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Key Points:
- Unusual increase of stratosphere temperature and amplitude of PW were observed in SH during the 2019 SSW, more severe than in the 2002 SSW
- A long-lasting (~20 days) mesosphere zonal wind reversal is noted before the peak SSW, and the mesosphere was greatly affected by the SSW
- KSS meteor radar observations detected the signature of 14- to 22-day PWs before the SSW and 8- to 12-day PWs following the SSW

Supporting Information:
- Supporting Information S1

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Unusual Changes in the Antarctic Middle Atmosphere During the 2019 Warming in the Southern Hemisphere

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Abstract A rare sudden stratosphere warming (SSW) occurred in the Southern Hemisphere polar region in 2019. The polar stratosphere temperature and planetary wave (PW) enhancements are found to be unusual from the history for 40 years; hence, it is an "Extremely-Rare" SSW. The distinct features of the mesosphere winds were observed during the SSW, in association with the traveling PWs in the stratosphere. The mesosphere zonal winds reversed for about 20 days before the peak SSW. Meteor radar (MR) and Modern-Era Retrospective Analysis for Research and Applications (MERRA)-2 observations indicate that the zonal wind reversal was descended with time, and the reversal was larger over ~72°S than the MR site (62°S). The MR detected the PWs of 14–22 days before and 8–12 days following the SSW in the mesosphere. We further noticed the enhancement of wavenumber 1 signature in the mesosphere during the peak SSW over the polar region. Thus, the polar middle-atmosphere is greatly affected by the SSW.

1. Introduction

In recent years, the sudden stratospheric warming (SSW) attained generous attention by the researchers due to its role in changing the Earth's atmosphere from the surface to the upper atmosphere on both the hemispheres (Pedatella et al., 2018). The SSW in the Northern Hemisphere (NH) is a fairly common phenomenon (Butler et al., 2017) but is very rare in the Southern Hemisphere (SH), due to the geographical conditions (Andrews et al., 1987). Thus far, one major SSW in 2002 (e.g., Baldwin et al., 2003) and a minor SSW in 2010 (Eswaraiah et al., 2016) have been reported and studied in earnest.

In 2019, the stratosphere modelers forecast the unexpected increase of temperature in the upper atmosphere of the SH polar region and stated that it will be a very rare warming over the SH and stronger than 2002 major SSW (Lewis, 2019; Rao et al., 2020). Yamazaki et al. (2020) provided the observational evidence of 2019 SSW. Further, the present warming over the SH has an eminent significance as it occurred during the descending easterly phase of the Quasi-Biennial Oscillation (QBO) since the QBO shows its effects on the modulation of the polar vortex strength and PWs (Lu et al., 2019; Niranjan Kumar et al., 2019; Watson & Gray, 2014). It has been known that the SSWs in the early spring are more intense, associated with larger planetary wave (PW) amplitudes for the easterly phase of the QBO (Anstey et al., 2010; Holton & Austin, 1991).

Although the mechanism of the SSW has been well noted (Matsuno, 1971), ambiguity still exists in its classification (Andrews et al., 1987; Butler & Gerber, 2018; Charlton & Polvani, 2007). The recent short-term forecast modelers with much more updated capabilities are facing a problem in defining the SSW: whether it is a wind reversal phenomenon, or a temperature gradient change event (Kim et al., 2017). Savenkova et al. (2017) classified the SSW based on the zonal wind reversal in the upper stratosphere as "High Stratosphere Warmings (HSW)." The HSW events usually show stronger impacts on the mesosphere and lower thermosphere (MLT) region in comparison with the traditional major SSW (Savenkova et al., 2017).

Since the first observational evidence of the mesosphere response to the SSWs (Quiroz, 1969), numerous studies have been made on the mesosphere coupling with the polar stratosphere during the SSW in the NH high and midlatitudes (e.g., Charlton & Polvani, 2007; de Wit et al., 2015; Medvedeva et al., 2019). However, similar studies for the SH are by far fewer than for the NH (Eswaraiah et al., 2018). A handful of studies have investigated the MLT thermal structure and dynamics during the 2002 major SSW (e.g., Cho et al., 2004; Dowdy et al., 2004) and in the 2010 minor SSW in the SH (Eswaraiah et al., 2016, 2017, 2018). Aside from the 2010 minor SSW, a minor SSW was noticed in 1988 in the SH, but it was fainter than the 2010 SSW (Kanzawa & Kawaguchi, 1990; de Laat & van Weele, 2011).

In the present communication, for the first time, we report the observational evidence of the 2019 SSW in the SH and its possible effects on the Antarctic mesosphere using meteor radar observations at King Sejong Station (KSS) (62.22°S, 58.78°W), Antarctica, and data from Modern-Era Retrospective Analysis for Research and Applications (MERRA).

