Effects of horizontal wind structure on a gravity wave event in the middle atmosphere over Syowa (69°S, 40°E), the Antarctic

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Key points

- Enhancement of gravity wave energy in the upper stratosphere and lower mesosphere was observed by Syowa lidar in the middle of August 2014.
- The enhancement was probably caused by the refraction of gravity waves emitted from various latitudes toward Syowa, due to the poleward tilting of the polar night jet with altitude.
- A depression of gravity wave energy during the enhancement could be induced by

critical level filtering due to a synoptic scale disturbance in the upper stratosphere.

Abstract

Nightly mean potential energy of gravity waves (GWs) per unit mass (E_p) over Syowa Station (69°S, 40°E) was calculated from temperature profiles observed by the Rayleigh/Raman lidar from 2011 to 2015. The E_p values in the upper stratosphere and lower mesosphere were significantly enhanced on August 8–21, 2014, except on August 12. A ray tracing analysis showed that large-scale GWs emitted from various latitudes could be refracted and forced to converge above Syowa due to the poleward tilting of the polar night jet (PNJ) with altitude. It should be noted that E_p on August 12 was smaller than the other values during the enhancement, despite similar PNJ conditions. A synoptic scale disturbance which passed on August 12 could have blocked the GWs from propagating upward through critical level filtering. These results suggest that convergence of the wave should be considered as a part of the intermittency of the GWs.

Plain language summary

Atmospheric waves of short horizontal scale, known as gravity waves (GW), transport momentum through the atmosphere from the Earth’s surface, and drive North-South circulations. These airflows profoundly influence the temperature structure at heights corresponding to the ozone layer. However, the small scale of GWs makes it necessary to artificially represent them in atmospheric models. GW activity is quite variable in space and time and the representation of this variation is a key to improve long-term climate forecasts. Previous observational studies mainly discussed variations of GW sources and wind filtering, but such variations do not explain the observations in this study. We suggest that the GWs generated at various latitudes converged to our observation area enhancing the local GW activity. Moreover, the convergence was found to be related to the structure of the polar night jet. This result suggests that the lack of wave horizontal propagation typical in model wave parameterizations could contribute to their cold bias and unrealistic representation of ozone hole over the Antarctic in spring.

Keyword: Gravity wave, Middle atmosphere, Lidar, Synoptic scale disturbance, Polar night jet, Intermittency.

1. Introduction.

Gravity waves (GWs) transport their energy and momentum vertically from the lower to upper atmosphere (Holton, 1983; Lindzen, 1981; Matsuno, 1982), which causes meridional circulation and influences temperature structures (Hitchman et al., 1989). The effect of the GWs is usually described by parameterizations in operational general circulation models (GCMs), because the GCMs cannot explicitly represent a full spectrum of GWs due to limitations of computational resources. However, GW parameters (e.g., local and temporal variation of GW activities) in the GW drag parametrization scheme are not well constrained by observations (Bühler and Mcintyre, 2003; Alexander et al., 2010; Hertzog et al., 2012; Gellar et al., 2013). In addition, parameterizations in most of practical GCMs take into account only vertical propagation of these waves neglecting horizontal propagation, which provides inaccurate magnitude, direction, and distribution of GW drag (Kalisch et al., 2014). In particular, some model studies such as Alexander et al. (2016), Dunkerton (1984) and Sato et al. (2009) highlighted that high GW activity near polar night jet (PNJ) are caused by the horizontal propagation of these waves. The GWs with westward wavenumbers are refracted toward the PNJ due to the meridional zonal wind shear and converge to this region. The unrealistic representation of the effect of the GWs in operational models causes a cold bias in winter and spring over the Antarctic, which leads to an unrealistic forecast of ozone depletion (Butchart et al., 2011; Garcia et al., 2017). Further observations to quantify actual GW characteristics, e.g., their amplitude, intermittency, and propagation are required in order to physically constrain the GW scheme. In particular, the observations near the southern PNJ region are important because of the uncertainty in the parametrization scheme and the high GW activity in this area. In addition, study of GW activity is easier in the southern PNJ region because sudden stratospheric warmings seldom happen.

