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Study of solar cycle dependence of the quasi-two-day wave in the MLT from an extratropical station

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The relationship between the quasi-two-day wave (QTDW) and solar variability during summer in the MLT is studied using long-term meteor wind observations from an extratropical station, Cachoeira Paulista (22.7°S, 45°W) in the Southern hemisphere. Overall, the seasonal (summer) mean and monthly mean zonal amplitude of the QTDW show a negative correlation and the meridional amplitude exhibits a positive correlation with the solar F10.7 flux in the MLT. Although the seasonal mean (summer) wave period shows positive correlation with the solar cycle, both positive and negative correlations are found in the monthly mean period in certain summer months at the present location. Additionally, both amplitude and period of the QTDW show slightly higher values in solar minimum and lower values in solar maximum within the limit of standard deviation indicating a weak, but measurable response to the solar cycle. The features of the present study bearing similarity as well as disagreement with the findings of the past investigators are also discussed in the perspective of current understanding.

Keywords. Quasi-two-day wave; solar cycle effect on waves; meteor radar observations.

1. Introduction

Quasi-two-day wave (QTDW) is a prominent wave signature in summer solstice at low and mid-latitude middle and upper atmosphere (Rodger and Prata 1981; Clark *et al.* 1994; Guharay *et al.* 2013). Behaviour of the QTDW is quite different at high latitude, i.e., increase in the activity in winter (Nozawa *et al.* 2003). Since its discovery in the meteor radar winds in the mesosphere and lower thermosphere (MLT) in early 1970s (Müller 1972), the wave features were studied by a number of investigators globally using satellite, ground-based measurements as well as numerical simulation (Salby 1981; Salby and Callaghan 2001; Garcia *et al.* 2005; Guharay *et al.* 2013). Simultaneous radar observations located around various longitudes over the globe revealed the longitudinal structure of the QTDW as a westward propagating disturbance with zonal wavenumber 3 (Glass *et al.* 1975; Craig *et al.* 1981). With the help of theoretical model, Salby and Callaghan (2001) concluded the QTDW as a Rossby-gravity normal mode enhanced in summer solstice due to baroclinic instability associated with easterly jet with a period lying within 2.0–2.2 days.

The amplitude of the QTDW is generally found to be much higher in the Southern hemisphere in comparison with the Northern counterpart (Tsuda *et al.* 1988; Clark *et al.* 1994) with a peak amplitude

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that can be as large as 45 m/s (Harris and Vincent 1993). Owing to its significant amplitude at certain times of the year, its interactions with other atmospheric waves, e.g., tides (Teitelbaum and Vial 1991), planetary waves (Pancheva *et al.* 2000; Guharay *et al.* 2015) can modify the ambient dynamical conditions significantly. The period of the QTDW is generally close to 48 hr in the Southern hemisphere (Harris 1994), but in the Northern hemisphere it can be as long as 53 hr (Salby and Callaghan 2001). Although the QTDW amplitude is almost equal in both zonal and meridional winds at mid-latitude, the amplitude is generally observed to be higher in the meridional wind in comparison with the zonal wind towards equator.

Solar radiation has a profound impact on the atmospheric physiochemical processes at various altitudes. Although variation of the total solar irradiance from maximum to minimum condition is only about 0.1%, the UV irradiance (200–250 nm) can vary 4–8% (Donnelly 1991; Lean *et al.* 1997) and it is able to modify the chemistry and dynamics of the MLT by altering the total energy deposited. In addition to the quasi-biennial oscillation (QBO) and El-Niño-Southern oscillation (ENSO), interannual variability of the MLT region is considerably affected by the 11-year solar cycle. A couple of previous studies reported the 11-yr solar cycle influence on the middle atmospheric temperature and ozone (Crooks and Gray 2005; Hood *et al.* 2013 and references therein). The perturbation in temperature due to solar cycle can modify the middle atmospheric circulation (Kuchar *et al.* 2015). Due to enhanced meridional temperature gradient, a zonal wind anomaly with stronger subtropical jet around stratopause is formed in solar maxima. As a consequence, planetary waves propagating from the high latitude are forced to deviate from their original course by the subtropical jet. Brewer–Dobson circulation is generally found to be weaker in solar maximum condition (Kuroda and Kodera 2001).

Utilising Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) onboard Thermosphere–Ionosphere–Mesosphere Energetics and Dynamics (TIMED) satellite, Ramesh *et al.* (2015) obtained good agreement between the solar UV flux and mesopause temperature, mesopause height and ozone mixing ratio over tropical (10–15°N) region. Sprenger and Schminder (1969) first reported the impact of solar cycle on the mesospheric wind and tides based on observations from the mid-latitude. Since then a couple of studies attempted to find a relationship between the tides and solar cycle in the MLT and a few studies reported appreciable relationship (Dartt *et al.* 1983; Greisiger *et al.* 1987; Guharay *et al.* 2019), while other investigations did not find any clear relationship (Fraser *et al.* 1989; Jacobi *et al.* 1997a) between them.

Although signature of the 11-yr solar cycle in the middle atmospheric temperature, wind, ozone concentration and tides are documented in the available literature, relationship between the solar cycle and the QTDW is not investigated enough, especially unavailability of any extensive study from the Southern hemispheric low latitudes urges the need of detailed investigation. Using radar observations from two Indian equatorial locations, Venkateswara Rao *et al.* (2017) reported anticorrelation between the QTDW and solar cycle only over an Indian tropical station. With MF radar measurements from Hawaii (22°N, 160°W), Gu *et al.* (2013) reported in-phase/anti-phase variation of the meridional/zonal QTDW amplitude with the solar cycle in the month of July. In the present study, we attempt to investigate the solar cycle dependence of the QTDW exclusively in terms of amplitude and period utilizing long term (almost two solar cycle) meteor wind observations from an extratropical Southern hemispheric station, Cachoeira Paulista (22.7°S, 45°W).

