Journal of Atmospheric and Solar--Terrestrial Physics 152 (2017) 20–29

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar–Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Seasonal, inter-annual and solar cycle variability of the quasi two day wave in the low-latitude mesosphere and lower thermosphere

N. Venkateswara Rao[a,*], M. Venkat Ratnam[a], C. Vedavathi[b], T. Tsuda[c], B.V. Krishna Murthy[d], S. Sathishkumar[e], S. Gurubaran[f], K. Kishore Kumar[g], K.V. Subrahmanyam[g], S. Vijaya Bhaskara Rao[b]

[a] *National Atmospheric Research Laboratory (NARL), Gadanki, India*
[b] *Department of Physics, Sri Venkateswara University, Tirupati, India*
[c] *Research Institute for Sustainable Humanosphere, Kyoto University, Uji, Japan*
[d] *B1, CEEBROS, 47/20, IIIrd Main Road, Chennai, India*
[e] *EGRL, Indian Institute of Geomagnetism (IIG), Mumbai, India*
[f] *Indian Institute of Geomagnetism (IIG), Mumbai, India*
[g] *Space Physics Laboratory, VSSC, Thiruvananthapuram, India*

ARTICLE INFO

Keywords:
Quasi-Two Day Wave
MF radar
Meteor radar
QBO
Solar cycle

ABSTRACT

We analyzed 17 years (1993–2009) of horizontal winds measured by the medium frequency (MF) radar located at Tirunelveli (8.7°N, 77.8°E) and 10 years (2005–2014) of horizontal winds measured by a meteor radar located at Thumba (8.5°N, 77°E) to examine the seasonal, inter-annual, and solar cycle variability of the Quasi-Two Day Wave (QTDW) in the mesosphere and lower thermosphere region. These two radars are nearly co-located, but differ in their measurement technique. Comparison of the estimated QTDW amplitudes by the two radars shows that the amplitudes are larger in the meteor radar than those in the MF radar. The difference between the amplitudes is larger in May in the zonal component and in April and September in the meridional one. Furthermore, the differences are larger in the meridional component. The QTDWs in both the radars show a strong semi-annual oscillation (SAO). In addition, the meridional QTDW amplitudes of both the MF and meteor radars show a distinct enhancement in the month of October. While the whole spectra of QTDWs contribute to the SAO amplitudes, only 45–50 h waves contribute to the October enhancement. The amplitudes of the QTDWs, in general, show large inter-annual variability. The QTDW amplitudes from both the radars show modulation at period of quasi-biennial oscillation. The QTDWs of the MF radar show a small negative correlation with solar activity while those of meteor radar do not show any correlation. The above aspects are discussed in the light of current understanding of the QTDWs.

1. Introduction

Quasi-Two Day Waves (QTDWs) are ubiquitous and are one of the largest amplitude planetary wave modes in the mesosphere and lower thermosphere (MLT) region with periodicity lying anywhere between 40 and 56 h. These waves are particularly important due to their interaction and thereby energy exchange with means winds, gravity waves, solar tides, and other planetary waves. Characteristics (such as short-term, seasonal, and inter-annual variability, sources of generation, and interaction with solar tides) of these waves have been extensively studied with ground and satellite based observations (Muller, 1972; Reddi et al., 1988; Tsuda et al., 1988; Wu et al., 1996; Gurubaran et al., 2001; Pancheva et al., 2004; Offermann et al., 2011; Tunbridge et al., 2011; Pedatella and Forbes, 2012; Huang et al., 2013; Ern et al., 2013; Moudden and Forbes, 2014; Gu et al., 2013a; McCormack et al., 2014) and model simulations (e.g., Salby and Callaghan, 2008; Yue et al., 2012).

The QTDWs are mostly observed to be westward propagating with zonal wave number 3 (W3) or 4 (W4) (Wu et al., 1996; Gu et al., 2013b; Huang et al., 2013). W3 is generally much stronger (nearly twice) than W4. Sources of QTDW generation include Rossby normal mode (Salby, 1981), baroclinic-barotropic instabilities (Plumb, 1983) or a combined effect of the both. One of the noticeable characteristics of this wave in the MLT region that has been consistently observed in all studies is its larger amplitudes in the meridional wind (monthly mean values ~30 m/s) than in the zonal wind (~20 m/s). Owing to their large phase

* Corresponding author.
E-mail address: nvrao@narl.gov.in (N.V. Rao).

http://dx.doi.org/10.1016/j.jastp.2016.11.005
Received 30 May 2016; Received in revised form 24 October 2016; Accepted 21 November 2016
Available online 22 November 2016
1364-6826/© 2016 Elsevier Ltd. All rights reserved.

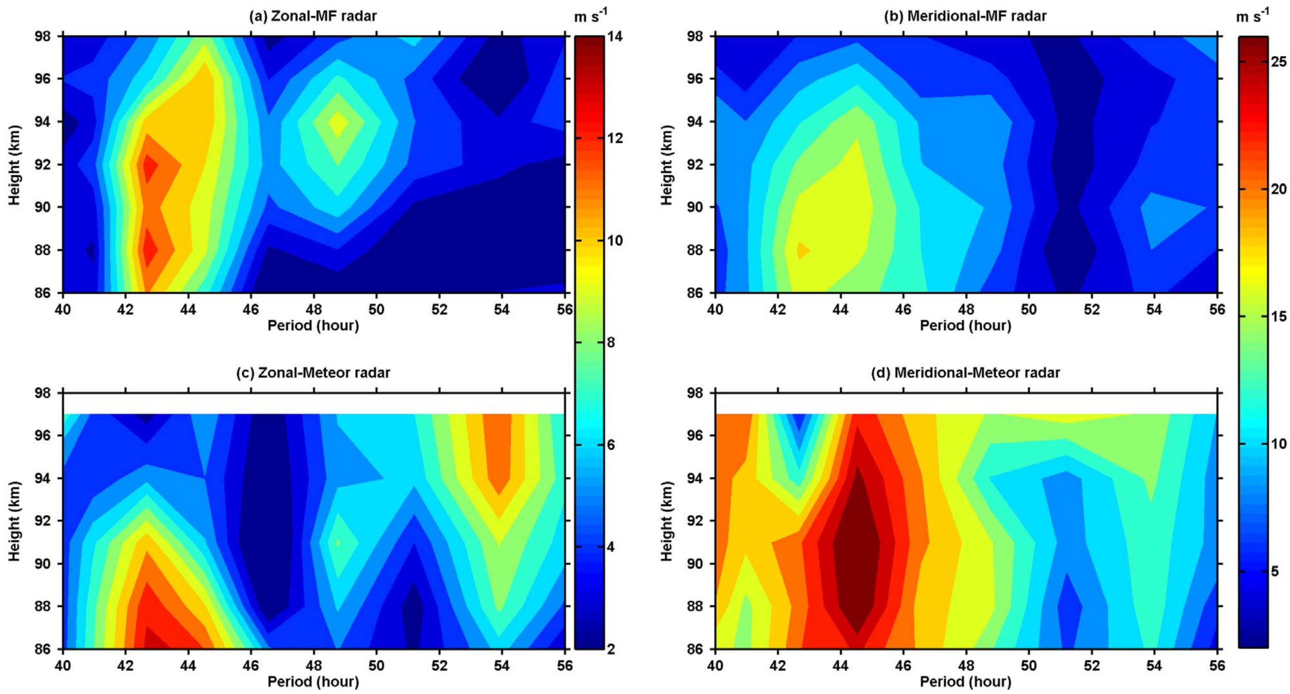

Fig. 1. Monthly mean spectra showing the QTDWs in (a and c) zonal and (b and d) meridional winds observed in January 2006. Top panels correspond to the MF radar and bottom panels to the meteor radar. The periods shown are for the QTDWs.

speeds (~70 ms^{-1} for W3 and 50 ms^{-1} for W4 at 30° latitude), these waves can propagate to higher altitudes and their effects are observed up to ionospheric altitudes (Chen, 1992; Forbes and Zhang, 1997; Pancheva et al., 2006; Yue et al., 2012; Chang et al., 2014).

QTDWs occur in the summer hemisphere shortly after the summer solstice in short bursts of wave activity, about 20–60 days long (e.g., Wu et al., 1996; Tunbridge et al., 2011; Ern et al., 2013). These waves can penetrate from the summer into the winter hemisphere (e.g., Tunbridge et al., 2011; Ern et al., 2013). The QTDWs show a strong semiannual variation with maximum amplitudes near solstices and minimum in equinoxes (Gurubaran et al., 2001; Suresh Babu et al., 2011; Gu et al., 2013a). Upper mesospheric OH temperature measurements over Wuppertal (51°N, 7°E) and Hohenpeißenberg (48°N, 11°E), on the other hand, showed three maxima in the amplitude of QTDW that are separated by 45–60 days, called triplet structures (Offermann et al., 2011). Significant seasonal and inter-annual variations of both W3 and W4 have been studied with satellite temperature observations (Wu et al., 1996; Palo et al., 2007; Tunbridge et al., 2011). The QTDWs are also found to be modulated at periods of stratospheric quasi-biennial oscillation (Huang et al., 2013; Araújo et al., 2014).