2. Data

To investigate the SSW characteristics, we used the daily zonal mean zonal wind and temperatures of the MERRA, Version 2 (MERRA-2) (Gelaro et al., 2017) from the surface to the highest available pressure level of 0.01 hPa (~80 km) during 1 July to 12 October 2019. The pressure levels of MERRA-2 data are shown in equivalent log-pressure heights. The PW amplitudes at 10 hPa at 60°S are estimated from the Geopotential heights of MERRA-2 (used in the supporting information).

For the mesosphere study, we used wind measurements by the KSS Meteor Radar (MR). The radar has been operating in an all-sky interferometric mode with 33.2 MHz and 12 kW, detecting ~30,000 to 40,000 meteors per day (Kam et al., 2019; Kim et al., 2010). The KSS MR provides winds from the altitude 70 to 100 km with 1 hr and 2 km height resolutions (Lee et al., 2013). In the present study, we used the KSS MR winds from 1 July to 12 October 2019. We also utilized Geopotential height anomalies from the Microwave Limb Sounder (MLS) measurements (Livesey et al., 2018).

3. Results and Discussions

3.1. Characteristics of the 2019 SSW

Figure 1 displays the SH polar stratosphere temperature, zonal winds, and amplitudes of PWs at 10 hPa estimated from the MERRA-2. For the quantification of the changes that occurred in 2019, the corresponding parameters during the 2002 major SSW are also shown. Figures 1a and 1b presents the daily variability of the polar cap (80–90°S) zonal mean temperature and the zonal mean zonal wind at 60°S, respectively. Figures 1c and 1d show growing amplitudes of PW 1 ($k = 1$) (PW1), and Wave 2 ($k = 2$) (PW2) at 60°S, respectively. We further compared the temperature, and PW amplitudes, with the 40 years (1979–2018) mean and standard deviation (SD) values from the MERRA-2. The SD has shown with the shaded region. The mean value estimation of the PW amplitudes includes the SSW years (1988, 2002, and 2010).

The onset of warming was observed on 30 August 2019 (Figure 1a) with a sudden rise in the temperature (~29 K) within 4 days and attained a peak value on 17 September 2019. During the warming period (~20 days) the total temperature increment observed was ~66 K. Wherein 2002, the increment in the polar cap temperature was ~50 K from the control day and the SSW lasted about a week. However, the wind reversal at 10 hPa (Figure 1b**)** was not observed in 2019, instead, it occurred between 10 and 1 hPa, but the magnitude (ΔU) of the wind weakening at 10 hPa is larger (~72 m/s) than 2002 (~66 m/s). Further, it can be noted that the anomalous amplification of PW1 is larger than in 2002 in the first week of September (Figure 1c**)**. However, the amplitudes of PW2 stayed at lower values (Figure 1d**)**. The unusual growth of PW1 indicates a strong disturbance in the southern polar vortex (Evtushevsky et al., 2019; Watson & Gray, 2014). The strong growth of the PW1 during 2019 could be due to the easterly phase of QBO in the SH tropical region (Anstey et al., 2010). Habitually in the SH the warmings occurred in late spring (Allen et al., 2003; Eswaraiah et al., 2016), but in 2019, the SSW occurred early in spring. Further, the amplitude of PW1 (Figure 1c) during 2019 was substantially amplified and is well outside the SD during the winter and in early spring (June–September) with a peak in the first week of September. The amplitude of PW2 (Figure 1d) moderately increased in August. Thus, the state of the Antarctic stratosphere during the 2019 winter and spring was unusual due to the large enhancement of the PWs. Noguchi et al. (2020) observed the effect of 2019 unusual warming due to PW1 enhancement in the B-D (Brewer-Dobson) circulation through the tropical and polar stratosphere temperature change.