2. Instruments, database and analyses

The horizontal wind information used in the present study is obtained from an all-sky interferometric meteor radar. It has an operational frequency of 35.24 MHz. The detailed description of the radar can be found elsewhere (Guharay *et al.* 2013). The position and range of the echoes are determined to obtain horizontal wind information. The algorithm for derivation of the wind parameters are detailed in the previous paper by Hocking *et al.* (2001).

The zonal and meridional winds with a spatial resolution of 3 km within the vertical range 80–100 km and temporal resolution of 1 hr during the interval 1999–2018 are utilised to investigate the QTDW parameters in the present study. A few data gaps exist due to technical faults. As the QTDW signature enhances during summer solstice, only December–February (continuous) interval of each year is considered for the analyses and interpretations. The short data gaps (< 24 hr) are filled up by linear interpolation. The solar monthly F10.7 flux values are obtained from the Natural Resources Canada.

The period of the QTDW is calculated by utilising complex demodulation technique (Harris and Vincent 1993) which is able to detect frequency variation of the wave in the time series considering a center period of 48 hr with cut-offs at 40 and 56 hr. The daily period of the QTDW is estimated with the help of slope of the instantaneous phase variation (Thayaparan *et al.* 1997). The daily amplitude is estimated using least square fit within a window of width 4 day which is shifted progressively by 1 day constraining the period within the range 40–56 hr to consider QTDW components. The mean values of the amplitude and period over the December–February interval for each year represent the summer QTDW characteristics. Monthly mean amplitude and period for individual summer month (December, January, and February) are also utilised for subsequent analysis as will be depicted later. The solar F10.7 flux data is also averaged (monthly/seasonally) similar to the QTDW amplitude and period to carry out further analysis. Additionally, a linear trend is removed from the mean time series data before carrying out further analysis. A correlation analysis is performed to verify any relationship between the wave parameters and solar flux. The values of correlation coefficient (r) greater than 0.53 with a significance level of at least 95% (availability of at least 14 data points in the respective time series) according to t test statistics are considered for any conclusive results in the present study.

3. Results

For comparison, the yearly zonal and meridional QTDW amplitudes at a representative altitude, i.e., 90 km and solar F10.7 flux values in SFU (1 SFU $= 10^{-22}$ $\mathrm{Wm^{-2}\,Hz^{-1}}$) are shown in figure 1(a). The vertical bars represent the standard deviation of the amplitude. The meridional QTDW is found to contain higher amplitude and variability as compared to the zonal one. The F10.7 flux shows two maxima in 2002 (most dominant), 2014 and a minimum in 2008–2009. The meridional amplitude shows four peaks where two peaks (2003 and 2015) follows the solar maxima. The zonal amplitude shows a relatively less prominent peak in 2003–2004, 2017 and a dip in 2001, 2018. Large

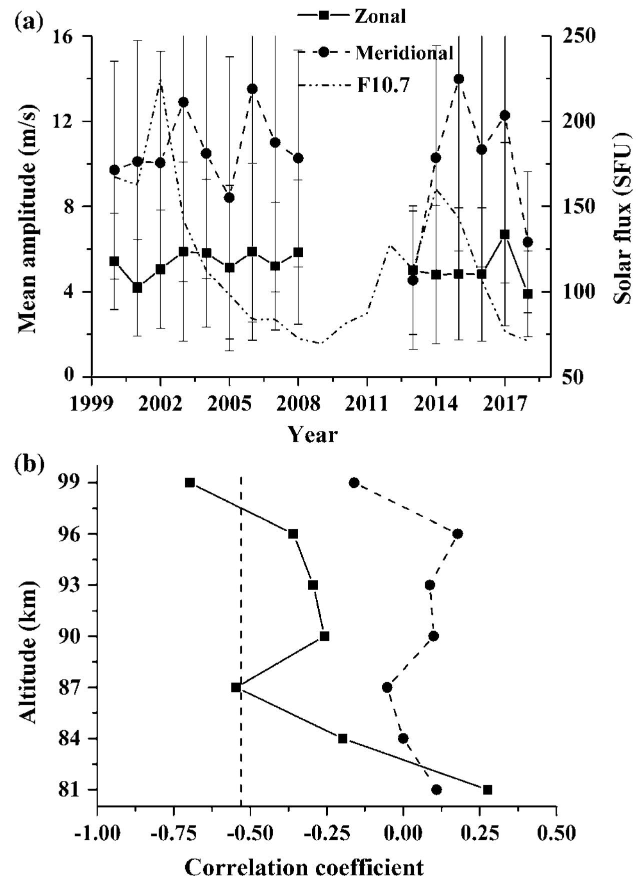

Figure 1. (**a**) Seasonal (summer) mean zonal, meridional QTDW amplitude at 90 km and solar F10.7 flux. The vertical bars represent standard deviation of the wave amplitude. (**b**) Vertical profiles of the correlation coefficient estimated between the detrended QTDW amplitude and solar flux at various altitude bins. The dashed vertical line in the present and following plots denotes an absolute value of 0.53 (95% significance level).

standard deviations indicate significant intra-seasonal variability of the wave activity. Overall, no visibly identifiable solar dependence of the QTDW amplitude is found over long temporal span. In order to quantify the long-term relationship between the QTDW amplitude and the solar F10.7 flux, vertical profiles of r are estimated as shown in figure 1(b). The vertical dashed line denotes $r = \pm 0.53$ in the abscissa in the present and all following figures. No evident relation is found between the meridional QTDW amplitude and solar flux. However, the zonal amplitude exhibits prominent negative correlation at 87 and 99 km.

