Seasonal and Interannual Variation of Mesospheric Gravity Waves Based on MF Radar Observations over 15 Years at Syowa Station in the Antarctic

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Abstract

The seasonal and interannual variations of the gravity waves (GWs) in the Antarctic mesosphere were examined using horizontal wind data at altitudes of 50–100 km above the medium frequency (MF) radar at Syowa Station (69.0°S, 39.6°E). The climatology of the GW variance reached a maximum in winter over a wide altitude range of 64–90 km, and the interannual variability was large below 80 km in spring and autumn. These features are consistent with observations from previous studies. In addition, we detected a weak but significant maximum in the GW variance in the height range between years with strong tropical precipitation and years with weak tropical precipitation. Moreover, we examined three possible mechanisms underlying the GW interannual variability observed in summer. The first mechanism was modulation by stratospheric sudden warmings in the Arctic through inter-hemispheric coupling, and it was not clearly observed at Syowa Station. The second mechanism was modulation of the vertical filtering of GWs in association with the breakdown of the polar vortex in the Southern Hemisphere, and it was identified as a potential mechanism. The third mechanism was tropical convection and propagation to the Antarctic region, and it was identified as another likely mechanism of interannual variability in the GWs. This result was supported by the consistency between years with strong tropical precipitation and years with large GW variances at Syowa Station.

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1. Introduction

In the mesosphere, gravity waves (GWs), tides (TWs), and planetary waves (PWs) drive meridional circulation by transporting momentum and heat and forming a thermal structure that is considerably different from what is formed through radiative balance. Thus, the seasonal and interannual variations in the mean fields should be closely related to variations in these mesospheric waves. To examine the seasonal and interannual variations of short period waves, such as GWs and TWs, long-term observational data with sufficiently high time resolutions are needed. Such data have recently become available for the Southern Hemisphere (SH) high latitudes from the MF radar observations that began in the 1990s. The MF radar has continuously operated at Syowa Station (69.0°S, 39.6°E) since March 1999, and it has provided horizontal wind at altitudes of 50–120 km in the mesosphere and lower thermosphere for approximately 17 years. Limura et al. (2011) reported seasonal variations and trends in the TWs observed at Syowa Station. Murphy et al. (2007) examined the climatology of the PWs at Davis Station (68.3°S, 77.6°E) for three wave period ranges and discussed their differences. Dowdy et al. (2007) defined GWs as fluctuations with wave periods from 20−480 min and examined their seasonal variations using MF radar data from 1994−2005 at Davis Station and from 1999−2003 at Syowa Station. The climatology of the GW wind variance exhibited a maximum at altitudes of 70−95 km in winter and increased with height. Here, u and v represent the GW zonal and meridional wind components, respectively. A characteristic seasonal variation in the zonal wind was also observed at Syowa Station. Hibbins et al. (2007) reported similar results for the periods 1997−1998 and 2002−2005 for Rothera Station (67.3°S, 68.8°W). However, these previous studies did not include detailed analyses of interannual variability.

In the present study, the seasonal and interannual variations of the GWs in the Antarctic are analyzed using 15 years (1999−2013) of wind data measured by the MF radar at Syowa Station, and the potential mechanisms underlying the summer interannual variability are examined.

2. Data and analysis

Horizontal winds from the MF radar at Syowa Station from 26 March 1999 to 31 December 2013 were analyzed. The time interval of the data was 10 min, and the height resolution was 4 km, although this resolution was over-sampled every 2 km. Although the data were archived for altitudes from 50−120 km, only data below 90 km were used because horizontal winds detected by MF radars are known to be underestimated above approximately 90 km (Tsutsumi and Aso 2005).

The GW components were extracted from the original data as follows. First, we obtained the TW components. Daily time series for each local time were constructed, and the long-period components were obtained from the daily time series by using a low-pass filter with a cutoff period of 30 days. These daily time series at their respective local times were rearranged to reconstruct time series at the original 10-min intervals, and the daily mean values were subtracted. Fluctuations with 24, 12, 8 and 6 h periods were designated as TWs and extracted using a least squares fitting method. The climatology of the TW zonal and meridional variances exhibited strong maxima in March and October and a weak maximum in May. The maximum value was approximately 300 m² s⁻² in March at approximately 90 km for both wind components. Next, the TW components were removed from the unfiltered original time series, and the GW components were extracted further using a high-pass filter with a cutoff period of 24 h. Although the inertial period, which is the lower limit of the GW intrinsic periods at Syowa Station, was approximately 13 h, we used 24 h as the cutoff period because the observed wave periods can be Doppler-shifted by the mean flow. Moreover, the GWs are known to be under-estimated above approximately 90 km because of a significant increase in the electron density. Therefore, the analyses of the

3. Results

3.1 Climatology and interannual variability of the mean winds

Figures 1a, c show the climatology and Figs. 1b, d show the interannual variability of the unfiltered zonal and meridional winds observed by the MF radar from 64–100 km, a region in which there is a small amount of missing data. Note that it is known that horizontal winds observed by MF radars are usually underestimated above approximately 90 km because of a significant increase in the electron density. Therefore, the analyses of the
GW characteristics in the subsequent sections were performed for altitudes below 90 km. The interannual variability was reported as variances of the daily mean winds and smoothed by a 10-day running mean. The climatology and interannual variability were also determined below 64 km using the MERRA data at (69.4°S, 39.4°E).

