An Inertial Gravity Wave Associated with a Synoptic-scale Pressure Trough Observed by the MU Radar

By Kaoru Sato

*Department of Geophysics, Faculty of Science, Kyoto University
Kyoto 606, Japan*

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Abstract

An inertial gravity wave related to a synoptic-scale pressure trough was revealed by observations made with the MU radar. Twelve beams were used to scan zonally to detect the spatial variation of the wind. According to hodograph analysis and theoretical considerations, the gravity wave propagated downward from the tropopause height of 11 km, had a horizontal wavelength of 300 km and a horizontal phase velocity of 20 m/s. The estimated parameters are consistent with all information obtained by the measurements.

The height-time section of the echo power shows that a severe turbulent layer was located near the tropopause height while the wave was appearing. A large vertical shear in the horizontal wind was coincidentally observed at the same altitude. This suggests that the inertial gravity wave originated from the atmosphere having low stability near the tropopause. During the measurements with the MU radar, a synoptic-scale pressure trough passed near the radar site. The gravity wave was observed just before the northward wind migrated. These results indicate that the synoptic-scale pressure trough is one of the possible sources of gravity waves.

1. Introduction

Through a lot of recent efforts, the important role of gravity waves in the wind structure in the middle atmosphere has been widely recognized. Lindzen (1981) made a pioneering work that relates the eddy diffusion responsible for the saturation of gravity waves by convective instability with the induced acceleration of the mean wind. By using this parameterization, Holton (1982) showed that more realistic wind features, *e.g.*, the reversal of zonal wind above the mesopause, are obtained in a model of the middle atmosphere. On the other hand, Matsuno (1982) obtained almost the same results as Holton with his own parameterization, which is the dissipation of gravity waves by the prescribed eddy diffusion. The theoretical and observational studies were reviewed by Fritts (1984).

These models assume that gravity waves are penetrating from the lower atmosphere and carrying the momentum. However, there have been only a few studies examining the sources of gravity waves. Investigation of sources of gravity waves is important not only for the certification and development of such theories, but also for understanding the characteristics and climatology of gravity waves in the atmosphere.

Ninomiya (1982) detected an internal gravity wave downstream of a heavy rainfall area over Japan. He examined the horizontal distribution of temperature, humidity, and wind using the upper-air data obtained by routine observation with sondes. Through the careful analysis he showed that the gravity wave had horizontal and vertical wavelengths of ~ 400 km and ~ 3 km respectively. However, more detailed information about the wave could not be obtained because of insufficient density of the data. Hirota and Niki (1986) observed and analyzed the inertial gravity waves propagating upward and downward from the strong subtropical westerly jet using the MU radar in winter. From the phase difference between horizontal and vertical components, it is found that the wavenumber vectors were southward and perpendicular to the jet axis.

The present study describes another kind of inertial gravity waves related to a synoptic-scale pressure trough. We have made a special observation with the MU radar in November, 1985, using several beams which scan the wind field zonally. Section 2 describes the observation and the method of data analysis. Parameters characterizing the inertial gravity wave are examined in Section 3-1. In Section 3-2, we investigate the source of the wave. Section 4 summarizes the results as concluding re-

Fig. 1. Beam configuration. The directions of beams are represented by open circles. The numerals show the zenith angle (degree).

marks.

2. Observation and data analysis

The multi-beam observation was carried out on 6–8 November, 1985. The observation period was about 31 hours. The time resolution was about 8 minutes. The observed height range was 2.4–24.6 km and the height resolution was 300 m along the beam direction. Although the resolution of the radial wind velocity depends on the atmospheric condition, it is about 0.1 m/s when the signal-to-noise ratio of the echo is sufficiently high. Observations with such fine resolution are suitable for the detection of small-scale phenomena like gravity waves.

The unique feature of this observation is the beam configuration, as presented in Fig. 1. The line-of-sight wind velocities of 15 different directions were measured almost simultaneously using the fast beam steerability of the MU radar. Details of the system are described by Fukao *et al.* (1985 a,b). Twelve beams out of 15 were directed zonally to scan the zonal wind field, in the region with the zenith angle of from 30° east to 30° west at the interval of 4°. Two beams were tilted meridionally, and the remaining beam was directed vertically. Such measurements provide us with the information not only of the vertical profile of the wind field above the radar site, but of the spatial variation of the wind field. The measurement method is almost the same as Sato and Hirota (1988), which should be consulted for details.

