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RESEARCH ARTICLE

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Temperature tele-connections between the tropical and polar middle atmosphere in the Southern Hemisphere during the 2010 minor sudden stratospheric warming

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Abstract

Southern Hemispheric (SH) sudden stratospheric warmings (SSWs) are relatively rare compared to their Northern Hemisphere counterparts. No study has so far investigated the impacts of the SH minor SSWs on the tropical atmosphere and connection between the tropical and polar atmospheres. Here, we analyze the MERRA-2 and ERA-interim datasets, and *Microwave Limb Sounder* satellite temperature measurements to investigate the tropical and polar atmosphere tele-connections during the SH minor SSW that occurred in 2010. Our analysis shows the strong anti-correlation between the polar and tropical temperatures during the 2010 minor SSW in the stratosphere and mesosphere. This is the first observational study over the SH that reveals the tele-connection between the tropical and polar middle atmospheres through the temperature during a minor SSW. We verified this tele-connection, using simulations of the Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) model during the 2010 minor SSW. GAIA model simulations show the temperature anti-correlation between the tropical and polar middle atmosphere and zonal wind variations. The feature of meridional circulation changes was also observed during the SSW period. Hence, the present study strongly suggests that even minor SSW in the SH can affect the meridional circulation in the middle atmosphere via planetary wave activity.

KEYWORDS

GAIA simulations, MLS, polar middle atmosphere dynamics, stratosphere-mesosphere temperature, sudden stratospheric warming, tele-connection, tropical middle atmosphere

1 | INTRODUCTION

Sudden stratospheric warming (SSW) events are the most dramatic episodes that occur coarsely every alternate year in the Northern Hemispheric (NH) polar region during the boreal winter (Gerber *et al*., 2012). The first SSW was noticed by Scherhag (1952), later numerous studies have been established to explain its mechanism. It is widely accepted that an SSW takes place in the wintertime when the circumpolar flow of the polar stratosphere interacts with the planetary waves (PWs) originating in the troposphere (Matsuno, 1971). The growth of PWs with the wavenumbers 1 and 2 ($k = 1, 2$) is the dominant component during the major SSW (Liu and Roble, 2002). Though the definition of major and minor SSWs was stated in 1964 by the World Meteorological Organization, later, several classical definitions have been suggested. For instance, Palmeiro *et al*. (2015) classified the different SSW definitions that existed in the literature. According to Labitzke and Naujokat (2000), a major SSW occurs with the reversal of the temperature gradient poleward of 60° along with the reversal of the zonal wind at 60° at 10 hPa pressure level. During minor SSWs, there will be a reversal of the temperature gradient but not the zonal wind reversal occurs poleward of 60° at 10 hPa. The discourse around the refinement of the SSW definition is still in progress (Butler *et al*., 2015, 2017).

The occurrence of major SSWs is relatively less frequent in the Southern Hemisphere (SH) than in the NH and this hemispheric disparity is mainly attributed to the less topographic forcing of PWs (Van Loon *et al*., 1973; Andrews *et al*., 1987). In the SH, so far, only one major SSW was recorded in 2002 (Baldwin, 2003) and a minor SSW in 2010 (Eswaraiah *et al*., 2016). The 2002 SH major SSW attained significant importance in addressing several dynamical issues (Shepherd *et al*., 2005; readers can see the special issue of the *Journal of Atmospheric Sciences*, 2005, Vol. 62, No. 3 for a detailed discussion about the 2002 SSW). Aside from the 2010 minor SSW, another minor SSW was also noticed in 1988, but it was fainter than the 2010 SSW (Kanzawa and Kawaguchi, 1990; de Laat and van Weele, 2011). Recently, a record stratospheric warming event occurred over Antarctica in September 2019 (Lim *et al*., 2020; Yamazaki *et al*., 2020). A handful of studies have investigated the thermal structure and dynamics of the mesosphere and lower thermosphere during the 2002 major SSW (e.g., Dowdy *et al*., 2004; Shepherd *et al*., 2005) and the 2010 minor SSW (Eswaraiah *et al*., 2016, 2017, 2018). However, the studies on the mesosphere response to the 2019 SH SSW are not yet reported.