In summer, the mean zonal wind ($\bar{u}$) was westward below about 95 km and maximized ($\sim -44.6$ m s$^{-1}$) at about 80 km, it was weakly eastward above 95 km. In winter, the $\bar{u}$ was eastward in the displayed height region, and a wind reversal was not observed, although a reversal may occur above this region. The mean meridional wind ($\bar{v}$) in summer was strongly equatorward and maximized ($\sim 12.4$ m s$^{-1}$) at about 88 km. In winter, the $\bar{v}$ was poleward below 90 km and stronger than 5 m s$^{-1}$ below 70 km. A weakly equatorward $\bar{v}$ was observed above 90 km, and the lower boundary of the equatorward $\bar{v}$ propagated downward after the beginning of August. These mean wind features are consistent with the results in Dowdy et al. (2007).

The interannual variability of the $\bar{u}$ was large above 80 km in summer, particularly in November and December, whereas it was large below 80 km in winter. The height region with large variability moved gradually upward in winter (see the upper level contour of 100 m$^2$ s$^{-2}$), and similar features were observed for $\bar{v}$, although its summer variability was not as large.

### 3.2 Climatology and interannual variability of GW variance

Figures 2a, b, c show the climatology of the $u\sigma_u^2$, $v\sigma_v^2$, and $uv\sigma_{uv}$, and Figs. 2d, e, f show the normalized interannual variabilities (i.e., variances in the $u\sigma_u^2$ and $v\sigma_v^2$, normalized by their squared climatology) that were averaged for the 64–92 km height range.

![Fig. 1.](image1.png)

Fig. 1. (Top) Climatology of the mean zonal (a) and meridional (c) winds observed by the MF radar at an altitude from 64 km to 100 km at Syowa Station and obtained with the MERRA reanalysis data for altitudes below 64 km near Syowa Station (69.4°S, 39.4°E), and (bottom) the interannual variability of the zonal (b) and meridional (d) winds. To clarify the features, a 10-day running mean was applied.

![Fig. 2.](image2.png)

Fig. 2. (Top) Climatology of the (a) $u\sigma_u^2$, (b) $v\sigma_v^2$, and (c) $uv\sigma_{uv}$ and (bottom) their interannual variabilities ((d)–(f)). The interannual variability for (a) [(b)] is defined as the variance of $u\sigma_u^2$ [$v\sigma_v^2$] in the respective years and normalized by the square of the climatology of $u\sigma_u^2$ [$v\sigma_v^2$].
Smoothing was performed using a low-pass filter with a cutoff of 30 days for all of the figures. Both the $\vec{u}^2$ and $\vec{v}^2$ climatologies maximize in mid-winter, and these features were consistent with those of Rothera Station reported by Hibbins et al. (2007). They use a similar definition of GWs to ours. However, the variance at Syowa Station is smaller. Dowdy et al. (2007) showed that the climatology of the $\vec{u}^2 + \vec{v}^2$ using a different GW definition (i.e., wave periods of 20–480 min) maximized in winter. In Fig. 2a, another weak maximum occurs in $\vec{u}^2$ in summer in the 70−78 km region.

The interannual variability of the $\vec{u}^2$ and $\vec{v}^2$ was large in winter below 80 km (not shown) where large $\vec{u}^2$ and $\vec{v}^2$ are observed (Figs. 2a, b). However, the normalized interannual variabilities presented different features (Figs. 2d, e) and were large in any season below 80 km and enhanced from spring to autumn for the $\vec{u}^2$ and in summer from November to February for the $\vec{v}^2$.

