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Key Points:
- The 2002 major and 2010 minor SSWs over Southern Hemisphere showed a significant effect on the mesospheric tides after a few days of SSW
- The ozone variability during SSWs reveals that the mesospheric tides were less predisposed by the ozone presence than other mechanisms
- The secondary waves generated by planetary wave-tidal interaction cause a major effect on the mesospheric tides after the SSW event

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Effect of Southern Hemisphere Sudden Stratospheric Warmings on Antarctica Mesospheric Tides: First Observational Study

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Abstract We analyzed the structure and variability of observed winds and tides in the Antarctica mesosphere and lower thermosphere (MLT) during the 2002 major sudden stratospheric warming (SSW) and the 2010 minor SSWs. We noted the effect of SSW on the variability of MLT tides for the first time in the Southern Hemisphere, although it has been well recognized in the Northern Hemisphere. We utilized the winds measured by Rothera (68°S, 68°W) medium frequency radar and King Sejong Station (62.22°S, 58.78°W) meteor radar for estimating the tidal components (diurnal, semi-diurnal, and ter-diurnal) in the MLT region. The unusual behavior of diurnal tide (DT) and semidiurnal tide (SDT) was observed in 2002. Zonal SDT amplitudes were enhanced up to 27 m/s after 18 days from the associated SSW day. However, the meridional tidal amplitudes of both DT and SDT suddenly decreased during the peak SSW, and SDT amplitudes slightly increased to 18 m/s afterward. In the normal years, SDT amplitude stays below 15 m/s. During the 2010 SSW, SDT zonal amplitudes increased up to 40 m/s and 50 m/s at altitudes of 80 km and 90 km, respectively, ~30 days after the associated SSW. Similar but weaker effect is noticed in the meridional components. The ter-diurnal tide does not show any significant variation during the SSW. The two SSWs offered a challenging issue to answer: why tidal amplitudes are enhanced with a delay after the SSW. The reasons for the delay are discussed in accordance with theoretical predictions.

1. Introduction

In the winter polar latitudes, sudden stratospheric warming (SSW) has been observed and well studied since its discovery by Scherhag (1952). The SSW event is characterized by a sudden increase of the polar temperature below the 10 hPa level in just a few days. The SSW is known to occur as a result of the interaction between vertically propagating large-amplitude planetary waves (PWs; generated in the troposphere by sources like large-scale topography and land-sea thermal contrast) and the circumpolar flow (Matsuno, 1971). The PWs can propagate poleward as they penetrate upward into the stratosphere, resulting in Eliassen-Palm (EP) flux divergence in the upper stratosphere that can decelerate the polar flow and induce a strong descent that promotes the observed polar stratospheric warming. The interaction between the PWs and mean flow causes a deceleration and/or reversal of the eastward winter zonal winds and also induces a downward circulation in the stratosphere. The same is causing adiabatic heating and simultaneously upward circulation in the mesosphere, leading to adiabatic cooling (Liu & Roble, 2002; Pancheva et al., 2008; Siskind et al., 2005). The aforementioned EP flux divergence in the upper stratosphere can elicit a polar mesospheric cooling, through the association of gravity waves propagated into the mesosphere due to the ensuing wind reversal in the stratosphere.

According to the World Meteorological Organization definition, minor SSWs are events having reversal of temperature gradient at 10 hPa poleward at 60°, while major SSWs, in addition to the temperature gradient reversal, entail reversal of the mean zonal wind westward at 60° (Chandran et al., 2014; Labitzke & Naujokat, 2000). The response of mesosphere to the related SSWs has been established by several observations from the ground and space-based instruments (Azeem et al., 2005; Cho et al., 2004; de Wit et al., 2014, 2015; Siskind et al., 2005; Walterscheid et al., 2000) and model predictions (Limpasuvan et al., 2016; Liu & Roble, 2002, 2005; Sassi & Liu, 2014; Wang et al., 2014) in both the hemispheres, during the major SSW events. Nevertheless, the sway of minor SSW events on the mesospheric dynamics has only been studied to a limited degree in both the hemispheres, except a few model simulations (Chandran et al., 2013; Siskind et al., 2010). Recently, Eswaraiah et al. (2016) studied the mesospheric dynamics during the 2010 Southern Hemisphere (SH) minor SSW for the first time, using the concurrent observations of winds by King Sejong Station (62.22°S, 58.78°W) meteor radar (KSS MR) and temperatures by Microwave Limb Sounder (MLS). They reported the zonal wind reversal at 82–92 km and the mesosphere cooling at 78–80 km altitudes. In another study, Eswaraiah et al. (2017) reported the coupling between the stratosphere-mesosphere-lower thermosphere during the 2010 minor SSW over the SH.

The topical studies well discerned that tides are playing a key role in coupling different regions of the atmosphere during SSWs (Goncharenko et al., 2012; Lima et al., 2012; Liu et al., 2010; Pedatella & Forbes, 2010; Sridharan et al., 2009). The tides may be subdivided into migrating and nonmigrating tides on the basis of their zonal phase velocity. Migrating tides have periods and zonal wave numbers such that they are Sun-synchronous, while nonmigrating tides do not. The migrating tides tend to dominate in the mesosphere and lower thermosphere (MLT) region, with the migrating diurnal tide (DT) largest in the low-latitude horizontal wind fields and the migrating semidiurnal tide (SDT) largest in the midlatitude to high-latitude horizontal wind fields. The seasonal and annual variability of SDT is well documented (Forbes et al., 1995; Riggin et al., 1999). Multiple mechanisms have been proposed for the generation of SDT, which include nonlinear interaction between the migrating SDT (s = 2) and the PW with zonal wave number 1 (PW1), an in situ excitation, or excitation from a lower atmospheric source (Portnyagin et al., 1998). Excitation sources for different migrating and nonmigrating tidal components vary but include absorption of solar radiation and latent heat release in the lower atmosphere, or generation through nonlinear interactions between the dominant migrating tides and stationary PWs.

The atmospheric migrating DTs are excited primarily by direct absorption of sunlight by water vapor in the troposphere and stratosphere, and their growth is high at the tropical latitudes due to an additional contribution of latent heat released by the convective processes in the tropics (Sridharan, Sathishkumar, & Gurubaran, 2012a). The SDTs are mainly excited by ozone absorption in the upper stratosphere and lower mesosphere (Chapman & Lindzen, 1970; Forbes & Garrett, 1978; Sridharan, Sathishkumar, & Gurubaran, 2012a). The enhanced PW activity prior to the occurrence of SSW strengthens the Brewer-Dobson (B-D) circulation (Sridharan, Sathishkumar, & Gurubaran, 2012a). However, observational studies on the stratospheric ozone variability and its relationship to the tides in the MLT region are very limited, especially during the minor SSW events.