Even if the SSW and its dynamical effects on the polar atmosphere are fairly understood, its connection to the tropical atmospheric temperatures was rather rarely studied (Gómez-Escolar *et al*., 2014). Although there exist several dynamical parameters and methods to check the possibility of tele-connection between the tropical and polar atmospheres during the SSW, the atmospheric temperature correlation will be one of the most suitable ways to address the tele-connection. It is well understood that the changes in the stratospheric temperature and the zonal wind in the polar region are due to the anomalous amplification of PWs during the SSW (Dunkerton *et al*., 1981). Furthermore, the SSW eventually shows the effect on the entire middle atmosphere through the variations in the temperatures and dynamics (Pedatella *et al*., 2018). Though numerous studies have been established to manifest the mesospheric temperature variability due to an SSW event at different latitudes in the NH (De Wit *et al*., 2014), its effect on the tropical mesospheric temperature is relatively less reported. Liu and Roble (2002), examined the difference of temperature change at various latitudes and altitudes up to 200 km in the NH during the SSW events using the Thermosphere Ionosphere Mesosphere Energetics-Global Circulation Model (TIME-GCM). Afterward, a few observational studies were reported in the NH on the variability of the low latitude mesospheric temperature during the SSW and the possible reasons (Shepherd *et al*., 2008; Vineeth *et al*., 2009). However, these kinds of theoretical and observational studies have not been established even for the first major SSW in 2002, let alone for the minor SSW in 2010.

To this end, the present study emphasizes the existence of tele-connection between the tropical and polar middle atmospheric regions in terms of mesospheric and stratospheric temperatures during the SH 2010 SSW using both the observations and model simulations.

2 | DATA AND METHODOLOGY

We utilize stratospheric zonal winds and zonal mean temperatures obtained from ERA-Interim reanalysis datasets provided by the European Center for Medium-range Weather Forecasts (ECMWF). ERA-Interim generates data in a sequential data assimilation scheme using four-dimensional variation analysis (4DVAR) (Dee *et al*., 2011). The daily zonal mean stratospheric winds and temperatures at the10 hPa (~32 km) level, with a spatial grid resolution of 0.75°, are obtained from ERA-Interim for the present study. We also used the daily zonal mean zonal and meridional winds and temperatures of Modern-Era Retrospective analysis for Research and Applications, Version2 (MERRA-2) (Gelaro *et al*., 2017).

The temperatures at the mesospheric altitudes are acquired from the Earth Observing System (EOS) Microwave Limb Sounder (MLS) measurements. MLS is one of the four instruments aboard NASA's Aura satellite (Schwartz *et al*., 2008). We use version 4.2 MLS temperature standard products from 2005 to 2015 in the analyses. The accuracies and altitude resolutions presented here are taken from the MLS V4.2 data quality document (Livesey *et al*., 2018). The vertical resolution is 6 km at 0.01 hPa, and the track resolution is ~165 km for 261–0.1 hPa and 280 km at 0.001 hPa and the precision range from 0.5 K in the lower stratosphere to ~2.5 K in the mesosphere (Livesey *et al*., 2018). Due to the limitation in the spatial resolution, the zonal mean temperatures in the polar region are considered between 78°S and 82°S and at the tropical region ~8°–12°S.

The Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) model is also utilized in the present study. GAIA model is a self-consistent, fully coupled model of the Earth's middle atmosphere, mesosphere, and thermosphere and estimates the wind and temperature information from the ground to ~500 km and at all latitudes. We used the GAIA model to simulate the responses of both the stratosphere and mesosphere to the 2010 minor SSW in the SH. GAIA simulations were run at a fixed F10.7 level of 70 sfu and fixed cross-polar cap potential of 30 kV. Besides, Japanese 25-year reanalysis data (JRA25A) were nudged to the GAIA simulations below 30 km height to obtain the stratosphere conditions in a better way. The complete details about the model can be found in Jin *et al.* (2012) and the simulations performed during the SSW events in Liu *et al.* (2013, 2014).

