Ann. Geophys., 32, 519–531, 2014
www.ann-geophys.net/32/519/2014/
doi:10.5194/angeo-32-519-2014

Annales Geophysicae
Open Access

Planetary wave seasonality from meteor wind measurements at 7.4° S and 22.7° S

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Received: 30 November 2013 – Revised: 24 February 2014 – Accepted: 26 March 2014 – Published: 22 May 2014

Abstract. In this study we have used wind observation data from the mesosphere and lower thermosphere (MLT) region, obtained from meteor radar measurements in São João do Cariri (7.4° S, 36.5° W) from July 2004 to December 2008 and in Cachoeira Paulista (22.7° S, 45.0° W) from January 2002 to July 2006 and from September 2007 to November 2008. From the spectral analysis it was possible to identify the presence of planetary-scale oscillations in the hourly winds for the two latitudes and to study their transient character, which allowed elaboration of a climatology of planetary oscillation signatures. Planetary waves with periods near 2-days, 6–7 days, and 16 days were focussed on in this study. The quasi-2-day waves in the meteoric winds showed a seasonal cycle, with intense amplitudes occurring after the austral summer solstice and extending until the end of the season. The vertical wavelengths of the 2-day wave over Cachoeira Paulista were larger than those at São João do Cariri. A possible modulation of the quasi-2-day wave amplitudes by the quasi-biennial oscillation (QBO) has been observed only at São João do Cariri. The 6–7 day oscillations presented more intense amplitudes during August–November but were present with lower amplitudes during March–April at both sites. The 6–7 day vertical wavelengths over São João do Cariri were larger than at Cachoeira Paulista. The 6–7 day amplitudes exhibited intra-seasonal and annual behavior, however, there was no clear evidence of QBO modulation. The 16-day oscillations showed a seasonal cycle at São João do Cariri, with amplifications from austral spring to mid-summer and weaker amplitudes from autumn until early winter, however, there was no clear seasonality over Cachoeira Paulista. The 16-day vertical wavelengths have assumed values of $\lambda_z \sim 45$–85 km over both sites. 16-day wave amplitudes at the two sites showed different long-term behaviors.

Keywords. Meteorology and atmospheric dynamics (climatology; middle atmosphere dynamics; waves and tides)

1 Introduction

It is known that zonal-averaged circulation of the middle atmosphere is controlled mainly by atmospheric waves. Studies using models (e.g., Pogoreltsev, 1999) emphasize the role of atmospheric waves in the variability of stratosphere and mesosphere dynamics. During the last few decades there have been a significant number of studies addressing planetary waves in the upper mesosphere and lower thermosphere (MLT) region using measurements from the ground and onboard satellite systems (e.g., Thayaparan et al., 1997; Manson et al., 2005; Lima et al., 2006; Day et al., 2011).

It is believed that many of the planetary waves observed in the MLT region does not originate locally, but propagate vertically from their sources in the lower altitudes to the upper atmosphere. We should remember that these same waves are also observed in the troposphere and stratosphere. However, results of theoretical and numerical studies have indicated that the planetary-wave ascending propagation from lower altitudes to the mesosphere is only possible under certain atmospheric conditions (Charney and Drazin, 1961; Salby, 1981a, b; Forbes et al., 1995).

Usually, planetary waves are observed with periods of about 2, 5–7, 8–10, and 12–22 days. These periods are also consistent with the Hough modes (3, 0), (1, 1), (1, 2) and

(1, 3) respectively, suggesting that the periods of 2, 5, 8.3 and 12.5 days for these modes are modified by Doppler shifting due to the basic flow (Forbes, 1995).

