associated with shearing and/or convective instability of primary gravity waves coming from the lower atmosphere (Satomura and Sato, 1999). Generation from dynamical instability around large-scale shear flow in the middle atmosphere may be occasional (Fritts, 1984). Joule heating associated with aurora in the upper atmosphere may be one of unique gravity wave excitation mechanisms in the polar regions.

To evaluate quantitative importance of gravity waves in the polar middle atmosphere, observational and modeling studies of gravity waves must be continued from various aspects. Spatial distribution of gravity waves excited from each generation mechanism is important, because gravity wave characteristics and hence their effects on the mean flow are highly dependent on the source mechanism. Studies using high spatial resolution models (*e.g.*, Sato *et al.*, 1999) and high vertical resolution satellite observation such as radio occultation observation with the Global Positioning System (Kursinski *et al.*, 1996) are promising. Direct measurements of momentum fluxes by MST radars with high vertical and time resolution in the polar region are important to see dynamical effects on the large-scale field. Lidar measurements of temperature cover the height regions of the upper stratosphere and lower mesosphere in which MST radar observations are not available. Radiosonde observations are also important although the temporal intervals are limited, because simultaneous measurements of horizontal winds and temperature are possible.

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