Studies related to the major SSW events and their association with the tidal variabilities are well established in the Northern Hemisphere (NH), both at high-latitude (Bhattacharya et al., 2004; Hoffmann et al., 2007; Jacobi et al., 1999) and at low-latitude regions (Lima et al., 2012; Sridharan et al., 2009; Sridharan, Sathishkumar, & Gurubaran, 2012a; Sridharan, Sathishkumar, & Gurubaran, 2012b). Such studies over the SH are sparse, due to low PW activity and the rare occurrence of SSWs. There are some observational studies on the variability of SDT in the SH during normal years (Baumgaertner et al., 2005; Murphy et al., 2003), whereas during the SSW year, the studies are limited to only few model predictions. Using TIME-GCM model simulations, Chang et al. (2009) described the global structure of both migrating and nonmigrating SDT during the 2002 SSW. Thus, it indeed articulates the necessity of more observation studies in the SH. The studies related to SSW effects on MLT region over the NH showed the enhancement of SDT during and after the onset of SSW. For instance, at the NH high-latitude region Resolute Bay (74.9°N, 94.9°W), Bhattacharya et al. (2004) noticed the enhancement of both DT and SDT amplitudes during the peak SSW at the mesopause region. At the low-latitude region, Tirunelveli (8.7°N, 77.8°E), Sridharan et al. (2009) showed that the equatorial electrojet current system was driven by mesospheric tides during the major SSW in the NH. Sridharan, Sathishkumar, and Gurubaran (2012a) also noticed the enhancement of SDT amplitude during the major SSW event and its suppression immediately after the event. In a different study, Sridharan, Sathishkumar, and Gurubaran (2012b) observed a decrease of SDT amplitude in zonal wind at 88 km over Tirunelveli prior to the onset of a minor warming event of 2011, and they argued that the decrease of SDT amplitude could be due to an increase of B-D circulation caused by enhancement of PW activity prior to the occurrence of SSW at the NH (Holton, 1990).

The recent observational studies on the coupling between the stratosphere and MLT region noticed the delay in the enhancement of tidal amplitudes after the mature stage of associated SSW over the NH

(Goncharenko et al., 2012; Lima et al., 2012). Goncharenko et al. (2012) demonstrated that the increment in the ozone density, due to PW-induced mean circulation at the tropics between 30 and 50 km altitude, lasted for ~35 days following the SSW, long after the collapse of the PWs. Hence, the nonmigrating SDTs may amplify accordingly. Forbes and Zhang (2012) reported the lunar tide amplification during the 2009 SSW over the NH using the satellite observations and theoretical predictions in the MLT region. They also noticed the delay (5 days in SABER and 30–40 days in CHAMP) in attaining maximum tidal amplitudes after the peak warming at 10 hPa. Most recently, Lima et al. (2012) showed that the amplification of both DT and SDT is related to the nonlinear interaction between the strong PWs and tides. In addition, they discussed that the delay in the tidal amplification could be due to 2 day waves.

The current understanding suggests that the nonlinear interaction between tides and PWs appears to be the most probable in the enhancement of SDT in the polar MLT (Angelats i Coll & Forbes, 2002; Yamashita et al., 2002). Earlier reports clearly revealed the amplification of secondary PWs with wavenumber 1 at the mesosphere altitudes after the SSW (Manney et al., 2008; Siskind et al., 2007, 2010). Here the term "secondary waves" was used to denote the perturbations that are not associated with the quasi-stationary or traveling wave field in the stratosphere; these waves often appear in the MLT following an SSW. The recent modeling studies of Chandran et al. (2013), using the SD-WACCM simulations during the 2012 minor SSW over the NH, suggested the variation of EP flux divergence and the generation of secondary waves (of periods 3 to 9 days) in the mesosphere at 80 km after the SSW and persist up to 30 days. Meyer and Forbes (1997) observed 6–7 day wave in the mesosphere after the 1993 SSW event and found that the wave was connected to atmospheric instability of the mesosphere. The recent SD-WACCM simulations during elevated stratopause of SSW (ES-SSW), made by Limpasuvan et al. (2016), also suggested that the generation of secondary waves after the onset of SSW provokes the enhancement of SDT, as aforementioned by Chandran et al. (2013).

The above discussions are all in regard to the NH SSW and its effects on MLT tides. In the SH, only one major SSW was recorded in 2002, and recently a minor SSW was observed in 2010 (de Laat & van Weele, 2011; Eswaraiah et al., 2016, 2017). de Laat and van Weele (2011) showed that ozone reduction has been enriched during the 2010 winter period and identified that it could be due to minor SSW in 2010. Although the ozone in the stratosphere is a major source of SDT, the coupling between stratosphere and MLT region through tides during SSW in the SH has not been studied.

In the present study, the authors investigated the variability of MLT tides during both the major SSW in 2002 and a minor SSW in 2010 and discussed the possible reasons for the variability in connection with ozone in the stratosphere and the secondary waves in the mesosphere, generated by the nonlinear interaction of PWs and tides. Section 2 describes the data and techniques used in the present study, followed by results and discussion in section 3, and the summary is given in section 4.

2. Data and Methodology

2.1. MLT Radar Data and Analysis

In the present study, we utilized wind measurements from Rothera Medium Frequency Radar (RMFR; 68°S, 68°W). RMFR is a coherent, spaced-antenna system and has been operated since 1997. The radar has a transmitting power of 25 kW at a frequency of 1.98 MHz and provides winds in the mesosphere at 4 km altitude resolution every hour (Hibbins et al., 2007). We also used KSS MR wind measurements in the mesospheric region during the 2010 SSW. The KSS MR was installed in March 2007 near the tip of Antarctica peninsula (Kim et al., 2010) and has been operating in an all-sky interferometric mode with one transmitting antenna and five receiving antennas at 33.2 MHz. The radar's peak power has upgraded from 8 kW to 12 kW in March 2012. The wind measurement technique of KSS MR is similar to the standard method given in Holdsworth et al. (2004), and it provides winds at the altitudes of 80–98 km at 1 h and 2 km resolutions (Lee et al., 2013).

Tidal parameters have been estimated using the hourly horizontal winds of both RMFR and KSS MR. The linear least square fit was performed to find the amplitude of each tidal component, along with the background prevailing wind magnitude. For the tidal fitting, a data window of 4 day length stepped in 1 day increments of

