Weakening of Polar Mesosphere Winter Echo and Turbulent Energy Dissipation Rates After a Stratospheric Sudden Warming in the Southern Hemisphere in 2019

M. Kohma¹, K. Sato¹, K. Nishimura², and M. Tsutsumi²

¹Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo, Tokyo, Japan, ²National Institute of Polar Research and the Graduate University for Advanced Studies (SOKENDAI), Tokyo, Japan

Abstract  Time variations in the polar mesosphere winter echo (PMWE) volume reflectivity and turbulent energy dissipation rates are examined during the sudden stratospheric warming (SSW) in September 2019 in the Southern Hemisphere. It was found that the frequency of PMWE occurrence decreased from early September to October, when the SSW occurred. We also found that the frequency of large turbulent energy dissipation rates (> 3 × 10⁻³ m²s⁻³) was reduced compared to the average for 2016–2018. This is likely due to the modulation of gravity wave (GW) propagation by the minor SSW, resulting in less GW breaking, which is the main source of the turbulence. This suggests that the decrease in turbulence intensity is at least partly responsible for the decrease in the frequency of PMWE.

Plain Language Summary  Polar mesosphere winter echoes (PMWEs) are coherent echoes from a height of 50–80 km observed by very high frequency clear-air Doppler radars. We examine the time variations of PMWE and turbulence intensity associated with a sudden stratospheric warming in September 2019 in the Southern Hemisphere. We found that the PMWE occurrence frequency and turbulence intensity were reduced during and after the stratospheric warming. Assuming that the PMWEs are attributable to scattering echoes from turbulence in the ionized atmosphere, weak turbulence intensity will lead to a decrease in the frequency of PMWE. Furthermore, we discuss the reason why the stratospheric warming affects turbulence by performing a simple theoretical diagnostic of gravity wave propagation.

1. Introduction

Polar mesosphere winter echoes (PMWEs) are coherent echoes from a height of 55–80 km observed by very high frequency (VHF) clear-air Doppler radars in both hemispheres (Czechovsky et al., 1989; Ecklund & Balsley, 1981; Morris et al., 2011). Previous studies suggested that PMWEs are attributed to strong air turbulence in the weakly ionized atmosphere, although other processes including damped acoustic waves may also play a role (Kirkwood, 2007; Lübken, 2014; Lübken et al., 2006, 2007; Tsutsumi et al., 2017). Thus, from the spectral widths of the PMWEs, the turbulent energy dissipation rates characterizing the turbulence intensity can be estimated (Hocking, 1983; T. Sato & Woodman 1982). Kohma et al. (2020) investigated the seasonal variation of turbulent energy dissipation rates based on four-year observations of PMWEs in the Antarctic region. They found that turbulent energy dissipation rates in the polar mesosphere are maximized in austral winter and that the winter-to-summer transition of the turbulent energy dissipation rates occurs in September. It is inferred that the transition is related to the change in gravity wave (GW) activity associated with the decaying polar vortex (e.g., Yasui et al., 2016). However, the year-to-year variability of PMWEs and turbulent energy dissipation rates has not yet been fully investigated.

The most prominent interannual variability in the polar middle atmosphere is the stratospheric sudden warming (SSW), which is a spectacular phenomenon associated with the rapid breakdown of the polar vortex, and is theoretically explained by means of the wave-mean flow interaction on a planetary scale (Haynes, 2005). While a major SSW occurs on average twice per 3 years in the Arctic region, only one major SSW and one minor but strong SSW with a deceleration of zonal mean zonal winds of about 60 m s⁻¹ are known to have occurred (thus far) in 2002 and 2019, respectively, in the Antarctic region. This is due to relatively weak planetary wave activity in the Southern Hemisphere (SH) compared to the Northern Hemisphere. Previous studies showed the significant impacts of SSWs on the global-scale meridional circulation.
in the troposphere and stratosphere (e.g., Baldwin & Dunkerton, 2001; Eguchi & Kodera, 2007), as well as in the mesosphere (e.g., Karlsson & Becker, 2016; Manney et al., 2009; Tomikawa et al., 2012). The deceleration of a westerly, and/or wind reversal, in the winter stratosphere associated with SSW modifies the wave forcing of GW and Rossby waves. The modulated wave forcing affects the meridional overturning circulation in the mesosphere by modulating the wave propagation characteristics.