3 | RESULTS AND DISCUSSION

To compare the SSW characteristics of the historical major SSW in 2002 and a minor SSW in 2010, we have shown the variability of the polar stratosphere temperature (PST), zonal mean zonal winds, and PWs in the SH polar stratosphere. In the present study, a major SSW is defined as an increase of PST above 35 K from the climatological mean with zonal wind reversal at 10 hPa and a minor SSW as the increase of PST above ~20 K without the zonal wind reversal. Figure 1 presents the daily variability of the polar cap (60°–90°S) zonal mean temperature (PST), zonal mean zonal winds, and amplitudes of PWs (PW1 and PW2) at 60°S at the 10 hPa level during 2002 major and 2010 minor SSWs in the SH estimated from the MERRA-2 data. We further compared the PST, and zonal mean zonal winds at 10 hPa and 60°S, with the 40 years (1979–2018) climatological mean (dashed line) and *SD* (shaded) obtained from the MERRA-2 data. The PW amplitudes of wave number 1, 2 ($k = 1$ and $k = 2$) (PW1, PW2) were computed from the distribution of the geopotential heights. Though the description of the 2002 SSW is well documented for a decade, ever since, here we use its basic characteristics to show the significance of the 2010 minor SSW. The minor warming days of the 2002 and 2010 SSWs are shown with the dashed vertical lines and the major warming day in 2002 with a solid line. In 2002, one major warming (Figure 1a) occurred around day 270 with an increase of PST by ~35 K relative

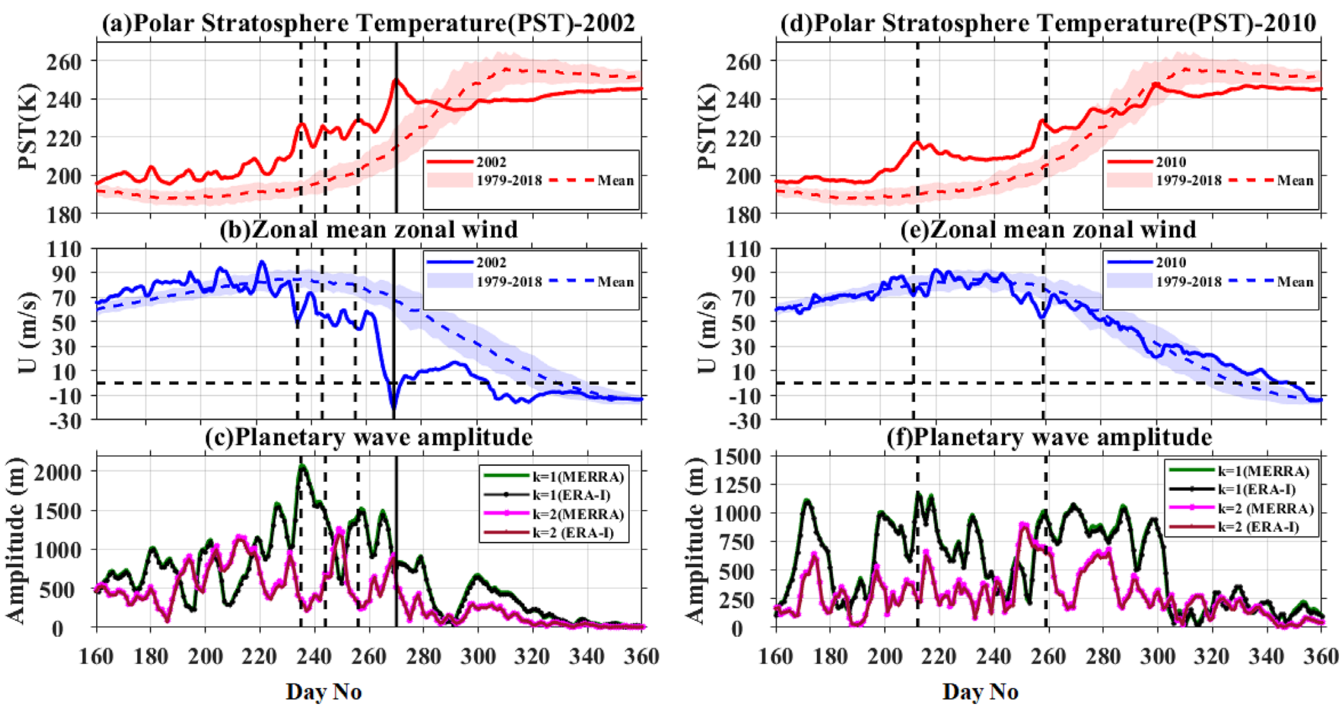

FIGURE 1 (a) Daily variation of zonal mean polar stratospheric temperature (PST) at 10 hPa. (b) Daily variation of zonal mean zonal wind at 10 hPa over 60°S. (c) Planetary wave amplitude of zonal wavenumbers 1 and 2 at 10 hPa over 60°S during the 2002 major SSW. (d–f) The same as (a–c) but for the 2010 minor SSW. The 40 years (1979–2018) mean and *SD* (temperature and zonal winds) are shown with a shaded region. All the parameters are estimated at 10 hPa level. The solid vertical line indicates the major warming period in 2002 and the dashed vertical line indicative of minor warming periods in 2002 and 2010. The dashed horizontal line in the middle panels shows the zero-wind level. All the parameters are obtained from the MERRA-2 dataset, but the planetary wave amplitudes are compared with ERA-I data

