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Key Points:
- Enhanced westward winds at the tropical stratopause during major Sudden Stratospheric Warming (SSW) events in the Northern Hemisphere
- Westward acceleration of stratospheric winds during both split and displacement type SSW events
- Poleward shift of the tropical zero wind line during the course of the warming

Supporting Information:
- Supporting Information S1

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Westward Acceleration of Tropical Stratopause Zonal Winds During Major Sudden Stratospheric Warming Events

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Abstract The tropical Mesosphere-Lower Thermosphere-Ionosphere system is found to show significant variabilities during Sudden Stratospheric Warming (SSW) events. Recent studies have highlighted the possible role played by modified background wind conditions in communicating the SSW-induced stratospheric perturbations to the Mesosphere-Lower Thermosphere-Ionosphere region. In the present study, changes in the background zonal winds at the tropical stratopause during major SSW events inferred from MERRA-2 reanalysis data sets, rocket observations, and model simulations are reported for the first time. The tropical stratopause shows enhanced westward winds during the course of major SSW events. Rocketsonde observations from a low latitude station Thumba (8.5 ° N,76.9 ° E) also showed significant westward acceleration during three major SSW events. Further, Specified Dynamics version of the Whole Atmosphere Community Climate Model simulations for the 2008–2009 SSW replicate the observed features.

Plain Language Summary The winter time polar stratosphere undergoes sudden reversal of climatological eastward winds to westward winds accompanied by a large increase in temperature during dramatic events called Sudden Stratospheric Warmings. Previous studies have shown that the upper atmosphere (Thermosphere/Ionosphere) over low latitudes show strong signatures associated with these polar phenomena. Changes in the tropical middle atmospheric background winds in response to Sudden Stratospheric Warming events are thought to have a significant role in causing the observed changes in the upper atmosphere. In the current study, abrupt changes in stratopause winds over the low latitudes are reported using reanalysis, observations, and model simulations. Present results can contribute to understanding several features observed in the low latitude upper atmospheric altitudes in connection with these polar sudden warming episodes.

1. Introduction

Strong quasi-stationary planetary wave disturbances in the winter polar stratosphere occasionally interact with the eastward zonal flow to result in weakening or disruption of the polar vortex (Matsuno, 1971). Such dramatic events which take place over the course of a few days are referred to as Sudden Stratospheric Warming (SSW) events. SSW events can lead to reversal of the poleward temperature gradient and can sometimes replace the climatological eastward winds with westward winds (Holton, 1980). According to Charney and Drazin (1961), the stronger background eastward winds in the winter stratosphere permit the upward transmission of planetary waves with Zonal Wave Numbers 1 and 2, restricting the propagation of higher wave numbers. During SSW events, the polar vortex may either split up into two or may be displaced from its original position. Displacement and split type SSWs are more often associated with Zonal Wave Numbers 1 and 2, respectively (Charlton & Polvani, 2007).

Reversal of eastward winds in the polar stratosphere following SSW events allows more eastward gravity waves to propagate upward to the mesosphere-lower thermosphere region (Liu & Roble, 2002). Altered filtering of gravity waves result in enhanced eastward forcing in the mesosphere, thus causing temperature and wind anomalies over high latitudes (Hoffmann et al., 2007; Zülicke et al., 2018). Over low latitudes, they are observed to affect mesospheric winds (Kishore Kumar et al., 2014), tides, and several ionospheric parameters (Chau et al., 2012). Even though there are evidences focusing on low latitude stratospheric signatures of SSW events, very few of them have addressed the dynamical changes in this region by employing model simulations and reanalysis data sets (e.g., Chandran & Collins, 2014; Sathishkumar et al., 2009). However, owing to the sparse measurements of winds in the upper stratosphere, these results have not been validated using observations.

In this context, the present study focuses on observed changes in zonal mean winds in the tropical stratosphere associated with SSW events by employing rocket observations to validate the reanalysis data sets as well as model simulations. The rocket soundings provide unique in situ measurement of winds in the upper stratosphere-lower mesosphere region. It is worth mentioning that these rocket observations are not fed into reanalysis data sets or model runs as inputs. Hence, they can act as an independent set of data to validate the aforementioned. In this study, for the first time, we report in situ observational evidence for westward acceleration of tropical stratopause zonal winds during major SSW events. The paper is structured as follows: Section 2 briefly describes the data used and methodology employed. Results and discussions are provided in sections 3 and 4, followed by conclusions in section 5.

