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Sudden stratospheric warming effects on the mesospheric tides and 2-day wave dynamics at 7°S

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ABSTRACT

The dynamics of the equatorial mesosphere have been investigated during austral summers of 2004–2005, 2005–2006 and 2006–2007 from meteor radar measurements obtained at São João do Cariri, Brazil (7.4°S, 36.5°W), together with stratospheric northern hemisphere polar parameters. Some recent studies have demonstrated coupling between high latitude northern hemisphere major Sudden Stratospheric Warming (SSW) events and mesospheric–ionospheric disturbances, including the equatorial region. Here we have analyzed the tides, quasi-two-day planetary wave and local mean zonal wind variability in the equatorial upper Mesosphere and Lower Thermosphere (MLT) region during three austral summers and found that upper mesospheric dynamics at 7°S has been affected when a remarkable major SSW event took place in January 2006. The more intense tides and quasi-two-day wave amplitudes during the major SSW event are suggestive of an association between them and high planetary wave activity in the northern stratospheric winter.

1. Introduction

The Sudden Stratospheric Warming (SSW) phenomenon, in the polar region during wintertime, is well known. These SSW events are characterized by a significant increase of the temperature below the 10 hPa level, which occurs rapidly in just a few days. The formation of this sort of event has been attributed to the growth of upward propagating transient planetary waves and their interaction with the zonal mean flow (Matsuno, 1971). This interaction causes a deceleration and/or reversal of the eastward winter winds and also induces a downward circulation in the stratosphere, causing adiabatic heating and upward circulation in the mesosphere, leading to its adiabatic cooling (e.g., Liu and Roble, 2002; Pancheva et al., 2008). When the increases of the mean temperature occurs at any stratospheric level in the wintertime hemisphere and does not lead to a mean zonal wind reversal at the 10 hPa level, the SSW is classified as a minor warming. However, if the latitudinal mean temperature increase poleward from 60° latitude (at 10 hPa or below) is accompanied by a wind reversal at 60° and 10 hPa, the SSW is classified as a major warming (e.g., Schoeberl, 1978; Andrews et al., 1987).

In several studies, planetary wave amplification in wintertime has been attributed to resonant excitation of free wave modes (Liu and Roble, 2002; Esler and Scott, 2005). Moreover, there is evidence that for SSWs to occur it is necessary that the composite SSW life cycle be preceded by preconditioning of the stratospheric zonal flow and anomalous, quasi-stationary wavenumber-1 forcing at stratospheric and near-surface levels (Limpasuvan et al., 2004). Most previous studies were conducted on the basis of observations having limitations (such as: poor resolution, limited vertical extent, lack of coverage), which did not allow the study of stratosphere and mesosphere evolution in detail for a complete SSW life cycle. However, recent experiments based on measurements made by instruments that provide data with good quality and high resolution have made it possible to study the evolution of the dynamics of the atmosphere during events like SSWs.

The temperature data obtained during the 2005–2006 Arctic winter from the Microwave Limb Sounder (MLS) and Sounding of the Atmosphere with Broadband Emission Radiometry (SABER) instruments were used by Manney et al. (2008) to provide a detailed picture of the stratopause and its relationship to polar vortex evolution during the 2005–2006 major SSW. In this study it was noted that vortex and stratopause breakdown followed strong planetary wave amplification as well as a preceding secondary temperature maximum extending westward and equatorward from

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the separated polar stratopause over the midlatitude stratopause before the peak of the SSW occurred. The 2005–2006 major SSW has also been examined from the Goddard Earth Observing System version 4 (GEOS-4) assimilated meteorological fields together with analyses and forecasts based on a high-altitude version of the US Navy Operational Global Atmospheric Prediction System-Advanced Level Physics, High Altitude (NOGAPS-ALPHA) by Coy et al. (2009). The results showed that an upper tropospheric forcing over the North Atlantic and large positive local values of meridional heat flux directly forced a change in the stratospheric polar vortex, leading to stratospheric subtropical wave breaking and warming.

Through vertical coupling between the atmospheric regions, major sudden stratospheric warming events have an influence on the mesosphere and thermosphere (Liu and Roble, 2002), as well as on the ionosphere (Goncharenko and Zhang, 2008). Recently, studies have demonstrated coupling between major SSW events during boreal wintertime and mesospheric and ionospheric perturbations at middle and low latitudes, and even in the equatorial region (Shepherd et al., 2007; Vineeth et al., 2009a; Sathishkumar et al., 2009; Chau et al., 2010; Pedatella and Forbes, 2010).

From temperature data for 20–90 km altitude range, obtained between 5° and 15°N during 3 winters, together with MF radar wind and UK Meteorological Office (UKMO) data, Shepherd et al. (2007) observed that mesospheric cooling and stratospheric warming in the tropical regions are correlated with stratospheric warming events at middle and high latitudes. Pancheva et al. (2008) have also studied the dynamical coupling in the stratosphere and in the mesosphere at high and low latitudes during major SSW event in 2003–2004 boreal wintertime. Sridharan et al. (2009) have shown that reversals in the equatorial electrojet during afternoon hours are related to the major SSW events. In their investigation, the authors showed that the semidiurnal tidal amplitude increases during days of major SSW and subsequently decreases. A study of the MLT winds over Tirunelveli (8.7°N, 77.8°E) during major SSW events showed a link between them, and the variable response of MLT dynamics to different SSW events has been attributed to variability of gravity waves (Sathishkumar et al., 2009). In another investigation, the variations of the mesopause temperature over Trivandrum (8.5°N, 76.5°E), during polar SSW events, indicates a dynamical coupling between the two regions through the intensification of planetary wave activity (Vineeth et al., 2009b).

Diurnal and semidiurnal fluctuations in the MLT region have been studied extensively from ground-based radar measurements of horizontal winds. The observational knowledge of the diurnal tides from satellite data have confirmed the general global and seasonal tidal structures found by ground based radars. Seasonal and inter-annual variability of the atmospheric diurnal and semidiurnal tides in the southern hemisphere (SH) equatorial and lower latitudes have been studied (Batista et al., 2004); however, the behavior of tides in these regions is still poorly understood. From analysis of model results, Liu et al. (2010) have suggested that the nonlinear interaction between tides and the quasi-stationary planetary wave in the winter stratosphere leads to large changes in tides and, therefore, can strongly impact the ionosphere at low and middle latitudes through the E region wind dynamo. An observational study, based on Global Positioning System (GPS) measurements of Total Electron Content (TEC), conducted by Pedatella and Forbes (2010), has revealed migrating and non-migrating perturbations to the semidiurnal tide in the equatorial ionization anomaly crest region during a 2009 major SSW. They also demonstrated a connection between the Planetary Wave-1 (PW1) activity at 60°N (at 10 hPa) and the non-migrating semidiurnal westward propagating tide with zonal wavenumber 1 (SW1) in the low latitude ionosphere, attributed to nonlinear interaction between tides and planetary waves.