Kogure et al. (2017) demonstrated seasonal and vertical variations of GW activity over Syowa Station in the Antarctic (69°S, 40°E), using a Rayleigh/Raman (RR) lidar during the period 2011 to 2013. However, they did not discuss shorter time variations, i.e., day-to-day variation. The present work focuses on a high activity event for August 8–21, 2014 which was discovered through a detailed analysis of 5 years of observational data.

The present paper is structured as follows: Observational systems and data sets are described in section 2. In section 3, evidence of enhanced GW activity in the upper stratosphere and the lower mesosphere (USLM) over Syowa on Augsut 8–21, 2014 is presented. We investigated the cause of this enhancement using meteorological reanalysis data and the results are presented in section 4. The conclusions are drawn in section 5.

2. Observation and Data Sets

The RR lidar was installed in January 2011 at Syowa by the 52nd Japanese Antarctic Research Expedition. Its transmitter is a pulsed neodymium: yttrium/aluminum/garnet laser (355 nm) with a 300 mJ pulse energy and a 20 Hz repetition frequency. Its receiver telescope has a primary mirror with an 82 cm diameter and is equipped with three photomultiplier tubes. For further details regarding this RR lidar system, see Suzuki et al. (2012). The RR lidar observed the photon count profiles at night since May 2011. In this study, the temperature profiles were derived and analyzed from 2011 to 2015 (except for summer periods).

The temperature profiles in an altitude of typically 10–80 km were derived from the photon counts acquired by the RR lidar, as was performed by Kogure et al. (2017). The effective vertical and temporal resolutions were 900 m and 1 h, respectively. A temperature perturbation associated with the GWs with vertical wavelengths (λ_z) in the range of 1.8–16 km and a period (τ) longer than 2 h (the Nyquist period) was derived from the temperature profile. The approach used was introduced by Kogure et al. (2017) and similar to a method of Duck et al. (2001). A background temperature profile which was estimated using a cubic polynomial function for the temperature corresponding to a 24 km altitude range, was subtracted from the observed temperature profile in order to derive the temperature perturbation of the GWs. The potential energy of the GWs per unit mass, E_p J kg^{-1}, was then calculated to measure the GW activity, as performed by Whiteway and Carswell (1994). For further details regarding this process and errors of the E_p values, see Kogure et al. (2017).

3. Result

Figures 1 (a), (b), and (c) show the nightly mean E_p at 40, 50, and 60 km altitudes, respectively, where the E_p values were logarithmically averaged over an altitude range of 5.4 km centered at the respective altitudes. This value increased by 2–3 times at each 10 km of altitude increase between 40 and 60 km altitudes and the winter (June to August) mean values at each altitude were 2–3 times larger than those of the fall (March to April) and spring (October) periods. These results are consistent with the results from previous studies in the Antarctic region (Kaifler et al., 2015; Kogure et al., 2017; Liu et al., 2014; Zhao et al., 2017). Most of the E_p values for the winter period were within $\overline{E_p}_{winter} \pm \sigma_{winter}$, i.e., 13.3–40.0 J kg^{-1} at 40 km, 23.4–61.4 J kg^{-1} at 50 km, and 65.2–186.9 J kg^{-1} at 60 km, where $\overline{E_p}_{winter}$ is the logarithmic mean of the nightly mean potential energy (E_p) in June–August for the five years and σ_{winter} is the logarithmic standard deviation of E_p. However, the most E_p values for August 8–21 in 2014 at 50 and 60 km altitudes were larger than $\overline{E_p}_{winter} + \sigma_{winter}$.

In order to investigate this enhancement in more detail, the plots for August 2014 are enlarged as shown in Figures 1 (d), (e), and (f). The E_p values at 40 km during that month are comparable to the other years. However, the E_p values at 50 and 60 km for August 8–21, 2014 (except for August 12) were larger than the winter mean by more than one standard deviation, i.e., larger than 61.4 J kg^{-1} at 50 km and 186.9 J kg^{-1} at 60 km, and the mean values in the periods at 60 km (506 J kg^{-1}) were about five times as large as the mean value for August 2015 (88 J kg^{-1}). Thus, in the next section, we highlight and discuss the causes of this enhancement for the observation period August 8–21, 2014 in addition to the depression on August 12.