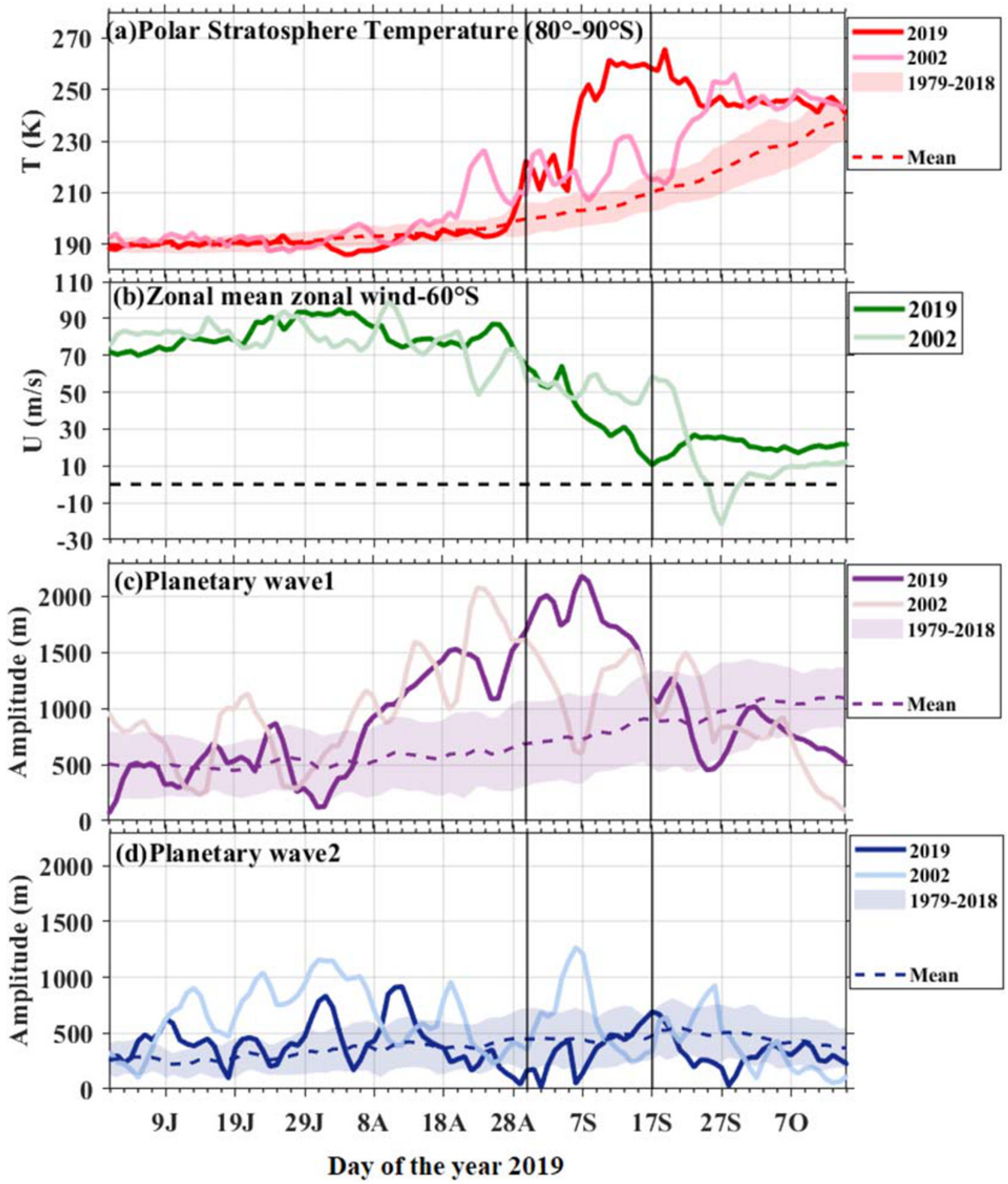

Figure 1. The daily mean variability of the (a) zonal mean polar stratosphere temperature (80–90°S), (b) zonal mean zonal wind at 60°S, and (c) amplitude of the Planetary Wave 1 ($k = 1$), (d) amplitude of the Planetary Wave 2 ($k = 2$) at 60°S obtained from MERRA-2 data set for the 2019 SH winter. The parameters of 2002 SH winter are also shown for the comparison. The 40 years (1979–2018) mean and the standard deviation (temperature and planetary waves) is shown with a shaded region. All the parameters are estimated at 10-hPa level. The vertical lines indicate the starting and peak warming days. The dashed horizontal line in (b) indicates the zero wind level.

Though the zonal wind did not reverse at 10 hPa at 60°S, the unusual changes observed in the polar temperature and PW1 enhancement are indicative of the preconditioning to set up the major SSW. Based on WMO criteria, Yamazaki et al. (2020) named the 2019 SSW as a minor SSW. The present 2019 warming features are more similar to HSW (Savenkova et al., 2017). Past studies (Matsuno, 1971) suggested that the source of the PWs for the SSW could be located in the troposphere. However, the recent studies (Birner & Albers, 2017; de la Cámara et al., 2017) have shown that they originate in the stratosphere or above the tropopause. Besides, the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre predicted the zonal wind reversal in the upper stratosphere (~2 hPa) rather than at 10 hPa during 2019 (www.cpc.ncep.noaa.gov/products/stratosphere/strat-trop). Based on the above discussions, we suggest that the warming recorded in 2019 is a rare minor SSW but similar to a major SSW.