On the other hand, it is well known that the quasi-two-day wave is a prominent feature of the MLT region, mainly during summer. Close to the equatorial region, amplifications of the quasi-two-day wave are observed in both boreal and austral summers as well as at other times of the year (Harris and Vincent, 1993; Lima et al., 2004). It has also been observed that the rapid growth of the quasi-two-day wave occurs simultaneously with a decrease in the diurnal tidal amplitudes (Walterscheid and Vincent, 1996; Palo et al., 1999; Lima et al., 2004).

The quasi-two-day wave has been interpreted as a Rossby normal mode manifestation (Salby, 1981). However, from atmospheric stability analysis, Plumb (1983) and Pfister (1985) suggested that the quasi-two-day wave could be generated by baroclinic instability above the summer stratospheric westward jet. The possibility of the quasi-two-day wave being produced by a combination of the two excitation mechanisms was suggested by Randel (1994) and Norton and Thuburn (1996) and has been confirmed by Salby and Callaghan (2001), who also state that the two-day normal mode in addition to interacting with an instability, can also be amplified by strong activity of transient planetary waves from the winter hemisphere. Results from observational studies indicate that the quasi-two-day wave appears to be triggered by amplifications of planetary wave activity in the winter hemisphere (Wu et al., 1996; Limpasuvan et al., 2000). Recently, the behavior of the two-day wave observed during the 2006 austral summer has been studied from MLS data, in which this wave appears to exist in an anomalously strong summer westward jet (Limpasuvan and Wu, 2009). In another study, McCormack et al. (2009) have also examined the evolution of the quasi-2-day wave, on the basis of the NOGAPS-ALPHA forecast-assimilation system, in the middle atmosphere during the 2006 austral summer, and their results indicate that planetary wave activity in the northern winter stratosphere may have produced zonal wind variations in the quasi-two-day source region in the extra-tropical upper mesosphere with subsequent amplification.

In this paper, we use equatorial meteor wind data, together with polar stratospheric parameters, to investigate equatorial mesospheric diurnal and semidiurnal tides, quasi-two-day waves and SH local mean zonal wind dynamics during high latitude NH SSW events in boreal winter.

2. Meteor radar winds and NCEP data

The MLT winds data used here are based on measurements made at São João do Cariri-PB (7.4°S, 36.5°W), Brazil, (hereafter Cariri), using an All-Sky Interferometric Meteor Radar (SKiYMET). The system employs a 12 kW peak-power transmitter operating at 35.24 MHz, transmitting 2144 pulses/s with a three-element Yagi transmitting antenna, and uses five receiver antennas forming an interferometric array. Meteor position is obtained from the relative phases of the echoes at the various antennas, together with the echo range. Radial velocity is determined from the Doppler shift of the returned signal. In this work, the zonal and meridional winds were obtained during the austral summers of 2004–2005, 2005–2006 and 2006-2007 and were estimated in 1-h time bins and in seven atmospheric layers of 4 km thickness each from 80 to 100 km.

In order to examine the evolution of the SSW events, we have used the meteorological reanalysis data produced by the National Centers for Environmental Prediction (NCEP). In the present study we employ longitudinally averaged data at 10 hPa ($\sim$30 km), including temperature in the polar cap (poleward of 60°N), zonal winds at 60°N (as an indicator of the strength of the polar vortex) and waves 1–2 (PW1 and PW2) in terms of the amplitude of the geopotential height oscillation at 60°N, which are also stratospheric disturbance indicators.

3. Results

In order to examine the variability in meteor radar data, the meridional winds spectra were obtained for all 7 heights, in the period interval between 8 and 72 h, using the S-transform method. This technique provides the absolute amplitude and phase in the time domain (Stockwell et al., 1996). Fig. 1 shows S-transform representations for three austral summers in the 90-km meridional wind component for 2004–2005 (panel a), 2005–2006 (panel b) and 2006–2007 (panel c). From the three spectra, enhancements with periods near 12, 24 and 48 h can be seen. It is also possible to observe a clear anti-correlation between the temporal evolutions of the quasi-two-day wave and the diurnal tide amplitudes. Comparison between the spectra reveals that amplitudes for tides (diurnal and semidiurnal) and for quasi-two-day waves were strongest during the December 2005–January 2006 time interval. In order to see if these larger amplitudes are associated with the major SSW event, the NH high latitude stratospheric parameters will be analyzed together with the meteor radar data.

To verify the evolution of the vertical structure of the perturbations, the wind data series were subjected to harmonic analysis supposing that semidiurnal, diurnal and quasi-two-day oscillations were present in the winds. The analysis was performed for a sliding 4-day window stepped by 1-h in time and has been smoothed by a 24-h running average.

In Fig. 2 are presented the diurnal tide and quasi-two-day wave amplitudes for meridional winds over Cariri at 90 km height (top panels), the NCEP zonally average temperatures for latitudes in the polar cap (second panels), as well as the longitudinally