to the climatological mean. Along with the major warming, episodic minor warmings are also noted on days 235, 244, and 256 with the increase of PST by ~33, 27, and 27 K, respectively. In 2010, two minor warmings were discerned (days 212 and 259) with an increase of PST by ~27, and 21 K, respectively (Figure 1d).

It may be noted that the amplitude of PW1 was predominant before the 2002 major SSW event (day 270) over 60°S (Figure 1c). During the first minor SSW episode in 2002 (day 235, Figure 1c) the PW1 amplitude was greatly enhanced, and PW2 amplitude suddenly diminished, later the PW1 amplitude decreased episodically. The decreasing amplitudes of PW1 could be due to the transient nature of the wave, by interacting with the mean flow to provide its westward acceleration. Though the amplitude of PW2 progressed after the first warming event (day 235), the PW1 dominated the PW2 during the other two minor warmings (day 244 and day 256). However, during the major SSW day (day 270), the PW1 amplitude reduced, while the PW2 grew (up to ~0.8 km) to be comparable with the amplitude of PW1. Indeed, the mean zonal wind over 60°S at 10 hPa reversed on the major warming day (day 270) due to large westward forcing by PW2 (Liu and Roble, 2005), and was weakened during the minor warming periods, as shown in Figure 1b. In contrast, in 2010 the amplitude of PW1 (~1.1 km) during the first minor event (day 212) (Figure 1f) is higher than that of the 2002 major SSW day (day 270) (0.8 km) (Figure 1c). However, the PW1 amplitude during the 2010 winter (days 210–260) was weaker (up to ~1.1 km) than that (up to ~2 km) in the 2002 SSW period (days 235–270) at 60°S, and hence, the PW interaction with the mean flow may lead to only the deceleration, not the reversal of the zonal wind during the 2010 SSW (Figure 1e). The noteworthy feature of the PWs observed in the 2002 and 2010 SSWs, is that the amplitude of PW1 dominated the PW2 during the episode of the peak minor SSW (Eswaraiah *et al.*, 2019). For consistency, we have compared all the parameters of MERRA-2 with the ERA-I data and no scientific difference was observed. For instance, the PW amplitudes comparisons were shown in Figure 1c and f. Furthermore, the span of the first minor event in 2010, in terms of temperature enhancement, is observed to be longer than all the minor events in 2002 (Figure 1d). These features suggest that the first minor SSW in 2010 may have affected the atmosphere like a major SSW.

It is believed that the amplification of PWs in the boreal winter causes the poleward transport of temperature in the stratosphere and influences the middle atmosphere transport (Kanzawa and Kawaguchi, 1990; Kodera, 2006; Eguchi and Kodera, 2007; Manney *et al.*, 2015; Vargin and Kiryushov, 2019). To see whether the enrichment of PWs linked with the stratosphere temperature in the polar region and any tele-connection existed between the tropical and polar atmospheres during the 2010 minor SSW, we have looked into the stratosphere and mesosphere temperatures. Figure 2a shows the time series of daily means of the PST and the tropical stratospheric temperatures (TSTs) at 10 hPa obtained from ERA-Interim data. Likewise, Figure 2b displays the polar mesospheric temperatures (PMT) and the tropical mesospheric temperatures (TMT) at 0.01 hPa (~81 km) obtained from the MLS measurements during the SH winter period. Owing to the coverage limits of the MLS satellite data, we have taken the temperature measurements over ~8°–12°S for TMT and ~78°–82°S for PMT. However, TSTs and PSTs were obtained from ERA-Interim data exactly at 10°S and 80°S, respectively. Furthermore, we have not observed any scientific difference between the stratosphere temperature and PW amplitudes of ERA-I and MERRA-2. For simplicity, Figure 2 displays temperatures of ERA-I to observe tele-connection.