The radial velocity V is expressed as

$$V_{\theta}(z, t) = u_{\theta}(z, t) \cdot \sin \theta + w_{\theta}(z, t) \cdot \cos \theta, \quad (1)$$

where θ is the zenith angle of the beam, z is the height, t is the time, u is the horizontal component of wind, and w is the vertical one. Using obtained radial velocities in each direction, we calculated each component of the wind field. The zonal and meridional components of wind are obtained from radial velocities of each symmetrical beam pair by Vincent and Reid (1983)'s method, where we assume the uniform wind field over the two beam positions:

$$[u(z, t)]_{\theta} = \frac{V_{\theta}(z, t) - V_{-\theta}(z, t)}{2 \sin \theta} \quad (2)$$

Since there are 6 symmetrical beam pairs zonally, the spatial mean of zonal wind component is obtained as follows:

$$[u(z, t)] = \frac{1}{N} \sum_{i=1}^N [u(z, t)]_{\theta_i}, \quad (3)$$

where N is the total number of symmetrical beam pairs and θ_i is the zenith angle of the i 's beam pair. On the other hand, the zonal component of wind at each zonal beam position is obtained simply using the following method, ignoring the vertical component, because the vertical component was much smaller than the zonal component during the whole observation:

$$u(\theta, z) = V(\theta, z) / \sin \theta. \quad (4)$$

This method provides the information on the spatial variation of the wind field, whereas only height profiles of the wind are obtained by (2) and/or (3).

3. Result and discussion

The zonal and meridional wind profiles during the whole observation period after removing fluctuations with periods smaller than 1 hour by lowpass filtering, are presented in Fig. 2. The zonal wind field is zonally averaged using (3), and the meridional one is obtained by (2). A remarkable oscillation having about 3.5 hours' period is found around a height of 10 km at 4:00–9:00 LST on 7th. Figure 3 shows the zonal and meridional components of the oscillation, which are extracted from the data using a bandpass filter with cutoff periods of 2 and 7 hours. The broad bandwidth of the filter was chosen so as not to reduce the power of the oscillation. It is found that the oscillation has large zonal and meridional components. The vertical wavelength is around 4 km. The phase migrates downward. The vertical wind component, however, was very weak (<0.2 m/s), and there was no wavelike structure. From the period, the vertical wavelength and the

Fig. 2. Vertical time-sections of zonal and meridional wind fields during the whole observation. The components with periods of less than 1 hour are removed using a lowpass filter. The contour interval is 5 m/s.

Fig. 3. Vertical time-sections of zonal and meridional wind components with a period of 2-7 hours. The contour interval is 1 m/s.

ratio of horizontal to vertical component, we speculate that the oscillation is due to an inertial gravity wave. In the following section, therefore, we investigate the oscillation under the assumption that it is an inertial gravity wave.

3.1 Parameter estimation

We begin our analysis with the estimation of the wave parameters. In order to examine the wavelength and period of the wave and/or the direction of the wave propagation, the hodograph analysis is useful (Hirota and Niki, 1985). According to the

theory of inertial gravity waves, the direction of rotation of the horizontal wind vector in height represents the direction of the wave propagation. The solid lines in Fig. 4 show the hodograph at 6:13 LST when the wave is distinctly found. Numerals in the figure show altitude in km of the wind vectors. Since the hodograph rotates anti-clockwise with altitude, the wave energy propagates downward. It is noteworthy that the direction of the vertical energy propagation is the same as that of the phase propagation, due to the Doppler effect of the mean wind. This is briefly explained as follows.

Fig. 4. Hodograph of the inertial gravity wave (solid line). Numerals in the figure show altitude (km) if the wind vectors. The dotted line shows the result of the fitting to the shape of ellipse. (a) The case with the constant "background" wind in height. (b) The case with the linear background wind in height.