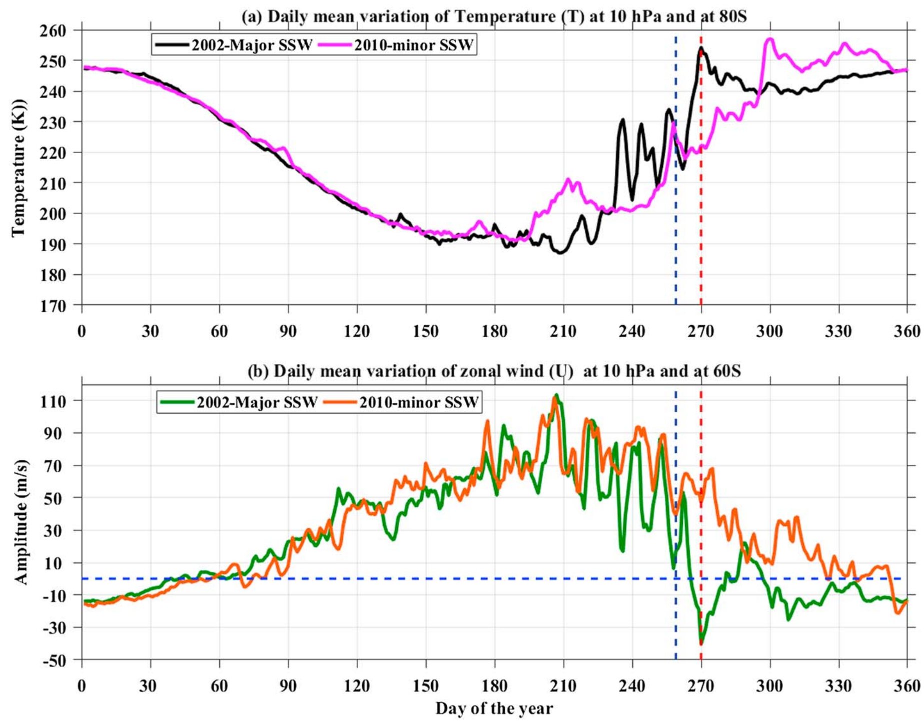

Figure 1. (a) Daily zonal mean temperature at 80°S obtained from ERA-Interim reanalysis data set for the year 2002 and 2010 at 10 hPa. (b) Same as (a) but for the zonal mean zonal wind at 60°S and at 10 hPa. The dashed vertical lines indicate the day of peak warming(s). The dashed horizontal line in (b) indicates the zero wind level.

the time series is used at each height bin (Davis et al., 2013; Kumar et al., 2008). The fit was applied for both zonal and meridional wind components, as expressed in equation (1).

$$A(t) = a_0 + a_{24}\cos\left(\frac{2\Pi t}{24h} - \Phi_{24}\right) + a_{12}\cos\left(\frac{2\Pi t}{12h} - \Phi_{12}\right) + a_8\cos\left(\frac{2\Pi t}{8h} - \Phi_8\right) \quad (1)$$

where a_0 is the prevailing wind component; a_{24}, a_{12}, and a_8 are the amplitudes of diurnal, semidiurnal, and ter-diurnal components, respectively; and Φ_{24}, Φ_{12}, and Φ_8 are the phases of the corresponding components.

2.2. Earth Observing System MLS Data

The Earth Observing System MLS is one of the four instruments aboard NASA's Aura satellite, and it has a radiometer that retrieves temperature from the bands near the O_2 spectral line at 118 and 239 GHz. It measures the temperature from 316 to 0.001 hPa pressure levels with a track resolution of 230 km, which includes the global coverage from 82°S to 82°N with ~15 orbits per day, providing ~30 samples daily for given latitude. Details of the MLS and temperature validation are given in Schwartz et al. (2008). In the present study, we have used the H_2O and ozone (O_3) profiles derived at 80°S.

2.3. ERA-Interim Data

We also make use of stratospheric zonal winds from ERA-Interim reanalysis data sets provided by the European Center for Medium-Range Weather Forecasts (Berrisford et al., 2009). The ERA-Interim reanalysis provides the data between the pressure levels 1,000 and 1 hPa (~0–48 km) with different latitudinal and longitudinal grids. In the present study, we have utilized zonal mean zonal winds at 10 hPa with the 0.75° × 0.75° grid.

3. Results and Discussion

3.1. PWs During the 2002 and 2010 SSW Years in the SH

Figure 1 shows daily variations of zonal mean temperature at 80°S (Figure 1a) and daily zonal mean zonal wind at 60°S (Figure 1b) obtained from ERA-Interim reanalysis data set at 10 hPa for the years 2002 and

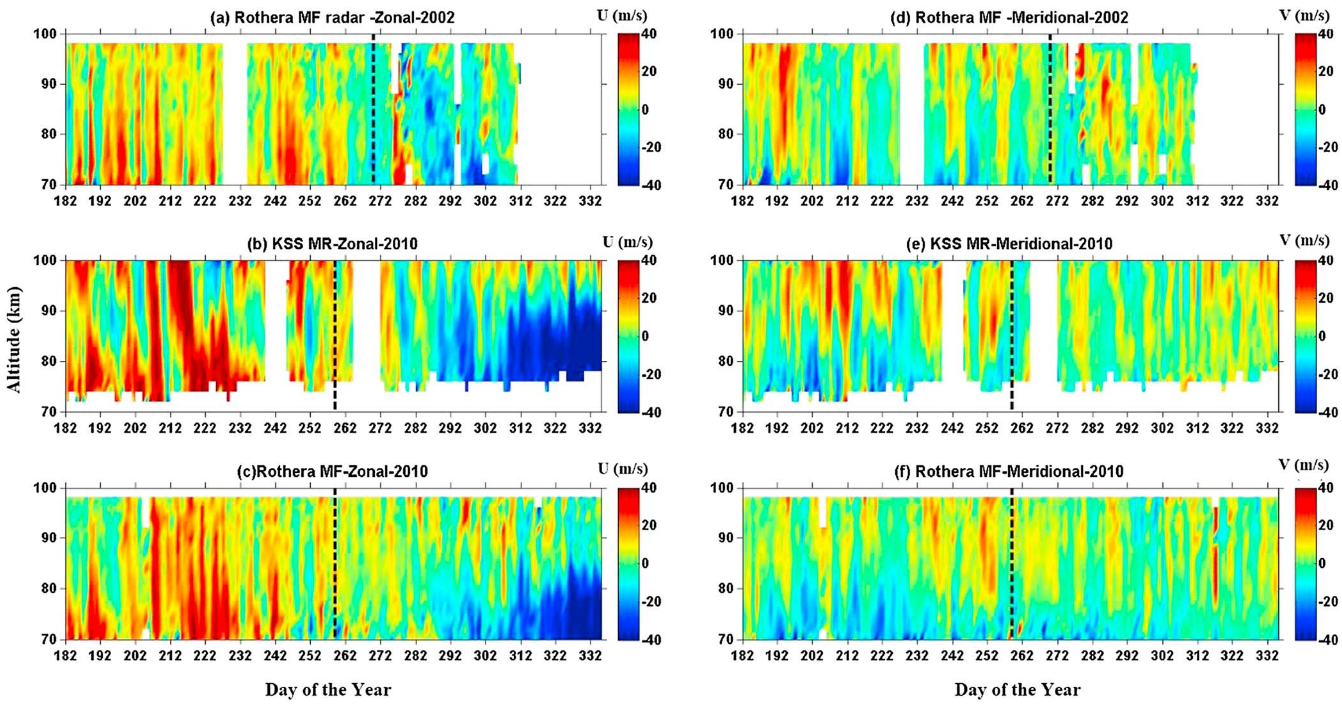

Figure 2. Variability of daily mean zonal and meridional winds measured by RMFR (68°S, 68°W) and KSS MR (62.22°S, 58.78°W) during the 2002 and 2010 SH winter periods, respectively. The top panel shows the 2002 winds, and the middle and bottom panels show the 2010 winds. Left panels (a–c) are for zonal components, and right panels (d–f) are for meridional components. The vertical dashed line indicates the day of peak warming.