2. Data and Methods

MERRA-2 reanalysis data sets (Gelaro et al., 2017) are used in the present study to examine zonal mean zonal winds in the 100–0.1 hPa region during winter months with Major SSWs. Data archived at 5° × 0.625° (latitude × longitude) resolution are used for the analysis. MERRA reanalysis data sets have been previously validated with rocketsonde observations (Kishore Kumar et al., 2015). Major SSW events are identified by zonal mean temperature in the polar cap (averaged poleward of 60°N) at 10 hPa and zonal mean zonal winds at 60°N, 10 hPa. The aforementioned parameters together with amplitudes of planetary waves with Zonal Wave Numbers 1 and 2 at 60°N, 10 hPa are taken from the MERRA reanalysis-based NASA online data service (https://acd-ext.gsfc.nasa.gov/Data_services/met/ann_data.html). Intensity of SSW events (classified as "strong" if the product of maximum westward winds and the number of days with westward winds at 60°N, 10 hPa exceeds 100 ms^{-1} day^{-1} and "weak otherwise) is adapted from Kishore Kumar et al. (2014). In this study, we follow the World Meteorological Organization (WMO) definition where the SSW period is defined as the period during which zonal mean zonal winds at 60°N, 10 hPa remain westward (Charlton & Polvani, 2007; Schoeberl, 1978). Details of SSW events identified for the present study are listed in Table 1.

The study also utilizes data from RH200 series of rockets launched from the low latitude station Thumba (8.5°N, 76.9°E) as a part of ISRO's Middle Atmosphere Dynamics program from 2002 to 2007. More details of the ISRO's Middle Atmosphere Dynamics campaign can be found in Ramkumar et al. (2006). Horizontal winds in the 20–65 km altitude region were derived using the copper chaff release technique. Error associated with rocketsonde wind measurements are ±2–2.7 m/s in the 20–50 km region and ± 3.8 m/s above 50 km (Devarajan et al., 1984). The simulations from Specified Dynamics setup of the Whole Atmosphere Community Climate Model (SD-WACCM) are also used to investigate the vertical structure of mean zonal winds as a function of latitude during SSW events. More details of the WACCM model can be found in Marsh et al. (2013). The model version used here has a resolution of 0.95° × 1.25° (latitude × longitude) and has 88 pressure levels from surface to 5.96×10^{-6} hPa. GEOS5/MERRA reanalysis data sets are used in SD-WACCM to constrain temperature and dynamical fields in the troposphere and stratosphere, and the model is free running above 50 km.

3. Results

Latitude-pressure sections of composites of zonal mean zonal winds from MERRA-2 during boreal winters (December-February) for the (top) eastward and (bottom) westward phases of the Quasi Biennial Oscillation (QBO) are depicted in Figure 1. Composites shown in Figure 1 are constructed from five and three events, respectively, for eastward and westward phases of the QBO (refer to Table 1 for details of SSW events). Left and middle panels indicate the composites of zonally averaged zonal winds in the 100–0.1 hPa region corresponding to quiet and SSW periods, respectively. Bold lines indicate zero wind lines. Right panels show the difference between the SSW and the quiet composites. Bold lines in right panels demarcate the regions with positive and negative anomalies. The overall structure of the quiet composites remains similar in both the cases, except near the tropics where zonal winds in middle and lower stratosphere alternate between eastward and westward, associated with the phase of the QBO. The strong negative anomalies poleward

Table 1

Details of SSW Events Presented in This Study: Duration of SSW Period, Quiet Period, Phase of QBO (From Zonal Mean Zonal Wind at 10 hPa Over the Equator), Type and Intensity of SSW Events, Observed Maximum Stratopause Zonal Wind Anomaly From Reanalysis and Rocket Measurements