There exist a few studies dealing with the long-term trends and solar cycle (SC) variations of the QTDWs (Jacobi et al., 1997; Gu et al., 2013a; Moudden and Forbes, 2014; Huang et al., 2013; Lilienthal and Jacobi, 2015). Jacobi et al. (1997) studied the QTDW variability using D1 LF wind observations over Collm (52°N, 15°E) and found that this wave has larger amplitudes during solar maximum. Gu et al. (2013a) reported that the QTDWs in the MLT region over Hawai (22°N, 160°W) have a strong SC signal with the meridional wave amplitudes during January and July and zonal amplitudes during January are lagging the 11 year SC by 1–2 years. The zonal QTDW during July, however, is out of phase with the SC. In this study, we investigate the seasonal, inter-annual, and solar cycle variations of the of the QTDWs in the low-latitude mesosphere and lower thermosphere using long-term observations of horizontal (zonal and meridional) winds measured by MF and meteor radars in the low-latitude MLT region.

2. Data and analysis

2.1. Tirunelveli MF radar

The Tirunelveli (8.7°N, 77.8°E) MF radar (Gurubaran and Rajaram, 1999) measures horizontal winds using spaced antenna technique with time and height resolutions of 1–2 min and 2 km, respectively. The system details, mode of operation and the method of wind determination are the same as described by Vincent and Lesicar (1991). The data used in the present study span from January 1993 to December 2009 and are nearly continuous except for some intermittent gaps in between. There are large gaps after 2009 and hence data are limited to 1993–2009 for the present study. We use winds between 86 and 92 km as the winds above 92 km are possibly contaminated by the equatorial electrojet (EEJ) currents and below 86 km there are large data gaps.

2.2. Thumba meteor radar

The Thumba (8.5°N, 77°E) radar is an All-Sky Interferometric Meteor (SKiYMET) radar (Hocking et al., 2001) operating at 35.23 MHz with a peak power of 40 kW and provides wind measurements between 82 and 98 km (Kumar et al., 2007). Four antennas (three-element crossed Yagi) at the corners of a square transmit the circularly polarized beam and five antennas (two-element crossed Yagi) in the form of an asymmetric cross receive back the signal. In order to avoid the effect of echoes from the EEJ region, which can interfere with the neutral wind derivations, one pair of transmitting antennas will be transmitting out of phase with the other such that a null field is formed at the overlapping region of the beams, thus avoiding echoes from EEJ region (Kumar et al., 2007). Despite, there were debates on the meteor radar observations at EEJ altitudes and hence we have limited the use of meteor radar observations to 92 km (Dhanya and Gurubaran, 2009; Kumar et al., 2009; John et al., 2011). The data used in the present study span from January 2005 to December 2014. Note that the location of the radar is close to that of Tirunelveli MF radar. The winds from the two radars are most reliable between 86 and 92 km (Gurubaran and Rajaram, 1999; Kumar et al., 2009).

The amplitudes of the QTDWs are obtained from the horizontal winds measured by the two radars in the following manner. The high time resolution (1–2 min) winds measured by the MF radar are averaged to get hourly values. These hourly winds are then binned by calendar month. The hourly winds in each month are then subjected to a fast Fourier transform (FFT) technique and amplitudes are extracted for periods between 40 and 56 h. The analysis is repeated independently for each height and for the zonal and meridional components. The same procedure is adopted for the meteor radar hourly winds to get monthly QTDW amplitudes.

3. Results

Fig. 1 shows the FFT spectra of the zonal (a and c) and meridional (b and d) winds between 86 and 98 km measured by the MF (top panels) and meteor (bottom panels) radars in January 2006. Here we show the amplitudes for periods between 40 and 56 h only as they correspond to the QTDWs. As can be seen from Fig. 1, the QTDWs are present in both the wind components and the largest amplitudes are associated with periods between 43 and 45 h at altitudes between 86 and 94 km. The amplitudes of the QTDWs are larger in the meridional wind than in the zonal wind. Moreover, the amplitudes measured by the meteor radar are larger than those by the MF radar. An examination of the QTDW spectra in different months suggests that the peak altitude of the QTDWs is not constant and varies between 86 and 92 km. Hence, the amplitudes of the QTDWs between 86 km and 92 km are averaged and these altitude averaged values are used for further study.

The monthly mean and altitude averaged QTDWs between 40 h and 56 h in each month are further averaged and their temporal variation between January 1993 and December 2014 are shown in Fig. 2. The top and middle panels correspond to the zonal and meridional components, respectively. In each panel, the magenta color represents the QTDWs of MF radar and the cyan color represents those of meteor radar. For comparison with solar activity in later sections, the monthly

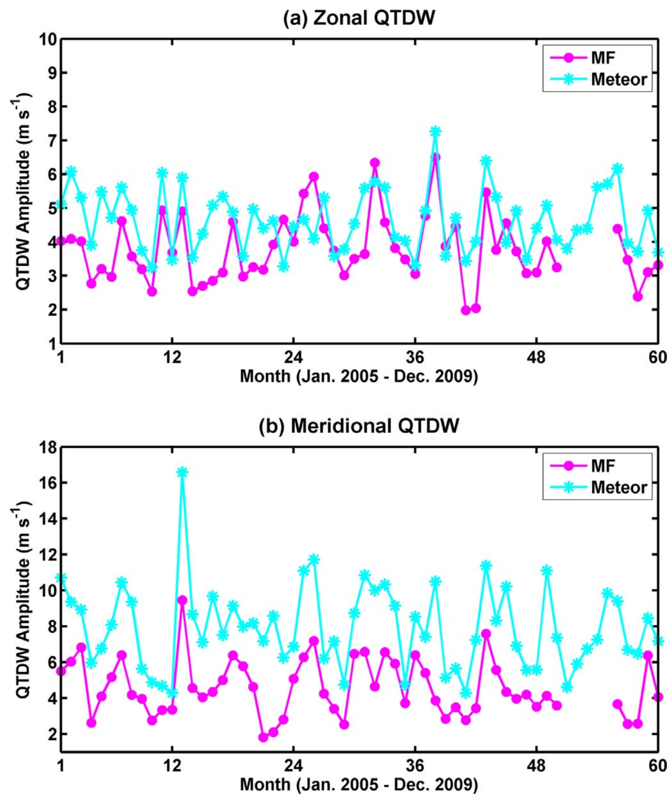

Fig. 3. Monthly mean amplitudes of the QTDWs for (a) zonal and (b) meridional components between January 2005 and December 2009. Magenta (cyan) line corresponds to the MF (meteor) radar. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mean sunspot numbers (SSN) are also shown at the bottom panels of Fig. 2. At first glance, we can note that the dominant variability of the