There are a few previous studies on the influence of SSW on the turbulent energy dissipation rates in the mesosphere. Hoffman et al. (2007) examined the turbulent kinetic energy dissipation rate ($\varepsilon$) using the Saura MF radar at Andoya (69.3°N, 16.0°E) during and after the Arctic SSW in January 2006. They pointed out the enhancement of $\varepsilon$ in the recovery phase of the westerly after the SSW. More recently, Triplett et al. (2018) showed from rocket-borne ionization gauge measurements at Poker Flat Research Range (65°N, 147°W) that the energy dissipation rates in the mesosphere decreases after the Arctic minor warming in January 2015. The present study examines the time variations of the PMWE and turbulent energy dissipation rates associated with the SSW in September 2019 in the Antarctic using PMWE observations by the Program of the Antarctic Syowa Mesosphere-Stratosphere-Troposphere/Incoherent Scatter (PANSY) radar, a VHF clear-air Doppler radar being operated at Syowa Station (69.00°S, 39.35°E) (K. Sato et al., 2014). Since a detailed description of the dynamical field in the austral spring of 2019 was documented in previous studies, such as Noguchi et al. (2020) and Rao et al. (2020), the present study focuses mainly on the modulation of the PMWE frequency and turbulent energy dissipation rates. In order to clarify the uniqueness of the SH mesosphere in 2019, observations for the 3 years of 2016–2018 are also examined. To our knowledge, the present analysis is the first investigation of the interannual variability of the PMWE and energy dissipation rates in the Antarctic mesosphere. Furthermore, we discuss the reason why the SSW affects the PMWE and turbulence by performing a simple theoretical diagnostic of GW propagation using a reanalysis data-set.

2. Data

The PANSY radar is the first (and currently only) Mesosphere-Stratosphere-Troposphere/Incoherent Scatter radar in the Antarctic region (K. Sato et al., 2014) that can detect PMWEs. Continuous observations have been made by a partial system of the PANSY radar since April 30, 2012. The radar has been in full-system operation since late September 2015. In the present study, we used observation data from the full radar system for August through October in the four-year period of 2016–2019. The radar parameters for this period are described in Kohma et al. (2020). Details of the PANSY radar system are given in K. Sato et al. (2014). The range resolution is 600 m along the beam direction. The time resolution is approximately 70 s, whereas the observation time intervals are approximately 200 s because of interleaving of the observations for the troposphere and stratosphere. We used the data from vertical beam measurements in order to avoid possible spectral broadening caused by the vertical shear of horizontal winds (shear broadening) (Fukao et al., 2014).

The calculation of the radar volume reflectivity $\eta$ was performed following K. Sato et al. (2014, 2017). The minimum $\eta$ detectable by the PANSY radar is on the order of $10^{-18}$ m$^{-1}$ (Kohma et al., 2020). The turbulence parameters were derived from the spectral widths of the PMWE following Hocking (1983) and T. Sato & Woodman (1982). The detailed procedure for calculating the turbulent velocity variance is described by Kohma et al. (2019; 2020), where beam broadening was subtracted by an algorithm developed by Nishimura et al. (2020). This algorithm does not assume antenna symmetry and can be applied to observations with an irregular beam pattern. The velocity variance due to turbulence in a stably stratified flow is related to the energy dissipation rate $\varepsilon$ as follows (Hocking, 1983; Weinstock, 1981): $\varepsilon = \varepsilon_g \nu^2 N$, where $\nu^2$ and $N$ is the velocity variance and buoyancy frequency, respectively. In the present study, $N$ and $\varepsilon_g$ were set to 0.02 s$^{-1}$ and 0.45, respectively, as typical values. In order to examine the impact of the minor SSW on the mesospheric turbulence in September 2019, the present study focused on the period from August to October, although PMWEs are frequently observed in March through October over Syowa Station (Kataoka et al., 2019; Kohma et al., 2020; Nishiyama et al., 2018; Tsutsumi et al., 2017).

