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Do minor sudden stratospheric warmings in the Southern Hemisphere (SH) impact coupling between stratosphere and mesosphere–lower thermosphere (MLT) like major warmings?

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Abstract

We have investigated the coupling between the stratosphere and mesosphere–lower thermosphere (MLT) in the Southern Hemisphere (SH) during 2010 minor sudden stratospheric warmings (SSWs). Three episodic SSWs were noticed in 2010. Mesospheric zonal winds between 82 and 92 km obtained from King Sejong Station (62.22°S, 58.78°W) meteor radar showed the significant difference from usual trend. The zonal wind reversal in the mesosphere is noticed a week before the associated SSW similar to 2002 major SSW. The mesosphere wind reversal is also noticed in "Specified Dynamics" version of Whole Atmosphere Community Climate Model (SD-WACCM) and Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) simulations. The similar zonal wind weakening/reversal in the lower thermosphere between 100 and 140 km is simulated by GAIA. Further, we observed the mesospheric cooling in consistency with SSWs using Microwave Limb Sounder data. However, the GAIA simulations showed warming between 130 and 140 km after few days of SSW. Thus, the observation and model simulation indicate for the first time that the 2010 minor SSW also affects dynamics of the MLT region over SH in a manner similar to 2002 major SSW.

Keywords: Sudden stratospheric warming (SSW), Mesosphere and lower thermosphere (MLT), Meteor radar, Stratosphere–MLT coupling, GAIA simulations, MLT dynamics

Background

The study on sudden stratospheric warmings (SSWs) has recently drawn more attention due to its role in altering the Earth's atmosphere at greater scales. Though SSW occurs at the polar stratospheric region it causes not only major effect on polar mesosphere and lower thermosphere (MLT) region but also influences the atmosphere at other latitudes. Ever since its discovery by Scherhag (1952), numerous studies have attempted to explain this phenomenon theoretically and experimentally, mainly in Northern Hemisphere (NH). However, in Southern Hemisphere (SH), SSWs rarely occur due to low planetary wave (PW) activity and thus are sparsely studied. A detailed review can be found in Chandran et al. (2014). SSWs are classified into two types based on the definition given by World Meteorological Organization (WMO) (Labitzke and Naujokat 2000; Chandran et al. 2014). They are minor SSWs (reversal of temperature gradient at 10 hPa poleward of 60°) and major SSWs (reversal of both the temperature gradient and zonal wind at 60°). Albeit the long record of the study on SSWs, the coupling processes between the stratosphere and the MLT are still not clearly understood, thus in needs of further advanced observations and theoretical modellings.

The widely accepted mechanism of SSWs is the interaction between planetary waves (PWs) and mean flow (Matsuno 1971). Further, it is thought that the interaction

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decelerates the stratospheric eastward jet during winter and induces poleward/downward mean residual circulation, which results in adiabatic heating in the polar stratosphere. At the same time, the adiabatic cooling is developed in the polar mesosphere due to the upward flow of mean circulation (Matsuno 1971; Liu and Roble 2002).

The occurrence of mesospheric cooling (MC) during major SSWs has been well established in both hemispheres (Walterscheid et al. 2000; Siskind et al. 2005; de Wit et al. 2015). However, such studies during minor SSWs are sparse and limited to few model simulations (Siskind et al. 2010; Chandran et al. 2013). Recently, Eswaraiah et al. (2016) studied the mesospheric dynamics during 2010 SH minor SSW for the first time. Using simultaneous observations of winds by King Sejong Station (KSS, 62.22°S, 58.78°W) meteor radar (KSS MR) and temperatures by Microwave Limb Sounder (MLS), they reported zonal wind reversal at 82–92 km and mesosphere cooling at 78–80 km.

Compared to the intensive studies in the mesosphere, responses to SSW events above the altitude of 110 km have only been recently investigated due to an increase of space-based observations and enhanced model simulation capabilities. For instance, Funke et al. (2010) noticed warming in the polar lower thermosphere during 2009 major SSW, and Kurihara et al. (2010) noticed the variations in MLT dynamics. These observations are in agreement with the TIME-GCM simulations (Liu and Roble 2002), which predicts warming at an altitude of 120–130 km during the SSWs. Liu et al. (2011, 2013) showed that thermosphere response to SSWs strongly depends on local time, altitude, latitude and longitude. A strong semidiurnal pattern exists in the thermosphere temperature and wind perturbations. Further, they noticed this pattern similar to those in the ionosphere temperature and plasma density as suggested by Goncharenko et al. (2013). Most of the above-mentioned studies are carried out for major SSWs in the NH. However, the effects of minor SSW on thermosphere and ionosphere are sparsely studied. Using incoherent scatter radar at 42.6°N, Goncharenko and Zhang (2008) reported the effect of minor SSW on thermosphere during January, namely warming at 120–140 km and cooling at 150–300 km. In our earlier study (Eswaraiah et al. 2016), we have shown the evidence of 2010 SH minor SSW signatures in the mesosphere and investigated the variability of mesosphere dynamics affected by PWs that were associated with SSW. In the present study utilizing some of our earlier results in the mesosphere, we investigate the coupling processes between stratosphere and MLT for the first time during 2010 minor SSW in the SH.