Figure 2c shows the $\vec{u}^2 + \vec{v}^2$ and its interannual variability. Note that the interannual variability was not normalized because the $\vec{u}^2$ and $\vec{v}^2$ can have positive and negative values. It is clear that $\vec{u}^2 < 0$ in summer and $\vec{v}^2 > 0$ in winter below 85 km, whereas above 85 km, $\vec{u}^2$ and $\vec{v}^2$ are consistent with previous works (e.g., Tsuda et al. 1990; Sato 1994), respectively. If we assume that dominant GWs have intrinsic zonal phase speeds with signs that are opposite to that of the $\vec{u}$ and that the GW energy propagation is mainly upward, which is consistent with previous works (e.g., Tsuda et al. 1990; Sato 1994), then the $\vec{u}^2 < 0$, ($\vec{v}^2 > 0$) and $\vec{u} < 0$, ($\vec{v} > 0$) values below 85 km in summer (winter) indicate that $l < 0$, ($l > 0$). Thus, these results suggest that the mesospheric GWs at Syowa Station propagate energy poleward in both summer and winter.

4. Discussion: Possible causes of interannual variability of GW variance in summer

A novel finding of this study is the occurrence of significant interannual variability in the GW wind variances in summer, and this feature is particularly obvious for the meridional wind variances. We examined three possible mechanisms that could potentially cause the observed interannual variability.

4.1 Interhemispheric coupling initiated by stratospheric sudden warmings (SSWs) in the Northern Hemisphere (NH)

First, the relation with SSW in the NH was examined. According to Körnich and Becker (2010), when a SSW occurs in the NH, GWs with eastward phase speeds can propagate upward and break in the NH mesosphere, where they weaken the winter poleward residual mean flow. Thus, a positive temperature anomaly occurs in the equatorial mesosphere. The resulting latitudinal gradient in the SH mesosphere weakens, and the westward mean wind in the SH mesosphere weakens following the thermal wind balance. Thus, GWs tend to break at lower altitudes, which causes the wave force in the upper mesosphere to weaken in the SH. As a result, the upwelling weakens and a positive temperature anomaly occurs in the SH polar region.

According to this scenario, GW activity in the upper mesosphere in the SH should weaken following an SSW in the NH, with a time lag that may be 4−10 days (Könich and Becker 2010; Karlsson et al. 2009). In addition, if the residual mean flow is mainly driven by the momentum flux divergence caused by GWs, the response to the SSW should be observed as a negative anomaly of the time (i.e. Eulerian) mean meridional flow (e.g., Sato et al. 2013). Thus, we examined the meridional winds and GW zonal wind variances in the height region of 70−86 km from Day = −20 to Day = +30 relative to each SSW central date (Day = 0). However, statistically significant common features with confidence levels greater than 90% were not observed among eleven SSW events that occurred from December to February during the analyzed time period. Figures 3a, b show the composite time and height sections of the GW zonal wind variance anomaly and the meridional wind anomaly, respectively, and the gray hatches denote a 50% significance level. The GW zonal wind anomaly was weakly positive, and the meridional wind anomaly was positive from Day = +5 to Day = +10. This feature was inconsistent with the theoretical expectation discussed by Körnich and Becker. This inconsistency may have been caused by limitations in the statistical analysis because the data were collected at insufficient number of SSW events and only one location and/or may indicate that the interhemispheric coupling scenario is not so simple. Thus, further studies using a combination of simultaneous observations at multiple locations and high-resolution model studies are necessary; however, such work is beyond the scope of the present paper.

4.2 Critical level filtering in the vertical in the stratospheric mean wind

GWs that propagate from the troposphere can suffer critical-level filtering by mean stratospheric winds before reaching the mesosphere. Lübken et al. (2014) showed that the timing of the zonal wind decrease associated with the stratospheric polar vortex breakdown in spring was consistent with the onset of polar mesospheric clouds (PMC), and the temperature decrease around the mesopause. These authors proposed that the simultaneous changes in the two separate height regions could be explained by an increase in the eastward forcing by GWs that can propagate into the mesosphere after the stratospheric winds have weakened; however, they did not show observational evidence of the GW modulation.

Figure 4a shows the time series of the GW zonal wind variance climatography averaged over the 70−80 km altitude range from the MF radar (solid line) and time series of the climatology of the zonal wind maximum in the stratosphere (300 hPa–1 hPa) at the grid nearest to Syowa Station from MERRA (dashed line) as a function of the calendar month. We also produced a composite time series of the same quantities shown in Fig. 4a but with reference to the stratospheric final warming (SFW) date (Fig. 4b). The SFW date for a particular year was defined as the first day when the stratospheric wind maximum decreased below 15 m s$^{-1}$ and remains less than 15 m s$^{-1}$ until January 1 of the next year.
SFW date in the climatology (Fig. 4a) is 4 December, whereas the dates for the years of 2000–2013 range from 7 November to 31 December. In the composite time series in Fig. 4b that references the SFW date, the GW zonal wind variance rapidly increased at approximately Day = 0, and this result is consistent with Lübken et al. (2014)’s theoretical prediction. A similar but relatively gradual increase in the mesospheric GW variance was also observed for the climatological time series shown in Fig. 4a. However, the difference was not statistically significant (not shown in detail), which can be attributed to various processes that contribute to interannual variability, such as GW sources and troposphere filtering.