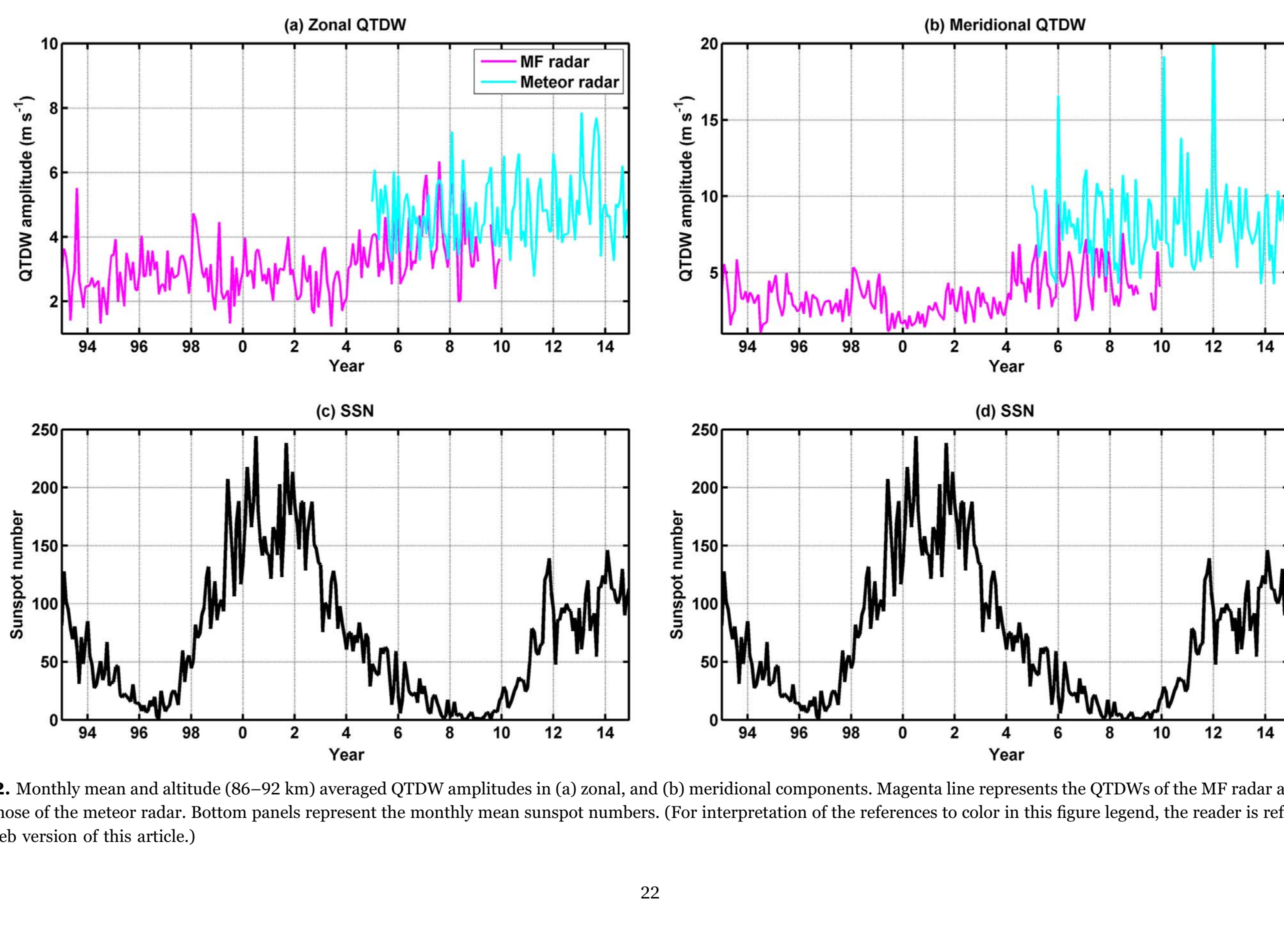

Fig. 2. Monthly mean and altitude (86–92 km) averaged QTDW amplitudes in (a) zonal, and (b) meridional components. Magenta line represents the QTDWs of the MF radar and cyan line those of the meteor radar. Bottom panels represent the monthly mean sunspot numbers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

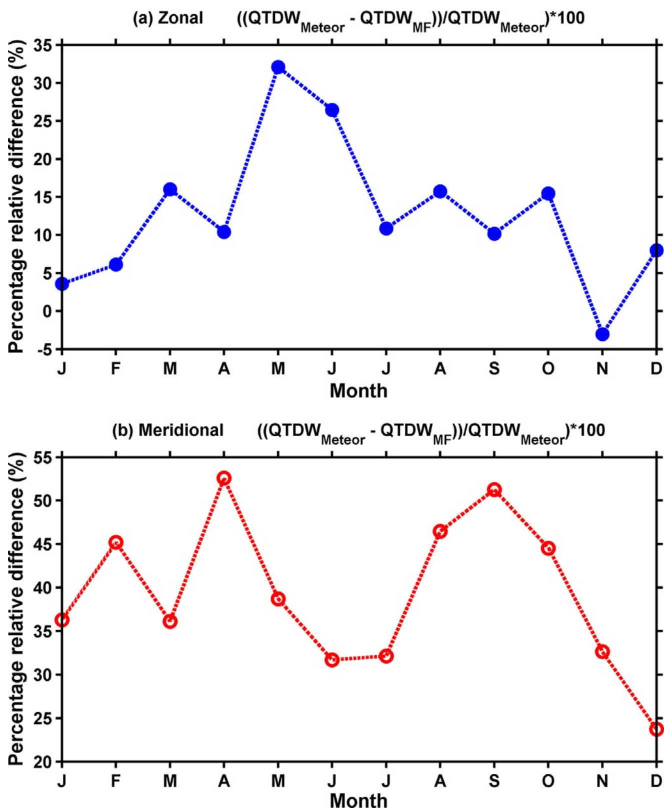

Fig. 4. Percentage relative differences between the QTDW amplitudes measured by the meteor and MF radars for (a) zonal and (b) meridional components in different months. The values are relative to the QTDW amplitudes of the meteor radar.

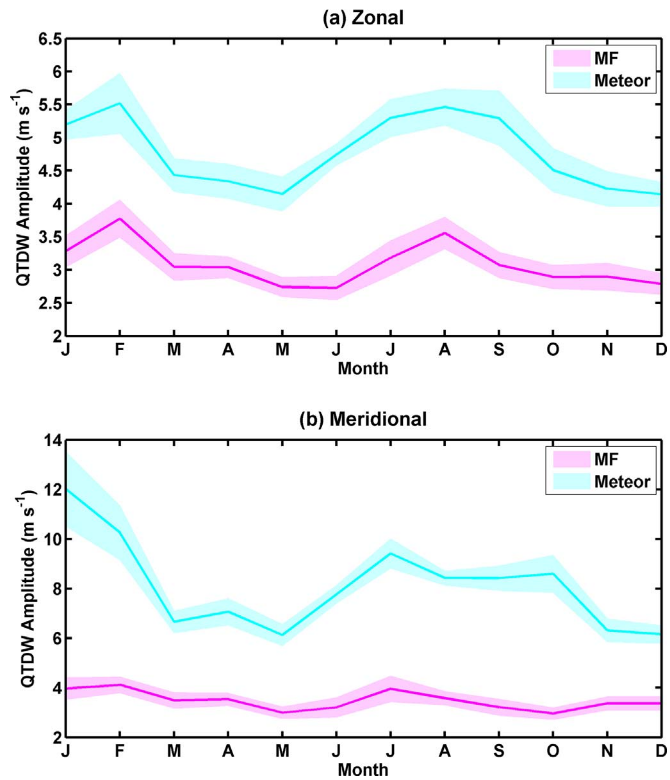

Fig. 5. Seasonal variation of the monthly composite QTDW amplitudes for (a) zonal and (b) meridional components. The composites of each radar and for each component are calculated by considering all the available data in each month. The corresponding standard errors over all years are shown by shaded color. Note that the scales of y-axes are different. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

QTDWs is semi-annual oscillation (SAO). There also exist some higher period oscillations which will be discussed in detail in subsequent sections.

3.1. Comparison of the QTDWs observed by the MF and meteor radars

Before examining the seasonal, inter-annual and solar cycle variabilities of the QTDWs, we first compare their amplitudes measured by MF and meteor radars using simultaneous observations during January 2005 - December 2009. Note that these two radars are nearly co-located and hence any differences in the simultaneous observations must be due to the difference in their measurement techniques. Fig. 3a and b show the amplitudes of the altitude averaged QTDWs in the zonal and meridional components, respectively. As is evident from Fig. 3, the variability of the QTDWs is nearly the same in both the radars, except for some difference in their amplitudes. In the zonal component, the amplitudes of the meteor radar are higher than those of the MF radar for most of the time, though the reverse is true on some occasions. In the meridional component, however, the QTDW amplitudes measured by the meteor radar are always larger than those of the MF radar.

Fig. 4 shows the percentage relative differences in the QTDW amplitudes between the meteor and MF radars with respect to those of the meteor radar. Here, relative differences are shown as the amplitude differences are dependent on the amplitudes themselves. For calculating the relative differences, we averaged the zonal QTDW amplitudes of all years (between January 2005 and December 2009) for each month. This is done separately for the MF and meteor radars and found the difference between the two radars at each month. These values are then divided by the meteor radar QTDW amplitudes at each month and the percentages are calculated. The percentage relative differences are calculated separately for the zonal and meridional components. The relative differences are almost always positive indicating that QTDWs measured by the meteor radar are larger than those of the MF radar. The maximum percentage relative difference in the zonal component is ~ 32% in the month of May. In the meridional component, the differences are maximum in April (53%) and September (51%). Thus, the difference between the QTDW amplitudes of the meteor and MF radars is more in the meridional component than the zonal one. An altitude profile of the percentage relative differences indicate that the differences are smaller at lower altitudes and increase gradually with altitude (figure not shown).