Database

To evaluate the 2010 minor SSW over SH, we utilized the zonal mean zonal winds at 60°S and temperatures at 80°S in the stratosphere at 10 hPa from the ERA-Interim reanalysis datasets of European Center for Medium-range Weather Forecasts (ECMWF) (Berrisford et al. 2009). For further confirmation of SSW event, we also made use of “Specified Dynamics” version of Whole Atmosphere Community Climate Model (SD-WACCM) simulations (Chandran et al. 2013; Eswaraiah et al. 2016) from the surface to mesosphere heights.

To quantify the mesosphere dynamics, we used KSS MR measured winds in the MLT region during the 2010 SSW. The complete details of KSS MR and its wind measuring capabilities can be found in Lee et al. (2013). The hourly measured zonal winds of KSS MR during 2010 have been utilized in the present study. The temperatures in the mesosphere are obtained from MLS (Schwartz et al. 2008). In the present study, we have used MLS_Level2 version of the data to obtain the zonal mean temperatures at 80°S.

The thermosphere wind and temperature parameters are obtained from Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) model simulations. The model provides the wind and temperature information from the ground to ~500 km. The complete details about the model and its role in simulating the winds and temperatures during SSWs are given in Jin et al. (2012) and Liu et al. (2013, 2014). The GAIA simulations used in the current study were run at a fixed F10.7 level of 70 sfu and fixed cross-polar cap potential 30 kV, representing the low solar and geomagnetic activity. Thus, variations in the simulated temperature and wind should be mainly due to forcing from the lower atmosphere.

All the datasets discussed above are utilized here to study the coupling between the stratosphere and MLT region during the 2010 rare minor SSW.

Results and discussion

Evaluation of SH 2010 minor SSW

Figure 1a shows the variability of daily zonal mean zonal wind at 60°S and temperature at 80°S derived at 10 hPa using ECMWF dataset during the 2010 minor SSW year. From Fig. 1a, three minor warming events are noticed in early August (day 212), mid-September (day 259) and in the end of October (day 300), marked with dotted vertical lines. The red line in Fig. 1a indicates that the warming lasted for more than 8 days with temperature increases of ~10–15 K from the normal trend and the second event (day 259) was the most prominent in terms of effect on the mesosphere dynamics as shown in Eswaraiah et al. (2016). The weakening of zonal wind at 10 hPa is