Furthermore, to extract the temperature variations during the SSW winter from the normal winters, we have estimated the mean and *SD* of the temperatures of 10 non-SSW years at respective altitudes both in the tropical and polar regions and over-plotted on the SSW year temperature behavior in Figure 2. The stratosphere temperatures of non-SSW years are from 2000 through 2011 except SSW years (2002 and 2010), and the mesosphere temperatures are from 2005 through 2015 except 2010. The correlation coefficients of PST-TST and PMT-TMT combinations are estimated for temperature anomalies using the linear correlation coefficient method and shown at the top of each panel. The temperature anomalies were computed by removing the mean of the non-SSW year temperatures from the SSW year temperature. It is evident from Figure 2 that the stratosphere in the tropical and the polar region is tele-connected by establishing the anti-correlation between TST and PST (Figure 2a) during the first minor SSW event (day 212). However, the tele-connection in the mesosphere (Figure 2b) through the anti-correlation of the temperatures occurred a few days before the first SSW event day (day 212). In fact, the early occurrence of tele-connection can also be seen in the stratosphere (Figure 2a). During the second minor SSW event (day 259), the PST and TMT increases are significant, but the tropical stratospheric cooling (TST) and the polar mesospheric cooling (PMT) are marginal. Therefore, from the figure, it can be stated that the sturdy tele-connection signal between the tropical and polar atmosphere regions occurred during the first minor SSW event due to robust SSW signal strength. During the first minor event (day 212) the PST warming