4.3 Propagation of GWs originating from tropical convection

One of the primary GW sources is convection in the troposphere. According to the theoretical calculations of Sato (2000), GWs originating from tropical convection and propagating upward and poleward (as well as in a zonal direction) can reach the polar region in the upper stratosphere and above. As an index of the convection activity, we used the precipitation data from the Global Precipitation Climatology Project (GPCP) (Adler et al. 2003) that were averaged over 0°E–80°E in December and January. Sato showed that the more poleward the propagation direction of the GW packet is, the lower altitude the packet reaches in the polar region. Thus, we selected a longitude region that was close to Syowa Station (39°E) and as wide as possible to obtain a statistically meaningful result. We examined the GW meridional wind variance for this analysis because GWs propagating poleward should be dominant.

Figure 5a shows the precipitation levels averaged over the longitudes 0°E–80°E from December to January as a function of latitude and year. Figure 5b shows the GW meridional wind variance averaged for December to January as a function of height and year.

It is seen that both precipitation levels and GW meridional wind variance exhibited strong interannual variability. The precipitation levels were strong in the tropical region and the interannual variability of the regions near the equator and around 15°S were different. It is worth noting here that the GWs originating from the latter convective region were less affected by filtering by the quasi-biennial oscillation (QBO) zonal winds at the equator because the half maximum half-latitudinal width of the QBO winds is approximately 12° (e.g., Andrews et al., 1987). Thus, if the GWs originating from convection at around 15°S reach the polar mesosphere, their interannual variations would be consistent with that of the convective activity. In fact, Fig. 5b shows that the GW activity was strong in 2002, 2003, 2006 and 2009 at and slightly below 75 km when strong precipitation was observed at around 15°S. To confirm this point, we constructed a time series of the GW meridional wind variance observed at Syowa Station and averaged over an altitude of 72–76 km (thick solid curve) and the precipitation averaged over a longitude of 0°E–80°E and latitude of 10°S–20°S (thick dashed curve) and the precipitation averaged over a longitude of 0°E–80°E and latitude of 0°S–9°S (thin long dashed curve). All of the quantities are averages for the austral summer period from December to January.
corresponded to years exhibiting strong precipitation over the 10°S–20°S range. A time series of the precipitation averaged over the 0°S–9°S range is also shown by the thin long dashed curve in Fig. 5c. It is clear that a better correlation with the GW meridional wind variance is observed for the precipitation averaged over the 10°S–20°S range than that over 0°S–9°S. In contrast, the correlation between the GW meridional wind variance and the years with strong precipitation at mid-latitudes was obscure (Fig. 5a). These results strongly suggest that the GWs generated by tropical convection reach the polar mesosphere. This inference is also consistent with the implication of the $\nabla^2 u$ sign detected by the MF radar (discussed in Section 3.2).

It is also worth noting that the GW variance above an altitude of 75 km did not clearly correspond to the tropical convection, particularly in 2006. This result may have been influenced by a weak meridional wind layer at approximately 76 km (Fig. 1c), which may have acted as a critical level for the GW spectrum reaching the mesosphere. The characteristics of the GW spectrum depend on the mechanisms that generate GWs from convection; however, such an investigation is beyond the scope of this paper.

5. Summary

We examined the climatology of the GW horizontal wind variance and its interannual variability using MF radar observations from Syowa Station over 15 years. The GW variance maximizes in winter for the 64–90 km altitude range, which is consistent with the results of previous work. In addition, a weak maximum in the GW zonal wind variances was observed in summer, especially for the 70–78 km altitude range. This study provides the first report of the occurrence of this summer maximum, and additional analyses of the possible mechanisms underlying the interannual variability of the GW variance in summer were performed.

First, the potential interhemispheric modulation of the GW variance by SSWs in the NH in winter was examined; however, a significant modulation was not detected. Second, the potential modulation of the mesospheric GW variance by critical level filtering in the stratospheric zonal winds in the SH was examined, and a composite time series identified a rapid increase in the GW zonal wind variance near the SH final warming date, whereas the increase was gradual for the climatology of the GW variance, suggesting that modulation by SH stratospheric winds with interannual variations in spring was also a possible mechanism. Finally, a potential modulation of high-latitude GW activity by a tropical convection was examined using precipitation as an index of the convective activity, and we found that the years with large mesospheric GW meridional wind variances corresponded to years when the tropical precipitation was strong. This result suggests that a significant component of the mesospheric GWs in the SH polar region originated and propagated poleward from the tropical convection. Moreover, the sign of the meridional flux of the zonal momentum observed by the MF radar supported this inference.

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