4. Discussion

4.1 Convergence of the GWs due to the poleward tilting of the PNJ with altitude

One possible cause of the aforementioned enhancement is the existence of an additional GW source for August 8–21, 2014 between 40 and 50 km. The possible source is the spontaneous adjustment near the PNJ region, because it is difficult for other sources, e.g., shear instability, to excite large-scale GWs (Plougonven and Zhang, 2014).

Sato and Yoshiki (2008) and Murphy et al. (2014) suggested that large amplitude GWs observed in the lower stratosphere could be emitted by spontaneous adjustment near the imbalance of the PNJ. In order to investigate this possibility, a residual of the nonlinear balance equation ($|\Delta NBE|$), which indicates the degree of imbalance, was calculated at 1 hpa (~43 km altitude) and 0.5 hPa (~47 km altitude) above Syowa. This is a similar approach to Zhang (2004) from the modern-era retrospective analysis for research and applications (MERRA) (Rienecker et al., 2011). $|\Delta\mathrm{NBE}|$ values during the GW enhancement were 4.7×10^{-9} s^{-2} and 6.0×10^{-9} s^{-2} on average at 1 hPa and 0.5 hPa, which is smaller than the value for August 1–7, 2014 before the enhancement (9.0×10^{-9} s^{-2} at 1 hPa and 1.0×10^{-8} s^{-2} at 0.5 hPa on average) (not shown). Another possibility is that the observed GW enhancement over Syowa was caused by the convergence of GW packets propagating from lower and higher latitudes due to their meridional propagation. Since the GWs observed by the RR lidar have a long wave period, i.e., longer than 2 h, they can travel a long horizontal distance during their vertical propagation. We evaluated this possibility by analyzing the ray paths of the GWs based on the ray-tracing method of Dunkerton (1984) and comparing the results for the enhancement period (August 8–21, 2014) and August 2015. The nightly mean wind and temperature fields acquired from MERRA for each observation duration on August 8–21, 2014 and August 2015 were used as the background for the ray-tracing procedure. It was also assumed that the background fields were uniform in longitude. The GWs were emitted upward from 10 km altitude between 20° S and 80° S at 5°

intervals. An initial horizontal wavelength and ground-based period were assumed to be 1000 km and 10 h, respectively, because such large-scale GWs are typically detected by lidars (Gardner et al., 1998; Wilson et al., 1991). An initial *k* value, i.e., zonal wavenumber, was assumed to be negative, i.e., westward. The GWs with westward wavenumber in the lower latitudes than the PNJ are refracted to the higher latitudes due to the meridional gradient of zonal wind. On the other hand, the GWs in the higher latitudes are refracted to lower latitudes, i.e., such waves refracted toward the PNJ (Dunkerton, 1984; Ehard et al., 2017; Sato et al., 2009). Moreover, the GWs with eastward wavenumber generally encounter their critical level in the middle atmosphere. The initial *l* value, i.e., meridional wavenumber, was also assumed to be negative, i.e., southward, because the GW activity in the lower stratosphere, i.e., near the sources, at the lower latitudes (<69° S) is generally greater than the activity near the south pole regions (>69° S) (Alexander et al., 2016; Allen and Vincent, 1995; Tsuda et al., 2000). The initial direction of the horizontal wavenumber vector was, therefore, assumed to be south–westward.

Figure 2 shows the altitude-latitude sections of the nightly mean zonal wind at the longitude of Syowa (40°E) on (a) August 8–21, 2014 and the monthly mean wind in (b) August 2015. Solid and dashed lines indicate the parts of the rays where the GWs have a vertical wavelength within and outside of 1.8–16 km, respectively. In Figure 2 (a), most of the GWs converged over Syowa at approximately 55 km altitude. However, this is not the case in Figure 2 (b). This could be accounted for if the PNJ in Figure 2 (a) is tilted poleward with altitude from ~50° S to ~70° S and the waves with westward wavenumbers are refracted toward ~70° S. It should be noted that the PNJ region in Figure 2 (b) is tilted equatorward with altitude from ~40° S to ~60° S. Under such a condition, the waves are refracted toward ~40° S. We also checked the case in 2011, 2012 and 2013, but no convergence was found (not shown). This is probably because the PNJ did not tilt poleward with altitude. There is possibility that the GWs with other initial wave parameter contributed to the enhancement of E_p values, because some studies (e.g., Nicolls et al. [2010] and Chen et al. [2013]) report that the GWs with equatorward wavenumber propagated from the pole to mid-latitude. The paths of the GW with other initial wavenumber, ground-based period, and azimuth angle were also analyzed during the enhancement and August 2015 (not shown). The results during the enhancement show the convergence of GWs with 1000–2500 km horizontal wavelengths, 10–20 h ground-based periods and 205–230° azimuth angles (i.e., clockwise from North). The GW parameters were similarly varied for the case of August 2015. However, the GWs did not converge. Thus, we conclude that the enhanced GWs shown in Fig. 1 are due to the convergence of GW packets with south-westward wavenumber.