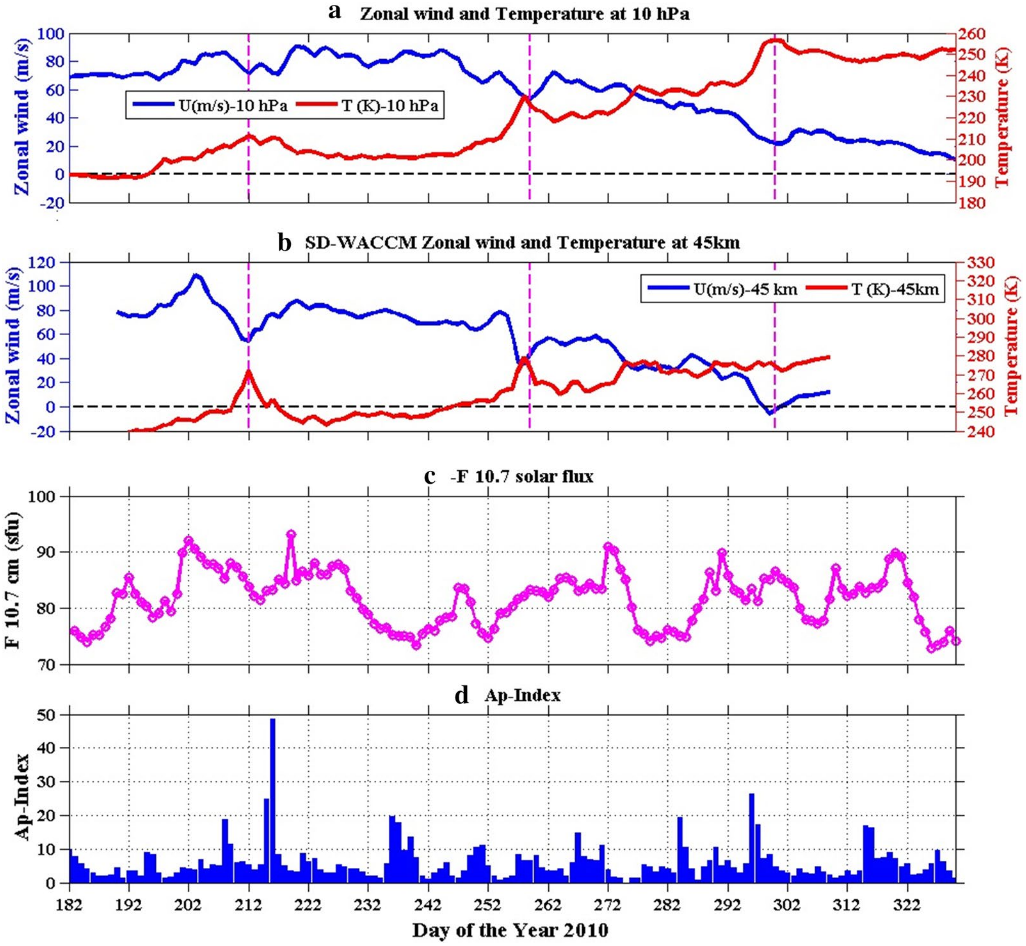

Fig. 1 **a** Zonal mean zonal winds (*blue line*) at 60°S and zonal mean temperatures (*red line*) at 80°S derived from ECMWF dataset during 2010 SH winter. The temperature scale is given on the right side. *Vertical dashed lines* indicate the day of peak warming. *Dashed horizontal line* indicates the zero wind level. **b** Same as **a** but using SD-WACCM simulations and are zonal mean values at 45 km. **c** Daily mean variability of F 10.7 cm solar flux. **d** Daily mean variability of Ap index

observed in all the three events, but the most significant (~20 m/s) for the second event.

Figure 1b presented SD-WACCM simulated winds and temperatures at 45 km over SH from mid-July (day 190) to early November (day 310). Zonal mean zonal winds at 60°S are plotted along with the zonal mean temperatures between 75°S and 90°S. The SD-WACCM reasonably well reproduced the 2010 minor SSW events that were noticed by ECMWF data as shown in Fig. 1a. The SD-WACCM has some limitation that during SSW, due to "cold pole problem," the change of temperature and wind is not reliable below ~45 km. This limitation has been discussed in the review of Chandran et al. (2014). More details about SH 2010 minor SSW are given in Eswaraiah et al. (2016). In the present study, we highlight their characteristics and impact on MLT dynamics with observations and model simulations.

Figure 1c, d shows the daily mean variability of F10.7 solar flux and daily mean variability of Ap index, respectively, indicating that the 2010 minor SSW days can be characterized as under the low solar and geomagnetic activity (since F10.7 < 100 and $A_p < 22$). Especially for the day 259 event we can totally ignore the geomagnetic activity ($A_p < 6.5$). The impact of magnetospheric and solar drivers is expected to be very low on the thermospheric changes during SSW (Goncharenko and Zhang 2008; Korenkov et al. 2012). Hence, the variability in MLT dynamics during the minor SSW events is primarily due to the lower atmospheric forcing.

In the upcoming sections, we present signatures of SSW effects on the mesospheric and lower thermosphere in terms of winds and temperatures.

Stratosphere and MLT coupling: zonal wind variations

In this section, we present the SSW effects on the mesosphere and lower thermosphere zonal winds obtained by KSS MR and computed by SD-WACCM and GAIA simulations. Figure 2a shows the variability of zonal winds in both the stratosphere and mesosphere in 2010 SH winter. The zonal winds in the stratosphere (blue line) were zonal mean values at 10 hPa from ECMWF database. To indicate the episodic warming events, the corresponding temperature at 10 hPa is also shown with red dashed line. For the mesosphere daily mean zonal winds are displayed at two different altitudes of 82 and 92 km. For comparison, SD-WACCM and GAIA simulations of mesospheric zonal mean zonal winds are shown in Fig. 2b and c.