The dispersion relation of the inertial gravity waves is given by

$$\omega^2 = f^2 + \frac{N^2 k^2}{m^2} \quad (5)$$

where ω is the intrinsic frequency of the wave and has no negative value without losing any generality, f is the inertial frequency, N is Brunt-Väisälä frequency, k is the horizontal wavenumber parallel to the wavenumber vector and m is the vertical wavenumber. It is noted that this dispersion relation

is valid only for hydrostatic waves. The intrinsic frequency ω is related to the observed frequency ω_{obs} as follows,

$$\omega = \omega_{\text{obs}} - U_h k, \quad (6)$$

where U_h is the mean wind parallel to the wavenumber vector. The vertical group velocity and vertical phase velocity are obtained from (5) and (6) as

$$C_{gz} = \frac{\partial \omega_{\text{obs}}}{\partial m} = -\frac{N^2 k^2}{\omega m^3} \quad (7)$$

and

$$C_z = \frac{\omega_{\text{obs}}}{m} = \frac{\omega + U_h k}{m} \quad (8)$$

respectively. Ignoring the Doppler effect of the mean wind, the vertical direction of energy propagation is different from that of the phase propagation. In the case of this inertial gravity wave, however, the directions are the same because of large Doppler effect of the mean wind compared with the intrinsic phase velocity.

On the other hand, the ratio of long to short axis of the ellipse presented in the hodograph gives the ratio of the intrinsic frequency of the inertial gravity wave to the inertial frequency (21 hours period at the MU radar site). In order to estimate the intrinsic frequency of this wave, we fitted a hodograph of the horizontal velocity vector to the shape of ellipse using the least squares method. The dotted line in Fig. 4 shows the result of the fitting. Since the data were filtered by a bandpass filter, components except for the inertial gravity wave (referred to as the "background") were approximately removed. However, it is difficult to remove the remaining "background". We have tried to validate the estimated parameters, by assuming two different simple functional forms and showing that the results are similar, that is, they are insensitive to the details of the assumed "background".

The assumed fitting function is

$$\begin{pmatrix} u(z) - U(z) \\ v(z) - V(z) \end{pmatrix} = \begin{pmatrix} \cos \psi & -\sin \psi \\ \sin \psi & \cos \psi \end{pmatrix} \begin{pmatrix} a \cos(mz + \varphi_0) \\ b \sin(mz + \varphi_0) \end{pmatrix}. \quad (9)$$

Here the following notations are used:

- a, b ; half lengths of the long and short axes of the ellipse,
- m ; vertical wavenumber,
- φ_0 ; phase at $z=0$,
- ψ ; inclination of the axis from the zonal direction,
- $u(z), v(z)$; zonal and meridional components of wind with periods of 2-7hrs,
- $U(z), V(z)$; zonal and meridional components of "background" wind profile.

Table 1. The parameters characterizing the structure of the inertial gravity wave obtained by fitting the hodograph. The units are m/s for a , b , U_0 , U_1 , V_0 , V_1 , and the value of the residual, km for λ_z , and degree for ψ and φ .

	a	b	$\lambda_z (= \frac{2\pi}{m})$	ψ	φ_0	U_0	V_1	V_0	V_1	Residual
(a)	3.4	2.0	3.7	57	66	2.4		1.3		0.31
(b)	3.4	1.6	3.4	53	352	4.6	-0.20	-4.2	0.55	0.21

The assumed "background" wind profile is

$$\begin{cases} U(z) = U_0 \\ V(z) = V_0 \end{cases} \quad (10)$$

for (a) and

$$\begin{cases} U(z) = U_1 z + U_0 \\ V(z) = V_1 z + V_0 \end{cases} \quad (11)$$

for (b), where U_1 , V_1 , U_0 , and V_0 are constant. The data used for the fitting are 12 points over the height range of 8.7–12 km. Table 1 represents the results. The results obtained by two methods are similar, suggesting that the parameters are plausibly estimated. The ratio of the inertial frequency to the intrinsic frequency of the wave obtained by b/a is 0.60 for (a) and 0.46 for (b), which is similar to the typical value, 0.2–0.4, in the stratosphere obtained using the data of the rocket observation by Hirota and Niki (1985). The intrinsic period ($2\pi/\omega$) of the wave is, therefore, estimated at 12 hrs for (a) and 9.7 hrs for (b).