3.2. Mean Winds During the 2019 SSW

Figures 2a and 2d displays the day-height contour of the daily mean zonal and meridional winds obtained from the KSS MR, respectively. Figures 2b and 2c show the zonal winds from the MERRA-2 between 0 and 75 km over the KSS MR grid (62°S, 58.75°W) and other polar grid (72°S, 58.75°W) point, respectively. Thus, Figures 2a and 2b together display the daily mean zonal winds from the surface to 100 km over the KSS MR location. The vertical dashed lines in each panel mark the onset and peak SSW days. Usually, in the mesosphere (75–90 km), eastward zonal winds dominate in the winter over the Antarctic (Lee et al., 2013), and the zonal wind transition (east to west) occurs in mid-October. However, during the 2019 SSW, the lower mesosphere zonal winds (75–85 km) (Figure 2a) exhibit episodic weakening with many brief periods of westward winds. These wind variations are unusual and may be attributed to the high PW activity associated with the SSW. The MERRA-2 data over the KSS radar location (Figure 2b) showed the eastward dominant winds in the lower mesosphere (60–75 km) until the onset of the SSW and started weakening afterward; later the wind reversed westward 5 days before the peak SSW. We further observed the zonal wind reversal in the stratosphere just above ~32 km (Figure 2b). However, at 72°S (Figure 2c) the mesosphere zonal winds started westward on the onset day of the SSW and descended up to ~32 km on the peak SSW day. The descending westward winds during the SSW period and wind reversal at ~32 km (10 hPa) at the polar region (72°S) could be attributed to the strong upward propagation of PWs. This suggests that 2019 SSW has shown major SSW features near the polar region (72°S).

Further, both the KSS MR and MERRA-2 data indicated that the mesosphere wind reversal occurred almost 2 weeks earlier than the peak SSW and descended at the polar region (62°S and 72°S). Thus, the 2019 SSW showed the long-lasting effects on the mesosphere, which was never seen before (Dowdy et al., 2004; Eswaraiah et al., 2016). The meridional winds (Figure 2d) were northward up to 85 km during zonal wind reversals after significant north-south fluctuations in the winter. The meridional wind fluctuations are evidence for the existence of PWs in the mesosphere. Following the SSW, strong northward winds prevailed at all the heights.

3.3. Stratosphere-Mesosphere Coupling

To see the connection between the stratosphere and mesosphere, Figures 3a and 3b display the daily mean zonal winds at 78 km from KSS MR and the zonal winds of MERRA-2 over KSS MR grid (62°S, 58.75°W) in the lower mesosphere (60, 70 km) along with the zonal mean zonal wind at 10 hPa and 60°S, respectively. Figure 3c depicts the variability of the zonal winds at 32, 60, and 70 km at other polar grid (72°S, 58.75°W). The mean and SD of the mesosphere zonal winds at 78 km of the non-SSW years 2007–2014 are also shown in Figure 3a for comparison. To eliminate short-period oscillations in the mesosphere winds, a 3-day running average has been applied. The 2019 zonal winds at 78 km (green) deviate from the usual mean zonal wind (black) during August and up to the peak SSW. After the peak SSW, the 2019 zonal winds follow the usual response of the zonal winds within the SD. The 2019 zonal winds (78 km) started wind reversal from 30 August, when the 10-hPa zonal winds at 60°S began to weaken, and reached a maximum wind reversal (~10 m/s) on 4 September, afterward they varied intermittently until the peak SSW. The moderate increment of eastward winds in the mesosphere during the warming period is a usual phenomenon (Eswaraiah et al., 2016). The magnitude of the mesosphere wind reversal in 2019 is comparable to the 2002 major SSW (Dowdy et al., 2004).

The zonal winds over the KSS MR grid (62°S, 58.75°W) (Figure 3b) started weakening on 26 August along with 10-hPa zonal wind and attained peak reversal ~2 and 5 days before the peak SSW, respectively. The zonal wind reversal observed at 60 km is ~5 m/s and at 70 km is ~10 m/s, and they returned to eastward direction after the peak SSW. Hence, the amount of zonal wind reversal is higher above 70 km over the KSS MR location. However, at the polar region (72°S, 58.75°W) (Figure 3c) the mesosphere zonal wind reversal started on the onset day of SSW, and the peak reversal was observed at 70 km (~11.5 m/s) and 60 km (~23 m/s) ~15 and 8 days before the peak SSW, respectively. Afterward, they turned eastward. The 10 hPa (~32 km) zonal wind at 72°S (Figure 3c) started weakening on the onset of SSW and reversed westward