Winter period	SSW period	Quiet period	Phase of QBO	SSW type	SSW Intensity	Stratopause zonal mean zonal wind anomaly (at pressure level) from reanalysis	Stratopause zonal wind anomaly (at height) from RH200 over Thumba
Dec 2001 to Feb 2002	30 Dec to 2 Jan	1 to 29 Dec and 3 Jan to 28 Feb	Eastward	Displacement	Weak	−39.3 m/s (0.5 hPa)	Not available
Dec 2002 to Feb 2003	18 Jan	1 Dec to 17 Jan and 19 Jan to 28 Feb	Westward	Split	Weak	−8.91 m/s (1 hPa)	−48 m/s (51 km)
Dec 2003 to Feb 2004	5 to 14 Jan	1 Dec to 4 Jan and 15 Jan to 28 Feb	Eastward	Displacement	Strong	−48.9 (0.7 hPa)	−54 m/s (50 km)
Dec 2005 to Feb 2006	21 Jan to 15 Feb	1 Dec to 20 Jan and 16 to 28 Feb	Eastward	Displacement	Strong	−13.4 m/s (1 hPa)	−73.5 m/s (49 km)
Dec 2008 to Feb 2009	24 Jan to 22 Feb	1 Dec to 23 Jan and 23 to 28 Feb	Westward	Split	Strong	−29.2 m/s (3 hPa)	Not available
Dec 2012 to Feb 2013	6 to 27 Jan	1 Dec to 5 Jan and 28 Jan to 28 Feb	Eastward	Split	Strong	−54.9 m/s (0.7 hPa)	Not available
Dec 2016 to Feb 2017	1 Feb	1 Dec to 31 Jan and 2 to 28 Feb	Westward	Displacement	Weak	−21.5 m/s (1 hPa)	Not available
Dec 2018 to Feb 2019	2 to 21 Jan	1 Dec to 1 Jan and 22 Jan to 28 Feb	Eastward	Displacement/ split	Strong	−50.6 (0.7 hPa)	Not available

of 50°N seen in the anomaly composites are associated with the well-known wind reversals due to SSW. The most interesting feature in the anomaly composites is the westward anomaly seen at the tropical upper stratosphere-lower mesosphere (10–0.1 hPa). This feature is seen irrespective of the phase of the QBO. The only notable differences between the eastward and westward QBO composites are the height and strength of occurrence of negative anomalies around the stratopause (1 hPa) level. Compared to the westward QBO composite, the negative anomaly is stronger and is found at a higher altitude for the eastward QBO composite. Here, it should be remembered that signatures of SSW events in the tropical stratopause region are found to have significant case to case variabilities (plots for individual cases are given in supporting information Figures S1 and S2), and those are diluted while constructing the composites. Strength and height of maximum tropical (averaged between 0° and 10°N) stratopause zonal wind anomalies for each of the identified SSW events are listed in Column 7 of Table 1. Apart from the westward anomaly around the stratopause, a minor eastward anomaly can also be noted around the 0.1 hPa level in both the cases.

To seek further insights into the enhanced westward winds in the tropical upper stratosphere, rocket observations from Thumba (8.5°N, 76.9°E) during the 2005–2006 SSW events are employed. During this event, a series of rockets with 1 day interval were launched to measure the winds in the 20–65 km altitude. The vertical profiles of zonal wind over Thumba during this event and the climatological profile obtained from 5 years of rocket observations in January (blue solid line) are depicted in Figure 2a. Top panel of Figure 2b depicts the mean polar cap temperature at 10 hPa (black line) and zonal mean zonal wind at 60°N, 10 hPa (blue line). The bottom panel in Figure 2b shows the amplitudes of Wave Number 1 (black) and 2 (blue) planetary waves at 60°N, 10 hPa. Vertical lines in Figure 2b are used to examine the state of the polar stratosphere on days corresponding to the rocket launches. The campaign period spanned from 20 January to 30 January with daily launches. The profiles corresponding to 11 January and 8 February are part of regular fortnightly observations from the station. Except for the 11 January profile, all the individual profiles correspond to the SSW period. It can be seen that during the SSW period, zonal winds in the upper stratosphere