The horizontal phase velocity is important for examining the interaction with the mean wind. We can estimate it using the dispersion relation of the inertial gravity waves (5), and the relationship between the observed and intrinsic frequency (6). We adapt $1.67 \times 10^{-3} \text{ sec}^{-1}$ (corresponding to 10 mins) as the Brunt-Väisälä frequency which was calculated from the temperature data obtained by sonde at Shionomisaki (150 km south of the MU radar site). Using m , ω , ω_{bv} , and the directions of energy and phase, we obtained U_h and k . The result is as follows:

$$\begin{aligned} \lambda_h = 2\pi/k &= 340 \text{ km}; & U_h &= 35 \text{ m/s} \cdots (a), \\ &= 220 \text{ km}; & &= 24 \text{ m/s} \cdots (b). \end{aligned}$$

The mean wind in the wavenumber direction U_h is close to the background wind when the inertial gravity wave appeared (see Fig. 2). The horizontal phase velocities corresponding to these horizontal wavenumbers are 27 and 18 m/s for (a) and (b), respectively. Note that these parameters characterizing the horizontal wave structure are very similar to the values assumed in the models of Matsuno (1982) and Holton (1982) including the effect of gravity

Fig. 5. Spatial variation of the zonal wind component. The dots show the component at each beam position. The solid line shows the mean profile over the scanned region.

waves, which simulated well the global wind structure in the middle atmosphere.

These estimated values are verified by examining the zonal variation of wind obtained by the multi-beam measurement. The zonal wavelength λ_x is obtained from the horizontal wavelength λ_h in the direction of the wavenumber vector by using

$$\frac{1}{\lambda_x} = \frac{1}{\lambda_h} \cos \psi. \quad (12)$$

It is 620 and 370 km for (a) and (b), respectively. Since the horizontal length of the region scanned zonally is about 11.5 km at the height of 10 km, the variation of the zonal wind should not be seen over the range if the estimated wavelength is correct. Figure 5 shows the variation of the zonal wind. The dots represent the zonal wind component at each beam position in the zonal scanned region, and the solid curve is the zonally averaged profile. The maximum deviation from the mean profile is about 0.8 m/s. Since the error in the radial velocity is

Fig. 6. Vertical profile of the ratio of upward to downward propagating component, in the period of the inertial gravity wave appeared.

about 0.1 m/s in this observation, the error in u is multiplied by the factor $(\sin \theta)^{-1}$ (θ : the zenith angle), and is about 0.6 m/s at $\theta = 10^\circ$. The real error in u may be a little larger than this value because the w component was ignored. This suggests that the variation of 0.8 m/s is within the error of u . Moreover, any systematic zonal variation of the wind could not be found. Thus the observed zonal variation of wind is consistent with the estimated values.

The results of the parameter estimation are also reconfirmed by examining the ratio of magnitude of the horizontal to vertical component. According to the theoretical consideration, the ratio is equal to that of the horizontal wavelength in the direction of the horizontal wavenumber vector to the vertical one. In the case of this gravity wave, the ratio of horizontal to vertical wavelength is of the order of 100, suggesting the vertical component corresponding to the horizontal amplitude of 3.4 m/s must be 0.034 m/s. Such a vertical component is too small to be detected by the measurement using the MU radar, which is consistent with the observation. Therefore, we confirm that the oscillation observed in Fig. 3 is due to the inertial gravity wave.

3.2 Source investigation

As mentioned in the previous section, the direction of the energy propagation is obtained by examining the direction of hodograph rotation at each height: Clockwise and anti-clockwise rotations indicate upward and downward propagation, respectively. Figure 6 shows the frequency of appearance

Fig. 7. Vertical time-section of the echo power observed by the east beam tilted by 30° from the zenith. Components with periods of less than 1 hour were removed. the contour interval is 5 dB.

of clockwise rotation at each height during 3:04–9:14 LST on 7th. The direction of rotation was judged in a small height range of 0.9 km. The ratio is less than 0.5 below 11 km and greater than this value above 11 km, suggesting that the gravity wave was originated near the height of 11 km. This is consistent with the fact that the energy of the inertial gravity wave is confined below the height of 11 km as shown in Fig. 3. The region of downward propagation in Fig. 6 stretches only for a few km. This is probably due to a small vertical group velocity of the gravity wave. In fact, according to the estimation using (7), the vertical group velocity ($5\text{--}8 \times 10^{-2}$ m/s) is very small compared with the horizontal group velocity (20–30 m/s). Thus it is possible that the gravity wave passed over the MU radar site before it propagated to lower altitude.