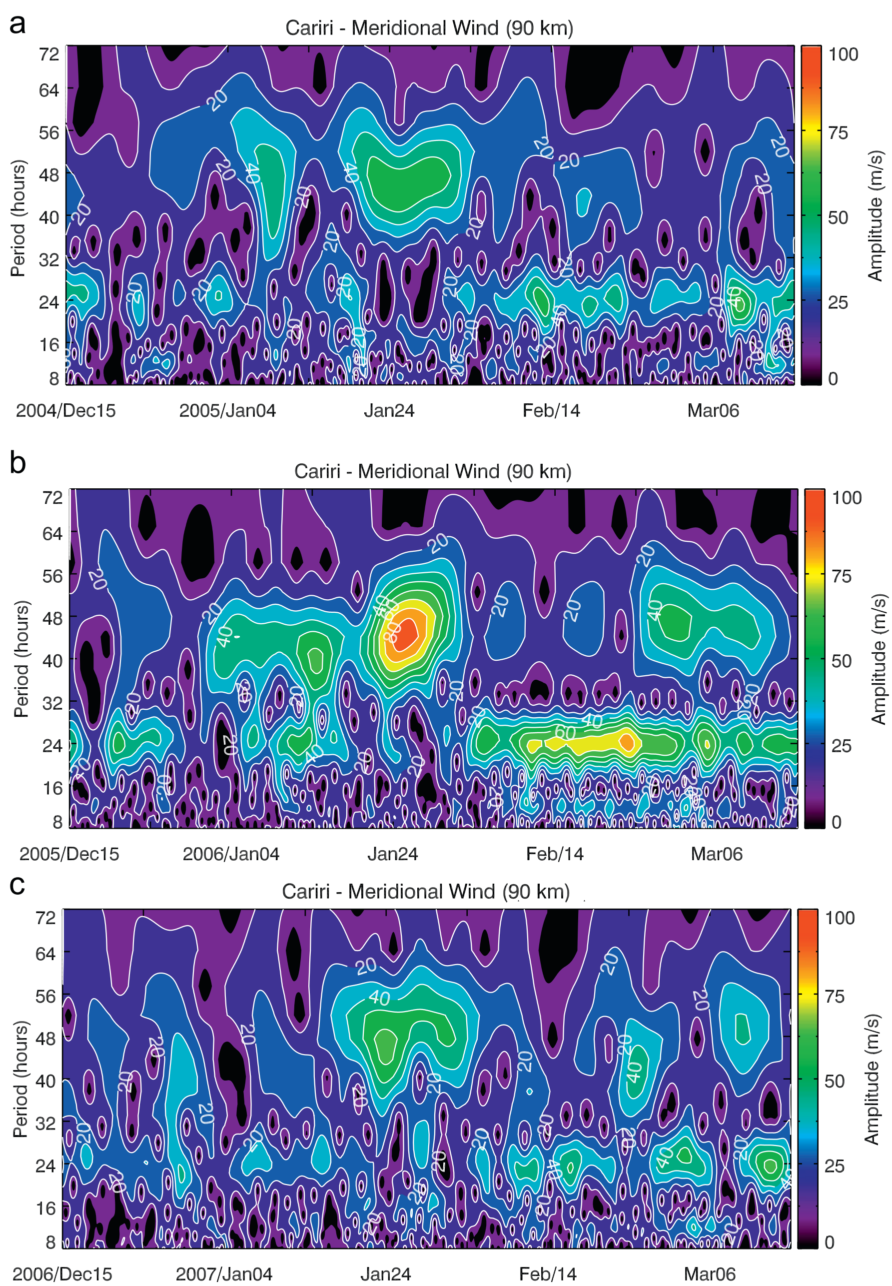

Fig. 1. S-transform amplitude spectra for Cariri meridional wind at 90-km for 2004/December-2005/March (panel a), 2005/December-2006/March (panel b) and 2006/December-2007/March (panel c).

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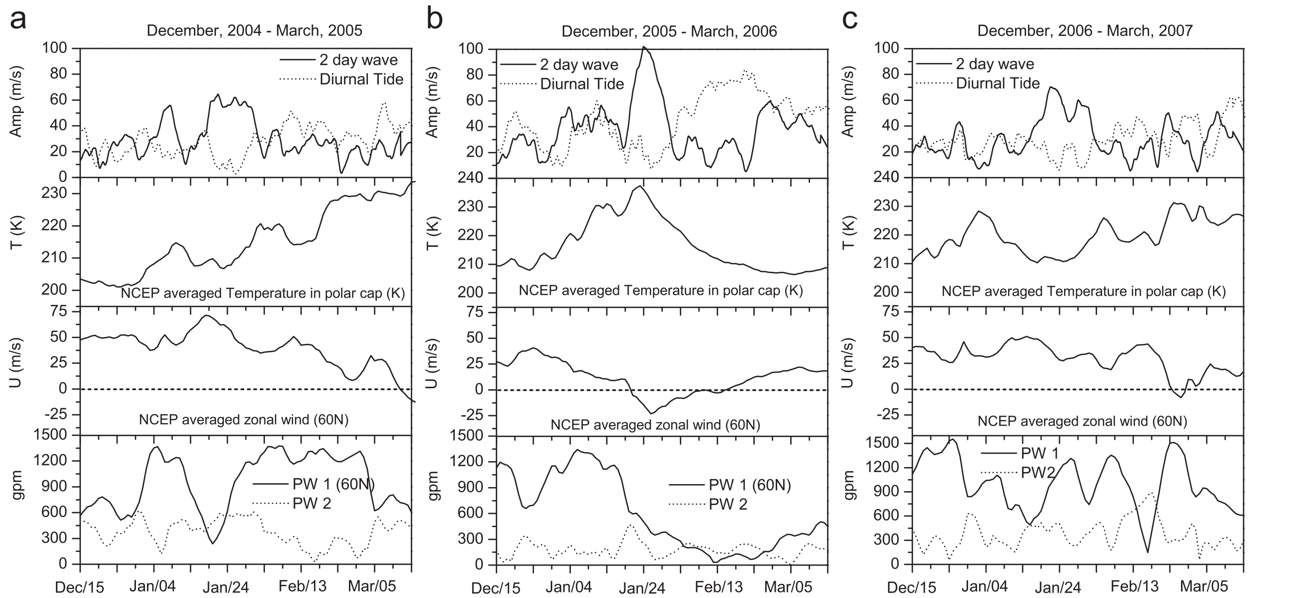

Fig. 2. Amplitudes for diurnal tide and quasi-two-day wave for Cariri meridional winds at 90 km height (first panels from top to bottom), NCEP zonal average of the temperature in the polar cap – poleward from 60°N – (second panels) and of the zonal winds (third panels), and the wave 1–2 amplitude of geopotential height at 60°N, at the 10 hPa pressure level, for (a) 2004–2005, (b) 2005–2006 and (c) 2006–2007.

averaged zonal winds (third panels) and the PW1 and PW2 at 60°N latitude, at 10 hPa pressure level, for 2004–2005 (Fig. 2a), 2005–2006 (Fig. 2b) and 2006–2007 (Fig. 2c).

From Fig. 2a, it is possible to see that the amplitude of the meridional winds for the quasi-two-day wave exhibits two bursts in January 2005, where the amplitude of the second intensification reaches nearly 60 m/s. The diurnal tide amplitude is more intense after the second peak of the quasi-two-day wave, and reaches 50 m/s. At this time the NH high latitude stratospheric fields showed behavior compatible with a minor SSW, in that the average zonal temperature at 10 hPa for latitudes between 60°N and 90°N showed moderate sudden warming events, followed by a weakening of the eastward flow of the average zonal wind for 60°N. The PW1 at 10 hPa and 60°N showed two intensification episodes, with the first enhancement starting at the end of December and the second beginning after January 20th and lasting until March 5th.

The diurnal tide and quasi-two-day wave amplitudes estimated in the equatorial MLT region during December 2005–January 2006, as presented in Fig. 2b, were larger than those usually observed for the meridional component in other periods. Intensifications were also observed in the quasi-two-day wave for the zonal wind component (not shown), but the amplitudes were weaker than for the meridional wind. The quasi-two-day wave amplitude reached maximum values of 100 m/s around January 27th lasting until February 3rd, whilst the diurnal tide amplitude increases at a rate of 3.4 ms^{-1}/day after the quasi-two-day wave activity reached values up to 80 m/s around February 20th. The NH high latitude stratosphere showed sudden warming with zonal mean temperature at 10 hPa reaching 235 K near January 23rd when the zonal mean flow reversed to westward, characterizing a major SSW event. Before the warming, the PW1 amplitude at 10 hPa and 60°N was intense until January 16th. Following the warming, the PW1 amplitude decreases rapidly. It is interesting to note that, according to the analysis of Manney et al. (2008), the upper stratospheric vortex had broken down by January 16th.