3.2. Seasonal variability

In Fig. 5, we show the seasonal variation of QTDW amplitudes considering all the available data from both the radars (1993–2009 for the MF radar and 2005–2014 for the meteor radar). The QTDW amplitudes show a clear SAO with larger values in winter (January/February) and summer (July/August) in both the zonal and meridional components. The largest values, in fact, are observed in February and August in the zonal component and in January and July in the meridional one. However, note that the QTDW is a global scale wave with a well reported SAO with larger values in local summer and winter. Moreover, the amplitude differences are smaller between January and February and also between July and August (Fig. 5). Therefore, we can neglect the one month phase difference between the zonal and meridional SAO and consider the SAO as phase- synchronous between the zonal and meridional components. In addition to the SAO, the meridional QTDWs of the meteor radar in Fig. 5 show another enhancement in the month of October. This enhancement can also be noted from monthly values of Fig. 3b. Such an enhancement in October, however, is not present in the zonal component. The October enhancement is not apparent in the MF radar measurements shown in

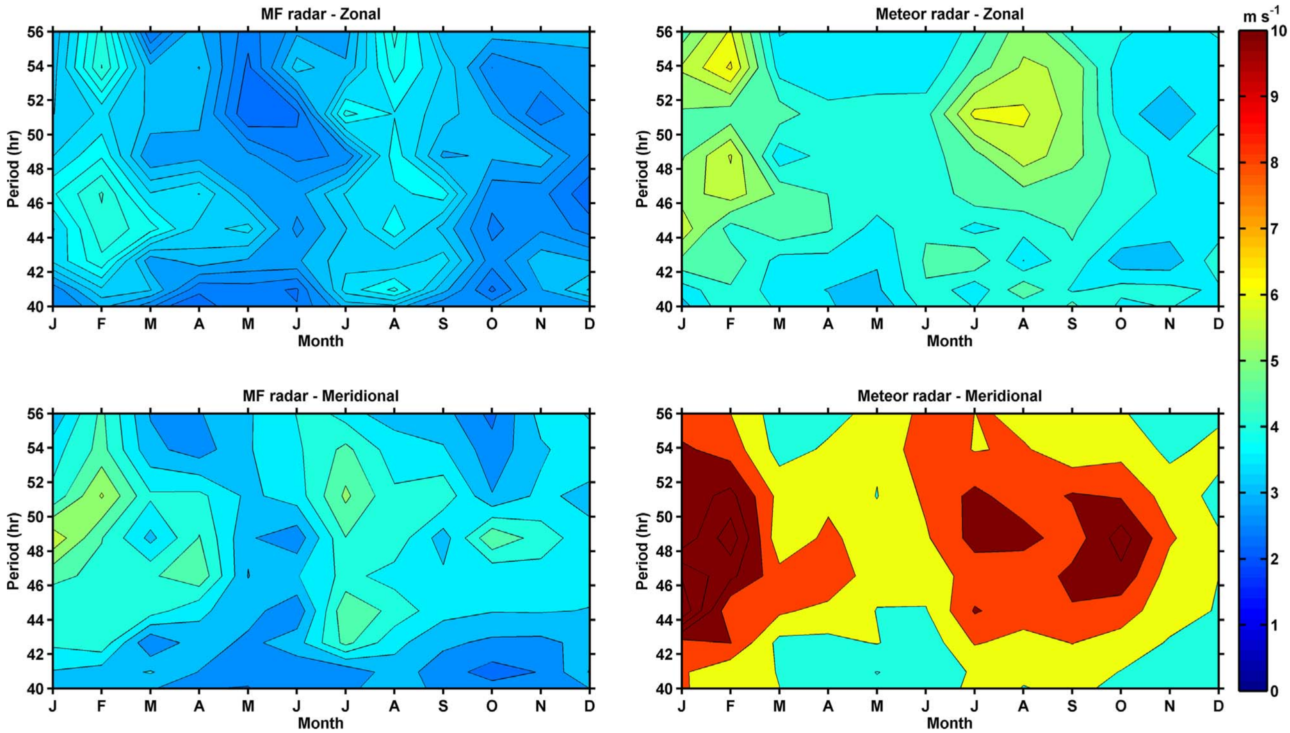

Fig. 6. Composite monthly spectra of the QTDW amplitudes measured by (left panels) MF and (right panels) meteor radars in (top panels) zonal and (bottom panels) meridional components.

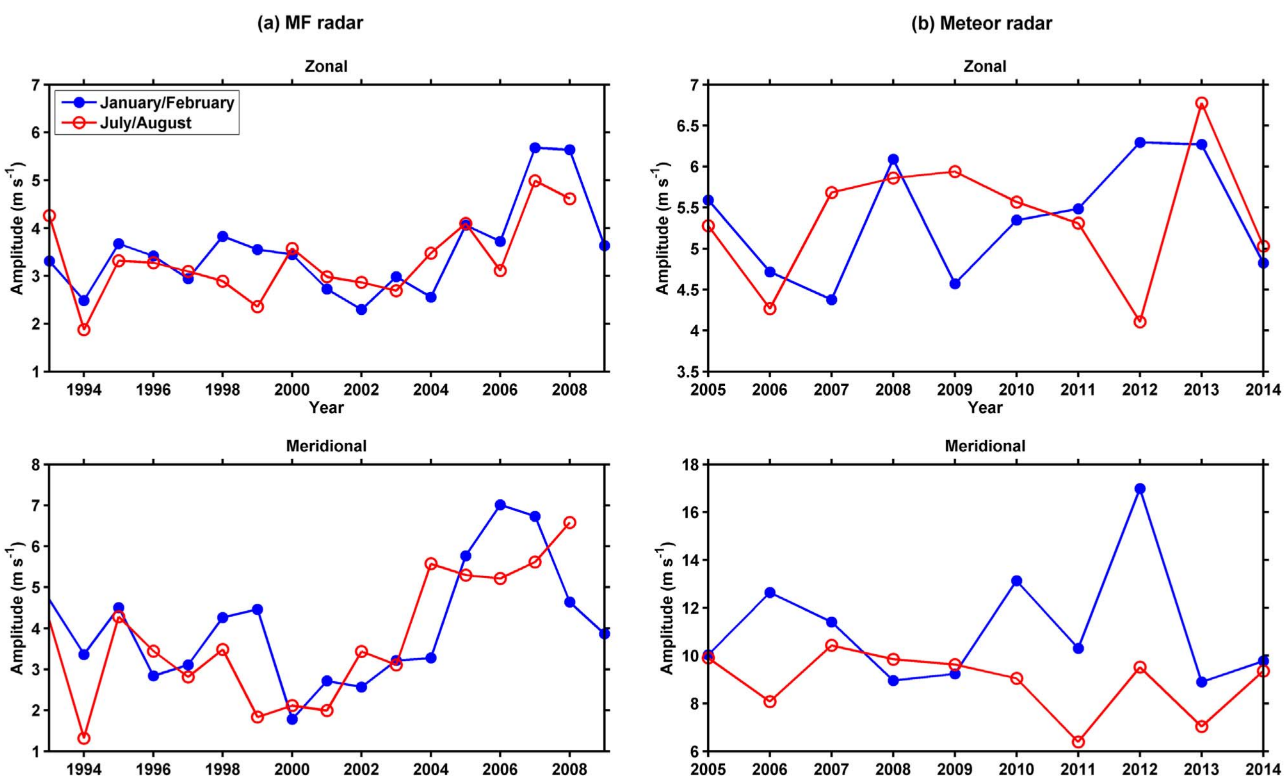

Fig. 7. Inter-annual variability of the January/February (blue) and July/August (red) QTDW amplitudes measured by (a) MF and (b) meteor radars in (top panels) the zonal and (bottom panels) meridional components. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 5.

The seasonal variation is further examined by considering the composite spectra of the QTDWs at each month as shown in Fig. 6. Note that here we use the spectral values computed by the FFT technique and are averaged between 86 and 92 km. The composite spectra is constructed by considering all the available data in each month. Nearly all periods between 40 and 56 h contribute to the SAO variability of the QTDWs. The composite spectra shows that the October enhancement in the meridional amplitude is also visible in the MF radar observations. For the October enhancement, most of the

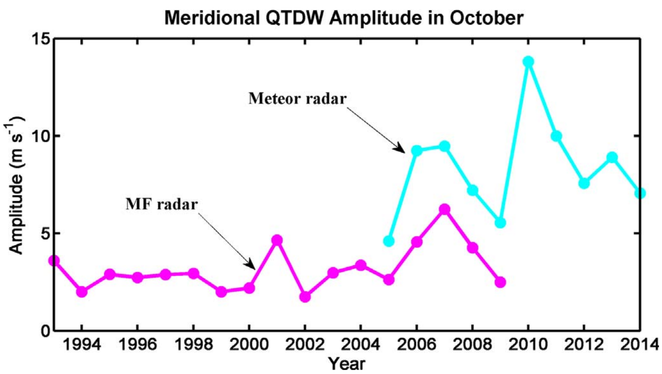

Fig. 8. Monthly mean meridional QTDW amplitudes in October for (magenta line) MF and (cyan line) meteor radars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

contribution comes from periods between 44 and 50 h. At other periods, the amplitudes are very small so that when averaged over all the periods, the October enhancement is not clearly visible in the MF radar (Fig. 5). Thus, the QTDWs in both the radars show an enhancement in the month of October, but the values are larger for the meteor radar than for the MF radar.