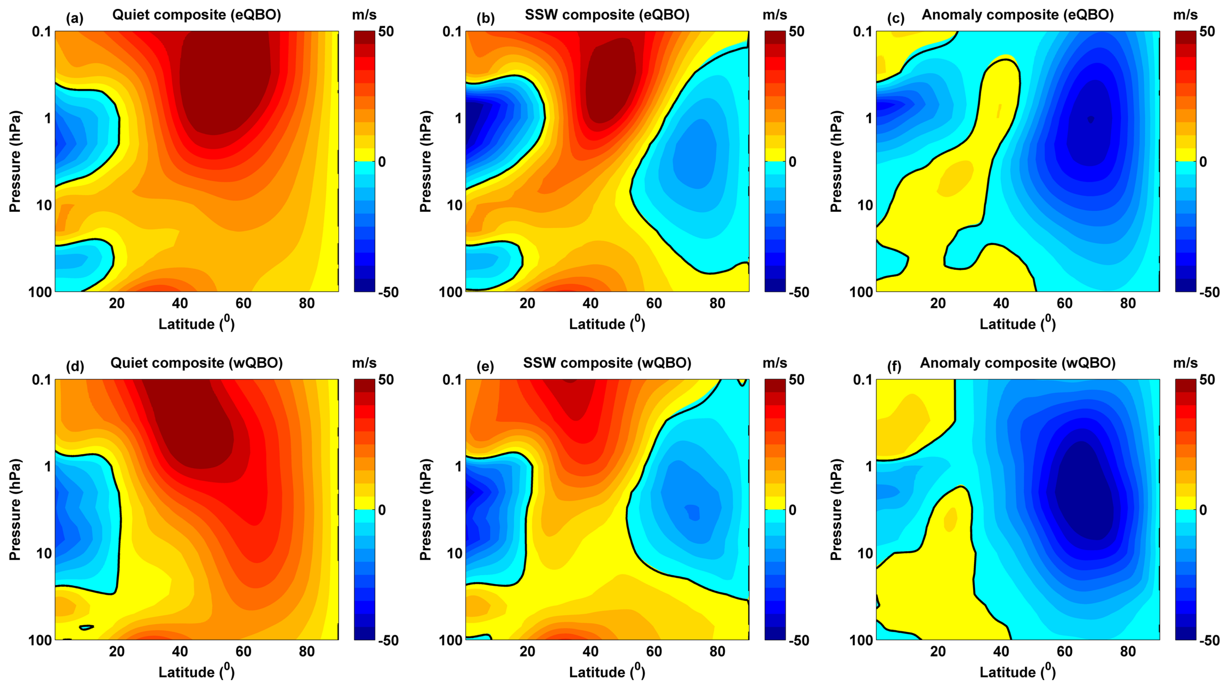

Figure 1. Latitude-pressure composites of zonal mean zonal winds derived from MERRA-2 reanlysis data sets for SSW events during (a–c) eastward QBO and (d–f) westward QBO: (a,d) quiet composite, (b,e) SSW composite, and (c,f) anomaly composite.

over Thumba are significantly westward, both compared to the climatological profile as well as the nonwarming day profile (11 January). Maximum westward winds (−99 m/s) were observed on 20 January, 1 day before the reversal of zonal winds at 60°N, 10 hPa. On the same day, amplitude of Wave Number 2 planetary wave in the polar stratosphere showed a peak as can be seen in bottom panel of Figure 2b. As time progresses, a clear progression of zonal winds toward lesser westward magnitudes can be visibly seen around 50 km. During the warming period, minimum westward zonal winds around 50 km are observed on 8 February, as the polar vortex recovers. Zonal wind profiles further reveal eastward acceleration above 60 km with enhanced eastward winds during the SSW period, which also happen to be higher than the corresponding climatological values. This eastward acceleration was also present above 1 hPa in the composites given in Figure 1.

To investigate whether the observed westward acceleration of zonal winds at the tropical stratopause is a consistent feature during SSW events, rocketsonde observations during January 2003, 2004, and 2005 are examined. Figure 3a shows the vertical profiles of zonal winds over Thumba during January month of (left) 2003, (middle) 2004, and (right) 2005 with four, two, and three launches, respectively. Similar to Figure 2b, state of polar stratosphere during the aforementioned winter period is depicted in Figures 3b–3d. On 1 January 2003, very strong westward winds are present around 50 km with peak values of −72 m/s at 51 km. From Figure 3b, it can be seen that 1 January does not come under SSW period as per the WMO definition. But on closer examination, it becomes evident that the polar cap temperature on 1 January was at a peak and the zonal mean wind at 60°N had started undergoing deceleration, leading us to infer that it belongs to the disturbed period. It can also be seen that Planetary Wave 1 amplitudes were also high on 1 January. In contrast, the 2 January profile remains close to the January climatological values. On 15 January, strong westward winds are present below 50 km. On the same day, strong eastward acceleration can be seen in the 38–45 km region as well as above 50 km. The zonal wind profile corresponding to 30 January remains closer to the climatological profile except in the 45–55 km region. As can be seen from Figure 3b, on 30 January, the polar stratosphere is recovering toward prewarming conditions. Among the two profiles in January 2004 (Figure 3a, middle panel), the profile on 14 January corresponds to the SSW period. It can be explicitly seen that strong westward winds are present throughout the upper stratosphere and lower mesosphere. Westward winds reach a peak value of −86 m/s at 50 km. On the other hand, the nonwarming day profile on 28 January (Figure 3d) remains