The SH equatorial MLT dynamics behavior during December 2006–March 2007 was characterized by a diurnal tide and quasi-two-day wave whose amplitudes achieved the same magnitude as those observed during December 2004–March 2005.

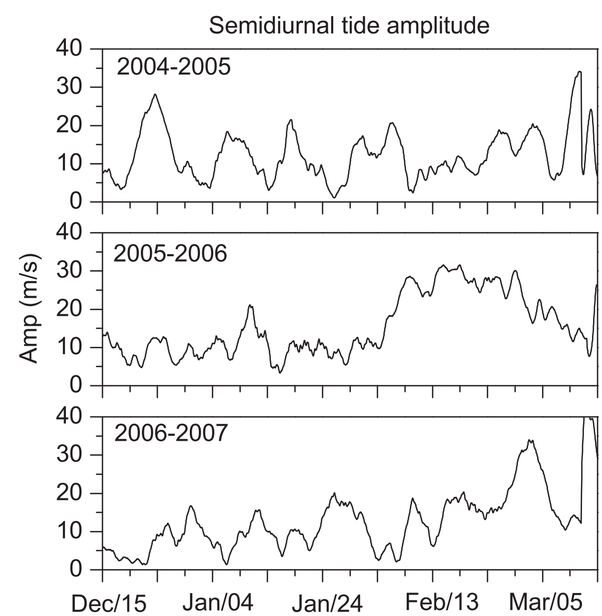

Fig. 3. Semidiurnal tide amplitudes for meridional component at 90 km height obtained from Cariri winds during 2004–2005 (upper), 2005–2006 (middle) and 2006–2007 (bottom).

The quasi-two-day wave amplitude starts to increase after January 13th, reaching 65 m/s around day 24 and starts to decrease after February 1. The diurnal tide showed amplifications after the main quasi-two-day wave event with maximum values near 50 m/s. Before February 20th, the NH high latitude stratospheric fields also showed characteristics compatible with minor SSW events, as can be seen in Fig. 2c. However, the NH stratospheric fields display a short warming event in which the zonal mean flow was reversed to westward on February 24th, two weeks after the main quasi-two-day wave event occurrence.

Fig. 3 shows the semidiurnal tide amplitudes obtained from Cariri meridional winds at 90 km height for the three time intervals considered in this study. As can be seen from this figure, the semidiurnal tide amplitude shows variability with time,

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reaching maximum values up to 30 m/s. The variability of the semidiurnal tide in the 2004–2005 austral summer exhibits amplitude modulation with a ~13-day period from mid-December to early February. For the time interval from December 2005 to March 2006 it is possible to observe that the semidiurnal tide amplitude showed a distinct behavior, with a rapid intensification centered on January 10th, but since February 3rd, the amplitude increases at 3.5 ms^{-1}/day rate reaching values near 32 m/s. After February 15th the amplitude decreases at 0.8 ms^{-1}/day rate. Looking at the diurnal tide behavior it is possible to see that the time variation of both tidal components, after the quasi-two-day wave event, showed similar amplitude evolution. The semidiurnal tide behavior during 2006–2007 austral summer indicates amplitude modulation with a ~14-day period from late December to early March.

In Fig. 4 are presented the time-altitude cross sections of the MLT zonal prevailing winds at Cariri obtained during the three austral summers for 2004–2005 (panel a), 2005–2006 (panel b) and 2006–2007 (panel c). As can be seen from the panels, the 2004–2005 MLT zonal prevailing wind reversed to westward first for the highest altitudes, whilst for the 81–87 km altitude range the reversal occurred in mid-January. After the reversal, the westward wind reached a maximum value of −30 m/s in late January and early February for altitudes below 90 km, just when the quasi-two-day wave amplitude maximizes. In the 2005–2006 austral summer the

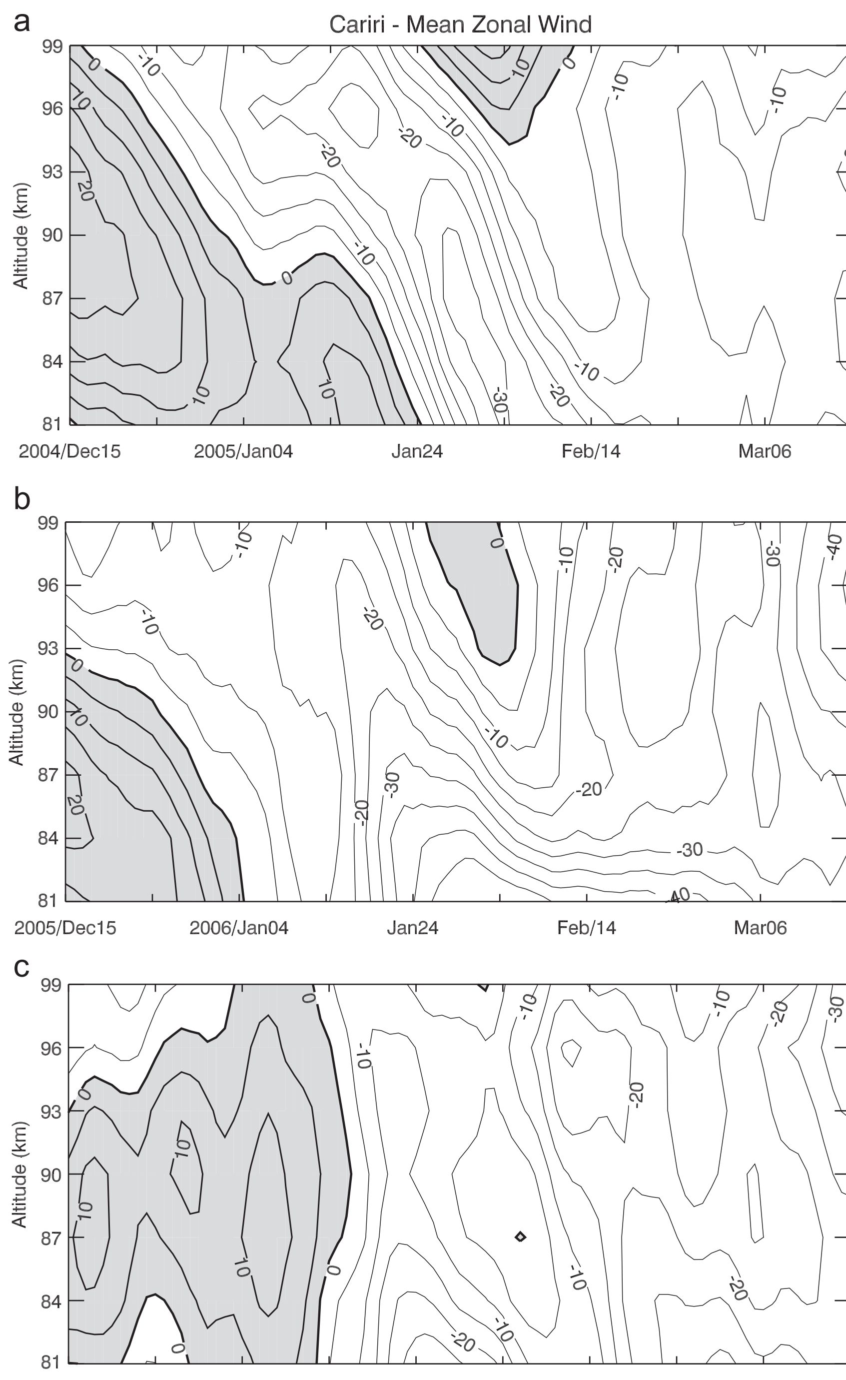

Fig. 4. Time–height cross section of the prevailing zonal wind obtained at Cariri for 2004/December-2005/March (panel a), 2005/December-2006/Mar (panel b) and 2006/December-2007/March (panel c).