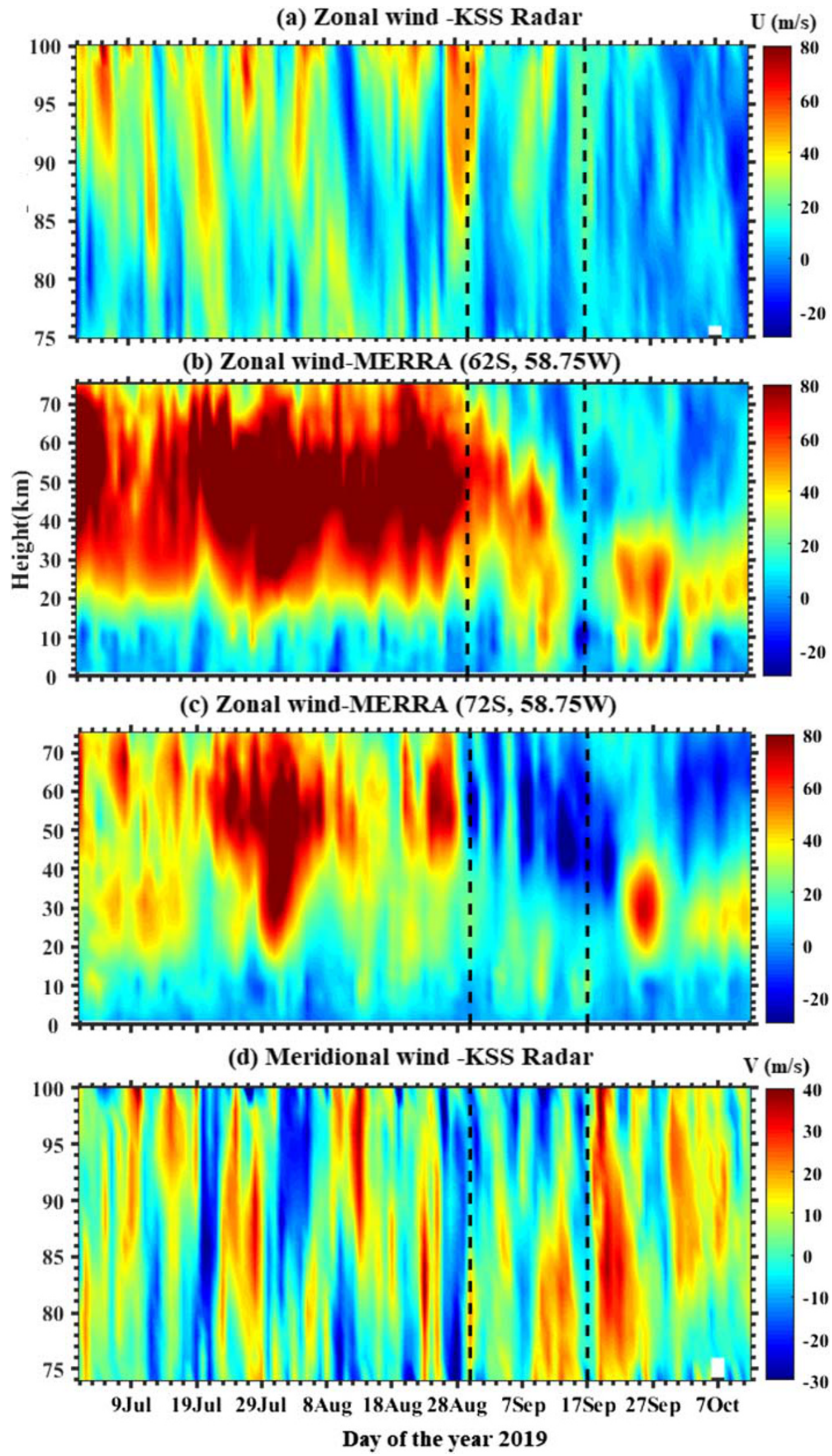

Figure 2. (a) The time-height contour of the daily mean zonal wind obtained from 1 July to 12 October 2019 using KSS MR shown from 75–100 km. (b) Same as (a) but using MERRA-2 data obtained nearby the KSS MR grid (62°S, 58.75°W) and shown from the surface to 75 km. (c) Same as (b) but at 72°S, 58.75°W polar grid point. (d) Same as (a) but for meridional winds using KSS MR. The vertical dashed lines indicate the starting and peak warming days.