3.3. Inter-annual variability

From Figs. 5 and 6, we note that larger values of QTDWs are observed in winter, summer and in October months. In the following, we will study the inter-annual variability of the QTDWs during these three periods. Fig. 7 shows the QTDW amplitudes of MF (left panels) and meteor (right panels) radars in winter (average of January and February months, blue solid line with closed circle) and summer (average of July and August months, red solid line with open circle). The QTDWs of both the MF and meteor radars in both the seasons show large inter-annual variability. The values of the MF radar are particularly larger after 2004. The overall variability in each season is nearly consistent in both the zonal and meridional components of the MF radar, except after 2006 in the meridional component. In case of meteor radar, no striking differences or similarities are observed between the two seasons.

The inter-annual variability of the October enhancement in the meridional QTDW is shown in Fig. 8. From Fig. 8, it is clear that the meridional QTDW amplitudes measured by the MF radar in October do not show much inter-annual variability before 2005, except larger values in 1993 and 2001. After 2005, the QTDW amplitudes in both the radars show large inter-annual variability. During 2005–2009, when simultaneous observations are available from both the radars, the amplitudes of the QTDWs show nearly similar inter-annual variability. Again the amplitudes are larger in the meteor radar than the MF radar. The largest values are ~6.2 m s^{-1} for the MF radar (observed in 2007) and ~13.8 m s^{-1} for the meteor radar (observed in 2010). In the case of meteor radar, a gradual decrease in amplitude is observed from 2007 to 2009 with a rise in 2010 and then decreasing gradually from 2010 to

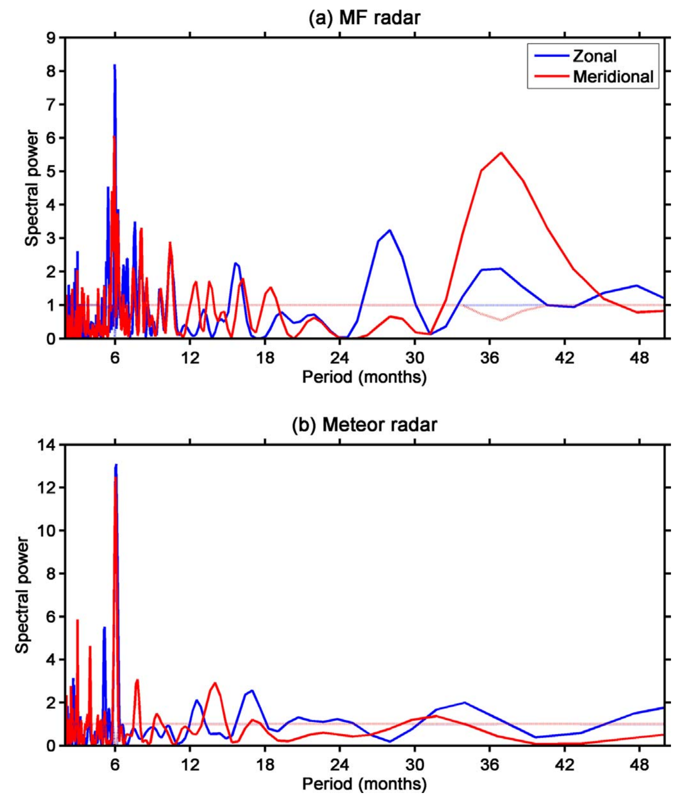

Fig. 10. Amplitude spectra of the monthly mean QTDW amplitudes measured by (a) MF and (b) meteor radars in (blue line) the zonal and (red line) meridional components. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

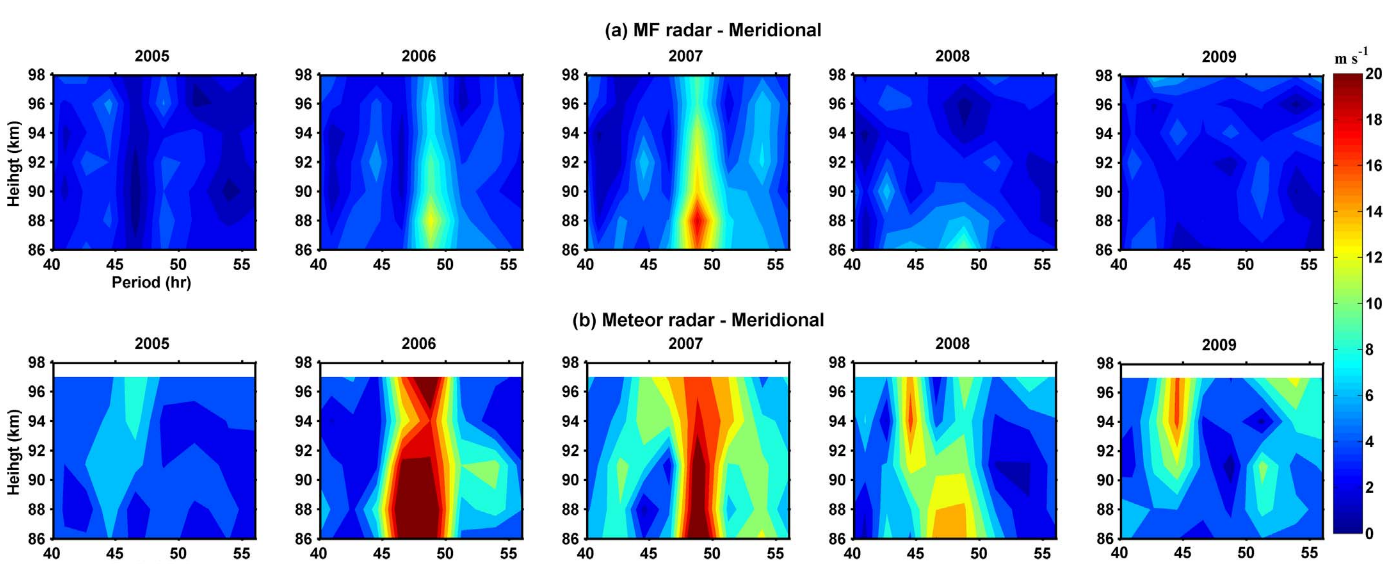

Fig. 9. Meridional wind spectra for the month of October during 2005–2009 measured by (a) MF radar and (b) meteor radar. The periods shown correspond to the QTDWs.