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local MLT zonal prevailing wind also reversed to westward first at the highest altitudes; however, the reversal was completed by January 4th, much earlier than in the previous summer, and the post-reversal westward mean flow reached a maximum value of -40 m/s after January 20th for altitudes below 90 km, again just when the quasi-two-day wave amplitude had maximized. It is it should be remembered that in this time interval a major SSW at NH high latitude was observed. For the last austral summer analyzed (2006–2007) the local MLT zonal prevailing wind reversal to westward occurs around January 15th for all altitudes. The strongest westward wind after reversal again occurs simultaneously with the quasi-two-day wave amplification around January 24th and reached a value of -20 m/s.

4. Discussion

From the three SH austral summer intervals investigated it was possible to verify that the tides and quasi-two-day wave dynamics in the SH equatorial MLT showed distinct behavior during January–February 2006, when a major SSW event was observed in the NH high latitude stratosphere. On this occasion, the meridional quasi-two-day wave amplitude in the equatorial region at 90 km increased following the temperature increase and the weakening of the 10 hPa zonal eastward NH high latitude mean wind, whose westward reversal was coincident with the maximum quasi-two-day amplitude, which occurred 4 days later than when the 10 hPa temperature at NH high latitude reached its maximum. During this time the quasi-two-day wave amplitude was about 55% larger than the values estimated for January–February 2005 and 2007. The diurnal and semidiurnal tide amplitudes began to increase just after the quasi-two-day wave amplitude starts its decreasing phase. The diurnal and semidiurnal tide amplitudes reached maximum values of 80 and 30 m/s, respectively, about 25 days after the peak of the quasi-two-day wave amplitude. The diurnal tide was about 50% larger than during January–February 2005 and 2007. It is interesting to note that the amplitudes of the diurnal tide and quasi-two-day wave derived from MF wind observations for January–March 1995, reported by Gurubaran et al. (2001) for Tirunelveli (8.7°N), were about twice those observed during January–March 1996. We now turn our attention to a possible connection between the SSW and the largest activity in 1995. At this time, a sudden warming was observed in the NH high latitude stratosphere, but in 1996 no stratospheric warming occurred. This reinforces our interpretation of an association between the occurrence of major SSWs and the unusually high amplitudes of tides and the quasi-two-day wave in the equatorial MLT region during 2005–2006 austral summer.

The atmospheric migrating diurnal tides are excited primarily by direct absorption of sunlight by water vapor in the troposphere and stratosphere with an additional contribution of latent heat released by convective processes in the tropics. The semidiurnal tides are mainly excited by ozone absorption in the upper stratosphere and lower mesosphere. So, it is possible that the remarkable diurnal and semidiurnal tidal intensification observed in the equatorial MLT region during January–February 2006 austral summer may have been due to the latent heat released by convective activity in the troposphere and to stratospheric ozone variability linked to the extreme SSW event. Studies conducted by Kodera (2006) suggest that increased wave activity associated with SSW induces upward motion in the equatorial troposphere associated with convective activity in the equatorial SH. It has been found that ozone decreases at high winter latitudes and increases at low latitudes are associated with midwinter stratospheric warmings (Randel, 1993). Furthermore, the migrating diurnal and semidiurnal tidal amplitudes can be modulated by the stratospheric quasi-biennial oscillation (SQBO) as the tides propagate from their tropospheric and stratospheric sources to the MLT region (Forbes et al., 2008). A correlation between NH polar vortex strength and SQBO has been reported by Holton and Tan (1980) in which the modulation occurs in both early and late winter (Anstey et al., 2010).

Nonlinear interaction between planetary waves and migrating tides may generate non-migrating tidal modes and modulate tides globally in association with SSWs (Hagan and Roble, 2001; Chau et al., 2010; Pedatella and Forbes, 2010). Although it is not possible to distinguish migrating from non-migrating components using measurements obtained at a single station, some indication can be found by studying the vertical structure of the tide before and after a stratospheric warming event. In this sense, we have used the diurnal tidal phases obtained by harmonic analysis to investigate the vertical structure evolution for the time interval from January until mid-March. Fig. 5 shows the time–height cross

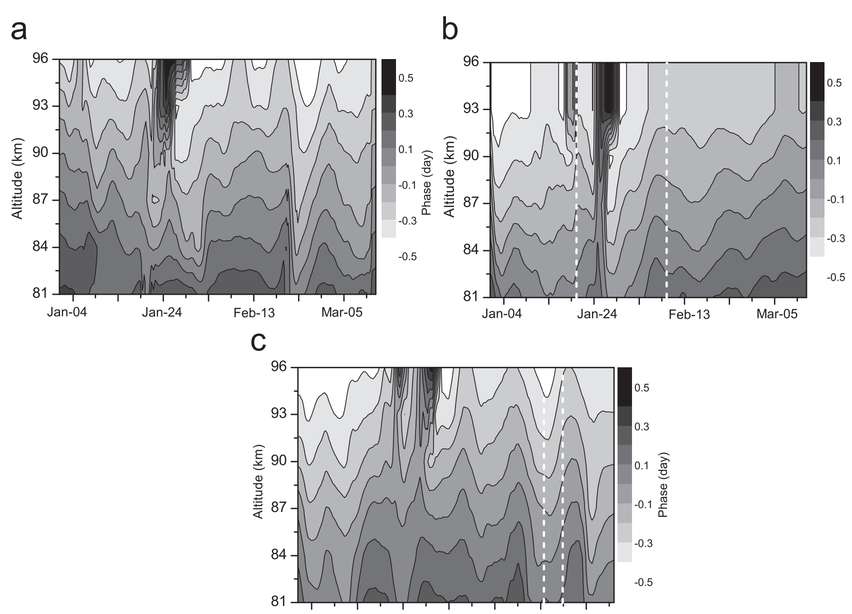

Fig. 5. Time–height cross section of the diurnal tidal phases obtained from Cariri meridional wind component during (a) 2005, (b) 2006 and (c) 2007 in the time interval from January-01 to March-12. The dashed white lines indicate the time intervals during which the longitudinally averaged zonal winds for 60°N were reversed in major SSWs.