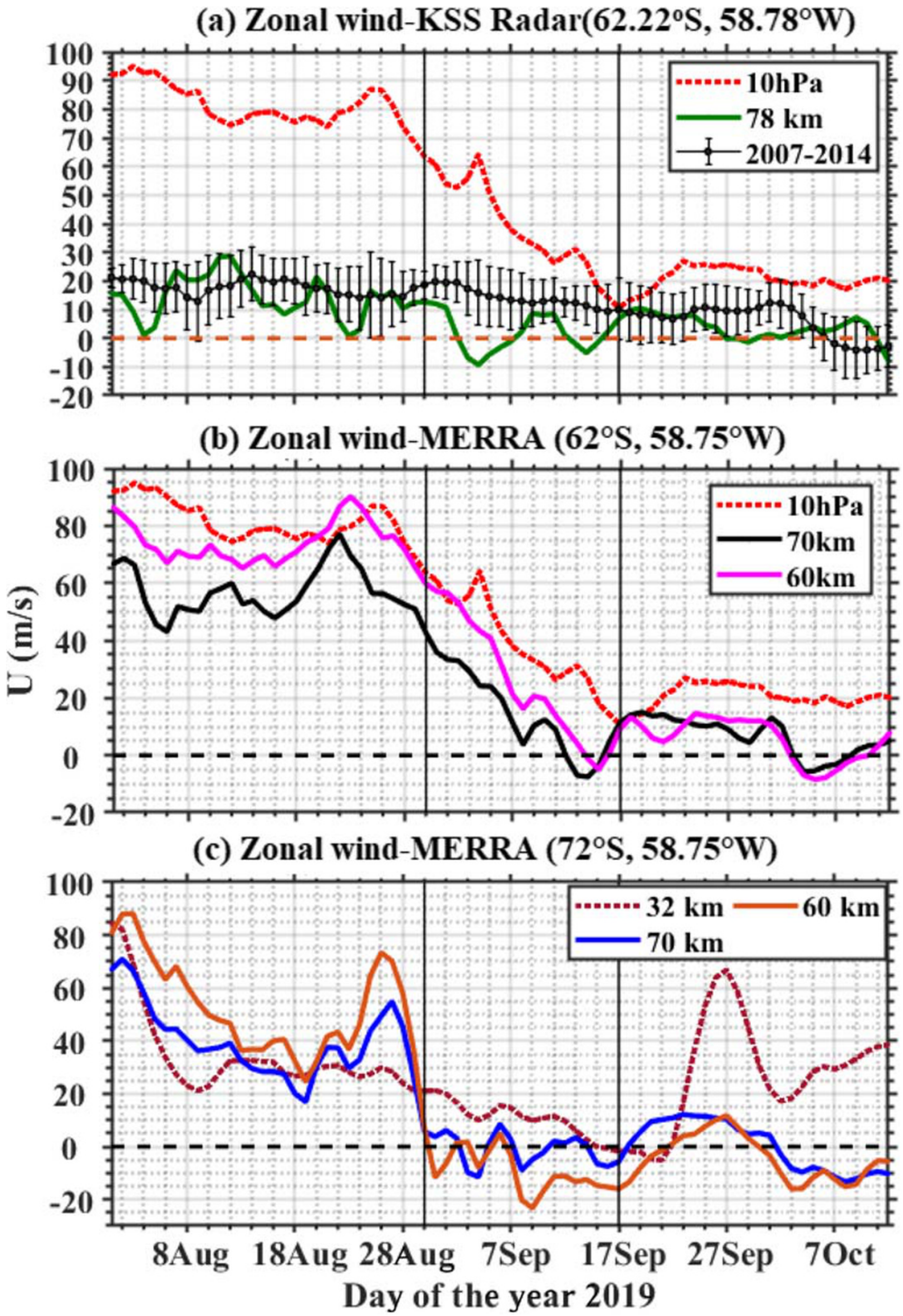

Figure 3. (a) The daily mean variability of the zonal wind at 78 km obtained from the KSS MR during 2019 (solid). The mean wind at 78 km during 2007–2014 (black) along with standard deviation is also shown. (b) Same as (a) but zonal winds at 60 and 70 km using MERRA-2 data of KSS MR grid (62°S, 58.75°W) location. The daily mean variability of the zonal mean zonal wind at 10 hPa at 60°S (dashed red) is also shown in (a) and (b). (c) Same as (b) but at a polar grid point (72°S, 58.75°W), the zonal wind at 10 hPa (~32 km) at 72°S (dashed maroon) also shown. The vertical lines indicate the starting and peak warming days. The dashed horizontal line indicates the zero wind level.

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on the peak SSW day. Thus, the combined observations of KSS MR and MERRA-2 suggest that the Antarctic mesosphere dynamics well responded to the stratospheric warming in terms of the mesosphere wind reversal when the 10-hPa stratosphere winds (60°S) were weakened near KSS MR location (62°S) and reversed at 72°S. Also, the entire middle atmosphere over the Antarctic was influenced by the 2019 SSW on a greater scale.

The unusual features of the 2019 SSW noted in the Antarctic mesosphere are summarized as (1) the long-lasting wind reversal in the mesosphere before the peak SSW, (2) higher wind reversal in the middle mesosphere (70–78 km) than the lower mesosphere (60 km) over KSS MR location, and (3) at 72°S, zonal wind reversal in the mesosphere was observed ~20 days before the peak SSW. However, in 2002 major (Dowdy et al., 2004) and 2010 minor SSWs (Eswaraiah et al., 2016), the mesosphere wind reversal lasted a few days (4–7 days). This unusual mesosphere wind response could be due to the pronounced PW enhancement in the polar stratosphere and long-lasting warming temperatures (Figure 1), and thus, the mesosphere wind structure is analogous to the polar stratosphere zonal wind variation (10 hPa, 60°S) (dashed red line in Figures 3a and 3b).

3.4. PWs

The daily mean zonal and meridional winds at 78 km obtained from the KSS MR are subjected to the wavelet (Torrence & Compo, 1998) analysis; the resultant wavelet spectra are portrayed in Figures 4a and 4b, respectively. The cone of influence is shown as the area between dashed lines and the 95% significance levels shown with thick contours, and the vertical lines mark the days of onset and peak SSW. Figure 4a depicts the wide spectrum (4–5, 5–6, 8–12, and 14–22 days) of waves in the zonal winds during the 2019 winter. The 8- to 12-day waves appeared in July and during the warming period, and the 4- to 5-day, 5- to 6-day waves were intermittently present before the warming. The 14- to 22-day waves started appearing from the third week of July and attained their peak amplitude around mid-August and faded before the onset of the SSW. The earlier studies by Dowdy et al. (2004) during 2002 SSW, and by Eswaraiah et al. (2016) during 2010 minor SSW, have shown that the presence of 14-day PWs in the mesosphere before the onset of SSW. Further, Chandran et al. (2013) have described that the existence of PWs of periods 16–20 days in the mesosphere is associated with the westward PW1 periods in the stratosphere. Our observations of the unusual growth of PW1 in the stratosphere, along with the earlier studies, can lead to speculate that the mesosphere wind reversal could be due to the dominant PWs of Wavenumber 1 generated during the 2019 SSW.