2010. It is clear from the figure that the 2002 major warming occurred in late September (day 270, red dashed line) with a sequence of minor warmings (Baldwin et al., 2003). The 2010 minor warming is evident in mid-September (day 259, blue dashed line). The 2002 major warming was well studied, and the 2010 minor SSW is found recently and less investigated. Recently, Eswaraiah et al. (2016) testified the occurrence of the 2010 minor SSW and its dynamical effects on the mesosphere. They identified that the September (day 259, blue line) event has caused a great impact on the Antarctica mesosphere dynamics. During 2002, the zonal wind is reversed remarkably in the stratosphere on the peak warming day, whereas only the weakening of zonal wind is noticed during the 2010 minor warming.

Figure 2 shows the daily mean variability of zonal and meridional winds during 2002 by RMFR and in 2010 by both RMFR and KSS MR. The left and right panels in the figure are zonal and meridional winds, respectively. The tenacity of using two different radars is to accomplish confident wind measurements from 70 to 100 km with a fine resolution. It is understood that the MF radar provides reliable wind measurements at 80 km, while the MR can offer winds at 90 km with better quality, due to a maximum number of meteor echoes, than at other altitudes (Lee et al., 2013; Rao et al., 2014).

During 2002, the zonal wind reversal (Figure 2a) is apparent a week before the major SSW event (day 270), and the meridional wind (Figure 2d) exhibits some signs of the 14–16 day PWs. The zonal wind becomes westward, and the magnitude of wind reversal is ~9 m/s at 80 km. The middle panel shows the winds measured by KSS MR during the 2010 winter; eastward winds (Figure 2b) are dominant up to 90 km until the mid-winter and becomes westward in the late winter. The zonal wind (Figure 2b) reversal (with magnitude ~12 m/s) starts nearly 1 week before the associated warming in the stratosphere and again eastward during the SSW event. Meridional winds (Figure 2e) show the hint of the 14–16 day wave structure before the SSW. Similar behavior is noticed in RMFR (bottom panel) during the 2010 SSW event. These features are more significant up to 80 km in RMFR (Figures 2c and 2f). The white patches indicate the data gaps.

The PWs have attained significant importance during the SSW period since their growth, propagation, and interaction with mean flow result in reversal of zonal wind and change in the global mean meridional circulation (Dowdy et al., 2007). It is also believed that the PW activity during SSWs play a dominant role in

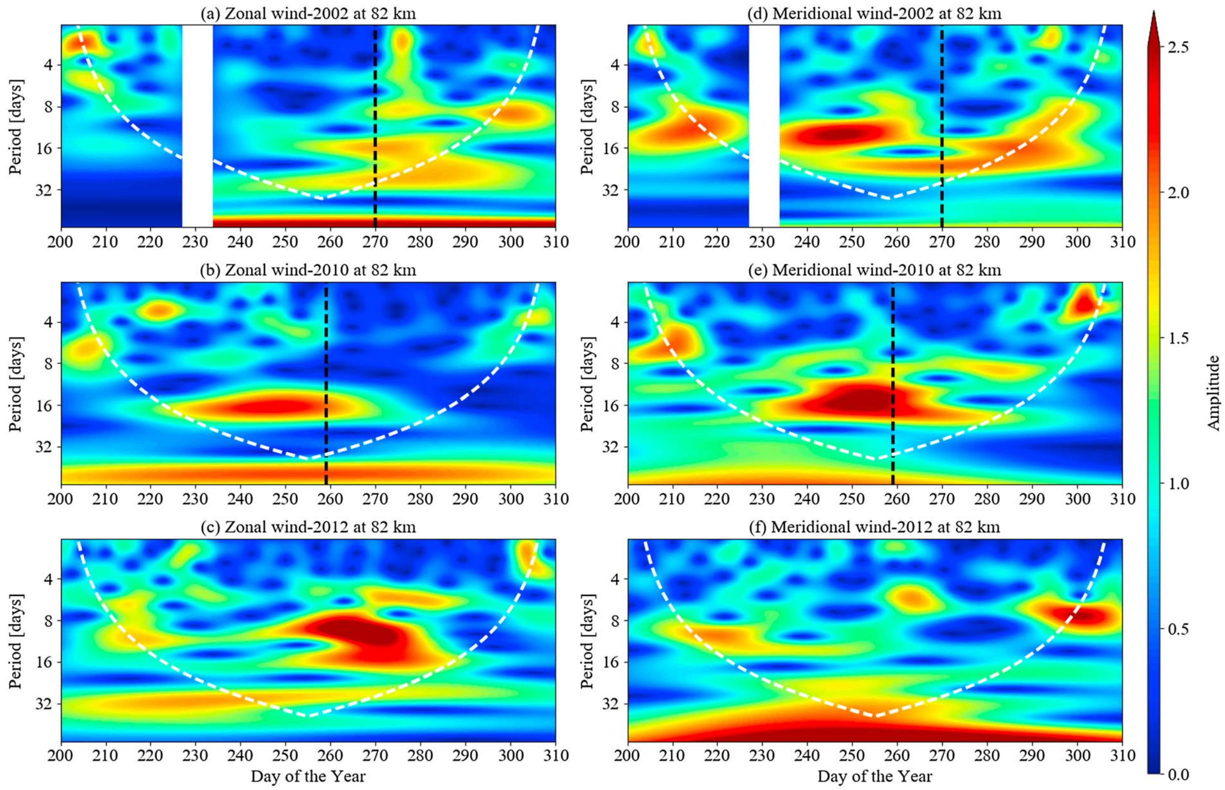

Figure 3. (a) Wavelet spectrum of zonal winds observed in the 2002 major SSW, using MF radar at 82 km. (b) Same as (a) but for 2010 minor SSW. (c) Wavelet spectrum during non-SSW year 2012. (d–f) Same as (a–c) but for meridional winds. The dashed vertical line indicates the warming periods in both 2002 and 2010, respectively. The dashed white line indicates cone of influence.

modulating the tides, and thus, the modified tides can lead to change in the mesosphere temperature to be as high as 20 K (Hagan et al., 1999). In fact, the meridional wind pattern in both the 2002 and 2010 SSW years (Figures 2d, 2e, and 2f) is indicative of the existence of PWs of large scales. Model simulations have revealed the existence of 16 day PW activity prior to the peak warming at the mesosphere altitudes over the NH (Coy et al., 2005; Liu & Roble, 2002). This aspect was observed with the ground-based radar data over Antarctica during the 2002 major SSW (Dowdy et al., 2004; Mbatha et al., 2010). In the current study, we carried out the wavelet spectra analysis of the both zonal and meridional winds in the mesosphere to find whether the 16 day PWs were indeed present during 2010 minor SSW and to compare them with those of the 2002 major SSW.