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section of the phases of the diurnal tide obtained from the Cariri meridional wind component during (a) 2005, (b) 2006 and (c) 2007. The dashed white lines indicate the time intervals in which the longitudinally averaged zonal winds for 60°N were reversed in major SSWs. In general, the behavior of the phase with height shows that the time of the maximum is earlier at greater heights, consistent with upward energy propagation.

The vertical wavelengths for the meridional diurnal tide, estimated from the phase structures, assumed values ranging between ~24 and ~28 km in January–February 2005. For January–March 2006, the vertical wavelengths have assumed values of ~30 km for all time intervals considered in this study. During 2007 austral summer, the vertical wavelengths for the diurnal tide were found to be ~24 km in January and ~28 km from mid-February until early March. Although these values are compatible with the westward symmetric propagating diurnal tidal mode (1, 1), the vertical structure evolution shows distinct episodes of phase modulation besides undergoing rapid phase changes just when the quasi-two-day wave exhibits strong amplification. During January–March 2005 and 2007, the diurnal tidal phases display modulation mainly in the 8–10 days period range. Yet, in 2006 austral summer, we do not observe well defined phase modulation before the major SSW. However, the diurnal tidal phase is clearly modulated by a 12–18 day oscillation after the major SSW event. These diurnal phase modulations are indicative of nonlinear interaction between the diurnal tide and planetary waves. On the other hand, the presence of the 16-day wave in the MLT region during summer has been interpreted as being due to inter-hemispheric leakage from the winter hemisphere (e.g., Forbes et al., 1995; Lima et al., 2006). A nonlinear interaction between two "primary waves" generates a family of "secondary waves", prominent among which are the sum and difference oscillations (e.g., Pancheva et al., 2008). Among the possibilities for nonlinear coupling including the diurnal tide and planetary waves, the interaction between the diurnal tide and the 16-day wave can generate two non-migrating diurnal components: a standing or zonally symmetric ($s=0$) diurnal oscillation and a westward-propagating diurnal tide with zonal wavenumber $s=2$. In this way, the nonlinear coupling processes can be responsible for generating additional tidal modes.

The quasi-two-day wave bursts observed in austral summer have been interpreted as the result of the Rossby-gravity mode amplification due to instability of the lower-mesospheric westward jet. The conspicuous quasi-two-day wave amplification detected in the 2005–2006 austral summer is thought to be due to intensification of the mean meridional circulation by enhanced planetary wave activity in the winter stratosphere. Amplification of the two-day mode can also be triggered indirectly by transient planetary waves in the winter hemisphere through inertial instabilities (Wu et al., 1996; Limpasuvan et al., 2000). Since the meridional circulation is coupled to the summer lower-mesospheric jet, its strengthening can temporarily enlarge the barotropic and baroclinic instabilities and, in turn, provide additional forcing for a Rossby-gravity mode (Salby and Callaghan, 2001). As pointed out by Manney et al. (2008) and Coy et al. (2009), planetary wave activity was high in the extra-tropical winter lower stratosphere prior to the 2005–2006 major SSW. The quasi-two-day wave behavior during the 2006 austral summer from EOS MLS observations showed that the W3 quasi-two-day wave structure was compatible with both normal and instability modes in an unusually strong summer westward jet (Limpasuvan and Wu, 2009). Study of the quasi-two-day wave evolution in the 2006 austral summer from NOGAPS-ALPHA fields by McCormack et al. (2009), indicated that the combination of enhanced horizontal momentum advection by the residual meridional circulation and inertially unstable circulations, related to planetary wave breaking in the subtropical northern stratospheric winter, has favored instability conditions in the tropical region and, hence, providing further quasi-two-day wave forcing at this time.

Furthermore, the nonlinear interactions between the migrating tides and quasi-two-day wave can generate a family of oscillations. Oscillations with periods of 9.7 and 16 h can be generated by coupling between the quasi-two-day wave and semidiurnal tide, while a coupling between the quasi-two-day wave and the migrating diurnal tide can yield oscillations with periods of 16 h and 2 days (e.g., $s=2$ eastward propagating 2-day wave). A cascade of nonlinear interactions between quasi-two-day waves and the migrating diurnal tide has been tested by Palo et al. (1999) to explain the fact that the MLT quasi-two-day amplitudes increase rapidly in the SH during austral summer, in which the maximum northward wind happens at the same local time each year. They have used the mechanism suggested by Walterscheid and Vincent (1996) in which the quasi-two-day wave could be locked in phase to the tidal component and, through a cascade of interactions, the energy could be transferred from the $s=6$ westward propagating non-migrating diurnal tide (1, 6) to the quasi-two-day oscillation. As can be seen in Fig. 2b, the quasi-two-day wave amplitude grows rapidly from January 20th 2006 (at 16.9 ms^{-1}/day at 90 km) while the diurnal tide amplitude decreases. It is also possible to observe from Fig. 1b that the quasi-two-day wave period was below 48 h (~42–46 h period range) during the main burst. Nevertheless, these observed characteristics are not sufficient evidence for a locked-phase interaction and more detailed studies need to be conducted. Hecht et al. (2010) have observed that the coupling of the diurnal tide appears to be more efficient when the quasi-two-day period is close to 48 h; however, if the period stays well below 48 h the phase-locked diurnal tide coupling to the two-day wave appears to be less efficient. On the other hand, analyses using the NOGAPS-ALPHA meridional winds by McCormack et al. (2010) have shown that the rapid amplification of the quasi-two-day wave observed during 2006 austral summer can be explained by a mechanism of nonlinear interactions involving a phase-locked 2-day wave. They have suggested that the unusually strong summer westward jet observed during January 2006 contributed to the excitation of the (1, 6) non-migrating diurnal tide and, hence, the rapid amplification of the quasi-two-day wave.

The Cariri MLT zonal prevailing wind is characterized by reversal to westward during austral summer, in which the strongest westward wind after inversion is coincident with the quasi-two-day wave amplification. The prior reversal to westward together with strongest mean zonal wind and quasi-two-day wave amplification observed during 2005–2006 austral summer, suggests that the local MLT zonal wind configuration was linked with the major SSW event, in other words, the local MLT zonal wind has also been affected by westward planetary wave energy migrating from the winter hemisphere. In this case, additional deposition of energy and momentum caused by the quasi-two-day wave dissipation appears to contribute to westward local MLT wind intensification.

5. Summary

The local MLT dynamics at 7°S observed during the 2005–2006 austral summer showed an unusual behavior, which was characterized by increased amplitude of the quasi-two-day and tidal oscillations. During this time interval a major SSW event was observed in the NH polar stratosphere. In this paper we have analyzed the SH equatorial meteor wind measurements obtained during the austral summers of 2004–2005, 2005–2006 and 2006–2007, at Cariri (Brazil), together with polar stratospheric parameters to investigate a possible coupling between the uncommon behavior of the equatorial MLT dynamics and the extreme major SSW event that occurred during 2005–2006 in NH winter.