It is evident from Fig. 2a that the weakening of zonal wind in the stratosphere during the SSW day and associated zonal wind reversal/weakening in the mesosphere occurred about a week before the warming events in the stratosphere. The radar observations clearly showed the wind reversal at both 82 and 92 km, well before the associated warmings at stratosphere, specifically 8 days before the second (day 259) and third (day 300) events and 2–3 days before for the first event. However, the eastward wind seems to increase on the day of peak warming for the second and third events and then to follow usual trend. In contrast, for the first event, the eastward wind is increasing after 2–3 days of warming day. The magnitudes of wind weakening/reversal from the mean trend are ~45, ~40 and ~30 m/s for the first, second and

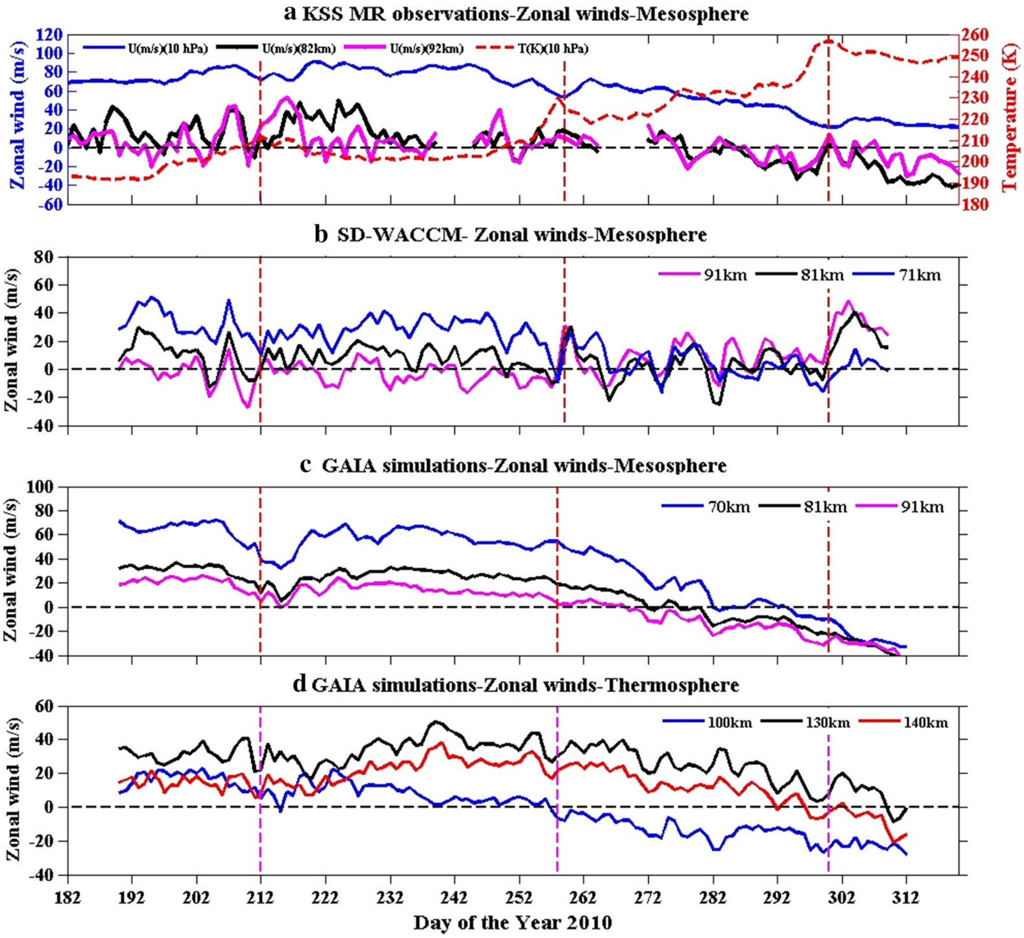

Fig. 2 **a** Zonal mean zonal winds (*blue line*) and zonal mean temperatures (*red dashed line*) at 10 hPa, same as in Fig. 1a. Zonal winds observed at 82 km (*black line*) and 92 km (*magenta line*) using KSS MR data. **b** SD-WACCM simulations of zonal mean zonal winds at 60°S for the altitudes 71, 81 and 91 km. **c** Same as **b** but using GAIA simulations at 70, 81 and 91 km. **d** GAIA simulations of lower thermospheric zonal winds at 100, 130 and 140 km. The *dashed vertical lines* indicate the days of peak warming

third event, respectively. Though there are some oscillatory structures in the zonal wind, the wind weakening/reversal is clearly apparent when compared to other years (Figure not shown). We have taken mean and standard deviation of 10 years (non-SSW years) zonal winds and compared with 2010 zonal winds and noticed that the 2010 wind line is well outside the mean and standard deviation of other years (Eswaraiah et al. 2016).