In addition, horizontal wind fields from the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2, Gelaro et al., 2017) were used for analyses of GW propagation characteristics.
3. Results

3.1. Polar Mesosphere Winter Echo Frequency

Figure 1a through Figure 1d show time-height sections of daily mean PMWE volume reflectivity for August through October of 2016–2019. The PMWEs are observed in the height range of 55–82 km, and most frequently at 65–75 km. In all four years, the PMWE frequency in October is small compared to that in August. It is found that the PMWE frequency of 2019 is smaller in mid- and late September than those in 2016–2018.

Time-pressure sections of zonal mean zonal winds at 69°S from MERRA-2 are also shown in the lower row of Figure 1. In August, a strong westerly jet at a pressure range of 1–10 hPa and a maximum wind velocity greater than 80 m s$^{-1}$ are seen in 2016–2019. In early September of 2019, the westerly rapidly decelerated in the middle stratosphere through the lower mesosphere and easterly winds are observed at 0.1–1 hPa in mid-September associated with the SSW. After that, easterly or weak westerly winds persisted at 0.1–5 hPa until October. The timing of the appearance of the easterly in the lower mesosphere largely corresponds to that of the decrease in PMWE frequency.

In contrast, in 2016, 2017, and 2018, westerly winds are observed in August through September in the entire pressure range. The westerly gradually weakens in September, and then wind reversals occur in the upper stratosphere and lower mesosphere in October. As in September 2019, the appearance of the easterly winds in the lower mesosphere in October 2016–2018 is also accompanied by a decrease in the PMWE frequency. In this way, in 2019, wind reversal to easterly winds in the lower mesosphere occurred approximately one month earlier than in the other years, and the timing of the decrease in the frequency of PMWE appearances was also approximately one month earlier.

Note that decrease in PMWE frequency is not always accompanied by a weak westerly or wind reversal in the stratosphere and lower mesosphere. For example, the PMWE frequency becomes small in mid-September of 2016 and early August of 2018, while strong westerly is maintained at 0.1–100 hPa. Since the PMWE appearance depends on the background electron density, which varies with magnetic/ionospheric disturbances (e.g., Lübken et al., 2007; Tsutsumi et al., 2017), the temporary decrease in the PMWE frequency might be related to variations in electron density.
In order to investigate the difference in the PMWE and turbulent energy dissipation rates before and after the minor SSW, we chose September 6, when the zonal wind reversal was observed at 0.1–0.5 hPa, as the onset date of the minor SSW in the present study. Note that the onset day is approximately two weeks earlier than the central date of the SSW defined by the highest temperature at 10 hPa at 70–90°S (e.g., Noguchi et al., 2020). In the following analyses, comparisons of the periods of August 6–September 5 (Period A) and of September 6–October 5 (Period B) are performed. The results for the average of 2016–2018 are also shown for reference. We confirmed that the results do not change significantly even if the analyzed period is shifted by 5 days. The height range of 65–75 km, where the PMWE is most frequently observed, is the focus.

Figure 2. (a–b) Histograms of the logarithm of $\eta$ in the height range of 65–75 km in (a) August 6–September 5 (Period A) and (b) September 6–October 5 (Period B) for 2019 (red) and the average of 2016–2018 (gray). Red (black) vertical lines indicate the median values for 2019 (2016–2018). (c–d) Same as (a–b), but for the logarithms of $\varepsilon$.

Figure 2a shows histograms of the logarithm of volume reflectivity in Period A for 2019 (red) and for the average of 2016–2018 (gray). The histograms are normalized by the total number of possible data points in the height range of 65–75 km in the analyzed period. The histograms for 2019 and the average for 2016–2018 are quite similar. Both are approximately log-normal, with a cutoff in the left tail. The median $\eta$ is slightly larger in 2019 ($2.4 \times 10^{-17}$ m$^{-1}$) than the median for 2016–2018 ($2.1 \times 10^{-17}$ m$^{-1}$). A significant difference is observed for Period B (September 6–October 5), that is after the warming onset date in 2019, as shown in Figure 2b. It can be seen that the frequency for each bin is roughly half as large for 2019 as for the average for 2016–2018.