Figure 3 depicts the wavelet spectra of PWs in both the 2010 and 2002 winters that were obtained from RMFR zonal and meridional winds at 82 km, respectively. This figure is drawn by applying a wavelet transform with a Morlet base (Torrence & Compo, 1998) to both zonal and meridional wind perturbations. The PW activity during non-SSW year (2012) is also shown in the lower panels. It is evident from Figure 3 that the 14–16 day PW is appearing in meridional wind during the 2002 major SSW (Figure 3d) and attains its maximum amplitude well before (~10 days) the onset of SSW at the stratosphere. However, during the 2010 minor SSW, the 14–16 day wave is appearing in both the zonal and meridional wind components (Figures 3b and 3e) and reaches its peak amplitude prior to the minor warming event. In addition to the 14–16 day PW, small-scale secondary waves with periods spanning 3 to 5 days can be seen after the SSW in both the 2002 and 2010 SSWs. In the following sections, we will discuss the consequence of 14–16 day PWs in changing the mesosphere tides during SSWs.

3.2. Variability of Mesospheric Tides During the SSW Years (2002 and 2010)

The tidal components have been extracted from the hourly winds of RMFR for 2002 and of both RMFR and KSS MR during 2010 winter, using the procedure discussed in section 2.1. The RMFR tidal amplitudes

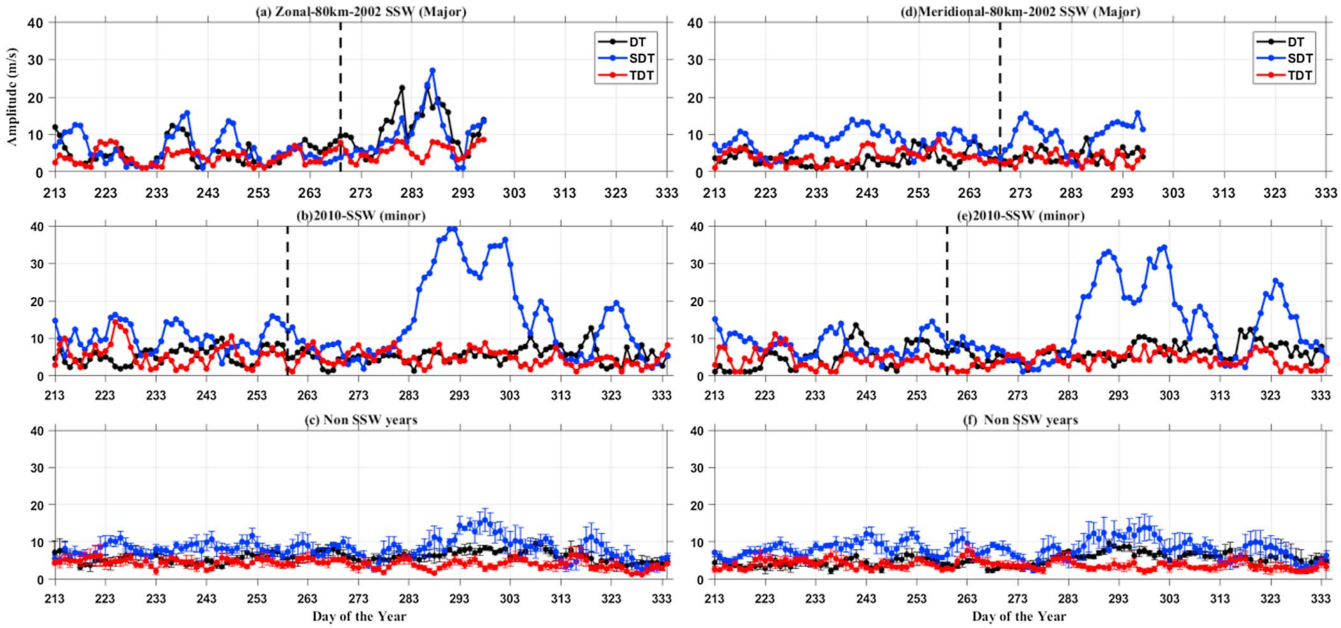

Figure 4. Variability of DT, SDT, and TDT amplitudes measured by RMFR (68°S, 68°W) during the SH winter at 80 km. Left panels (a–c) are for zonal components and right panels (d–f) are for meridional components, respectively. Top two panels (a–b and d–e) are SSW years (2002, 2010) and bottom panels (c and f) show a mean of non-SSW years. The vertical dashed line indicates the day of peak warming.

are shown in Figure 4. All the data are taken at 80 km since MF radar is capable of measuring accurate winds at 80 km. The top panels (Figures 4a and 4d) show the variability of tides during the 2002 major SSW event, while the middle panel (Figures 4b and 4e) displays for the 2010 minor SSW. The behavior of tidal components in the normal (non-SSW) winter period (2007–2013 except 2010) can be checked in the bottom panel (Figures 4c and 4f). The left and right panels are for zonal and meridional components, respectively.

From Figure 4, it is obvious that the SDT enhanced in both the 2002 and 2010 SSW years, a few days later in the accomplishment of the associated SSW event. Usually, in non-SSW winters, the tidal amplitudes (both zonal and meridional) stay below 20 m/s (Figures 4c and 4f). In contrast, during SSW winter, the amplitude of SDT is more than 30 m/s and sometimes reaches to even 40 m/s. During the 2002 major SSW, both diurnal and semidiurnal zonal components start amplifying after 8 days of peak SSW and reach maximum amplitude (~27 m/s) after 18 days. However, in the meridional wind components, the tidal amplitude (DT and SDT) suddenly falls during the peak SSW, and later the SDT component slightly increases (up to 18 m/s). In contrast, during the minor SSW (2010), both zonal and meridional SDT started enhancing their amplitude after 22 days of peak SSW and reached a maximum value after nearly 1 month from the SSW day. The maximum amplitude noticed in the zonal component of SDT is ~40 m/s, whereas in meridional components, it is ~35 m/s. The ter-diurnal tide (TDT) has not been affected during SSW years. It is observed from Figures 4a, 4b, and 4e that for both major and minor SSWs, the tidal amplitudes increased after 20 days and 30 days of SSW day in 2002 and 2010, respectively. The reasons for the tidal enhancement after the cessation of SSWs are discussed in light of their causing mechanisms in the upcoming subsection.