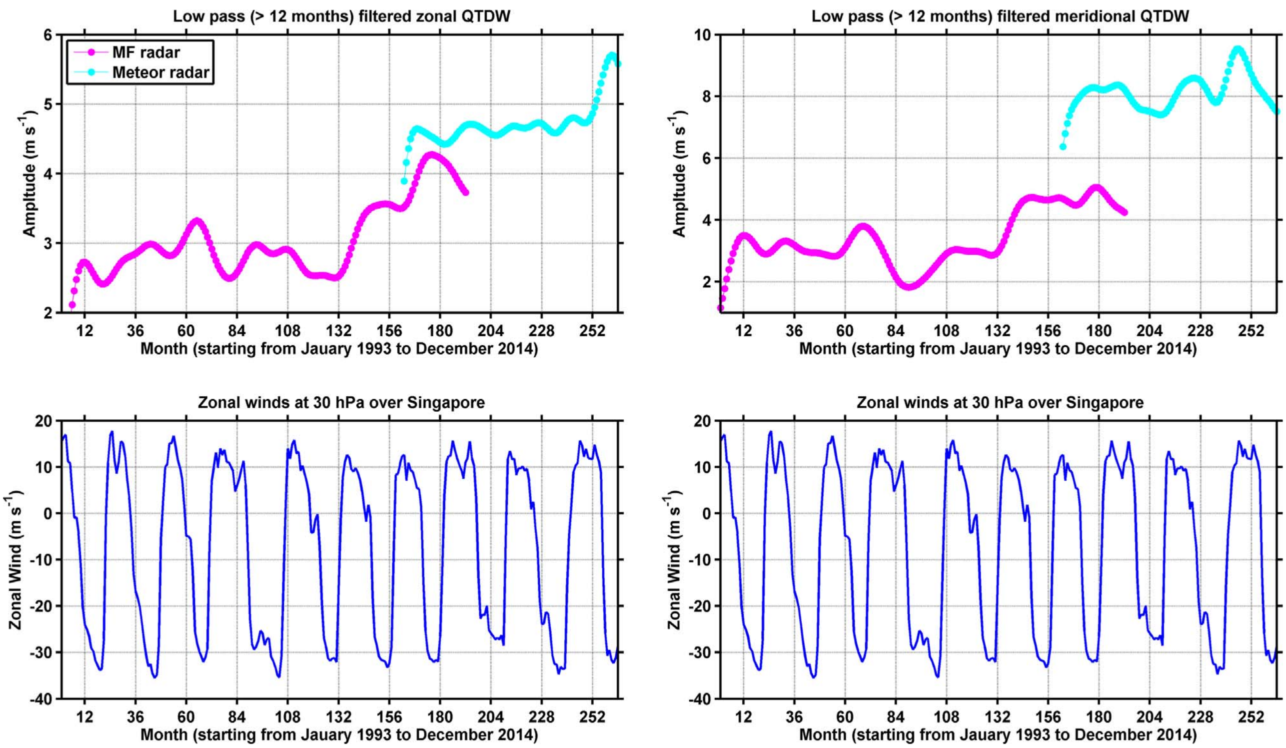

Fig. 11. (top panels) Low-pass (> 12 months) filtered QTDW amplitudes in (left panel) the zonal and (right panel) meridional components. (bottom panels) 30 hPa zonal winds over Singapore.

2014.

The QTDW amplitudes of October are further studied through Fig. 9 wherein we show the spectra of QTDWs measured by the MF and meteor radars in Fig. 9. During 2006–2008 when the QTDW amplitudes are stronger (see Fig. 8), the QTDWs are also seen in the spectra (Fig. 9). The QTDWs in this case are confined to 45–50 h. In 2005 and 2009, when the QTDW amplitudes are smaller, their presence can be seen only in meteor radar spectra. Similarly, the QTDWs are clearly seen in their spectra in 1993 and 2001. The QTDW periods in these years also lie between 45 h and 50 h. Thus, the larger QTDW amplitudes in October are not spurious and they show noticeable inter-annual variability.

From Fig. 2, we can note that the QTDWs have variabilities larger than the SAO period. To further examine these periodicities, we subjected the monthly mean QTDW amplitudes of both the radars to Lomb-Scargle periodgram (Lomb, 1976; Scargle, 1982) and the results are show in Fig. 10. From Fig. 10, it is again clear that the SAO is the dominant periodicity of the QTDWs. In addition to this, there exists 24–36 months periodicity which is stronger in the MF radar observations than the meteor radar. This periodicity is reminiscent of the quasi-biennial oscillation (QBO) commonly observed in the tropical stratosphere (Baldwin et al., 2001). The amplitudes of QBO period are much smaller than those of the SAO, particularly in the meteor radar.

The QBO variability of the QTDWs are further studied by subjecting the monthly QTDWs to a low pass filter (with periods > 1 year). The filtered QTDWs are shown in Fig. 11. For comparison, we also show the 30 hPa zonal winds from Singapore radiosonde data in the bottom panels of Fig. 11. A comparison between the top and bottom panels suggest that the QTDWs of both the radars, in fact, display a QBO signature. However, because of longer dataset of the MF radar and several QBO cycles, the QBO is much clearly noticeable in the amplitude spectrum of MF radar in Fig. 10.

3.4. Relation between QTDW amplitudes and solar activity

In this section, we will examine the relation between the QTDW amplitudes and the solar activity. As mentioned before, we use SSN as a proxy for solar activity and its temporal variation is shown in Fig. 2. In Fig. 2, the QTDW amplitudes of the MF radar are smaller during solar maximum and higher during other times. This solar cycle dependence of QTDWs, however, doesn't seem to be too striking. The QTDWs of meteor radar, on the other hand, do not show any variation with SSN. The relation between QTDWs and solar activity is further examined in Fig. 12 through correlation analysis. Here we use Pearson's rank correlation (Gibbons, 1985) as a tool to quantify the cross-correlation between the QTDWs and SSN. Fig. 12 shows the cross-correlation analysis between the monthly mean QTDW amplitudes of the MF radar and the monthly mean SSN (left panels) and those of the meteor radar and SSN (right panels). As shown, the QTDW amplitudes of the MF radar show a slight negative correlation (the Pearson's coefficient, R=−0.3 to −0.36) with SSN. For the meteor radar, the Pearson's coefficients are close to zero in both the zonal and meridional components, indicating that there is almost no relation between the QTDW amplitudes and the solar activity.

4. Discussion and conclusions

Seventeen years (1993–2009) of horizontal winds measured by an MF radar located at Tirunelveli (8.7°N, 77.8°E) and ten years (2005–2014) of horizontal winds measured by a meteor radar at Thumba (8.5°N, 77°E) are used to study the seasonal, inter-annual, and SC variability of the QTDW in the MLT region. The salient features of the present study are:

Simultaneous observations by both the radars reveal that there is a systematic bias in QTDW amplitudes with larger values for the meteor radar than the MF radar. The bias increases with altitude and is more in the meridional component than the zonal one. The bias has seasonal dependence with larger values in May (percentage relative difference ~ 32%) in the zonal component and in April (53%) and September (51%) in the meridional component.

The QTDW amplitudes are larger in the meridional component than in the zonal one. This is true for both the MF and meteor radars.

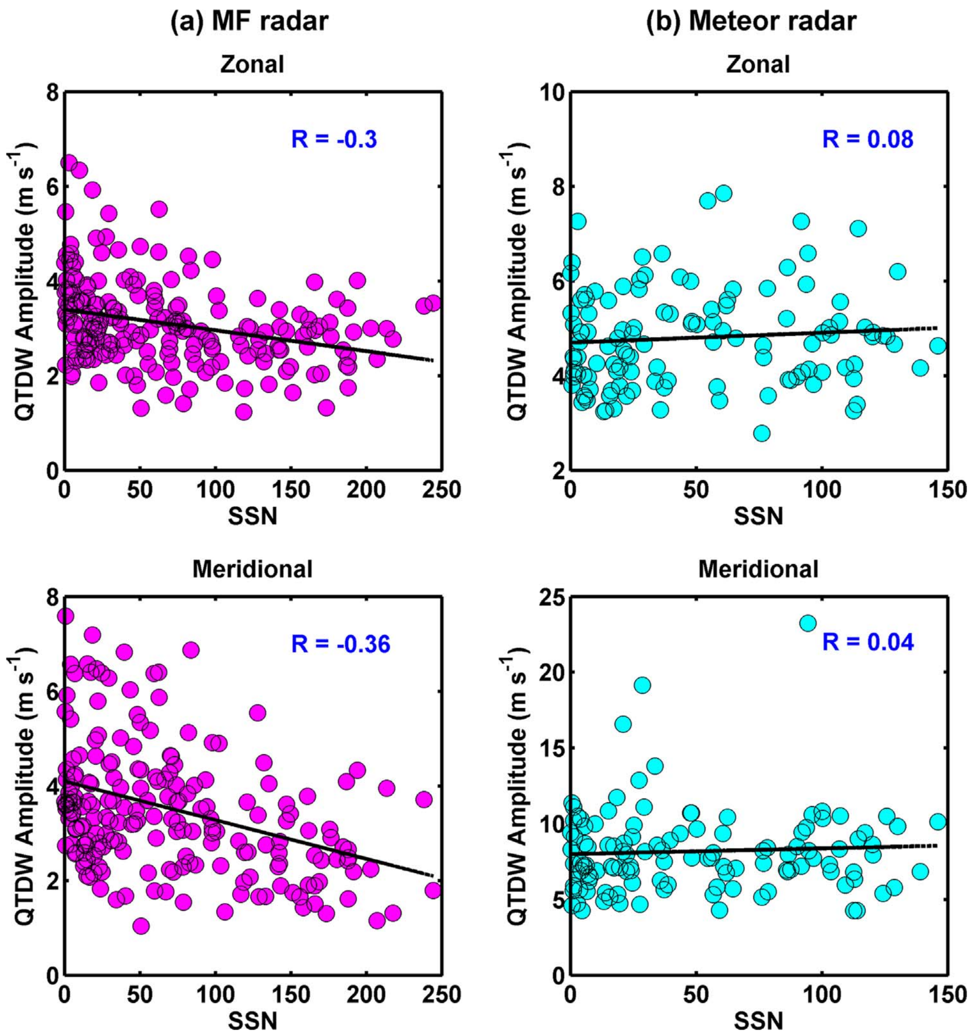

Fig. 12. Correlation between (a) monthly mean QTDW amplitudes of the MF radar and SSN, (b) monthly mean QTDW amplitudes of the meteor radar and SSN for the (top panels) zonal and (bottom panels) meridional. 'R' represents the Pearson's coefficient of correlation.