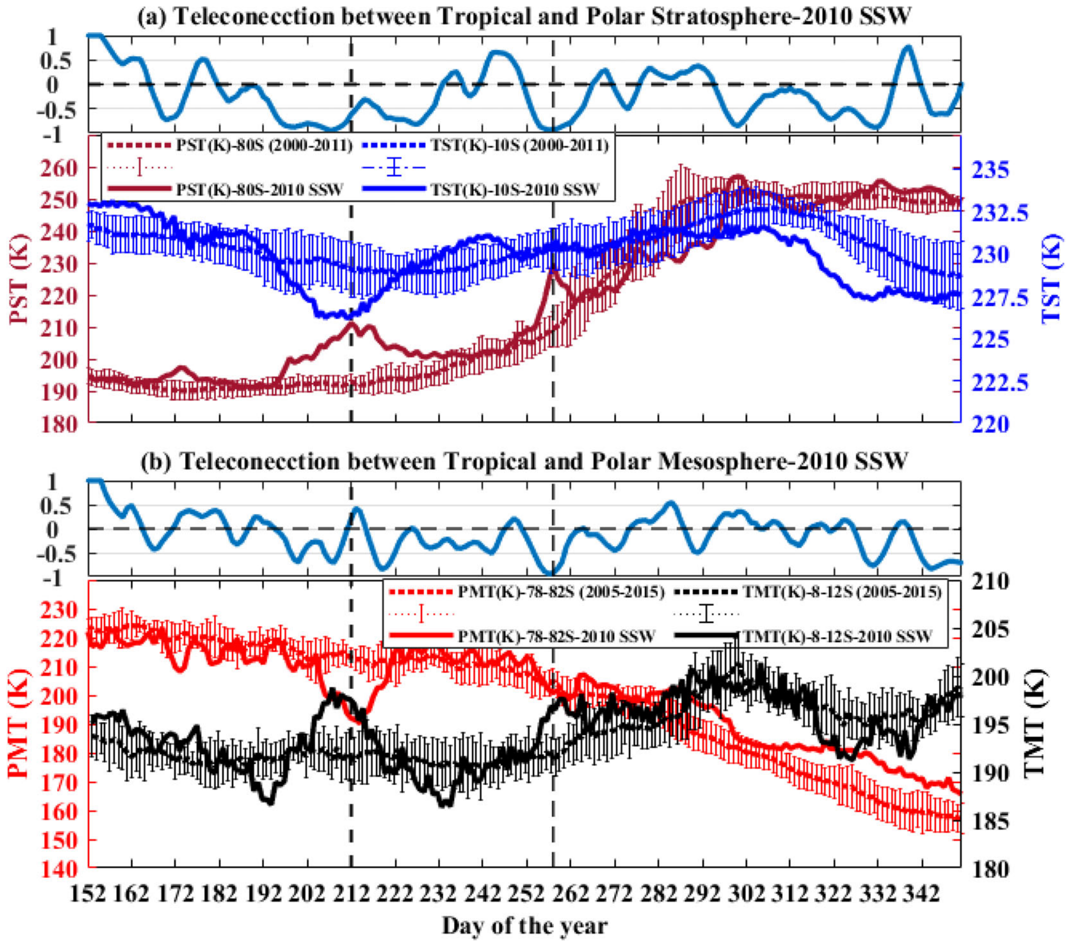

FIGURE 2 (a) Daily mean variation of tropical stratosphere temperatures (TST) and polar stratosphere temperatures (PSTs) at 10 hPa obtained using ERA-interim data. (b) Daily mean variation of polar mesosphere temperatures (PMT) and tropical mesosphere temperatures (TMT) obtained using MLS data at 0.01 hPa during the 2010 minor SSW period. Mean and *SD*s of normal years are shown with dashed lines. The correlation between TST-PST and TMT-PMT is shown on the top box of each figure, respectively. The vertical dashed lines indicate the peak warming days in 2010

of ~27 K and TST cooling of ~15 K are observed, and at the same time, the TMT peaked by ~15 K and the PMT was dipped by ~25 K from the 10 years mean temperatures (Figure 2b). Furthermore, the TMT started decreasing from the usual trend 2 weeks before the first two events and then increased to the maximum value significantly before that of PST.

Though it is believed the tidal bias in the mesosphere could be attributed to some degree of warming/cooling in the mesosphere, it depends on the instrument and the span of the data used (Shepherd *et al*., 2007; Eswaraiah *et al*., 2019). Forbes and Wu (2006) reported the mesosphere temperature tides using the MLS observations and showed that during the SSW winter period the variabilities in diurnal and semidiurnal tides at 86 km are ~4.5 and ~2.4 K, respectively. However, the tidal variabilities are not large enough to account for the observed changes in the present mesosphere temperatures. For instance, during the episodes of warming the observed temperature change in the mesosphere was in the order of greater than 20 K, which is much larger than the winter mesosphere tidal amplitude (4.5 K).

For further confirmation of the temperature tele-connection, GAIA simulations have been performed and are presented in Figure 3. The zonal mean temperatures and zonal wind anomalies computed between the days 212 and 182 are displayed with color and line contours, respectively, for the first minor SSW event (day 212). It is well noted from Figure 3 that there is a clear mesospheric cooling (~15–20 K) in the altitudes of 65–80 km and stratospheric warming (~25–30 K) around 40 km in the SH polar region. Furthermore, the wind field shows the existence of dominant eastward winds at about 55 km in the polar region and the westward winds in the mid-latitude region in the SH. GAIA simulations (Figure 3) shows the vertical coupling between the stratosphere and