Figures 2c and 2d show histograms for the logarithm of $\varepsilon$. In Period A, the distributions for $\varepsilon$ in 2019 and the average for 2016–2018 are similar and have almost the same median values ($2.3 \times 10^{-2}$ m$^2$s$^{-3}$). Note that the negatively skewed distributions for $\varepsilon$ estimated from the PMWE spectral widths are mainly due to the
fact that PMWE at night and at high altitudes can only be detected when $e$ is large (Kohma et al., 2020). In Period B, the frequency for $e$ greater than $3 \times 10^{-4} \text{m}^2\text{s}^{-3}$ is smaller in 2019 than the average for 2016–2018, while there is little difference in the frequency for $e$ smaller than $3 \times 10^{-4} \text{m}^2\text{s}^{-3}$. This means that the decrease in the frequency of large $e$ values is mainly responsible for the small PMWE frequency in Period B of 2019. In fact, the median value of $e$ for 2019 ($5.6 \times 10^{-3} \text{m}^2\text{s}^{-3}$) is smaller than that for the average for 2016–2018 ($8.8 \times 10^{-3} \text{m}^2\text{s}^{-3}$). Assuming that PMWEs are attributable to scattering echoes from turbulence in the ionized atmosphere, weak turbulence intensity will lead to small $\eta$, and thus a decrease in the frequency of detected PMWEs. Note that the time variation of the PMWE frequency is not only attributable to the turbulence intensity, but also to the electron density and Schmidt number (e.g., La Hoz & Havnes, 2008; Lübken et al., 2014). The decrease in PMWE appearance in September 2019 may be related to the time variations of electron density and/or electron diffusivity. Several previous studies have suggested that weak mesospheric circulation associated with the SSW results in weakening of the downwelling in the polar winter mesosphere, as well as a reduction in meteoric dust (e.g., Marsh et al., 2013), which may play a role in electron diffusivity. Nevertheless, the decrease in frequency for large $e$ after the SSW shown in our analyses indicates that the weakening of the turbulence intensity is at least partly responsible for the decrease in the frequency of PMWE.

### 3.2. Gravity Wave Propagation Characteristics After the Minor Sudden Stratospheric Warming

Since the main source of turbulence in the mesosphere is GW breaking, the variation of turbulent energy dissipation rates in the mesosphere is likely related to the modulation of GW activity associated with the SSW (Kogure et al., 2021). In this section, we discuss the wave propagation characteristics in Periods A and B using the Hines' critical circle, which is defined as a circle drawn to have the background horizontal wind vector as a diameter (Dunkerton, 2015; Hines, 1992, 1997). For waves with a phase velocity vector that coincides with a point on the circle, the component of background wind in the direction of horizontal wave propagation equals the horizontal wave phase velocity, and thus the intrinsic phase velocity is equal to zero. Thus, any wave whose phase velocity lies on the circle will cease propagating. Hines (1992) applied the concept of the critical circle to vertical profiles for horizontal winds from a VHF radar and evaluated GW breaking in the mesosphere.

Using the critical circle, we performed a diagnostic regarding the transparency of GW propagation. First, the daily mean horizontal wind from the reanalysis data (Figure 3a) over the pressure range of 250–0.1 hPa is drawn as a hodograph. This pressure range corresponds to the range from the stratosphere (approximately 11 km) to the lower mesosphere (approximately 65 km). The reanalysis data are interpolated vertically at a constant log-pressure height interval of 1 km in to avoid the effects of the original uneven vertical interval. Second, critical circles are drawn for each level (Figure 3b) to map phase velocities that are blocked

![Figure 3](image-url)
in this height range. Third, we made a 0 / 1 distribution in the phase-velocity space, where 1 indicates an area where critical circles do not traverse, and 0 indicates otherwise (Figure 3c). The binning is performed in polar coordinates \((c_p, \theta)\), where \(c_p\) is the magnitude of the horizontal phase velocity, and \(\theta\) is the angle representing the direction of the phase velocity vector. The bin sizes are 5 m s\(^{-1}\) and 2° for \(c_p\) and \(\theta\), respectively. Figure 3c shows an example of the 0 / 1 distribution. Note that, for the purpose of clear visualization, the bin sizes in the plot are 5 m s\(^{-1}\) and 5° for \(c_p\) and \(\theta\), respectively. The red area indicates 0 (not transparent), whereas the white area indicates 1 (transparent). In the red area, GWs cannot propagate from the troposphere to the mesosphere because they encounter their critical levels at some pressure levels. The 0 / 1 distributions are made for each latitude/longitude point, and 0 / 1 distributions are averaged over the longitude range of 30–50°E and then over a latitude range of 60–80°S. The temporal average is performed over the analyzed periods (i.e., Period A and B). The averaged value is referred to as the probability of GW arrival \(p(c_p)\), where \(c_p\) is the horizontal phase velocity vector. Note that a small \(p(c_p)\) means that GWs with that phase velocity have a lower chance to propagate from the troposphere to the mesosphere.