Figure 2(a) plots the summer mean period of the QTDW at 90 km and the F10.7 flux for comparison. The vertical bars represent standard deviation. The meridional period shows minima corresponding to the peaks in solar flux. Both zonal and meridional period show higher values when

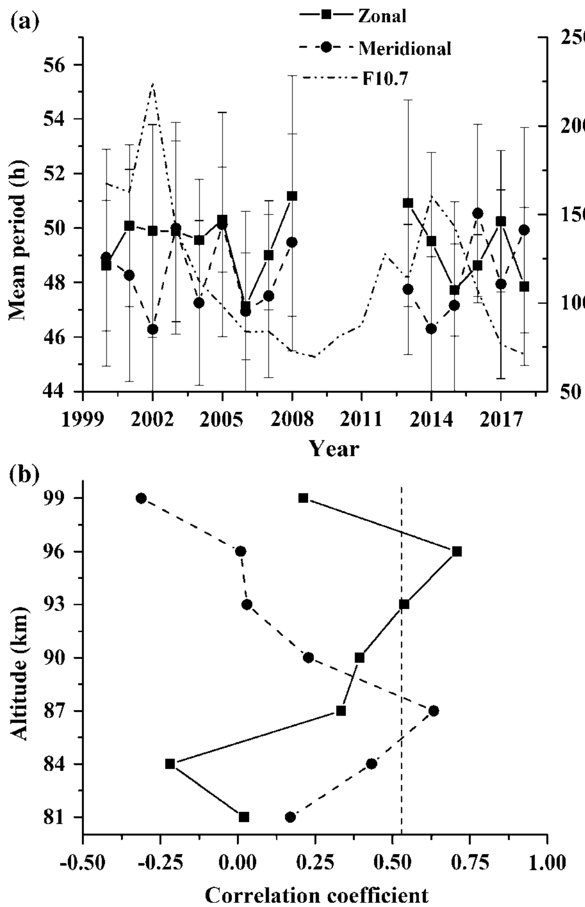

Figure 2. Same as figure 1, but for the period of QTDW.

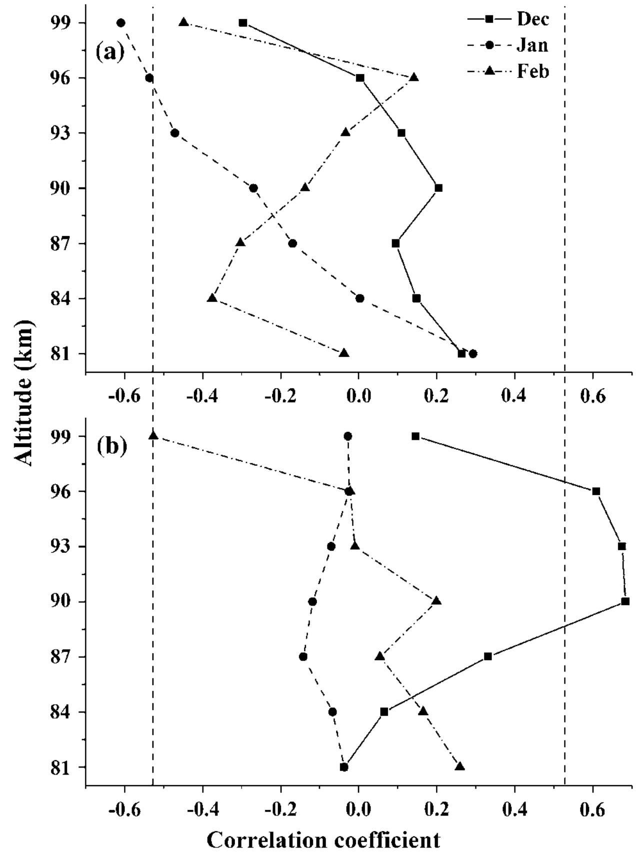

Figure 3. Vertical profiles of the correlation coefficient estimated between the detrended QTDW amplitude and solar F10.7 flux for individual summer months, i.e., December, January and February obtained from (**a**) zonal and (**b**) meridional components.

solar flux is relatively smaller. Overall, no evident relationship can be found between the QTDW period and the solar flux at this altitude bin. To determine the absolute relationship between the QTDW period and solar flux, r values are estimated and shown in figure 2(b). Prominent positive correlation can be observed at 93 and 96 km in the zonal period. In the meridional period, appreciable correlation is found at 87 km. Therefore, evident relationship between the QTDW period in the MLT and solar flux can be interpreted from the results.

In order to investigate relationship of the QTDW amplitude with solar flux for an individual summer month, correlation profiles for the three months, December, January and February are independently estimated and shown in figure 3. In the zonal amplitude, no evident correlation is observed in December and February. However, in January appreciable negative correlation can be noted in the upper MLT. Furthermore, the correlation profile in the zonal amplitude shows regular vertical variation in January unlike other months where profiles are relatively irregular. On the other hand, in December the meridional amplitude exhibits prominent positive correlation in the upper MLT. Another appreciable negative correlation is found at 99 km in February, although profile in January does not show any interesting signature. Therefore, dissimilar behaviour of the correlation in the individual months in the zonal and meridional amplitude can be noted.

Figure 4 illustrates the relationship between the QTDW period (zonal and meridional) and solar flux for individual months similar to the previous result. The zonal period exhibits notable relation only in December with a positive correlation at the bottom and a negative correlation at the top within the considered vertical extent. The meridional period shows appreciable negative correlation around 84–90 km in February. Therefore, relationship between the QTDW period and solar flux is found to be noteworthy in summer months except January.