We examine the atmospheric condition near 11 km with some information obtained by this measurement. The echo-power profile describes the intensity of turbulence. Figure 7 shows the height-time section of the echo power measured using the beam tilted by 30° from the zenith. A layer having a strong echo power is observed near 11 km from 0:00 to 9:00 LST, when the inertial gravity wave was dominant. Since the zenith angle of the beam is large and the echo power of the layer is almost independent of the zenith angle, the echo at 11 km is not due to the effect of partial specular reflection which is frequently observed near the tropopause (Green and Gage, 1980). This suggests that the atmosphere is unstable near the height of 11 km and that severe turbulence occurs, which is probably related to the source of the inertial gravity wave. It is noted that there is an ascending layer of the strong echo

Fig. 8. Height-time section of the vertical shear of the horizontal wind. The contour interval is 5 (m/s)/km.

at 10:00. The echo is likely due to a front because we had a severe rainfall during the time the echo appeared.

Figure 8 shows the vertical shear of the horizontal wind, dV_h/dz , using the wind data of adjacent height ranges, that is,

$$\frac{dV_h}{dz} = \sqrt{\left(\frac{du}{dz}\right)^2 + \left(\frac{dv}{dz}\right)^2}, \quad (13)$$

where u and v are the zonal and meridional components of the wind, respectively. A large shear is observed at 3:00–13:00 LST on 7th with the maximum value of about 30 (m/s)/km at 7:00–8:00 LST. The time and height the large shear appeared are coincident with those for the strong turbulent layer, suggesting that the turbulence occurred due to the Kelvin-Helmholtz instability. We can examine the stability of the atmosphere quantitatively with the Richardson number. The Richardson number is defined as the square of the ratio of the Brunt-Väisälä frequency N to the vertical shear of the horizontal wind dV/dz . Using the temperature data measured with a sonde at Shionomisaki, we obtain N^2 of around 1.8×10^{-4} near 11 km. Although the temperature profile at Shionomisaki might be different from that at the MU radar site because of the distance of 150 km, the difference should not be so significant for rough estimation. The maximum value of the vertical wind shear calculated from the wind data is around 28 (m/s)/km near 11 km at 8:00 LST on 7th. Thus the Richardson number is estimated at 0.23, suggesting that the atmosphere has stability low enough for the Kelvin-Helmholtz instability to occur.

When we discuss the wind shear obtained with the VHF radar measurement, the finite range volume effect (referred to hereafter as FRVE) must be

Fig. 9. The detailed height profile of the echo power (a) and the vertical shear of the horizontal wind (b) at 8:00 LST on 7th, when and where the severe turbulent layer was observed.

noted (Fukao *et al.*, 1988a, b). The effect works when a thin turbulent layer is simultaneously located in several vertically-adjacent range volumes. Since we observed a large wind shear near 11 km where a strong turbulent layer located, the effect may be critical. However, we can explain by several features of the data that the effect is not significant in this case.

Figure 9-a is the detailed echo-power profile showing the turbulent layer when the large vertical shear of the horizontal wind appeared. The dots in the figure show the heights where the data were sampled. Large echoes are seen over at least 3 ranges near 11 km within a difference of 5 dB. When such a broad turbulent layer exists, the pretended shear due to FRVE should not appear at the center of the turbulent layer. However, Fig. 9-b shows that the peak of the large vertical shear of the horizontal wind exists just at the center of the layer. Another feature is the sign of the shear. The shear due to FRVE has a characteristic shape, that is, the magnitude of the horizontal wind is observed to be greater at the upper side of the turbulent layer, and smaller at the lower side. In this case, the vertical shears of the zonal and meridional wind components had opposite signs whereas the sign of each wind component was the same, which is inconsistent with the character of FRVE. And last but not least, the shear due to FRVE must be canceled after averaging in the height range suffering the effect. Judging from the fact that the horizontal winds below and above the height of the shear were apparently different, such a large shear as we observed must have existed. These

Fig. 10. Weather charts produced by objective analysis at 250 mb. The solid line shows isobar. The broken line shows isotherm.

facts suggest that FRVE is not significant for the present wind data near the height where the severe turbulent layer was observed.