Figure 5 shows the variability of tidal components from the KSS MR winds at 90 km (the most reliable altitude for the MR measurements). The variability of DT, SDT, and TDT amplitudes is shown for zonal and meridional components in Figures 5a and 5b, respectively. Similar to the RMFR data, the KSS MR data also exhibit the maximum enhancement in SDT after ~30 days from the peak SSW. The meridional components of SDT amplitude approach even 50 m/s around day 293, whereas the zonal components are reaching more than 45 m/s on the same day. The DT and TDT components stay below 15 m/s. The difference in the peak tidal amplitudes between the two radar winds could be due to wind measuring techniques, although it is believed that MRs tend to provide more accurate winds than MF radars (Rao et al., 2014); the latitudinal separation of the radars

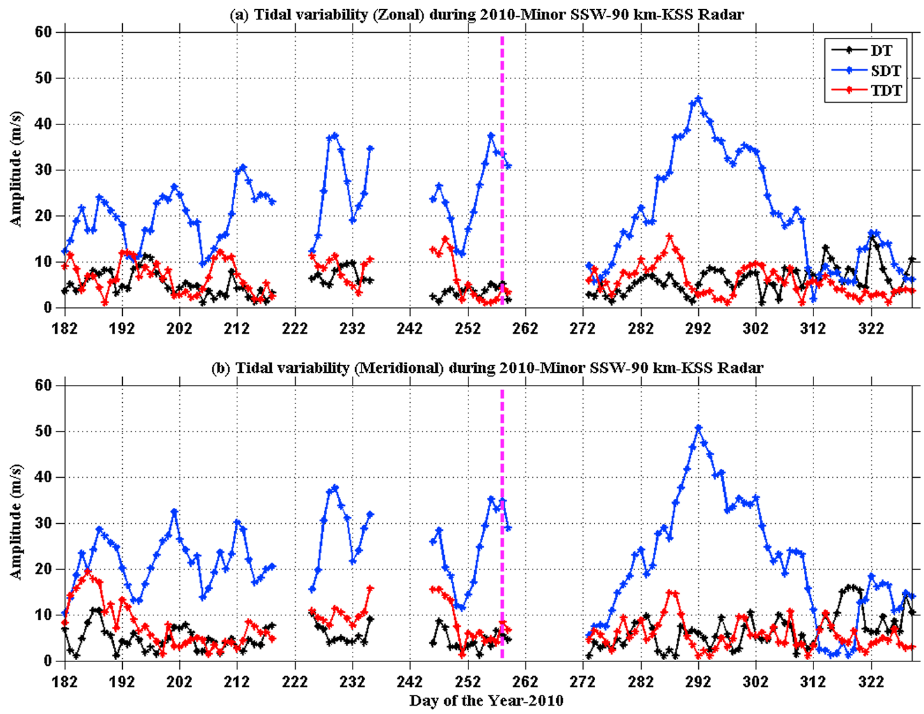

Figure 5. Variability of DT, SDT, and TDT amplitudes measured by KSS (62.22°S, 58.78°W) MR at 90 km. The top panel is zonal components, and bottom is meridional components. The vertical dashed line indicates the day of peak warming.

could also contribute to the difference. Also, MF radar results are more reliable at lower altitudes (80 and 82 km), whereas the MR provides the best quality winds at 90 km where a maximum number of meteors is usually detected, although it can nominally measure winds between 70 and 110 km.

3.3. Discussion

The variability of Antarctic MLT structure and dynamics due to the SSW is an interesting topic since the high-latitude MLT region plays a key role in the global mean circulation (Charlton & Polvani, 2007; Randel et al., 2002). Regarding the SDT enhancement in the polar MLT region associated with the SSW, the earlier theoretical studies suggested the nonlinear interaction between PWs and tides appears to be the most plausible for the changes in SDT amplitude (Angelats i Coll & Forbes, 2002; Yamashita et al., 2002). In addition, the amplification of secondary PWs of wave number 1 was observed at the mesosphere altitudes after the SSW (Manney et al., 2008; Siskind et al., 2007, 2010). The simulations by Liu et al. (2010) showed the connection between the peak PW activity and SDT and suggested that the SDT enhancement took place ~1 day after the cessation of PW activity. However, observations showed that the maximum MLT and ionosphere disturbances appeared several days later (Chau et al., 2009; Goncharenko, Chau, et al., 2010; Goncharenko, Coster, et al., 2010; Liu et al., 2011), that is, when PW activity has already decreased. Although these studies were carried out at low and middle latitudes, the discrepancies between the model simulations and observations indicate that, in addition to the nonlinear interaction between PWs and tides, other mechanisms might be involved in causing the delay in tidal enhancement. The delay in the enhancement of SDT after a few days of SSW could be due to (1) the increase of ozone mixing ratio or ozone density at an altitude level of ~2 hPa due to PW-forced mean circulation, causing a large enhancement of SDT; and (2) the nonlinear interaction of PW and tides leading to the generation of quasi-secondary waves, and thus the secondary waves will change the tidal amplitudes. It needs to be quantified which mechanism is dominating for the tidal enhancement.

The role of stratospheric ozone in coupling the low-latitude stratosphere and MLT region has been studied by Goncharenko et al. (2012). In their study, Goncharenko et al. (2012) suggested that the increase in the ozone density at 2 hPa (~43.5 km) lasts ~35 days following the SSW long after the downfall of PWs, causing an

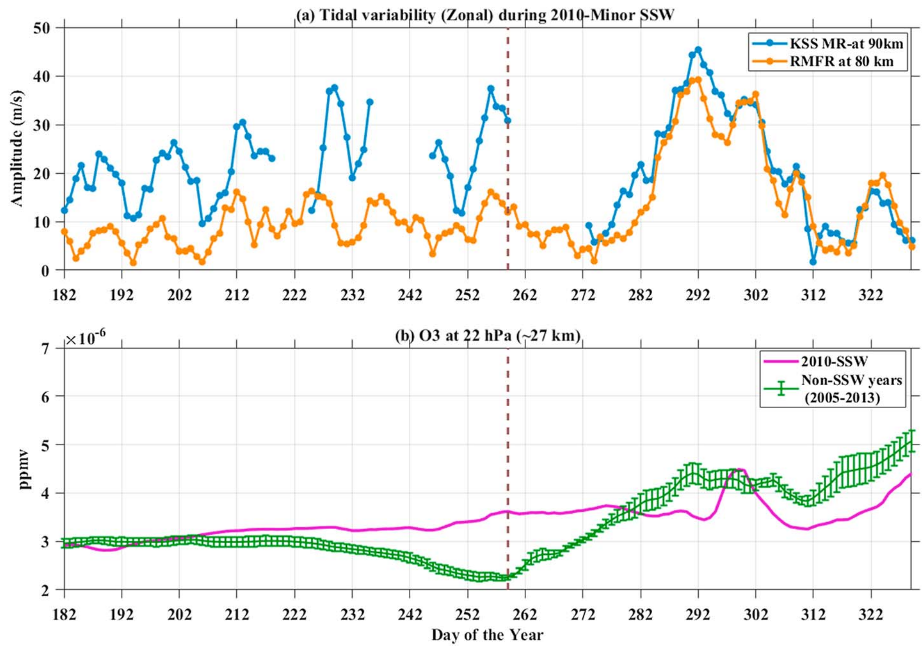

Figure 6. (a) Variability in the SDT amplitude of zonal components measured by KSS (62.22°S, 58.78°W) MR at 90 km and 80 km, during the 2010 SH winter. (b) Daily mean variability of ozone (O_3) in the stratosphere at 22 hPa (~27 km) observed using MLS measurements during the non-SSW years and comparison with minor warming event year 2010. The vertical dashed line shows the day of peak warming.