The QTDW amplitudes measured by both the radars display a strong SAO with larger values in solstices. Composite spectra suggests that full spectrum of QTDWs (40–56 h) contribute to the enhancement of SAO.

The meridional component of QTDWs in both the radars show an enhancement in the month of October. The October enhancement, however, is much clearer in the meteor radar than the MF radar. When the QTDW amplitudes are larger, the October enhancement in clearly seen in the spectra of both the MF and meteor radars. 45–50 h period waves contribute more to QTDW amplitudes in October month.

The October enhancement and the SAO related enhancements in solstices show large inter-annual variability.

QTDWs of both the MF and meteor radars show a periodicity of 24–36 months, which is related to the QBO in the tropical stratosphere. Since the MF radar has larger dataset compared to the meteor radar, the QBO is much more clearly seen in the MF radar.

The QTDWs of the MF radar show a slight negative correlation with the sunspot number while the QTDWs of meteor radar show almost no correlation with the sunspot number.

It is well known that the horizontal winds measured by the MF radars underestimate the actual winds (Hines et al., 1993; Hocking and Thayaparan, 1997; Manson et al., 2004; Jacobi et al., 2009). The present study shows that the QTDW amplitudes measured by the MF radar are also lower than those of the meteor radar. This is a new result and to our knowledge has not reported earlier. The altitude variation of the bias and its larger values in meridional compared to zonal are similar to the bias in the horizontal winds.

Several studies reported that the QTDW is a summer time phenomenon (e.g., Wu et al., 1996; Tunbridge et al., 2011; Ern et al., 2013). However, the QTDWs can penetrate from summer hemisphere to the winter hemisphere (e.g., Tunbridge et al., 2011; Ern et al., 2013). As a result, a secondary peak can also be observed in the local winter. This leads to a SAO of the QTDWs. This variation is nearly consistent with other previous low-latitude studies from the same locations (Gurubaran et al., 2001; Suresh Babu et al., 2011) and from a different location (Gu et al., 2013a). At southern hemisphere low latitudes, however, there was enhancement only during the austral summer (Araújo et al., 2014). The enhancement of meridional QTDWs in October is interesting. Such an enhancement was previously reported by Suresh Babu et al. (2011) using three years of Thumba meteor radar observations between March 2006 and March 2009. In the present study we show this enhancement using both MF and meteor radar observations which reveal that while the entire spectrum of QTDWs contribute to the SAO, only 45–50 h periodicity contributes to the October enhancement. Furthermore, the October enhancement in the QTDWs is stronger in the meteor radar than the MF radar. Such a difference from the co-located instruments is intriguing and needs to be examined further.

The QTDWs in the low-latitude MLT region also show a clear QBO modulation with periodicity between 24 and 36 months. Such a QBO modulation of QTDWs were previously reported from São João do Cariri (7.4°S, 36.5°W) (Araújo et al., 2014). This kind of modulation was also observed at mid to high latitudes (Huang et al., 2013). The horizontal winds in the low-latitude MLT region showed such a QBO modulation (Ratnam et al., 2008; Sridharan et al., 2010; Venkateswara Rao et al., 2012). Since, the QTDWs interact with mean winds (Fritts et al., 1999), it is possible that the QTDWs also display a similar periodicity. However, a more detailed study is required to understand the QBO modulation of the QTDWs.

The QTDW amplitudes of the MF radar from 1993 to 2009 show a small (the Pearson's coefficient, R=~–.0.3) negative correlation with the solar activity (Fig. 12, left panels). The QTDW amplitudes from meteor radar, on the other hand, do not show any correlation with the solar activity (Fig. 12, right panels; the Pearson's coefficients are close to zero). Recently, Gu et al. (2013a) studied the SC variability of the QTDW from Hawaii (22°N, 160°W) using MF radar wind measurements. They showed that the amplitudes of the January monthly mean QTDW in both meridional and zonal winds and the July monthly mean QTDW in meridional component are nearly in phase with the SC but with the solar maxima leading the QTDW maxima by 1 - 2 years. The July monthly mean QTDW in zonal wind, on the other hand, is out of phase with the SC. Huang et al. (2013) study also indicated a SC modulation of QTDW strength in the SH with stronger QTDW amplitudes in the solar maximum than in the solar minimum. In the NH, on the other hand, larger QTDW amplitudes are observed during 2002, 2006, and 2009 and smaller amplitudes during other years. Moudden and Forbes (2014) have shown that the QTDWs have their lowest amplitudes in the deep solar minimum years of 2008/2009 compared to other years. The present study, on the other hand, shows that the QTDW amplitudes almost have no relation/slightly negative to solar activity. It is interesting to note that while Jacobi et al., (1997) have shown that QTDWs at Collm (52°N, 15°E) are larger during solar maximum, Lilienthal and Jacobi (2015) from the same location do not found any clear relation between them. Note that the observations of Jacobi et al. (1997) span from 1983 to 1995, while that of Lilienthal and Jacobi (2015) span from 2004 to 2014. Thus, there seems to be a change in the QTDWs relation to solar activity over the time. The present results are nearly consistent with those of Lilienthal and Jacobi (2014). From all these studies, we can clearly see that at present there is no consistent picture on the relation between QTDWs and solar activity.

Thus, the present study points towards further investigations on the QBO and SC modulation of the QTDWs using long-term observations and model simulations. The bias between the MF and meteor radar measurements of QTDWs also needs to be reconfirmed using co-located measurements elsewhere. The sources of the enhanced QTDWs in the month of October need to be investigated further.

Acknowledgements

We wish to thank technical staff of EGRL and SPL for effective maintenance of the MF and meteor radars, respectively, that enabled obtaining the long-term data used in the present study. The sunspot number data is downloaded from http://www.ngdc.noaa.gov. The 30 hPa zonal winds are taken from http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/.

References

Araújo, L.R., Lima, L.M., Batista, P.P., Clemesha, B.R., Takahashi, H., 2014. Planetary wave seasonality from meteor wind measurements at 7.4°S and 22.7°S. Ann. Geophys. 32, 519–531. http://dx.doi.org/10.5194/angeo-32-519-2014.

Baldwin, M.P., Gray, L.J., Dunkerton, T.J., Hamilton, ., Haynes, P.H., Randel, W.J., Holton, J.R., Alexander, M.J., Hirota, I., Horinouchi, T., Jones, D.B.A., Kinnersley, J.S., Marquardt, C., Sato, K., Takahashi, M., 2001. The quasi-biennial oscillation. Rev. Geophys. 39, 179–229.

Chang, L.C., Yue, J., Wang, W., Wu, Q., Meier, R.R., 2014. Quasi two day wave-related variability in the background dynamics and composition of the mesosphere/thermosphere, and the ionosphere. J. Geophys. Res. Space Phys., 119. http://dx.doi.org/10.1002/2014JA019936.

Chen, P.-R., 1992. Two day oscillation of the equatorial ionization anomaly. J. Geophys. Res. 97, 6343–6357.

Dhanya, R., Gurubaran, S., 2009. Comment on "Initial results from SKiYMET meteor radar at Thumba (8.5°N, 77°E): 1. Comparison of wind measurements with MF spaced antenna radar system". Karanam Kishore Kumar et al. Radio Sci. 44, RS5004. http://dx.doi.org/10.1029/2008RS004024.

Ern, M., Preusse, P., Kalisch, S., Kaufmann, M., Riese, M., 2013. Role of gravity waves in the forcing of quasi two-day waves in the mesosphere: an observational study. J. Geophys. Res. Atmos., 118. http://dx.doi.org/10.1029/2012JD018208.

Forbes, J.M., Zhang, X., 1997. The quasi 2-day ionospheric oscillation: a statistical study. J. Atmos. Sol. Terr. Phys. 59, 1025–1034.

Fritts, D.C., Isler, Joseph, R., Lieberman, Ruth, S., Burrage, Mark, D., Marsh, Daniel, R., Nakamura, T., Tsuda, T., Vincent, Robert, A., Reid, Iain M., 1999. Two-day wave structure and mean flow interactions observed by radar and High Resolution Doppler Imager. J. Geophys. Res. 104 (D4), 3953–3969.