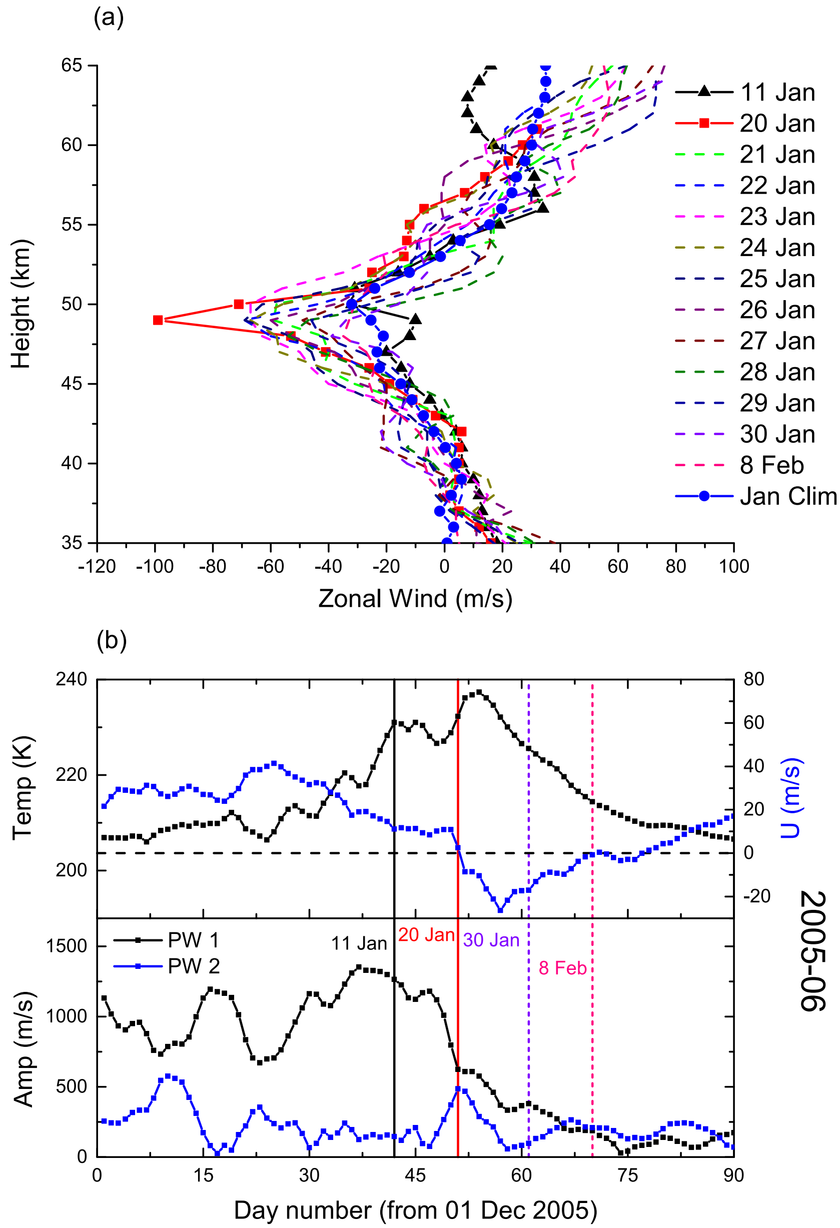

Figure 2. (a) Vertical profiles of zonal winds derived using rocketsonde measurements over Thumba from 11 January to 8 February 2006. Blue solid line with circles represents the climatological mean profile. (b) Polar stratospheric parameters derived from MERRA reanalysis data sets during 2005–2006. (top) Zonal mean temperature in the polar cap at 10 hPa (black) and zonal mean zonal wind (blue) at 60°N, 10 hPa. (bottom) Amplitude of Wave Number 1 planetary wave (black) and Wave Number 2 planetary wave (blue). Vertical lines indicate the days corresponding to the rocket profiles.

closer to the climatological profile. For both 2002–2003 and 2003–2004 cases, the rocket observations show enhanced westward wind around 50 km. The rocket observations thus confirm the zonal wind features reported using reanalysis data sets during SSW events. January 2005 can be regarded as a quiet period as there were no major SSWs in that winter. It is very interesting to note that all the three profiles in January 2005 remain very much closer to the climatological profile. Given in Column 8 of Table 1 are the zonal wind anomalies at the stratopause for individual SSW events taken from rocketsonde observations. Climatological zonal winds are subtracted from the peak westward winds to obtain the zonal wind anomalies. In all three cases, there is a significant westward anomaly present in the stratopause region. The rocketsonde observations thus provide observational evidences for the westward acceleration of low latitude stratopause zonal winds during major SSW events.