In the meridional winds (Figure 4b) intraseasonal period (~24–32 days) waves were observed before the August and are laying outside the cone of influence and hence not discussed here. The 8- to 12-day waves attained their peak amplitude following the onset day of SSW, and 5- to 9-day waves appeared just before the onset day of SSW and faded afterward. The presence of 5- to 9-day and 8- to 12-day PWs during/after the onset of SSW is of significant importance in recent days (Gong et al., 2018; Yamazaki et al., 2020). Manifold studies reported the presence of the short-period waves of period ~5–12 days (Chandran et al., 2013; Gong et al., 2018) during the SSW. Further, we have noticed the presence of a long period (above 14 days) and a short-period (5–12 days) PWs of zonal Wavenumber 1 in the polar stratosphere (55–70°S) during the SSW (Figure S1). This suggests that the PW source might exist in the stratosphere. Recently, Yamazaki et al. (2020) presented the source mechanism of short-period (Quasi 6 day) waves during the 2019 SSW, and they noted the PW source in the stratosphere (~30 km) and waves exited by the barotropic/baroclinic instability. Earlier reports (e.g., Liu et al., 2015; Merzlyakov et al., 2013) also suggested that the short-period (5 day) waves observed at the MLT region are mostly generated in the stratosphere first by barotropic/baroclinic instability and then propagate upward into MLT. Further, we also analyzed the PWs signatures globally between 75 and 80 km using MLS geopotential heights before, during, and after the SSW event, as shown in Figures 4c–4e, respectively. The figure, along with the supporting information, shows that the strong PWs with Wavenumber 1 were present over the SH polar region during the SSW period, which was weak before and after the SSW event.

From the above discussions, we suggest that the short-period PWs (5–12 days) observed in the mesosphere during the SSW are the manifestation of the barotropic/baroclinic jet instability in the polar stratosphere at 30 km. However, further studies are required on the PW generation mechanism to critically evaluate whether the shorter period waves are in situ generated or propagated from the polar stratosphere region.