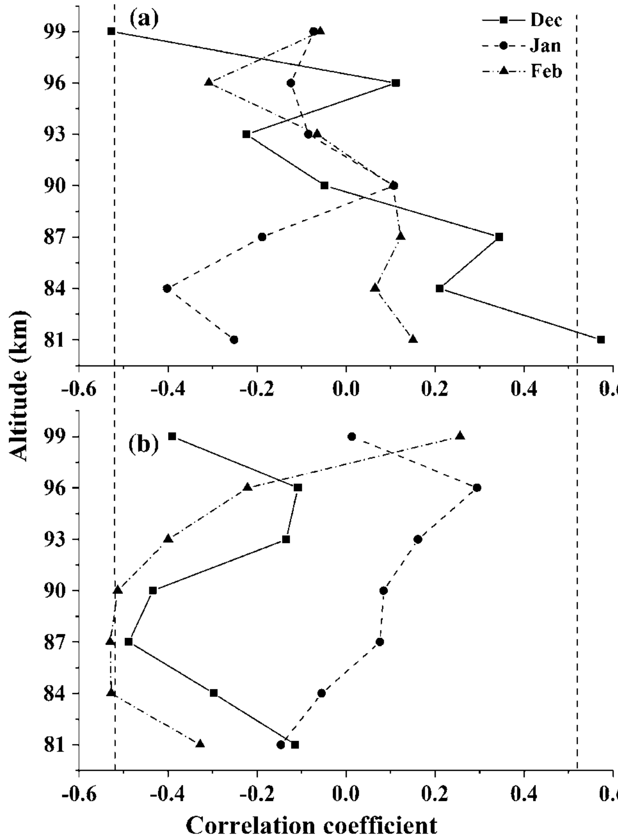

Figure 4. Same as figure 3, but for the period of QTDW.

The behaviour of the QTDW amplitude in solar maximum (2002) and minimum (2008) is studied and plotted in figure 5. The summer mean amplitudes in 2002 and 2008 for the zonal and meridional components are shown in figure 5(a and b), respectively. The horizontal lines represent the standard deviation. Evident from the plot is little higher QTDW amplitude in solar minimum as compared to the maximum in both the winds except at 81 km in the zonal and 99 km in the meridional amplitude. However, since the difference between the amplitudes in the maximum and minimum is generally smaller than the corresponding standard deviation it is difficult to reach any statistically significant conclusion. To address this issue, the occurrence rate (OR) (in counts) of the amplitude in solar maximum and minimum are shown for the zonal and meridional components in figure 5(c and d). Apparently, the maximum OR is remarkably higher in the zonal amplitude (figure 5c) than the meridional one (figure 5d) which should not be too different. The reason for such discrepancy can be attributed to longer tail of the distribution in the meridional amplitude as compared to the zonal counterpart. In solar maximum, OR is generally higher as compared to the solar minimum, which can be ascribed to smaller number of observational days in 2008 due to a few data gaps. Important point from the plot to note is the position of the distribution peak in the abscissa. In the zonal amplitude the distribution peaks lie in the range 4–5 m/s and 5–6 m/s in solar maximum and minimum, respectively. The distribution peak in the meridional amplitude can be found to be in the range 6–7 m/s and 9–10 m/s in solar maximum and minimum, respectively. Therefore, both the plots (figure 5a and b) unanimously indicate slightly larger QTDW amplitude in solar minimum as compared to the maximum.

Similar to the previous results, the behaviour of the QTDW period in solar maximum (2002) and minimum (2008) is investigated as shown in figure 6. Figure 6(a and b) shows the vertical profiles of the summer mean period in the MLT in the zonal and meridional components, respectively. The horizontal bars denote the standard deviation. In general, the period is longer in solar minimum as compared to the maximum except at 81 and 87 km in the zonal amplitude. However, the difference between the maximum and minimum is mostly smaller than the corresponding standard deviation precluding any statistically significant inference. Therefore, to substantiate the interpretation, OR of the QTDW period in the zonal and meridional components are shown in figure 6(c and d), respectively. From the visual inspection we can find higher magnitude (in the abscissa) of the central maximum of the distribution in the zonal wind as compared to the meridional counterpart. In the zonal period the peaks of the distribution lie in the range 48–49 and 49–50 hr in solar maximum and minimum, respectively. The peak of the distribution in the meridional period is found to be in the range 45–46 and 48–49 hr in solar maximum and minimum, respectively. Therefore, the results of figure 6 indicate the relatively longer period in solar minimum as compared to the maximum.

4. Discussions

The relationship between the QTDW and solar variability in summer is looked into in the present study utilising long-term meteor wind database from an extratropical station in the Southern hemisphere. Both the QTDW parameters, i.e., amplitude and period exhibit evident relationship with the solar F10.7 flux at various altitudes in the