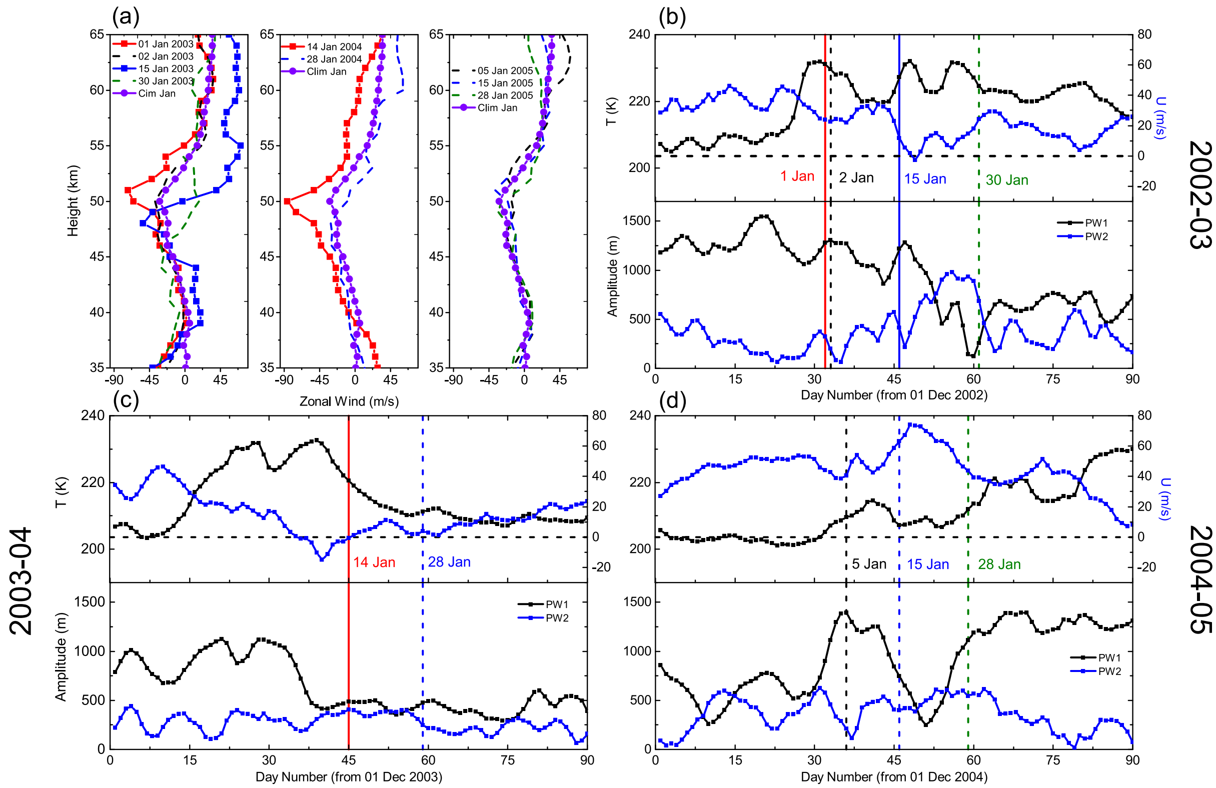

Figure 3. (a) Vertical profiles of zonal wind over Thumba during January (left) 2003, (middle) 2004, and (right) 2005. The violet line indicates the climatological profile for January. (b) Polar stratospheric parameters derived from MERRA reanalysis data sets during 2002–2003. (top) Zonal mean temperature in the polar cap at 10 hPa (black) and zonal mean zonal wind (blue) at 60°N, 10 hPa. (bottom) Amplitude of Wave Number 1 planetary wave (black) and Wave Number 2 planetary wave (blue). (c) Same as (b) except for 2003–2004. (d) Same as (b) except for 2004–2005. Vertical lines indicate the days corresponding to the rocket profiles.

To examine the current models' capability to simulate the observed westward acceleration at the low latitude stratopause level as well as to note up to which altitude the wind anomalies extend, simulations from SD-WACCM for the 2008–2009 SSW event are employed. Figure 4 shows the latitude-day sections of the zonal mean zonal winds as simulated by the model at 30, 40, 50, 60, 70, and 80 km during 1 January to 20 March 2009. As per the WMO definition, SSW event started on 24 January when the zonal winds at 60°N, 10 hPa reversed, which can be clearly seen in Figure 4a at 30 km (~10 hPa). In the 30–50 km (Figures 4a–4c) height region, it can be seen that wind reversal extends up to ~20°N, merging with the tropical zero wind line. At 50 km (Figure 4c), a significant enhancement of westward winds can be seen from Days 20 to 45 in the 0–20°N latitudes. At 60 km, the zero wind line initially at ~15°S around Day 20 moves northward to reach ~20°N during the course of the warming, creating a westward wind regime in low latitudes. A minor reversal of eastward winds can be seen at 70 km, near Day 25. It should be noted that in the high latitudes, wind reversal at 70 km precedes the reversal at 30 km by about a week. Westward enhancement at 80 km seems to be negligible in the low latitudes, clearly showing that direct reversal of zonal mean zonal winds is not present in the low latitude MLT region, which are consistent with previous meteor radar observations (Koushik et al., 2018).