The mesospheric wind reversals can also be seen in the SD-WACCM simulation at three altitudes (71, 81 and 91 km) during the three SSW events (Fig. 2b). Although the SD-WACCM wind values are zonal mean estimates, they are in good comparison with those of one-point KSS MR observations. However, the SD-WACCM winds are not following seasonal trend after the day 280 as in the radar measurements. The magnitude of wind reversal/weakening is ~30 m/s for the first event at 81 and 91 km, and it is low at other two events. However, at 71 km, the wind reversal is noticed a few days (2–3 days) before the second and third events. The eastward wind seems to increase on the peak day of the second event, as in radar observations.

Figure 2c shows the mesosphere wind variations at 70, 81 and 91 km using the GAIA simulations. The GAIA simulations seem to display the SSW effects on the mesosphere winds only at the first event, but not later two events. The GAIA wind, however, tends to follow its seasonal behavior after the day ~270, as in the MR observation. The discrepancy between the direct radar observations and the model simulations may be mainly due to the individual limitations of each model, in addition to the variability caused by one-point observations and observational errors.

To investigate the SSW effects on the lower thermosphere, we present the GAIA zonal mean zonal winds at three altitudes (100, 130 and 140 km) in Fig. 2d. At the upper mesopause/lower thermosphere altitude (100 km), the wind reversal can be noticed only for the second event, whereas in remaining altitude levels (130 and 140 km) the weakening of eastward wind occurred at all three events. The wind variations in the stratosphere and mesosphere during SSW are due to the westward forcing of PWs, according to the model simulation of Liu and Roble (2002). It has been observationally noted that the mesospheric winds are affected by PWs that were associated by 2010 SSW (Eswaraiah et al. 2016). However, in the thermosphere, the variability of zonal winds is different than mesosphere, as indicated in Fig. 2d. The variations in MLT zonal winds during the associated SSW events could be due to the growth of in situ PWs in the MLT that were generated by filtered gravity waves (GWs) and their nonlinear interaction with tides, as suggested by the model simulation of Liu and Roble (2002).

Stratosphere and MLT coupling: temperature variations

Figure 3 shows the variability of mesospheric and thermospheric temperatures during the SH 2010 SSW year. Zonal mean temperatures (daily averaged) at ~80°S from MLS measurements are shown in Fig. 3a. The temperatures are taken from MLS measured profiles at pressure levels; 10, 0.1 and 0.01 hPa. Figure 3a clearly demonstrates that the mesospheric cooling (MC) (at 0.1 hPa) is apparent in anti-correlation with stratosphere temperatures (at 10 hPa), and moderate MC lingers up to ~0.01 hPa. The magnitude of MC observed in 2010 is comparable to that of the 2002 major SSW event (Eswaraiah et al. 2016 and references therein). Further, the MC during the 2010 SSW events is clearly predicted in SD-WACCM simulations as in Fig. 3b. The GAIA model shown in Fig. 3c also seems to simulate the MC around the SSW events, but to less degree of clearness than the SD-WACCM. The differences in the MC feature among the observation and model simulations are significant and need to be investigated for better model development in the future. However, the MC can be interpreted in a nutshell as adiabatic cooling in the mesosphere where the mean meridional circulation reverses from poleward/downward to equatorward/upward during the peak warming day due to PW forcing (Liu and Roble 2002; Matsuno 1971).

In the lower thermosphere, the variability of temperatures from the GAIA simulation is presented in Fig. 3d. At 100 km (blue line), which may be considered as mesopause altitude (Ratnam et al. 2013), slight cooling is predicted around the first event, but for other events, the temperature is not much changed. It indicates that the mesopause region is not greatly affected by the 2010 SSW. It has been suggested that the eastward GW forcing during SSW induces an equatorward/upward flow at mesopause altitudes (90–105 km), resulting in adiabatic cooling there. The same GW forcing causes a poleward/downward flow just above 105 km, resulting in warming in the lower thermosphere region (Liu and Roble 2002; Siskind et al. 2005). In the lower thermosphere, at 130 and 140 km (black and red lines), significant warming can be noticed for the first and last events, whereas the temperature enhancement is difficult to identify for the second event. The GAIA model seems to predict a decreasing trend of temperature before the second event that might have compensated the warming after the second event. Further, the warming at 140 km is greater than 130 km, which is consistent with the previous reports (Funke et al. 2010; Kurihara et al. 2010; Liu et al. 2011, 2013). The oscillation in temperature before and after the SSW event, especially after the second event, could be due to traveling PWs (Funke et al. 2010; Kurihara et al. 2010). Funke et al. (2010) observed that the amplitude of wave 1 structure is maximized around 140 km (Fig. 4b in