In the 2004–2005 and 2006–2007 austral summers, the local MLT dynamics were characterized by a diurnal tide and quasi-two-day oscillations with similar magnitudes. During these time intervals the semidiurnal tide showed amplitude modulation with a period of $\sim$13 days in 2004–2005 and $\sim$14 days in 2006–2007. The local MLT zonal prevailing wind reversed to westward with maximum values in late January, just when the quasi-two-day wave amplitudes peaked.

In the 2005–2006 austral summer the quasi-two-day wave dynamics in the SH equatorial MLT region showed unusual behavior in which the amplitude evolution followed both the NH polar stratospheric warming and the averaged zonal wind reversal associated with the major SSW event. The rapid amplification of the quasi-two-day wave observed during January 2006 can also be understood as being the result of nonlinear interactions involving a phase-locked 2-day wave. The diurnal and semidiurnal tidal components display long duration variations with similar amplitude evolution following quasi-two-day wave activity. After the 2006 NH stratospheric warming the diurnal tidal phase was modulated by $\sim$16-day period, allowing the generation of further tidal modes by tidal/16-day nonlinear interactions. The MLT zonal prevailing wind also reversed to westward, but the reversal occurred much earlier than in the other two summers and the strongest maximum westward wind occurred together of the quasi-two-day burst. This set of unusual events observed in the local MLT dynamics during the 2005–2006 major SSW event are suggestive of a coupling between them through the combination of several factors related to planetary wave breaking in the subtropical northern stratospheric winter which, in turn, has engendered favorable conditions in the tropical region and, hence, provided further forcing at this time. This interpretation is supported by model and observational studies reported in the present paper.

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References

Anstey, J.A., Shepherd, T.G., Scinocca, J.F., 2010. Influence of the quasi-biennial oscillation on the extratropical winter stratosphere in an atmospheric general circulation model and in reanalysis data. J. Atmos. Sci. 67, 1402–1419. doi:10.1175/2009JAS3292.1.

Andrews, D.G., Holton, J.R., Leovy, C.B., 1987. Middle Atmosphere Dynamics. Academic Press, Orlando 490.

Batista, P.P., Clemesha, B.R., Tokumoto, A.S., Lima, L.M., 2004. Structure of the mean winds and tides in the meteor region over Cachoeira Paulista, Brazil (22.7°S, 45°W) and its comparison with models. J. Atmos. Sol. Terr. Phys. 66, 623–636. doi:10.1016/j.jastp.2004.01.014.

Coy, L., Eckermann, S., Hoppel, K., 2009. Planetary wave breaking and tropospheric forcing as seen in the stratospheric sudden warming of 2006. J. Atmos. Sci. 66, 495–507. doi:10.1175/2008JAS2784.1.

Chau, J.L., Aponte, N.A., Cabassa, E., Sulzer, M.P., Goncharenko, L.P., González, S.A., 2010. Quiet time ionospheric variability over Arecibo during sudden stratospheric warming events. J. Geophys. Res. 115, A00G06. doi:10.1029/2010JA015378.

Esler, J.G., Scott, R.K., 2005. Excitation of transient Rossby waves on the stratospheric polar vortex and the barotropic sudden warming. J. Atmos. Sci. 62, 3661–3682. doi:10.1175/JAS3557.1.

Forbes, J.M., Zhang, X., Palo, S., Russell, J., Mertens, C.J., Mlynczak, M., 2008. Tidal variability in the ionospheric dynamo region. J. Geophys. Res. 113, A02310. doi:10.1029/2007JA012737.

Forbes, J.M., Hagan, M., Miyahara, S., Vial, F., Manson, A.H., Meek, C.E., Portnyagin, Y.I., 1995. Quasi 16-day oscillation in the mesosphere and lower thermosphere. J. Geophys. Res. 100 (D5), 9149–9163. doi:10.1029/94JD02157.

Goncharenko, L., Zhang, S.-R., 2008. Ionospheric signatures of sudden stratospheric warming: ion temperature at middle latitude. Geophys. Res. Lett. 35, L21103. doi:10.1029/2008GL035684.

Gurubaran, S., Sridharan, S., Ramkumar, T.K., Rajaram, R., 2001. The mesospheric quasi-2-day wave over Tirunelveli (8.7°N). J. Atmos. Sol. Terr. Phys. 63, 975–985. doi:10.1016/S1364-6826(01)00016-5.

Hagan, M.E., Roble, R.G., 2001. Modeling diurnal tidal variability with the national center for atmospheric research thermosphere–ionosphere–mesosphere–electrodynamics general circulation model. J. Geophys. Res. 106, 24869–24882. doi:10.1029/2001JA000057.

Harris, T.J., Vincent, R.A., 1993. The quasi-two-day wave observed in the equatorial middle atmosphere. J. Geophys. Res. 98 (D6), 10481–10490. doi:10.1029/93JD00380.

Hecht, J.H., Walterscheid, R.L., Gelinas, L.J., Vincent, R.A., Reid, I.M., Woithe, J.M., 2010. Observations of the phase-locked 2 day wave over the Australian sector using medium-frequency radar and airglow data. J. Geophys. Res. 115, D16115. doi:10.1029/2009JD013772.

Holton, J.R., Tan, H.-C., 1980. The influences of the equatorial quasi-biennial oscillation on the global circulation at 50 mb. J. Atmos. Sci. 37, 2200–2208. doi:10.1175/1520-0469(1980)037 < 2200:TIOTEQ > 2.0.CO;2.

Kodera, K., 2006. Influence of stratospheric sudden warming on the equatorial troposphere. Geophys. Res. Lett. 33, L06804. doi:10.1029/2005GL024510.

Lima, L.M., Batista, P.P., Clemesha, B.R., Takahashi, H., 2006. 16-day waves observed in the meteor winds at low latitudes in the southern hemisphere. Adv. Space Res. 38, 2615–2620. doi:10.1016/j.asr.2006.03.033.

Lima, L.M., Batista, P.P., Takahashi, H., Clemesha, B.R., 2004. Quasi-two-day wave observed by meteor radar at 22.7°S. J. Atmos. Sol. Terr. Phys. 66, 529–537. doi:10.1016/j.jastp.2004.01.007.

Limpasuvan, V., Leovy, C.B., Orsolini, Y.J., 2000. Observed temperature two-day wave and its relatives near the stratopause. J. Atmos. Sci. 57, 1689–1701. doi:10.1175/1520-0469(2000)057 < 1689:OTTDWA > 2.0.CO;2.