Before proceeding, we note briefly the assumptions used in the present diagnostics: (a) GWs propagate only in the vertical direction. In other words, lateral propagation is negligible; (b) most GWs in the mesosphere originate from the troposphere; and (c) GW reflection is negligible. The lateral propagation of GWs has been ignored in most GW parameterization schemes, although it is important for the distribution of the momentum deposited by GWs, particularly in the polar winter mesosphere (e.g., K. Sato et al., 2009). Since the zonal mean zonal winds up to 30 hPa do not differ between Periods A and B in 2019 (Figures 1c and 1d), the effect of modulation in horizontal shear due to the SSW is not expected to have a significant effect on the time variation of the GW activity. Secondary generation of GWs, especially around the polar night jet, can occur (e.g., Vadas et al., 2018). However, the secondary GWs generally have smaller amplitudes than primary GWs and the occurrence frequency of the secondary generation is still unclear. Wave reflection occurs only for non-hydrostatic GWs, which usually have small horizontal wavelengths comparable to or smaller than the vertical wavelengths. The present diagnostic ignores such waves and focuses on hydrostatic waves. Note that the value of \(p(c_p)\) depends on the bin size of the 0 / 1 distribution and the vertical resolution of the reanalysis data. However, a slight change in the bin size or vertical resolution does not change the results significantly. We also confirmed that the results for the entire longitude range are quite similar to those averaged over the local longitude range. Lastly, we note that, although the wave breaking condition used in the present analyses ignores the Coriolis effect (Hines, 1997), it is considered that the inclusion of the Coriolis effect (i.e., Jones critical level) only slightly changes the results below.

Figures 4a and 4b show the probability of arrival of GWs \(p(c_p)\) at 0.1 hPa from the 250 hPa level for Periods A and B of 2019. It is found that \(p\) with an eastward phase velocity tends to be small compared with the values for a westward phase velocity in both periods. The minimum values of \(p(<0.1)\) are found for a small eastward phase velocity, whereas \(p\) is larger than 0.8 in the phase-velocity space for \(c_{px} < -20\) m s\(^{-1}\), where \(c_{px}\) is the eastward component of \(c_p\). This is because the westerly is dominant in the lower stratosphere (Figure 1h) making the atmosphere less transparent for GWs with eastward phase velocities. Interestingly, in Period B, GWs with \(|c_{px}| < 10\) m s\(^{-1}\) have a lower chance to propagate to the mesosphere compared to those in Period A (Figure 4c). The difference is attributable to the dominance of easterly winds in the upper stratosphere and lower mesosphere in Period B (Figure 1h). In contrast, the atmosphere is more transparent for GWs with \(c_{px} > 20\) m s\(^{-1}\) to propagate to the mesosphere in Period A than Period B (Figure 4c). However, the differences for \(p\) with a phase velocity larger than \(20\) m s\(^{-1}\) might be of less importance because the frequency of GWs with such a large phase velocity is quite small (Yoo et al., 2018; Yoshiki et al., 2004).