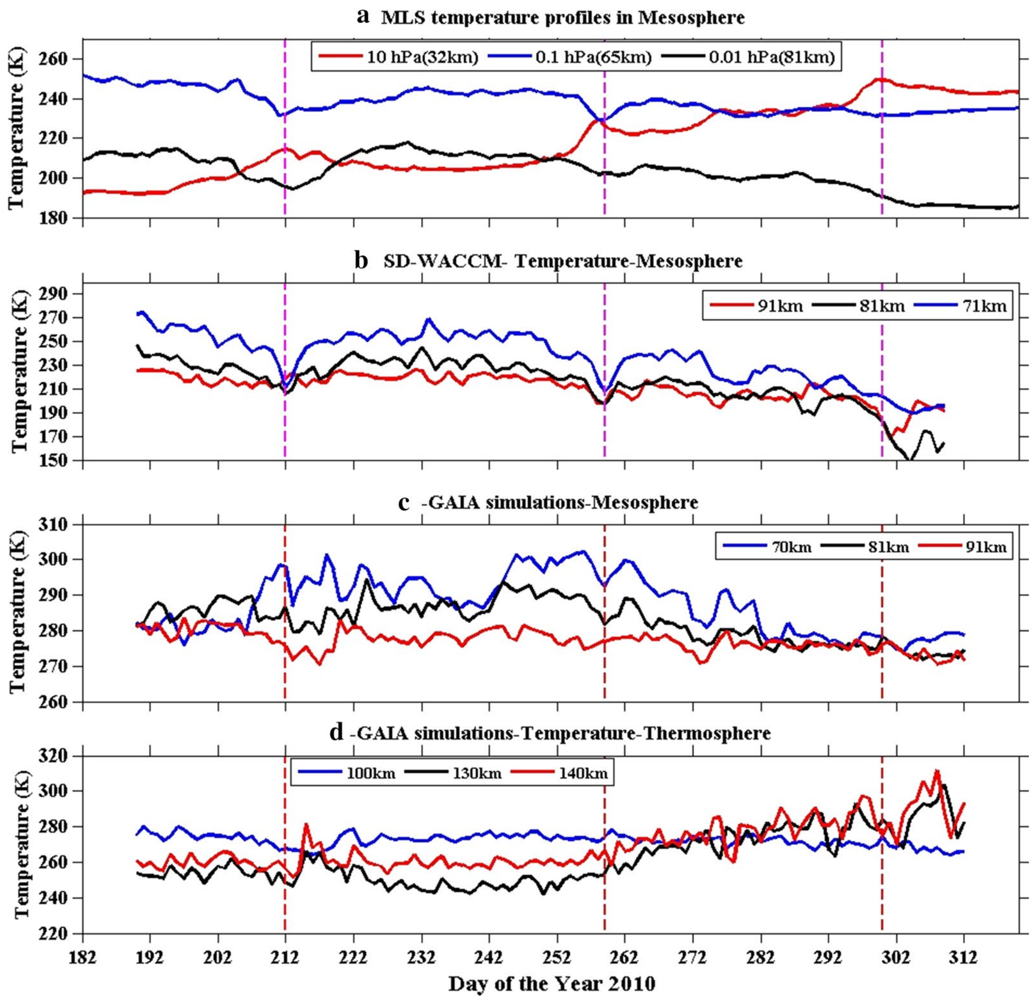

Fig. 3 **a** Daily mean temperatures observed at 10, 0.1 and 0.01 hPa using MLS measurements at ~80°S during 2010 SH winter. **b** SD-WACCM simulations of zonal mean zonal temperatures (75–90°S) at the altitudes 71, 81 and 91 km from day 182 to 314 of 2010. **c** Same as **b** but at the altitudes 70, 81 and 91 km from GAIA simulations at ~70–82°S. **d** GAIA simulations of lower thermospheric temperatures at 100, 130 and 140 km. The *dashed vertical lines* indicate the days of peak warming

Funke et al. (2010)). The wave 1 structure was probably produced by in situ PWs that were forced by breaking of zonally asymmetric GW in the MLT region (Smith 1996).

Note that the GAIA simulations were run at fixed low solar and geomagnetic conditions to avoid the space storm effect if any at polar region. Hence, we conclude that the variations of zonal wind and temperature in thermosphere are mainly due to the SSW in the stratosphere, but not due to disturbance by solar and geomagnetic conditions.