Gibbons, J.D., 1985. Nonparametric Statistical Inference 2. M. Dekker, ISBN: 0-8247-4052-1.

Gu, S.-Y., Li, T., Dou, X., Wang, N.-N., Riggin, D., Fritts, D., 2013a. Long-term observations of the quasi two-day wave by Hawaii MF radar. J. Geophys. Res. Space Phys., 118. http://dx.doi.org/10.1002/2013JA018858.

Gu, S.-Y., Li, T., Dou, X., Wu, Q., Mlynczak, M.G., Russell, J.M., 2013b. Observations of Quasi-Two-Day wave by TIMED/SABER and TIMED/TIDI. J. Geophys. Res. Atmos. 118, 1624–1639. http://dx.doi.org/10.1002/jgrd.50191.

Gurubaran, S., Rajaram, R., 1999. Long-term variability in the mesospheric tidal winds observed by MF radar over Tirunelveli (8:7°N, 77:8°E). Geophys. Res. Lett. 26, 1113–1116.

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.

Hines, C.O., Adams, G.W., Brosnahan, J.W., et al., 1993. Multi-instrument observations of mesospheric motions over Arecibo: comparisons and interpretations. J. Atmos. Terr. Phys. 55, 241–287.

Hocking, W.K., Thayaparan, T., 1997. Simultaneous and collocated observations of winds and tides by MF and meteor radars over London, Canada (43_N, 81_W), during 1994–1996. Radio Sci. 2, 833–865.

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

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

Jacobi, C., Schminder, R., Kürschner, D., 1997. The quasi 2-day wave as seen from D1 LF wind measurements over central Europe (52°N, 15°E) at Collm. J. Atmos. Sol. Terr. Phys.. http://dx.doi.org/10.1016/S1364-6826(96)00170-8.

Jacobi, Ch., Arras, C., Kürschner, D., Singer, W., Hoffmann, P., Keuer, D., 2009. Comparison of mesopause region meteor radar winds, medium frequency radar winds and low frequency drifts over Germany. Adv. Space Res. 43, 247–252. http://dx.doi.org/10.1016/j.asr.2008.05.009.

John, S.R., Kumar, K.K., Subrahmanyam, K.V., Manju, G., Wu, Q., 2011. Meteor radar measurements of MLT winds near the equatorial electro jet region over Thumba (8.5°N, 77°E): comparison with TIDI observations. Ann. Geophys. 29, 1209–1214.

Kumar, K.K., Ramkumar, G., Shelbi, S.T., 2009. Reply to comment by R. Dhanya and S. Gurubaran on "Initial results from SKiYMET meteor radar at Thumba (8.5°N, 77°E): 1. Comparison of wind measurements with MF spaced antenna radar system". Radio Sci. 44, RS5005. http://dx.doi.org/10.1029/2008RS004123.

Kumar, K.K., Ramkumar, G., Shelbi, T., 2007. Initial results from SKiYMET meteor radar at Thumba (8.5 N, 77 E): comparison of wind measurements with MF spaced antenna radar system. Radio Sci. 42, RS6008. http://dx.doi.org/10.1029/2006RS003551.

Lilienthal, F., 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.

Lomb, N.R., 1976. Least-squares frequency analysis of unequally spaced data. Astrophys. Space Sci. 39, 447–462.

Manson, A.H., Meek, C.E., Hall, C.M., et al., 2004. Mesopause dynamics from the Scandinavian triangle of radars within the PSMOS-DATAR Project. Ann. Geophys. 22, 367–386.

McCormack, J.P., Coy, L., Singer, W., 2014. Intraseasonal and interannual variability of the quasi 2 day wave in the Northern Hemisphere summer mesosphere. J. Geophys. Res. Atmos., 119. http://dx.doi.org/10.1002/2013JD020199.

Moudden, Y., Forbes, J.M., 2014. Quasi-two-day wave structure, interannual variability, and tidal interactions during the 2002–2011 decade. J. Geophys. Res. Atmos., 119. http://dx.doi.org/10.1002/2013JD020563.

Muller, H.G., 1972. Long-period meteor wind oscillations. Philos. Trans. R. Soc. Lond. Ser. A 271, 585–599. http://dx.doi.org/10.1098/rsta.1972.0026.

Offermann, D., Hoffmann, P., Knieling, P., Koppmann, R., Oberheide, J., Riggin, D.M., Tunbridge, V.M., Steinbrecht, W., 2011. Quasi 2 day waves in the summer mesosphere: triple structure of amplitudes and long-term development. J. Geophys. Res. 116. http://dx.doi.org/10.1029/2010JD015051.

Palo, S.E., Forbes, J.M., Zhang, X., Russell, J.M., Mlynczak, M.G., 2007. An eastward propagating two-day wave: evidence for nonlinear planetary wave and tidal coupling in the mesosphere and lower thermosphere. Geophys. Res. Lett. 34, L07807. http://dx.doi.org/10.1029/2006GL027728.

Pancheva, D.V., et al., 2006. Two-day wave coupling of the low-latitude atmosphere–ionosphere system. J. Geophys. Res. 111, A07313. http://dx.doi.org/10.1029/2005JA011562.

Pancheva, D.V., et al., 2004. Two-day wave coupling of the low-latitude atmosphere–ionosphere system. J. Atmos. Sol. Terr. Phys. 66 (6–9), 539–565.

Pedatella, N.M., Forbes, J.M., 2012. The quasi 2 day wave and spatial-temporal variability of the OH emission and ionosphere. J. Geophys. Res. 117, A01320. http://dx.doi.org/10.1029/2011JA017186.

Plumb, R.A., 1983. Baroclinic instability of the summer mesosphere, a mechanism for the quasi-two-day wave? J. Atmos. Sci. 40, 262–270. http://dx.doi.org/10.1175/1520-0469.

Ratnam, M.V., Kumar, G.K., Murthy, B.V.K., Patra, A.K., Rao, V.V.M.J., Rao, S.V.B., Kumar, K.K., Ramkumar, G., 2008. Long-term variability of the low latitude mesospheric SAO and QBO and their relation with stratospheric QBO. Geophys. Res. Lett. 35, L21809. http://dx.doi.org/10.1029/2008GL035390.

Reddi, C.R., Geetha, A., Lekshmi, K.R., 1988. Quasi 2-day wave in the middle atmosphere over Trivandrum. Ann. Geophys. 6, 231–238.

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

Salby, M.L., Callaghan, P.F., 2008. Interaction of the 2-day wave with solar tides. J. Geophys. Res. 113, D14121. http://dx.doi.org/10.1029/2006JD007892.

Scargle, J.D., 1982. Studies in Quasi 2-day wave in the middle atmosphere over Trivandrumastronomical time series analysis. II. Statistical aspects of spectral analysis of unevenly spaced data. Astrophys. J. 263, 835–853.

Sridharan, S., Tsuda, T., Gurubaran, S., 2010. Long-term tendencies in the mesosphere/lower thermosphere mean winds and tides as observed by medium-frequency radar at Tirunelveli (8.7°N, 77.8°E). J. Geophys. Res. 115, D08109. http://dx.doi.org/10.1029/2008JD011609.

Suresh Babu, V., Kishore Kumar, K., John, S.R., Subrahmanyam, K.V., Ramkumar, G., 2011. Meteor radar observations of short-term variability of quasi 2 day waves and their interaction with tides and planetary waves in the mesosphere–lower thermosphere region over Thumba (8.5°N, 77°E). J. Geophys. Res. 116, D16121. http://dx.doi.org/10.1029/2010JD015390.

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

Tunbridge, V.M., Sandford, D.J., Mitchell, N.J., 2011. Zonal wavenumbers of the summertime 2 day planetary wave observed in the mesosphere by EOS Aura Microwave Limb Sounder. J. Geophys. Res. 116, D11103. http://dx.doi.org/10.1029/2010JD014567.

Venkateswara Rao, N., Tsuda, T., Riggin, D.M., Gurubaran, S., Reid, I.M., Vincent, R.A., 2012. Long-term variability of mean winds in the mesosphere and lower thermosphere at low latitudes. J. Geophys. Res. 117, A10312. http://dx.doi.org/10.1029/2012JA017850.

Vincent, R.A., Lesicar, D., 1991. Dynamics of the equatorial mesosphere: first results with a new generation partial reflection radar. Geophys. Res. Lett. 18, 825–828.

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.

Yue, J., Liu, H.-L., Chang, L.C., 2012. Numerical investigation of the quasi 2 day wave in the mesosphere and lower thermosphere. J. Geophys. Res. 117, D05111. http://dx.doi.org/10.1029/2011JD016574.