4. Discussion

Present results obtained using reanalysis, observations, and model simulations clearly show that zonal winds in the tropical upper stratosphere and lower mesosphere tend to be more westward in association with major SSW events. A few studies have earlier observed similar features in the low latitudes in connection with SSW events. Using U.K. Met Office reanalysis data, Sathishkumar et al. (2009) observed enhanced westward winds in the lower mesosphere and strong eastward winds in the stratosphere in association with SSWs in the Northern Hemisphere. In a study using SD-WACCM, Chandran and Collins (2014) noticed westward

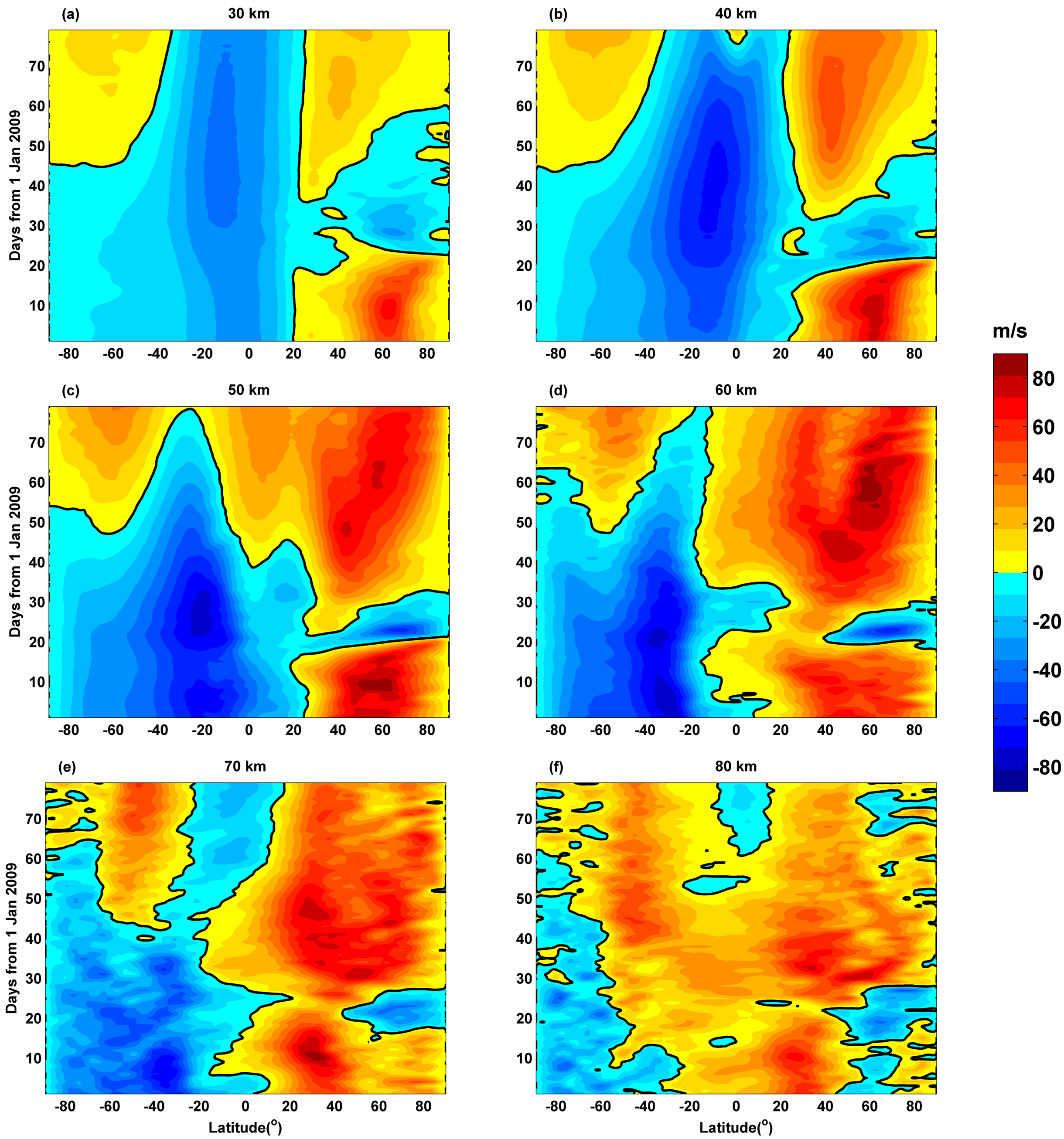

Figure 4. Zonal mean zonal winds at (a) 30, (b) 40, (c) 50, (d) 60, (e) 70, and (f) 80 km during January–March 2009 obtained from SD-WACCM simulations.

acceleration to be present in the low latitudes in the 40–60 km region. With the help of Eliassen Palm flux diagnostics, the authors also demonstrated the propagation of planetary waves into the tropical stratosphere which was found to be dependent on the phase of the QBO. In the present study, using rocketsonde measured winds, a conclusive evidence for enhanced westward winds at the tropical stratopause is provided.

The additional westward acceleration could be brought about by (1) propagation of stronger planetary waves originating in high-midlatitudes to lower latitudes following modified background conditions resulting from SSWs (Chandran & Collins, 2014) and (2) presence of inertial instabilities in the extratropical stratosphere associated with large meridional gradients of zonal mean zonal wind during SSWs as suggested by Sassi et al. (1993). However, the possible mechanism for the observed westward acceleration of the zonal winds at the stratopause cannot be conclusively brought out as it requires substantial diagnostic work, which is beyond the scope of the present study.

During eastward phase of the QBO, strong westward wind anomalies were observed in the tropical mesosphere during early spring period by Kishore Kumar et al. (2014). This feature was found to be absent when there was a strong SSW event in the Northern Hemisphere. Later, Zülicke and Becker (2017) suggested that strengthened residual circulation passing through the tropical stratopause could be responsible for missing of the aforementioned enhanced westward winds in the mesosphere. In the framework of interhemispheric coupling in the mesosphere, Becker (2012) indicated that amplified planetary wave activity in the winter high latitudes, of which SSW event is an extreme case, is accompanied by a westward wind anomaly in the stratopause region over low latitudes. This amplified