Summary and conclusions

Three minor SSW events occurred in the SH during early August to late October in 2010, when a low solar and geomagnetic activity conditions prevailed. They provide a good opportunity to study the coupling processes between stratosphere and MLT. In the present study, the mesosphere and thermosphere response for the rarely occurring SH minor warming is investigated for the first time using combined observations of KSS meteor radar, MLS measurements and SD-WACCM and GAIA simulations. The summary of main results is given as follows;

1. Both ECMWF datasets and SD-WACCM simulations have clearly proven the occurrence of very rare minor SSW over SH in 2010. The minor SSW events are noticed during the days 212, 259 and 300.
2. In the mesosphere, the variability of KSS MR zonal wind at 82 and 92 km is clearly different from other

years and wind reversal occurred few days (2–8 days) earlier than the corresponding minor SSW events in the stratosphere. The mesospheric cooling (MC) is noticed at 0.1 hPa in MLS observations, and clear anticorrelation is evident between the mesosphere and stratosphere temperatures. The MC has extended up to ~0.01 hPa. SD-WACCM and GAIA simulations show the characteristics of zonal wind weakening/reversals and cooling at the mesospheric height around the SSW event, but with some significant differences.

3. The GAIA simulations of zonal winds in thermosphere clearly showed the wind reversal at 100 km and weakening at other altitudes (130 and 140 km) on SSW days of 2010. The variations in thermospheric zonal winds during the associated SSW events could be due to the growth of in situ PWs and their nonlinear interaction with tides in the MLT region.
4. The GAIA simulations of thermospheric temperatures at 130 and 140 km showed a clear warming after three to 4 days of the associated SSWs and varied in the oscillatory pattern in reminiscence of traveling PWs. The oscillatory amplitude is maximized at 140 km.
5. The study suggests that the magnitude of both mesospheric wind reversal and mesospheric cooling during 2010 minor SSW is comparable to that of 2002 major SSW over SH.

Thus, we conclude that the effects of minor SSW in SH on mesosphere and thermosphere are evidenced for the first time with combination of observations and model simulations. However, it is still unclear whether the PWs directly propagated from the stratosphere can affect the MLT dynamics or it could be due to PWs which are forced in situ by filtered GWs at MLT region. It can be resolved by studying the PWs in a detailed manner simultaneously at different latitudes in the MLT region. In addition, the occurrence of secondary warming in the thermosphere and its causative mechanism should be further investigated.

Abbreviations

ECMWF: ERA-Interim reanalysis datasets of European Center for Medium-range Weather Forecasts; GAIA: Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy; GW: gravity wave; KSS: King Sejong Station; MC: mesosphere cooling; MLS: Microwave Limb Sounder; MLT: mesosphere and lower thermosphere; MR: meteor radar; NH: Northern Hemisphere; PW: planetary wave; SD-WACCM: Specified Dynamics version of Whole Atmosphere Community Climate Model; SH: Southern Hemisphere; SSW: sudden stratospheric warming.

Authors' contributions

SE initiated the study and prepared the manuscript. YK and MVR are given the suggestions and scope of the manuscript and also involved in the discussions and preparation of the manuscript. HL involved in the preparation of GAIA simulations and discussions. JL involved in data analysis. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

Meteor radar data at King Sejong Station can be shared by contacting the corresponding author (YHK). All other data used in the manuscript are available publicly at the referenced sources.

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Human and animal rights

This work does not involve humans

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References

Berrisford P, Dee D, Fielding K, Fuentes M, Kallberg P, Kobayashi S, Uppala S (2009) The ERA-interim archive. European Centre for Medium Range Weather Forecasts, Shinfield Park, Reading, Berkshire RG2 9AX, UK, pp 1–16

Chandran A, Garcia RR, Collins RL, Chang LC (2013) Secondary planetary waves in the middle and upper atmosphere following the stratospheric sudden warming event of January 2012. Geophys Res Lett 40:1861–1867. doi:10.1002/grl.50373

Chandran A, Collins RL, Harvey VL (2014) Stratosphere-mesosphere coupling during stratospheric sudden warming events. Adv Space Res 53:1265–1289. doi:10.1016/j.asr.2014.02.005

de Wit RJ, Hibbins RE, Espy PJ, Hennum EA (2015) Coupling in the middle atmosphere related to the 2013 major sudden stratospheric warming. Ann Geophys 33:309–319. doi:10.5194/angeo-33-309-2015

Eswaraiah S, Kim YH, Hong J et al (2016) Mesospheric signatures observed during 2010 minor stratospheric warming at King Sejong Station (62.22°S, 58.78°W). J Atmos Solar Terr Phys 140:55–64. doi:10.1016/j.jastp.2016.02.007