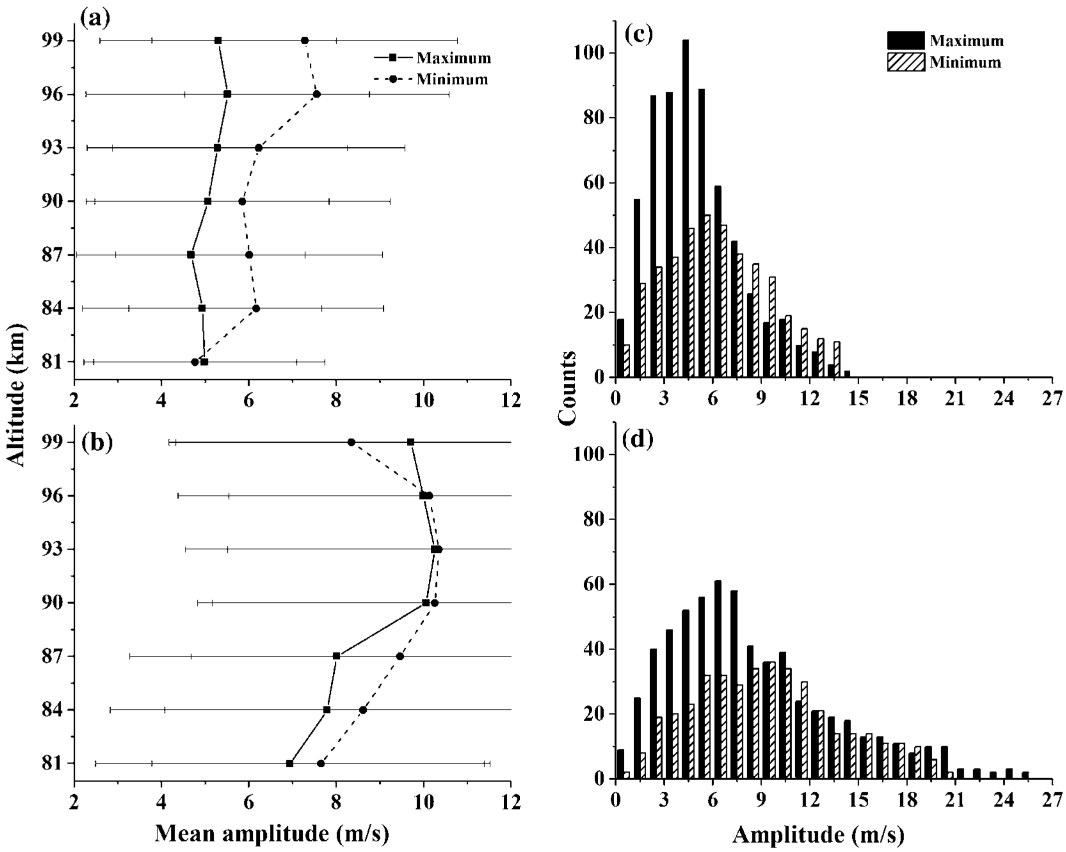

Figure 5. Vertical profiles of the seasonal (summer) mean amplitude of the QTDW in solar extrema derived from (**a**) zonal and (**b**) meridional components. The horizontal bars represent the standard deviation. Occurrence rate of the wave amplitude in solar extrema obtained from (**c**) zonal and (**d**) meridional components.

MLT. The observed features of the present study will be discussed in view of current understanding on this topic.

In general, the QTDW is found to be greater in the meridional amplitude as compared to the zonal one (figure 1a). However, figure 1(b) exhibits presence of correlation in the zonal component and no evident correlation in the meridional amplitude. This is possibly due to the influence of the other dominant components, e.g., planetary waves, tides, etc., bearing greater amplitude in the meridional wind that may affect the actual QTDW trend. In this context, one may additionally note larger standard deviation in the meridional component. On the other hand, opposite phenomenon is also possible, i.e., prominent correlation in the meridional component only, e.g., figure 3(b) shows appreciable correlation in the meridional component in December without any signature in the zonal profile. Such occurrence can be attributed to very weak zonal QTDW long-term trend.

Using long-term wind observations in the MLT from three Northern hemispheric stations spread over low and mid-latitudes, Clark *et al.* (1994) found strong solar influence on the 2-day wave, although their study did not focus on the solar cycle dependence of the QTDW explicitly. The summer mean zonal amplitude in the present study is found to exhibit negative correlation with the solar F10.7 flux at certain altitudes although meridional amplitude does not show any correlation. With MF radar observations from Indian low latitude station, Venkateswara Rao *et al.* (2017) reported slightly negative correlation consistent with the present finding.

With the help of MF radar observations from Hawaii (22°N, 160°W), Gu *et al.* (2013) found in-phase variation of the meridional amplitude and anti-phase variation of the zonal amplitude with the solar cycle in the month of July (Northern summer). The results of the past study agree with the present ones as we find preferential negative correlation in the zonal amplitude in January and positive correlation in the meridional amplitude in December (figure 3). Observed good correlation between the wave amplitude and solar flux in December is possibly due to solar cycle dependence of the mesospheric instability processes that

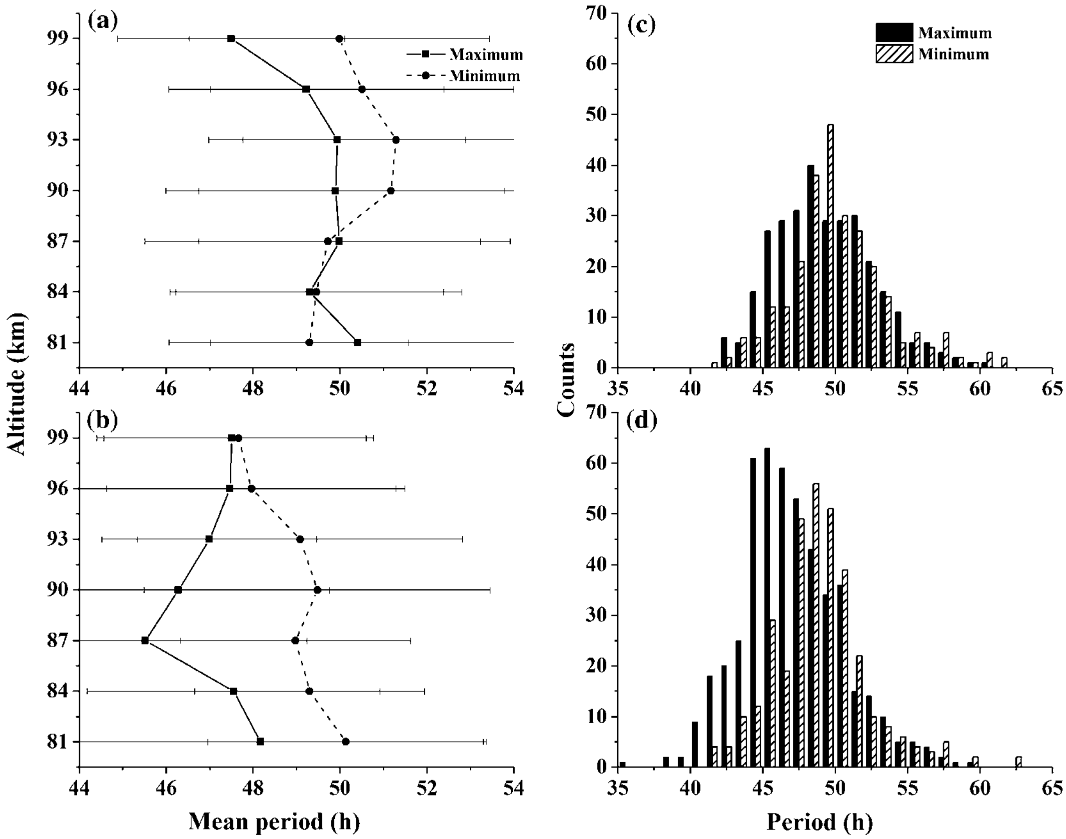

Figure 6. Same as figure 5, but for the period of QTDW.

support the QTDW activity which will be discussed later in detail. Furthermore, in the present results one can note a difference in the correlation values between the seasonal mean profiles and individual month profiles (December, January and February) in the case of both amplitude and period. Such disparity implies significant variability of the QTDW activity with respect to the month of the year which is probably owing to the sources and other dynamical processes containing high short-term temporal and/or inter-annual variability that affect the concerned wave feature.