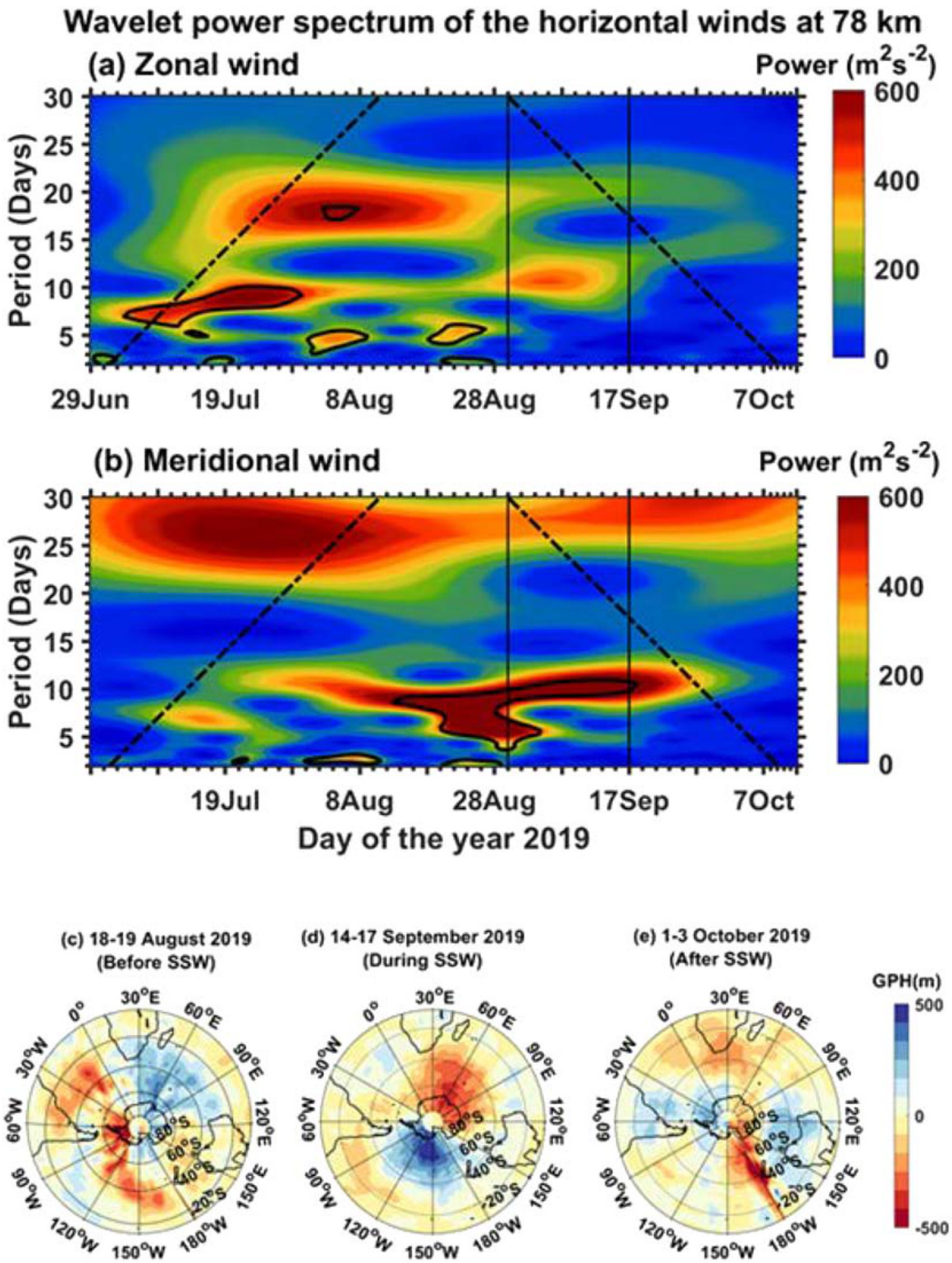

Figure 4. (a) Continuous wavelet spectrum of the mean zonal winds at 78 km observed using the KSS MR data between 1 July and 12 October 2019; (b) same as (a) but for the meridional winds. The dashed curved black line in the wavelet spectrum shows the cone of influence and the thick contours show the 95% significance levels. The vertical lines indicate the starting and peak warming days. (c–e) The global projection of MLS geopotential heights averaged between 75 and 80 km, before the SSW, during and after the SSW event, respectively.

4. Summary

The present communication describes the Antarctic mesosphere response to the unusual 2019 SSW in the SH using the simultaneous observations from the KSS meteor radar (62.22°S, 58.78°W) and the MERRA-2 data. An effort was made to comprehend the effects of the 2019 SSW on the mesosphere winds, waves, and potential reasons for the observed effects were discussed. To the best of our knowledge, this is the first report on the observational mesospheric signatures due to the 2019 SSW. The main conclusions are summarized as follows.

1. The sudden rise in the SH polar cap temperature was observed in 2019 winter and early spring. The onset of warming was observed on 30 August and attained its peak on 17 September. The temperature enhancement and the change in the zonal mean zonal wind at 10 hPa were ~66 K and 72 m/s, respectively, during the SSW. This was more than the 2002 major SSW, albeit no zonal wind reversal at 10 hPa. Besides, the abnormal growth of the PWs observed and found to be the strongest in the record for 40 years. Hence, by considering these features we propose that this is an unusual SSW and the longest warming event on record in the SH.
2. The combined observations of MERRA-2 and KSS MR at ~62°S showed that the zonal wind reversal at 78 km occurred about 20 days prior and lasted mostly until the peak SSW. The magnitude of the mesosphere wind reversal was greater at 78 km (~10 m/s) and decreased to ~5 m/s at 60 km, suggesting the middle mesosphere being affected by the SSW more than the lower mesosphere.
3. The MERRA-2 observations at ~72°S indicate zonal wind reversal in the stratosphere (~32 km) at the peak SSW (the major SSW signature), and larger wind reversals in the mesosphere (~11.5 m/s at 70 km and ~23 m/s at 60 km) well before the peak SSW. It suggests that the 2019 SSW caused major impacts over ~72°S, compared to 62°S.
4. In the wavelet spectra of the zonal winds at 78 km observed by the KSS radar, PWs with periodicity 14–22 days appeared before the SSW and later diminished steadily and seemed to turn into shorter-period waves with 8–12 days following the SSW. In the meridional winds, 5- to 9-day waves appeared just before the SSW and turned into 8- to 12-day waves after the SSW. The global projection of PWs between 75 and 80 km clearly shows the strong PW1 signatures during the SSW over the polar region, which were weak before and after the SSW period.

Our interpretations of observations suggest that the unusual warming in the SH polar region seriously disturbed the middle atmosphere through the anomalous hike in the polar stratosphere temperature and abnormal growth of the PWs. Since the strong PWs were observed in both the stratosphere and mesosphere, the SSW effect may not be limited to the polar mesosphere, but other regions of the atmosphere over the globe. Further extensive studies are highly demanded to address the unusual 2019 warming effects on the entire middle and upper atmosphere using different techniques.

Data Availability Statement

The KSS meteor radar data used in the present study can be obtained online (https://doi.org/10.5281/zenodo.3975459).

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