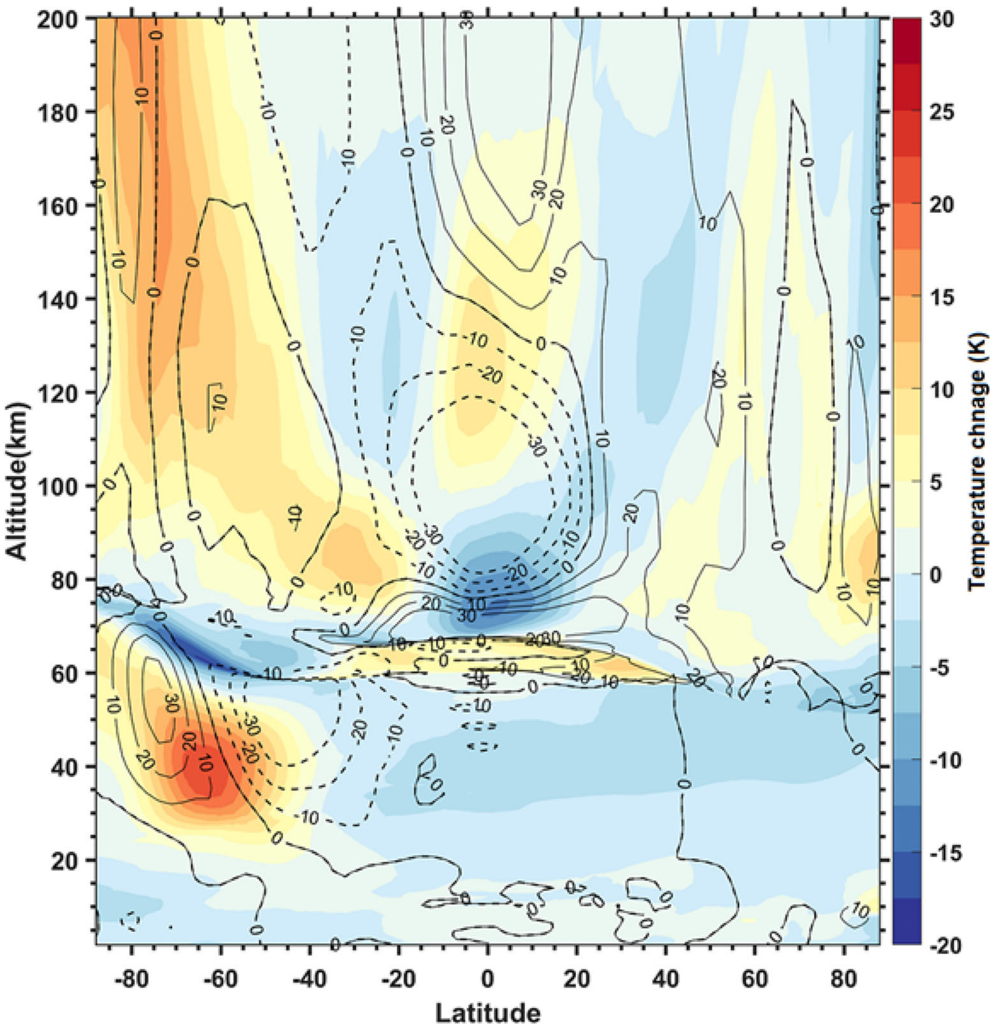

FIGURE 3 The difference in zonal mean temperature (K) and zonal mean zonal wind ($m \cdot s^{-1}$) between days 212 and 182 in the stratosphere, mesosphere, thermosphere using GAIA simulations during 2010 minor SSW over the SH. The color contour indicates the zonal mean temperature and line contours show the zonal mean zonal wind

mesosphere both in the polar and tropical regions and the tele-connection between the tropical and polar atmosphere. Specifically, the mesosphere cooling is associated with the stratosphere warming in the polar region and its opposite effect (mesospheric warming and stratosphere cooling) at similar altitudes in the tropical region. Hence, the observed anti-correlation of PST/TST and PMT/TMT on day 212 is following the GAIA simulations. The present model simulations are also consistent with the earlier theoretical predictions reported by Liu and Roble (2002). Figure 3 also indicates that the SH polar SSW phenomenon extends its signatures in the low latitudes (20°S to 20°N) of both the SH and NH.

The mechanism for the observed tele-connection between the tropical and polar middle atmosphere, and the stratosphere-mesosphere coupling during the SSW is as follows. The enhanced upward and westward propagating PWs during the SSW intensify significantly and act to weaken the background winds, which further causes the gravity wave (GW) filtering and results in a change in residual meridional circulation. The recent investigations (Iida *et al.*, 2014; Laskar *et al.*, 2019) in the NH have reported the meridional circulation changes in the middle atmosphere during the major SSW. To check the meridional circulation in the present case, we have compared the flow of zonal mean meridional winds in the middle atmosphere during the SSW period and pre-SSW period and displayed in Figure 4. During the pre-SSW period (Figure 4a) the meridional wind at the SH polar (60°–80°S) mesosphere heights (70–80 km) is southward (poleward), but during the first minor SSW event day (Figure 4b) the wind (around 60 km) turned to northward (equatorward). In fact, the enhanced equatorward wind appeared in 50–65 km and the weakening of poleward wind exists in 65–80 km. Furthermore, the changes in the meridional wind were estimated by removing the non-SSW meridional wind from the SSW event (day 212) (Figure 4c). The difference in the meridional wind indicates significant changes in the meridional circulation both in the mesosphere and stratosphere in the entire SH. However, the circulation changes were not observed in the NH. Thus, the tropical and polar middle