Using long-term observations in the MLT from a mid-latitude station, Jacobi (1998) reported QTDW enhancement in solar maxima indicating a positive correlation between the QTDW amplitude in summer and solar cycle, although their result was statistically significant only in a single month. However, the present study reports statistically significant positive and negative correlation between the wave amplitude and solar flux for individual summer months over an extratropical station. The partial discrepancy may be attributed to the consideration of total amplitude (zonal and meridional together) in the past study and in the present work zonal and meridional amplitudes are considered independently.

With the MLT wind observations over Collm (52°N, 15°E) during 1983–1995, Jacobi *et al.* (1997b) found positive correlation between the wave amplitude and solar cycle. On the other hand, observations during 2004–2014 from the same location, Lilienthal and Jacobi (2015) reported a negative tendency of the correlation although it was not very evident implying a change of relationship between the parameters with time. Therefore, our results (1999–2018) related to the zonal QTDW amplitude are consistent with the latter study to some extent, probably due to considerable overlapping between the observational intervals.

In the present study, both zonal and meridional QTDW amplitudes generally show a common behavior in solar extrema, i.e., slightly higher values in solar minimum and smaller amplitude in solar maximum. Higher wave amplitude during solar minimum may indicate greater effect of lower atmospheric forcing on the MLT dynamics from below than direct solar impact from above. Using TIMED/SABER long-term temperature data during 2002–2011, Huang *et al.* (2013) investigated QTDW characteristics over both hemispheres and found stronger/weaker QTDW activity in solar maxima/minima implying an opposite behaviour with respect to the present finding which is possibly due to the latitudinal and/or hemispheric difference. Therefore, evident from the above discussion is notable difference in the relationship between the QTDW amplitude and solar cycle among various investigations carried out over a number of locations on the globe and hence further investigations may throw some light on our limited understanding on this topic. The number of days in solar minimum year is less than that of the solar maximum (figures 5 and 6). However, the behaviour of the distribution of OR is not likely to be affected significantly due to the difference in observational data points since the data gaps are sufficiently smaller as compared to the number of observational days as well as they are almost uniformly distributed over the observational interval.

The mean summer period of the QTDW in the present study shows positive correlation although the individual summer months reveal both positive and negative values of r. However, both zonal and meridional periods exhibit a common feature of greater value in solar minimum as compared to the maximum similar to the amplitude as depicted before. Overall, the distribution peaks of period lie in the range 45–49 and 48–50 hr in solar maximum and minimum, respectively. Observations from Adelaide (35°S, 138°E), Harris (1994) observed generally larger QTDW period in summer (January) during solar maxima years (1980–1982, 1990–1991). Later, Gu *et al.* (2013) reported a tendency of lengthening of the QTDW period in solar maxima years unlike the present study. Although the reasons for such difference with the previous studies are not known at present, the possibility could be latitudinal variability of the complex ambient dynamical processes that favour/hinder the QTDW activity.

The presence of strong easterly background wind may enhance the QTDW activity through barotropic/baroclinic instability. However, we have not found any strong mean easterly zonal wind in the summer MLT corresponding to the QTDW enhancement. However, the mean zonal wind is found to change downward from westerly to easterly in the vertical range 80–100 km (not shown here). Unfortunately, wind data below 80 km is not available to verify whether there is a concurrent strengthening of the easterly wind to favour the QTDW activity. In this connection it can be noted that Jacobi (1998) reported increase of the wave amplitude due to strong zonal wind gradient associated instability and hence a positive correlation with the solar cycle. Recently, observations from the same location as the previous one by Lilienthal and Jacobi (2015) also reported the similar signature. Using drift measurements over a mid-latitude location, Jacobi *et al.* (2006) found notable correlation between the sunspot number and gravity wave activity and they attributed it to a possible solar cycle influence on the mesospheric jet. Additionally, a few studies (Bremer *et al.* 1997; Jacobi 1998) reported presence of a weak lower thermospheric easterly mean wind in concert with strong positive vertical zonal wind gradient below in solar maximum implying a strong mesospheric easterly jet. Therefore, one can expect a concurrent enhancement of the QTDW activity due to increased instability supported by mesospheric jet/wind shear. Furthermore, such solar cycle dependence of the zonal wind shear and associated barotropic/baroclinic instability has also implication on the period of the QTDW. Using numerical simulation, Merzlyakov and Jacobi (2004) demonstrated that in presence of a strong instability there is a potential of nonlinear interaction between the QTDW and longer period planetary waves giving rise to a spread of the QTDW period as a result of secondary wave generation.

On the other hand, Gu *et al.* (2013) did not find any weakening of westerly (strong easterly) in the years of high QTDW activity within the observational vertical range (84–94 km). Furthermore, they argued that a number of factors, e.g., gravity wave QTDW interaction, modification of the mean zonal wind due to gravity wave breaking, ENSO, etc., could considerably change the long-term behaviour of the QTDW. Therefore, certain differences in the solar cycle dependence of the QTDW among various investigators as discussed before urge the necessity of further coordinated studies from various locations on the globe.