Funke B, Lpez-Puertas M, Bermejo-Pantalen D et al (2010) Evidence for dynamical coupling from the lower atmosphere to the thermosphere during a major stratospheric warming. Geophys Res Lett 37:1–5. doi:10.1029/2010GL043619

Goncharenko L, Zhang SR (2008) Ionospheric signatures of sudden stratospheric warming: Ion temperature at middle latitude. Geophys Res Lett 35:4–7. doi:10.1029/2008GL035684

Goncharenko L, Chau JL, Condor P et al (2013) Ionospheric effects of sudden stratospheric warming during moderate-to-high solar activity: case study of January 2013. Geophys Res Lett 40:4982–4986. doi:10.1002/grl.50980

Jin H, Miyoshi Y, Pancheva D, Mukhtarov P, Fujiwara H, Shinagawa H (2012) Response of migrating tides to the stratospheric sudden warming in 2009 and their effects on the ionosphere studied by a whole atmosphere-ionosphere model GAIA with COSMIC and TIMED/SABER observations. J Geophys Res 117:A10323. doi:10.1029/2012JA017650
Korenkov YN et al (2012) The global thermospheric and ionospheric response to the 2008 minor sudden stratospheric warming event. J Geophys Res Space Phys 117(10):1–11. doi:10.1029/2012JA018018
Kurihara J, Ogawa Y, Oyama S et al (2010) Links between a stratospheric sudden warming and thermal structures and dynamics in the high: latitude mesosphere, lower thermosphere, and ionosphere. Geophys Res Lett 37:1–4. doi:10.1029/2010GL043643
Labitzke K, Naujokat B (2000) The lower arctic stratosphere in winter since 1952. SPARC Newsl 15:11–14
Lee C, Kim YH, Kim JH et al (2013) Seasonal variation of wave activities near the mesopause region observed at King Sejong Station (62.22°S, 58.78°W), Antarctica. J Atmos Solar Terr Phys 105–106:30–38. doi:10.1016/j.jastp.2013.07.006
Liu HL, Roble RG (2002) A study of a self-generated stratospheric sudden warming and its mesospheric-lower thermospheric impacts using the coupled TIME-GCM/CCM3. J Geophys Res Atmos 107:1–18. doi:10.1029/2001JD001533
Liu H, Doornbos E, Yamamoto M, Tulasi Ram S (2011) Strong thermospheric cooling during the 2009 major stratosphere warming. Geophys Res Lett 38:1–5. doi:10.1029/2011GL047898
Liu H, Jin H, Miyoshi Y et al (2013) Upper atmosphere response to stratosphere sudden warming: local time and height dependence simulated by GAIA model. Geophys Res Lett. doi:10.1002/grl.50146
Liu H, Miyoshi Y, Miyahara S et al (2014) Thermal and dynamical changes of the zonal mean state of the thermosphere during the 2009 SSW: GAIA simulations. J Geophys Res Space Phys 119:6784–6791. doi:10.1002/2014JA020222
Matsuno T (1971) A dynamical model of the stratospheric sudden warming. J Atmos Sci 28:1479–1494
Ratnam MV, Kishore P, Velicogna I (2013) Global distribution of pauses observed with satellite measurements. J Earth Syst Sci 122:515. doi:10.1007/s12040-013-0278-y
Scherhag R (1952) Die explosionsartige Stratosph¨arenerwarmung des Sp¨atwinters 1951/52. Ber Deut Wetterdienstes (US Zone) 6:51–63
Schwartz MJ et al (2008) Validation of the Aura Microwave Limb Sounder temperature and geopotential height measurements. J Geophys Res. doi:10.1029/2007JD008783
Siskind DE, Coy L, Espy P (2005) Observations of stratospheric warmings and mesospheric coolings by the TIMED SABER instrument. Geophys Res Lett 32:L09804. doi:10.1029/2005GL022399
Siskind DE, Eckermann SD, McCormack JP et al (2010) Case studies of the mesospheric response to recent minor, major, and extended stratospheric warmings. J Geophys Res 115:1–16. doi:10.1029/2010JD014114
Smith AK (1996) Longitudinal variations in mesospheric winds: evidence for gravity wave filtering by planetary waves. J Atmos Sci 53:1156–1173
Walterscheid RL, Sivjee GG, Roble RG (2000) Mesospheric and lower thermospheric manifestations of a stratospheric warming event over Eureka, Canada (80°N). Geophys Res Lett 27(18):2897–2900