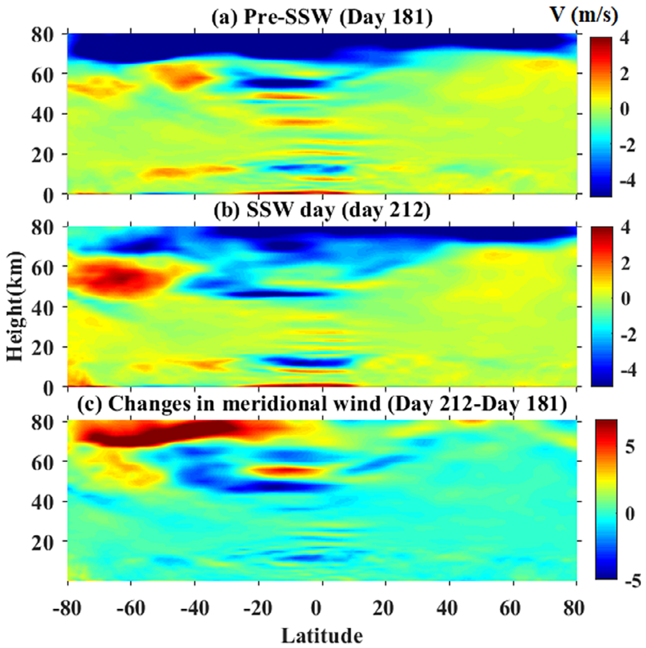

FIGURE 4 Height-latitude cross sections of zonal mean meridional wind obtained from MERRA-2, (a) before the 2010 SSW period (day 181), and (b) during the SSW event day (day 212), and (c) the change/difference in the meridional wind (day 212–day 181)

atmospheres are coupled through the changed meridional circulation.

Furthermore, the meridional circulation associated with the SSW can induce upwelling in the tropical stratosphere but down welling in the tropical mesosphere, causing a substantial cooling in the tropical stratosphere and warming in the mesosphere (Liu and Roble, 2002; Randel *et al.*, 2002; Charlton and Polvani, 2007), and vice versa in the polar region to produce the reverse phenomenon. This aspect was proposed and tested in the NH, where the large amplitude PWs are discerned during the SSW (Alexander and Rossi, 2013). For the first time, we report here this kind of temperature tele-connection during the 2010 minor SSW, which has not been tested experimentally in the SH.

4 | SUMMARY

We have analyzed the MERRA-2 and ERA-Interim reanalysis datasets and MLS temperatures to study the temperature connection between the tropical and polar middle atmosphere during the 2010 minor SSW in the SH. From the PW analysis, we noted that the amplitude of PW1 increased during all the minor warmings both in the 2002 major and 2010 minor SSWs. From the temperature analysis, we found the consistent tele-connection between the PST and the tropical stratosphere temperatures (TST) and also between the polar mesosphere temperature (PMT) and the tropical mesosphere temperature (TMT) during the first minor warming event (day 212). The significant cooling and warming of ~15 K in TST and TMT, respectively, were observed while the opposite change of 27–25 K in PST and PMT occurred during the first minor SSW event. The observed tele-connection of the temperatures in the SH was further verified with GAIA model simulations. The model clearly shows the opposite temperature response between the tropical and polar region stratosphere and mesosphere and hence the anti-correlation between the PST and TST and between PMT and TMT for the first minor warming event in 2010. The change in the meridional circulation was also observed during the SSW period, and the temperature anti-correlations observed in the SH middle atmosphere could be due to the change in the circulation during the SSW.

The above findings, for the first time, have provided the experimental evidence along with the model simulations for the tele-connection of the temperatures in both the stratosphere and mesosphere during a minor SSW in the SH and circulation charges. The temperature tele-connection may be the usual phenomena during the NH major SSW, especially when there is a strong PW forcing. However, the similar features in minor SSW in the SH is perhaps unique and a rare phenomenon, which was not reported elsewhere. The change of meridional circulations in both the stratosphere and mesosphere that connect vertical flows in the tropical and polar regions during minor SSW seems to be the responsible factor for the observed temperature anti-correlation or tele-connection. Further studies are needed, however, to quantify the temperature tele-connection and the residual circulation of the middle atmosphere during minor SSWs.

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All the data used in this analysis are publicly available. ERA-Interim reanalysis datasets provided by the European Center for Medium-range Weather Forecasts (ECMWF) are available at https://www.ecmwf.int/en/forecasts/datasets, and MERRA-2 data at https://earthdata. nasa.gov.

Daily temperature data from the Earth Observing System (EOS) Microwave Limb Sounder (MLS) measurements are available at https://mls.jpl.nasa.gov/products/temp_product.php.

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