In order to discuss this more quantitatively, we place an assumption on the probability density function (PDF) of upward propagating GWs in the lower stratosphere. According to previous studies using radiosonde observations (e.g., Yoo et al., 2018; Yoshiki et al., 2004), the PDF of ground-based phase speed of GWs around 10 km altitude in the Antarctic coastal region has a peak around 0 m s\(^{-1}\). It is noted that radiosonde observations suffer from the effects of instrumental filtering (Alexander, 1998) and that the GW phase speed spectrum could be more complex than described below. However, the assumed character used here
provides a starting point for this analysis. In the present study, the probability density is assumed to have a two-dimensional Gaussian shape centered on a phase velocity of zero, that is,

\[ p(\vec{c}_p) = \frac{1}{2\pi\sigma^2} \exp \left( -\frac{c_{\text{v}}^2 + c_{\text{p}}^2}{2\sigma^2} \right), \]

where \( \sigma \) is the variance of the distribution and \( c_{\text{p}} \) is the meridional component of \( \vec{c}_p \). Based on previous observational studies (e.g., Yoshiki et al., 2004), \( \sigma \) is set to 5 m s\(^{-1}\) in the present analyses. The results are qualitatively similar if we take \( \sigma = 10 \) m s\(^{-1}\). Note that the PDFs for Periods A and B are assumed to be same, which is reasonable since the tropospheric winds for both periods are not significantly different (Figures 1c and 1d). Then, we define \( T(c_p) \) (dimensionless) as the probability of GW arrival multiplied by the PDF of upward propagating GWs. Figures 4d and 4e show \( T(c_p) \) in Periods A and B of 2019. As expected, the difference in \( p \) for a phase velocity smaller than 15 m s\(^{-1}\) (Figures 4a and 4b) is emphasized in the \( T \) distributions due to the Gaussian probability density centered at the origin. The integral of \( T \) over the entire phase-velocity space is calculated for evaluating possible GW activity. The integrated \( T \) value in Period B of 2019 is 0.248, which is approximately half as large as that in Period A (0.437). Furthermore, the integrated values in Period B (Period A) for 2016, 2017, and 2018 are 0.473, 0.405, and 0.437 (0.466, 0.528, and 0.460), respectively. These results suggest that GWs are less likely to propagate into the mesosphere in Period B of 2019.
In summary, under several assumptions, including the PDF of upward propagating GWs and propagation direction, the modulation of the propagation characteristics associated with the SSW is clearly shown. This result is consistent with those of previous observational studies showing that the GW activity weakens with the decay of the polar vortex (Kaifler et al., 2015; Kogure et al., 2017). A sufficient number of GWs propagating into the polar mesosphere will induce instabilities due to the amplification associated with upward propagation (e.g., Dunkerton, 1987; Klostermeyer, 1991). Since GW breaking is the main source of turbulence, the weakening of the GW activity is likely to reduce the turbulent energy dissipation rates and, consequently, the PMWE frequency. Note that the analysis using Hines’ critical circle can be used to study propagation characteristics of secondary GWs as well as GWs from the troposphere if an appropriate PDF can be given.

4. Summary and Concluding Remarks

Using the four years of PANSY radar data, we examined the characteristics of the time variations of PMWE volume reflectivity and turbulent energy dissipation rates associated with the minor SSW in the SH that occurred in 2019. Such interannual variability of PMWE and turbulent energy dissipation rates in the mesosphere in the Antarctic region has not been investigated in previous studies. The obtained results can be summarized as follows:

1. A significant decrease in PMWE frequency is observed after the SSW. Note that, to our knowledge, the decrease in PMWE associated with stratospheric warming events, even for the Arctic, has not been reported in previous studies.
2. The frequency of turbulent energy dissipation rates greater than $3 \times 10^{-4}$ m$^2$s$^{-3}$ is significantly reduced after the SSW. This suggests that the decrease in PMWE is attributable to the decrease in frequency of strong turbulent energy dissipation rates.
3. Using a simple theoretical model diagnostic based on the Hines’ critical circle, it is shown that a small number of GWs can propagate from the troposphere to the mesosphere during and after the SSW as compared to that before SSW, as well as compared to that in the other 3 years for the same time period. The GW propagation characteristics during and after warming onset should be related to weakening of the turbulent energy dissipation rates, and consequently the decrease in PMWE frequency.

Data Availability Statement

The PANSY radar observational data in this study are available at https://doi.org/10.5281/zenodo.4661609 and https://doi.org/10.17592/002.2020070384. The MERRA-2 data-set (M2I3NPASM) is provided by NASA's Global Modeling and Assimilation Office (https://disc.sci.gsfc.nasa.gov/uuid/data-sets?keywords=MERRA-2.,NASAGESDISC,2020).

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