One important aspect from the present study to note is appearance of the significant correlation between the QTDW parameters and the solar flux at selective heights and wind components, i.e., zonal or meridional. Such outcomes may raise questions to the readers why such relationship is not ubiquitous and consistent in nature. Actually, the reason for such phenomenon is the weak relationship between the two parameters as pointed out by the previous investigators discussed before. Due to such weak impact of the solar cycle on the QTDW, the correlation in most cases are not even visible/detectable. However, manifestation of at least a few statistically significant correlation values affirms the existence of such relationship. Therefore, missing/absent correlation values at certain altitudes do not actually rule out the possibility of the link between these two quantities rather it indicates extant other dynamical entities that have greater influence on the QTDW and may overshadow/screen the weaker solar response of the concerned wave component. Furthermore, in some cases the correlation behaviour reverses (positive to negative and vice versa) with altitude. In this context it can be mentioned that in the most recent study, Guharay *et al.* (2019) observed similar peculiar altitudinal variation of the correlation values as they investigated the solar cycle dependence of the dominant atmospheric tides. Furthermore, the contrary behaviour of the correlation among zonal and meridional components as found in the present study were also reported by the past investigators (Gu *et al.* 2013; Lilienthal and Jacobi 2015; Guharay *et al.* 2019). Although the reasons for such peculiar behaviour are not known at present, we believe that further coordinated studies could lend some useful insights in this regard.

5. Summary and conclusions

Variability of the QTDW in terms of amplitude and period with respect to the solar flux is investigated in the MLT from an extratropical station located in the Southern hemisphere using long-term meteor radar observations. Both the summer mean and monthly mean (January) zonal QTDW amplitudes show negative correlation with the solar flux at certain altitudes. The monthly mean (December) meridional amplitude shows positive correlation in the upper MLT although summer mean meridional amplitude does not show any clear relationship with the solar cycle. The summer mean period exhibits positive correlation with the solar flux at specific altitudes. The zonal monthly mean period in December shows both positive and negative correlation and the monthly mean meridional period in February exhibits negative correlation with the solar flux in the lower MLT. Both the amplitude and period of the QTDW slightly higher magnitude in solar minimum and lower in solar maximum condition limited by standard deviation implying a small variability of the concerned wave over a solar cycle. Since the observed features point out consistency as well as disagreement with the past investigations, more coordinated studies are being sought.

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References

Bremer J, Schminder R, Greisiger K M, Hoffmann P, Kürschner D and Singer W 1997 Solar cycle dependence and long-term trends in the wind field of the mesosphere/lower thermosphere; *J. Atmos. Sol.-Terr. Phys.* **59** 497–509.

Clark R R, Current A C, Manson A H, Meek C E, Avery S K, Palo S E and Aso T 1994 Hemispheric properties of the two-day wave from mesosphere–lower-thermosphere radar observations; *J. Atmos. Terr. Phys.* **56** 1279–1288.

Craig R, Vincent R, Fraser G and Smith M 1981 The quasi-2-day wave in the Southern Hemisphere mesosphere; *Nature* **287** 319–320.

Crooks S A and Gray L J 2005 Characterization of the 11-year solar signal using a multiple regression analysis of the ERA-40 dataset; *J. Climate* **18** 996–1015.

Dartt D, Nastrom G and Belmont A 1983 Seasonal and solar cycle wind variations, 80–100 km; *J. Atmos. Terr. Phys.* **45** 707–718.

Donnelly R F 1991 Solar UV spectral irradiance variations; *J. Geomagn. Geoelectr.* **43** 835–842, https://doi.org/10.5636/jgg.43.supplement2_835.

Fraser G J, Vincent R A, Manson A H, Meek C E and Clark R R 1989 Inter-annual variability of tides in the mesosphere and lower thermosphere; *J. Atmos. Terr. Phys.* **51** 555–567.

Glass M, Fellous J, Massebeuf M, Spizzichino A, Lysenko I and Portniaghin Y 1975 Comparison and interpretation of the results of simultaneous wind measurements in the lower thermosphere at Garchy (France), and Obninsk (USSR) by meteor radar technique; *J. Atmos. Terr. Phys.* **37** 1077–1087.

Garcia R R, Lieberman R, Russell J M and Mlynczak M G 2005 Large-scale waves in the mesosphere and lower thermosphere observed by SABER; *J. Atmos. Sci.* **62** 4384–4399, https://doi.org/10.1175/JAS3612.1.

Greisiger K M, Schminder R and Kürschner D 1987 Long-period variations of wind parameters in the mesopause region and the solar cycle dependence; *J. Atmos. Terr. Phys.* **49** 281–285.

Gu S-Y, Li T, Dou X, Wang N-N, Riggin D and Fritts D 2013 Long-term observations of the quasi two-day wave by Hawaii MF radar; *J. Geophys. Res. Space Phys.* **118** 7886–7894, https://doi.org/10.1002/2013ja018858.

Guharay A, Batista P P, Clemesha B R and Schuch N J 2013 Study of the quasi-two day wave during summer over Santa Maria, Brazil using meteor radar observations; *J. Atmos. Sol.-Terr. Phys.* **92** 83–93, https://doi.org/10.1016/j.jastp.2012.10.005.

Guharay A, Batista P P and Clemesha B R 2015 Variability of the quasi-2-day wave and interaction with longer period planetary waves in the MLT at Cachoeira Paulista; *J. Atmos. Sol.-Terr. Phys.* **130–131,** https://doi.org/10.1016/j.jastp.2015.05.010.

Guharay A, Batista P P and Andrioli V F 2019 Investigation of solar cycle dependence of the tides in the low latitude MLT using meteor radar observations; *J Atmos Sol.-Terr. Phys.* **193** (105083), https://doi.org/10.1016/j.jastp.2019.105083.

Harris T J and Vincent R A 1993 The quasi-two-day wave observed in the equatorial middle atmosphere; *J. Geophys. Res.* **98** 10,481–10,490.

Harris T J 1994 A long-term study of the quasi-2-day wave in the middle atmosphere; *J. Atmos. Sol.-Terr. Phys.* **56(5)** 569–579.

Hocking W K, Fuller B and Vandepeer B 2001 Real-time determination of meteor related parameters utilizing modern digital technology; *J. Atmos. Sol.-Terr. Phys.* **63** 155–169.