enhancement in SDT amplitude. However, at the polar latitudes, the mechanism is different. The meridional circulation forced by PWs in the polar region during SSW leads to transport of ozone from pole to equator (Garcia, 1987; Randel, 1993) and thus increases the peak ozone heating rate at ~43 km at low latitudes, resulting in the amplification of SDT in the MLT region (Goncharenko et al., 2012; Lin et al., 2012). In fact, a similar feature was noticed during the 2010 minor SSW, and the same is depicted in Figure 6. Figure 6a shows the enhancement of SDT amplitude at 90 km using KSS MR and at 80 km using RMFR during the 2010 minor SSW. In the figure, KSS MR zonal SDT amplitude reached ~45 m/s on day 293, whereas RMFR shows the maximum value ~40 m/s. It is worth pointing out that the SDT amplitude of both the radars follows a similar trend although the wind measuring techniques are different. As shown in Figure 6b, the ozone density at 22 hPa (the ozone is usually generated at this altitude) is gradually increasing in the winter from day 200 onward and attains maximum value during warming day (259), and after that, it extremely deviates from the normal seasonal trend, except a small hike around day 300.

The variation in ozone trend in 2010 winter could be due to the strong B-D circulation forced by enriched PWs at the polar region. The circulation transported the ozone from SH to NH high latitudes as a consequence of pole-pole circulation (Butchart, 2014), or it could be transported to low latitudes. Alternatively, the ozone could be downward transported to lower altitudes in the SH itself. The small upturn in the ozone density around day 300 could be due to the minor warming that occurred on day 300 (Eswaraiah et al., 2016). Since MLS satellite is located in a Sun-synchronous orbit, the zonal mean values of ozone might have been aliased with the migrating tides. Figure 6 indicates that even when ozone density is lower than the usual value, the SDTs are enhanced during days 270–310. This may suggest that ozone alone may not play a dominant role in the amplification of tides over the Antarctic MLT region.

In order to probe the alternative process, we have plotted both the O_3 and H_2O anomalies from 15 km to 50 km during days 100–350 in Figure 7. Earlier studies (e.g., Sridharan, Sathishkumar, & Gurubaran, 2012a) suggested that ozone and water vapor at 2 hPa (~43 km) are main elements to generate the SDTs in the low-latitude region.

Figure 7 clearly shows that both ozone and water vapor are transported downward during winter, due to PW-forced mean downward circulation. Resulting from the downward transport, both water vapor and ozone at

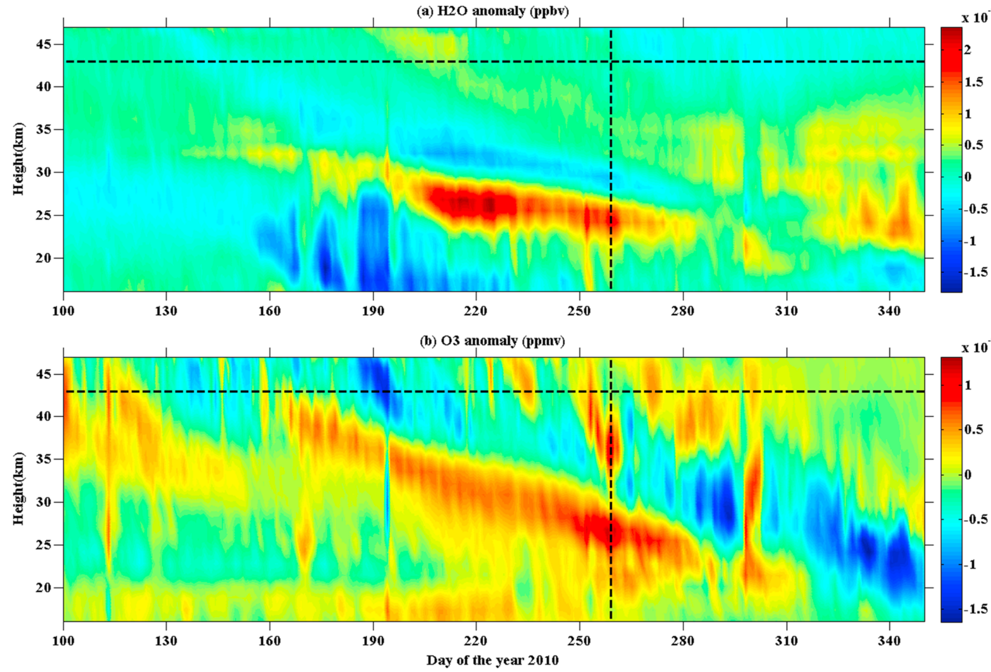

Figure 7. Time-altitude section of (a) water vapor (H_2O) and (b) ozone (O_3) anomalies observed using MLS data during 2010. The dashed vertical line indicates the day of peak warming. The dashed horizontal line indicates 2 hPa (43 km) altitude level.

2 hPa altitude level reduce to very low concentration, except a few hikes in the ozone during the peak SSW (day 259) and sporadic increments up to day 310. The results shown in both Figures 6 and 7 suggest that the effect of ozone and water vapor seems less significant on the Antarctic mesospheric tides, unlike at the low latitudes (Chapman & Lindzen, 1970; Forbes & Garrett, 1978; Sridharan, Sathishkumar, & Gurubaran, 2012a). Thus, the above discussion turns to consider the other reason for the SDT enhancement, namely, PW-tidal interaction.

Nonlinear interaction of PWs with tides is well documented in earlier studies. Pancheva and Mitchell (2004) has shown the nonlinear interaction between PWs and SDTs over Esrange (68°N, 21°E) using the 39 month MR observations. They suggested that during the polar winter, the SDT modulation is due to the process of nonlinear interaction between PWs and SDTs. Further, Mthembu et al. (2013) suggested that the nonlinear interaction between the 16 day wave and SDT modulates the SDT amplitudes more than other periods of PWs over the SH. Lima et al. (2012) discussed the relationship between quasi 2 day wave growth and variability of DT and SDT amplitudes during SSW. They suggested that the nonlinear interaction between 16 day PWs and tides during SSW leads to produce secondary waves. Additionally, they depicted the anticorrelation between the 2 day waves and DT/SDTs at a tropical station, Sao Joao do Cariri, Brazil (7.4°S, 36.5°W). They found that the DT and SDT amplitudes began to increase just after the quasi 2 day wave amplitude started decreasing, and the tidal amplitude reaches the maximum value, about 25 days after the peak of quasi 2 day wave amplitude. But in the present case at the high-latitude region, quasi 2 day waves are not significant, but 3–9 day waves are significant (see Figure 3) during the 2002 major SSW and 3–5 day waves during the 2010 minor SSW. The secondary waves generated in the mesosphere after the SSW are in accordance with the earlier reports at the NH (Chandran et al., 2013; Lieberman et al., 2003; Liu et al., 2004; Meyer & Forbes, 1997).