4.2 Critical level filtering by a synoptic scale disturbance on August 12, 2014.

The E_p value on August 12, 2014 was much smaller than the value of the other days during August 8–21 despite a similar tilted PNJ condition to the condition of Figure 2 (a). It is notable that the behavior of the meridional wind at Syowa on August 12 was unusual. Figure 3 shows a time-altitude section of the meridional wind over Syowa during the enhancement. The meridional wind at approximately 50 km altitude was primarily confined to −40 and 0 m s^{-1} on the lidar observation days. However, on August 12 the meridional wind changed drastically from +56 m s^{-1} to −70 m s^{-1}. Horizontal maps of these winds at 0.5 hPa near this meridional wind change are shown in Figure 4. A meridional wind disturbance with ~4000 km horizontal scale is clearly seen near Syowa, which moved eastward. The passage of this disturbance drastically changed the meridional wind from −80 m s^{-1} to +80 m s^{-1} in a region between 55 and 75° S, throughout which the GWs with a non-zero meridional wavenumber could easily reach their critical level. Thus, it is concluded that the depression of the GW activity on August 12 was likely due to the passage of a synoptic-scale disturbance in the upper stratosphere over Syowa.

5. Conclusion.

The nightly mean E_p over Syowa Station (69° S, 40° E) was calculated from temperature profiles observed by the RR lidar over a five-year period from 2011 to 2015, except for the summer periods. It was observed that $\mathrm{E_p}$ for August 8–21, 2014, except on August 12, was significantly larger than the winter mean. The results of ray-tracing analysis revealed the possibility of convergence of large-scale GWs with the south-westward wavenumbers near ~55 km altitude over Syowa, which were emitted from various latitudes. This suggests that the GWs were refracted toward Syowa by the poleward titling of the PNJ region with altitude. It was also observed that the E_p value obtained on August 12 was the smallest recorded value during the enhancement. This depression of the GW activity could be caused by a synoptic disturbance passing over Syowa.

This study demonstrated that the GW activity in the Antarctic upper stratosphere and lower mesosphere can be significantly enhanced by meridional propagation of the GWs, i.e., refraction and suppressed by local wind fields due to a synoptic-scale disturbance, i.e., critical level filtering. Although horizontal propagation has not been taken into account for the GCMs, it has the potential to cause day-to-day variations of the GW activity; in other words, intermittency of the GWs.

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Figure 1

Day-to-day variations of the nightly mean E_p at (a) 40, (b) 50, and (c) 60 km. The purple, green, yellow, red, and blue asterisks indicate the E_p values in 2011, 2012, 2013, 2014, and 2015, respectively. The dashed lines indicate $\overline{E_p}_{winter} \pm \sigma_{winter}$. The variations for August are enlarged at (d) 40, (e) 50, and (f) 60 km.

Figure 2

Latitude-altitude sections of the nightly mean zonal wind acquired from MERRA in (a) August 8–21, 2014 and (b) August 2015. Black and white lines indicate rays of the GWs whose vertical wavelength can and cannot be observed by the RR lidar, respectively. Arrows indicate the latitude of Syowa.

Figure 3

Time-altitude section of meridional wind at Syowa acquired from MERRA. The bars on the top indicate the observation time ranges of the RR lidar and a red bar indicates the results for August 12, 2014.

Figure 4

Meridional wind fields acquired from MERRA at 0.5 hPa at (a) 18 UT August 12 and (b) 00 UT August 13, 2014. The red star represents the location of the Syowa Station.