Limpasuvan, V., Thompson, D.W.J., Hartmann, D.L., 2004. The life cycle of Northern Hemisphere sudden stratospheric warmings. J. Clim. 17, 2584–2596. doi:10.1175/1520-0442(2004)017 < 2584:TLCOTN > 2.0.CO;2.

Limpasuvan, V., Wu, D.L., 2009. Anomalous two-day wave behavior during the 2006 austral summer. Geophys. Res. Lett. 36, L04807. doi:10.1029/2008GL036387.

Liu, H.-L., Wang, W., Richmond, A.D., Roble, R.G., 2010. Ionospheric variability due to planetary waves and tides for solar minimum conditions. J. Geophys. Res. 115, A00G01. doi:10.1029/2009JA015188.

Liu, H.-L., Roble, R.G., 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. 107 (D23), 4695. doi:10.1029/2001JD001533.

McCormack, J.P., Coy, L., Hoppel, K.W., 2009. Evolution of the quasi 2-day wave during January 2006. J. Geophys. Res. 114, D20115. doi:10.1029/2009JD012239.

McCormack, J.P., Eckermann, S.D., Hoppel, K.W., Vincent, R.A., 2010. Amplification of the quasi-two day wave through nonlinear interaction with the migrating diurnal tide. Geophys. Res. Lett. 37, L16810. doi:10.1029/2010GL043906.

Manney, G.L., Krüger, K., Pawson, S., Minschwaner, K., Schwartz, M.J., Daffer, W.H., Livesey, N.J., Mlynczak, M.G., Remsberg, E.E., Russell, J.M., Waters, J.W., 2008. The evolution of the stratopause during the 2006 major warming: satellite data and assimilated meteorological analyses. J. Geophys. Res. 113, D11115. doi:10.1029/2007JD009097.

Matsuno, T., 1971. A dynamical model of the stratospheric sudden warming. J. Atmos. Sci. 28, 1479–1494. doi:10.1175/1520-0469(1971)028 < 1479:ADMOTS > 2.0.CO;2.

Norton, W.A., Thuburn, J., 1996. The two-day wave in a middle atmosphere GCM. Geophys. Res. Lett. 23 (16), 2113–2116. doi:10.1029/96GL01956.

Palo, S.E., Roble, R.G., Hagan, M.E., 1999. Middle atmosphere effects of the quasi-two-day wave determined from a General Circulation Model. Earth Panets Space 51, 629–647.

Pancheva, D., Mukhtarov, P., Mitchell, N.J., Andonov, B., Merzlyakov, E., Singer, W., Murayama, Y., Kawamura, S., Xiong, J., Wan, W., Hocking, W., Fritts, D., Riggin, D., Meek, C., Manson, A., 2008. Latitudinal wave coupling of the stratosphere and mesosphere during the major stratospheric warming in. Ann. Geophys. 26, 467–483. doi:10.5194/angeo-26-467-2008.

Pedatella, N.M., Forbes, J.M., 2010. Evidence for stratosphere sudden warming-ionosphere coupling due to vertically propagating tides. Geophys. Res. Lett. 37, L11104. doi:10.1029/2010GL043560.

Pfister, L., 1985. Baroclinic instability of easterly jets with applications to the summer mesosphere. J. Atmos. Sci. 42, 313–330. doi:10.1175/1520-0469(1985)042 < 0313:BIOEJW > 2.0.CO;2.

Plumb, R.A., 1983. Baroclinic instability of the summer mesosphere: a mechanism for the quasi-two-day wave? J. Atmos. Sci. 40, 262–270. doi:10.1175/1520-0469(1983)040 < 0262:BIOTSM > 2.0.CO;2.

Randel, W.J., 1993. Global variations of zonal Mean ozone during stratospheric warming events. J. Atmos. Sci. 50, 3308–3321. doi:10.1175/1520-0469(1993)050 < 3308:GVOZMO > 2.0.CO;2.

Randel, W.J., 1994. Observations of the 2-day wave in NCM stratospheric analyses. J. Atmos. Sci. 51, 306–313. doi:10.1175/1520-0469(1994)051 < 0306:OOTDWI > 2.0.CO;2.

Salby, M.L., Callaghan, P.F., 2001. Seasonal amplification of the 2-Day wave: relationship between normal mode and instability. J. Atmos. Sci. 58, 1858–1869. doi:10.1175/1520-0469(2001)058 < 1858:SAOTD > 2.0.CO;2.

Salby, M.L., 1981. The 2-day wave in the middle atmosphere—observations and theory. J. Geophys. Res. 86 (C10), 9654–9660. doi:10.1029/JC086iC10p09654.

Sathishkumar, S., Sridharan, S., Jacobi, C., 2009. Dynamical response of low-latitude middle atmosphere to major sudden stratospheric warming events. J. Atmos. Sol. Terr. Phys. 71, 857–865. doi:10.1016/j.jastp.2009.04.002.

Schoeberl, M.R., 1978. Stratospheric warmings: observations and theory. Rev. Geophys. 16, 521–538. doi:10.1029/RG016i004p00521.

Shepherd, M.G., Wu, D.L., Fedulina, I.N., Gurubaran, S., Russell, J.M., Mlynczak, M.G., Shepherd, G.G., 2007. Stratospheric warming effects on the tropical mesospheric temperature field. J. Atmos. Sol. Terr. Phys. 69, 2309–2337. doi:10.1016/j.jastp.2007.04.009.

Sridharan, S., Sathishkumar, S., Gurubaran, S., 2009. Variabilities of mesospheric tides and equatorial electrojet strength during major stratospheric warming events. Ann. Geophys. 27, 4125–4130. doi:10.5194/angeo-27-4125-2009.

Stockwell, R., Mansinha, L., Lowe, R., 1996. Localization of the complex spectrum: the S-transform. IEEE Trans. Signal Process. 44, 998–1001. doi:10.1109/78.492555.

Vineeth, C., Pant, T.K., Sridharan, R., 2009a. Equatorial counter electrojets and polar stratospheric sudden warmings—a classical example of high latitude–low latitude coupling? Ann. Geophys. 27, 3147–3153. doi:10.5194/angeo-27-3147-2009.

Vineeth, C., Pant, T.K., Kumar, K.K., Ramkumar, G., Sridharan, R., 2009b. Signatures of low latitude–high latitude coupling in the tropical MLT region during sudden stratospheric warming. Geophys. Res. Lett. 36, L20104. doi:10.1029/2009GL040375.

Walterscheid, R.L., Vincent, R.A., 1996. Tidal generation of the phase-locked 2-day wave in the southern hemisphere summer by wave–wave interactions. J. Geophys. Res. 101 (D21), 26567–26576. doi:10.1029/96JD02248.

Wu, D.L., Fishbein, E.F., Read, W.G., Waters, J.W., 1996. Excitation and evolution of the quasi-2-day wave observed in UARS/MLS temperature measurements. J. Atmos. Sci. 53, 728–738. doi:10.1175/1520-0469(1996)053<0728:EAEOTQ>2.0.CO;2.

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