westward wind regime in the tropical stratopause during SSWs, for which the present study gives observational evidence, can result in the enhanced filtering of westward gravity waves. The reduced westward forcing by gravity waves can lead to the absence of strong westward winds in the mesosphere as observed by Kishore Kumar et al. (2014). Thus, the present rocket observations of enhanced westward winds at tropical stratopause provide an explanation for the absence of enhanced westward winds in the mesosphere following SSW events. It should be noted that winds near the tropical stratopause region show a persistent semiannual oscillation as a part of which winds are westward during the northern winter period (Antonita et al., 2007; Garcia et al., 1997). The present analyses show that an additional westward acceleration is present in the stratospheric semiannual oscillation region during the SSW period. The present results also suggest that the presence of the tropical stratopause zonal wind anomaly does not depend on the phase of the stratospheric QBO, although their strength and height of occurrence may vary. The differences in strength of stratopause zonal wind anomalies derived from rocket observations and reanalysis data sets indicate the presence of large longitudinal variabilities. Statistics presented in Table 1 indicate that strength of the zonal wind anomaly is also independent of the strength or type of the SSW involved.

5. Conclusions

Using reanalysis data sets, rocketsonde observations, and SD-WACCM simulations, the present study conclusively shows that the zonal winds in the tropical stratopause undergo westward acceleration during northern hemispheric major SSW events, irrespective of the type of the SSW event or the phase of the QBO. Though relatively small in the zonal mean, the westward enhancement at the stratopause was found to be anomalously strong over Thumba especially for the 2005–2006 SSW event as seen in rocketsonde observations. This suggests the fact that there are significant longitudinal as well as temporal asymmetries in the response of the zonal winds in the tropical upper stratosphere-lower mesosphere to major SSW events. It is noted that the observed wind variabilities over low latitude upper stratosphere-lower mesosphere are very well simulated by SD-WACCM. Present results are of particular importance for the Mesosphere-Lower Thermosphere-Ionosphere studies in that changes in zonal winds in the underlying atmosphere brought about by SSW events can directly or indirectly affect the Mesosphere-Lower Thermosphere-Ionosphere region by modulating planetary waves, tides, and gravity waves.

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