Since the MU radar observation is available for only one location, we examine other types of data. Figure 10 shows the weather charts by the objective analysis at 250 mb, which were made by the Japan Meteorological Agency (JMA). The synoptic-scale pressure trough passed over the MU radar site during the observation. The phase of the advection of the northward wind is consistent with the observation by the MU radar, *i.e.*, the *v*-component strengthening at 6:00 LST (Fig. 2). The temperature profiles at from 9:00 LST on 6th to 12:00 LST on 8th measured by radio sondes at Shionomisaki are presented in Fig. 11. Each profile is shifted at the interval of 50°. The tropopause heights shown by ">" are about 11 km and slightly descending about 9:00 LST, which may indicate the occurrence of the tropopause folding related to the synoptic-scale pressure trough.

The height of the turbulent layer and the top of the inertial gravity wave propagating downward observed by the MU radar are almost the same

Fig. 11. Vertical profiles of the temperature at Shionomisaki.

as that of the tropopause. This suggests that the inertial gravity wave was closely related to the synoptic-scale pressure trough and occurred near the tropopause.

4. Concluding remarks

An inertial gravity wave related to a synoptic-scale pressure trough was revealed by observations with the MU radar. Twelve beams were scanned zonally to detect the zonal structure. By analyzing the MU radar data with fine height and time resolutions, the operational upper-air observation data by sondes, and the weather charts by the objective analysis, we have investigated the detailed structure and source of the gravity wave. The characteristics are as follows.

1. The inertial gravity wave propagated downward from the height of 11 km, where the tropopause located.
2. The horizontal wavelength is about 300 km and the horizontal phase velocity is about 20 m/s.
3. A severe turbulent layer and a large vertical shear in the horizontal wind were observed near the tropopause height, indicating that the atmosphere was unstable there.
4. During the measurement by the MU radar, the synoptic-scale pressure trough passed near the radar site. The gravity wave was

observed just before the northward wind migrated.

These results indicate that the synoptic-scale pressure trough is one of the possible sources of gravity waves. The mechanism of the occurrence of such gravity waves is an interesting problem. For example, we do not know why the gravity wave with such a scale was selected and occurred monochromatically. Re-examining the detailed structure including the temperature, which is measured simultaneously by sondes at the same location with the radar, may provide other useful information. Gravity waves are now regarded as important in the lower atmosphere as well as in the middle atmosphere. Drag effects due to gravity waves reduce some systematic errors in the general circulation models. It is interesting to examine the profiles of momentum fluxes due to gravity waves directly, using high-resolution data obtained with the VHF radars. Moreover, quantitative examinations of the seasonal variation of the wave activity and the momentum fluxes will also be important.

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MU レーダーにより観測された総観規模の気圧の谷に伴う慣性重力波 佐藤 薫

(京都大学理学部地球物理学教室)

総観規模の気圧の谷に関連した慣性重力波を MU(Middle and Upper atmosphere) レーダー観測により検出した。本研究では、特に風の東西変化も調べるため、MU レーダーの多数方向同時観測可能という特長を生かし、12 ビームを用いた東西スキャン観測を行った。風の水平成分のホドグラフ解析及び理論的考察により、この重力波は圏界面高度より下向きに伝播しており、水平波長は約 300km、水平位相速度は約

20m/sであることがわかった。これらのパラメータは観測で得られる東西風成分の空間変化など、この重力波に関するほかの情報と矛盾しない。

次にエコーパワーの高度時間断面を調べてみると、この重力波が現れていた期間、圏界面付近に強い乱流層があったことがわかった。この乱流層は同じ高度、同じ時間に観測された水平風の強い鉛直シアーに関連している。また、重力波の運動エネルギーは圏界面より下の高度に顕著であり、局所的な水平風の回転方向から求めた上向きと下向きの伝播方向の割合は圏界面付近で逆転している。したがって、この慣性重力波は低い安定度をもった圏界面付近から発生したものと考えられる。

観測期間中、総観規模の気圧の谷が MU レーダ上空を通過していた。重力波はその南風が入りこむ直前に観測されている。これらの結果は総観規模の気圧の谷が重力波の主要な発生源の一つであることを示唆するものである。