Utilizing the fast Fourier transform spectral analyses and band-pass filter, we have picked up the 3–5 day waves from the zonal winds during 2010 minor SSW. The growth and propagation of quasi-secondary waves (3–5 day) in the mesosphere and their relation to SDT during 2010 winter are displayed in Figure 8.

The top panel (Figure 8a) shows the relation between the amplitudes of SDT and 3–5 day waves at 80 km. It can be noticed from Figure 8a that the amplitude of the 3–5 day wave decreases when the SDT amplitude

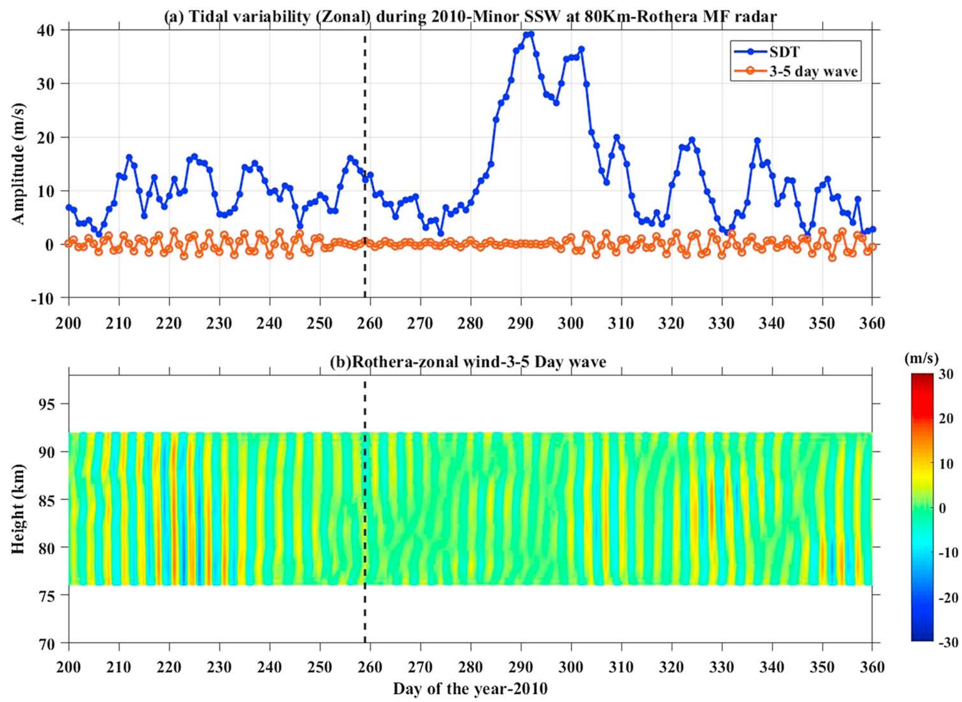

Figure 8. (a) Day-to-day variability of the SDT amplitude (blue line) of the zonal component measured by RMFR (68°S, 68°W) at 80 km and 3–5 day wave at 80 km is overlaid. (b) Propagation of 3–5 day waves observed in zonal winds of RMFR at different altitudes. The vertical dashed line shows the day of peak warming.

increases. After the SSW, the amplitude of 3–5 day wave starts decreasing and attains its low value up to day ~280. Around day ~280 the SDT begins to increase its amplitude and reaches maximum amplitude (40 m/s) on day 293, whereas the 3–5 day wave almost falls down to zero amplitude. The middle panel (Figure 8b) shows the existence of 3–5 day waves in the mesosphere using RMFR zonal winds. We can observe that the decreasing phase of secondary wave amplitudes starts after the onset of SSW and attains its minimum value between days 285 and 295 at all the altitudes in the mesosphere. This may imply that the SDT amplitudes in the mesosphere are enhanced due to the decrease of secondary waves after the SSW.

The recent model by Limpasuvan et al. (2016) during major SSW with elevated stratopause predicted the existence of secondary waves for about 25 days after the onset of SSW, and they suggested that the nonlinear interaction between the tides and secondary waves leads to modulating the SDT. Thus, we suggest here a scenario that secondary waves (3–5 day), which were generated from 14 to 16 day PW before SSW, caused the enhancement of mesosphere SDTs after the SSW. In the SH, the current study is the first observational attempt to elucidate the reasons for the variability of the mesospheric tides during both the major and minor SSWs.

4. Summary

In the present communication, we described the structure and variability of winds and tides in the MLT region during both the 2002 major SSW and 2010 minor SSW years over the SH. The tidal components (DT, SDT, and TDT) in the MLT region have been derived from the hourly wind data observed by both RMFR and KSS MR. We found a large enhancement of SDT after both major and minor SSW events. The main findings are summarized as follows:

1. During the major SSW in 2002, enhancement of DT and SDT amplitudes in zonal winds is noticed ~18 days after the SSW. In the meridional wind components, DT and SDT amplitudes suddenly fell during the peak SSW, and subsequently SDT amplitudes slightly increased.
2. During the 2010 minor SSW, the tidal enhancement is greater than the 2002 major SSW. During the 2002 major SSW, both DT and SDT amplitudes of zonal winds measured by RMFR increased up to 27 m/s from

the normal value of 15 m/s, whereas SDT zonal amplitudes were raised up to 40 m/s in 2010. KSS MR also measured the enhancement of SDT amplitudes up to 50 m/s at 90 km after the 2010 SSW event.

It is a challenging issue to understand why the enhancement of SDT amplitudes is greater for the minor SSW than the major SSW.

We further tested the causative mechanism for the enhancement of SDT, as suggested by earlier studies, which includes (1) the increase of ozone mixing ratio or ozone density at an altitude of ~2 hPa (Goncharenko et al., 2012); and (2) the nonlinear interaction of PW and tides leading to the generation of quasi-secondary waves and modulation of tides after the SSW (Lima et al., 2012). The following are the test results:

1. From the water vapor and ozone anomalies, we noticed the existence of the very low amount of ozone and water vapor at 43 km altitude over 60°S, except a few sporadic increments in the ozone. This implies that the tidal enhancement after SSW may not be directly related to the variation of ozone and water vapor at high latitudes.
2. We estimated the growth and propagation of quasi-secondary waves (3–5 days) in the mesosphere and their relation to the variability of SDT amplitudes during 2010 winter. We noticed an anticorrelation relationship between the SDT and 3–5 day wave amplitudes at 80 km in the mesosphere after the 2010 SSW; during the decreasing phase of 3–5 day wave amplitude, the SDT started increasing its amplitude and reached a maximum amplitude after about a month of the SSW day.

The reason for tidal enhancement after 3 to 4 weeks of associated SSW should be further investigated by studying the ozone analysis over the Antarctica and nonlinear interaction between PWs and tides. Bispectral analysis of wind data in MLT may provide evidence for the nonlinear interaction of waves. In addition, the study on the interaction between PWs and gravity waves over Antarctica mesosphere region may offer an alternative reason for the tidal enhancement.

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