Hood L L, Schimanke S, Spangehl T, Bal S and Cubasch U 2013 The surface climate response to 11-yr solar forcing during northern winter: Observational analyses and comparisons with GCM simulations; *J. Climate* **26** 7489–7506, https://doi.org/10.1175/jcli-d-12-00843.

Huang Y Y, Zhang S D, Yi F, Huang C M, Huang K M, Gan Q and Gong Y 2013 Global climatological variability of quasi-two-day waves revealed by TIMED/SABER observations; *Ann. Geophys.* **31** 1061–1075, https://doi.org/10.5194/angeo-31-1061-2013.

Jacobi C, Schminder R, Kürschner D, Bremer J, Greisiger K M, Hooffmann P and Singer W 1997a Long-term trends in the mesopause wind field obtained from D1 LF wind measurements at Collm, Germany; *Adv. Space Res.* **20** 2085–2088.

Jacobi Ch, Schminder R and Kurschner D 1997b The quasi two-day wave as seen from D1 LF wind measurements over Central Europe (52ºN, 15ºE) at Collm; *J. Atmos. Terr. Phys.* **59** 1277–1286.

Jacobi C 1998 On the solar cycle dependence of winds and planetary waves as seen from mid-latitude D1 LF mesopause region wind measurements; *Ann. Geophys.* **16** 1534–1543, https://doi.org/10.1007/s00585-998-1534-3.

Jacobi Ch, Gavrilov N M, Kürschner D and Fröhlich K 2006 Gravity wave climatology and trends in the mesosphere/lower thermosphere region deduced from low frequency drift measurements 1984–2003 (52.1°N, 13.2°E); *J. Atmos. Sol.-Terr. Phys.* **68** 1913–1923.

Kuchar A, Sacha P, Miksovsky J and Pisoft P 2015 The 11-year solar cycle in current reanalyses: A (non)linear attribution study of the middle atmosphere; *Atmos. Chem. Phys.* **15** 6879–6895, https://doi.org/10.5194/acp-15-6879-2015.

Kuroda Y and Kodera K 2001 Variability of the polar night jet in the Northern and Southern Hemispheres; *J. Geophys. Res. Atmos.* **106** 20,703–20,713.

Lean L, Rottman J, Kyle G J, Woods H L, Hickey T N and Pugga J R 1997 Detection and parameterization of variations in solar mid and near-ultraviolet radiation (200–400 nm); *J. Geophys. Res.* **102** 29,939–29,956.

Lilienthal F and Jacobi Ch 2015 Meteor radar quasi two-day wave observations over 10 years at Collm (51.3°N, 13.0°E); *Atmos. Chem. Phys.* **15** 9917–9927, http://dx.doi.org/10.5194/acp-15-9917-2015.

Merzlyakov E G and Jacobi Ch 2004 Quasi-two-day wave in an unstable summer atmosphere – some numerical results on excitation and propagation; *Ann. Geophys.* **22** 1917–1929, https://doi.org/10.5194/angeo-22-1917-2004.

Müller H G 1972 Long-period meteor wind oscillations; *Phil. Trans. Roy. Soc. London Series A: Math. Phys. Sci.* **271(1217)** 585–599.

Nozawa S, Imaida S, Brekke A, Hall C M, Manson A, Meek C, Oyama S, Dobashi K and Fujii R 2003 The quasi-2-day wave observed in the polar mesosphere; *J. Geophys. Res.* **108(D2)** 4039, http://dx.doi.org/10.1029/2002JD002440.

Pancheva D, Beard A G, Mitchell N J and Muller H G 2000 Nonlinear interactions between planetary waves in the mesosphere/lower-thermosphere region; *J. Geophys. Res.* **105(A1)** 157–170, https://doi.org/10.1029/1999ja900332.

Ramesh K, Sridharan S and Vijaya Bhaskara Rao S 2015 Influence of solar cycle and chemistry on tropical (10°N–15°N) mesopause variabilities; *J. Geophys. Res. Space Phys.* **120** 4038–4051, https://doi.org/10.1002/2014ja020930.

Rodger C D and Prata A J 1981 Evidence for a traveling two-day wave in the middle atmosphere; *J. Geophys. Res.* **86** 9661–9664.

Salby M 1981 The 2-day wave in the middle atmosphere: Observations and theory; *J. Geophys. Res.* **86(C10)** 9654–9660.

Salby M L and Callaghan P F 2001 Seasonal amplification of the 2-day wave: Relationship between normal mode and instability; *J. Atmos. Sci.* **58** 1858–1869, http://dx.doi.org/10.1175/1520-0469(2001)058/1858:SAOTDS2.0.CO;2.

Sprenger K and Schminder R 1969 Solar cycle dependence of winds in the lower ionosphere; *J. Atmos. Terr. Phys.* **31** 217–221.

Teitelbaum H and Vial F 1991 On tidal variability induced by nonlinear interaction with planetary waves; *J. Geophys. Res. Space Phys.* **96** 14,169–14,178.

Thayaparan T, Hocking W K and MacDougall J 1997 Amplitude, phase and period variations of the quasi-2-day wave in the mesosphere and lower thermosphere over London, Canada (43°N, 81°W), during 1993 and 1994; *J. Geophys. Res.* **102** 9461–9478.

Tsuda T, Kato S and Vincent R A 1988 Long period oscillations observed by the Kyoto meteor radar and comparison of the quasi-2-day wave with Adelaide HF radar observations; *J. Atmos. Terr. Phys.* **50** 225–230.

Venkateswara Rao N, Venkat Ratnam M, Vedavathi C, Tsuda T, Krishna Murthy B V, Sathishkumar S, Gurubaran S, Kishore Kumar K, Subrahmanyam K V and Vijaya Bhaskara Rao S 2017 Seasonal, inter-annual and solar cycle variability of the quasi two day wave in the low-latitude mesosphere and lower thermosphere; *J. Atmos. Sol.-Terr. Phys.* **152–153** 20–29, https://doi.org/10.1016/j.jastp.2016.11.005.

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