The quasi-two-day wave (QTDW) is a remarkable feature of the MLT region during the solstice months. Generally, it is observed that the meridional wind amplitudes are twice the zonal wind component and are more intense in the Southern Hemisphere. During the boreal summer, QTDW periods between 44 and 56 h have been found (Clark, 1994; Meek et al., 1996), whilst periods close to 48 h have been observed for the austral summer (Craig and Elford, 1981). Observations from low latitudes also have revealed the presence of QTDW during both the austral and boreal summer as well as during other times of the year (Harris and Vincent, 1993; Lima et al., 2004). Recently, Huang et al. (2013) reported the global climatology of QTDW from temperatures obtained by Sounding of the Atmosphere using Broadband Emission Radiometry from the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (SABER/TIMED) observations.

The westward (1, -2) symmetric mode planetary wave with a period of nearly five days is already known to propagate in the troposphere and stratosphere. In accordance with the first studies, the 5-day wave on troposphere showed an external Rossby wave character with little vertical phase inclination (Madden and Julian, 1972), so it can not transport much heat or momentum (Riggin et al., 2006). However, the global structure of the 5-day wave identified in the middle atmosphere, from Upper Atmosphere Research Satellite (UARS) observations, showed transient wave activity with a significant vertical phase slope (Wu et al., 1994), in which the observed periods with more than six days were attributed to a Doppler-shifted 5-day normal mode, due to the prevailing winds. On the other hand, their presence in the MLT region has been connected with mesospheric instabilities (Meyer and Forbes, 1997; Lieberman et al., 2003). The 6–7 day oscillation is amplified before and during the spring and autumn seasons in equatorial latitudes (Kishore et al., 2004; Lima et al., 2005). From simulations, Liu et al. (2004) have demonstrated that the seasonal variability of the 6.5 day wave is dependent upon the variability of the waveguide, baroclinic/barotropic instability, and the critical layer of the wave, which in turn are defined by wind. Pancheva et al. (2010) have presented the global distribution and climatology of the 5–6 day waves from SABER/TIMED temperatures.

The atmospheric oscillations with periods between 12 and 20 days are generally referred to as 16-day waves. In accordance with their horizontal structure from Laplace's tidal equations, the westward traveling 16-day wave has been identified as a manifestation of the second symmetric (1, -4) Hough mode. Several studies concerning 16-day waves at mid- and low-latitudes in the MLT region have revealed a seasonal behavior with the largest amplitudes during wintertime and smaller amplitudes in summer (e.g., Mitchell et al., 1999; Luo et al., 2002). From five years of meteor radar winds at Cachoeira Paulista (hereafter C. Paulista) (22.7° S), Lima et al. (2006) did not observe a clear seasonality for 16-day waves: the strongest activity occurred during austral autumn–winter for some years and in austral spring–summer for others.

In the present study, we investigate the quasi- 2-day, 6.5-day and 16-day planetary waves in MLT region at equatorial and low latitudes of the Southern Hemisphere. Thus, further insights are supplied for better understanding planetary wave seasonality and the mean zonal circulation in the MLT region.

2 Radar systems and data series

This study is based on hourly mean wind measurements collected over São João do Cariri (7.4° S, 36.5° W), (hereafter Cariri), and Cachoeira Paulista (22.7° S, 45,0° W), Brazil. The wind data were obtained by similar All-Sky Interferometric Meteor Radars (SKiYMET). Each system employs a 12 kW peak-power transmitter operating at 35.24 MHz, transmitting 2144 pulses s^{-1} with a three-element Yagi transmitting antenna, and using 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 estimated in seven height intervals of 4 km thickness, separated by 3 km, centered at 81, 84, 87, 90, 93, 96 and 99 km. The data series at C. Paulista include the time interval from December 2001 to July 2006 and from September 2007 to October 2008. At Cariri, the data were obtained from August 2004 to January 2009.

Because the atmospheric tides, primarily the diurnal tides (Batista et al., 2004; Lima et al., 2007), are one of the remarkable features of the MLT winds over C. Paulista and Cariri, the data series were subjected to a low-pass filter in order to remove the variances associated with high frequencies. For this, a low-pass filter with a cutoff period of 1.5 days was used.

In order to separate waves from wind measurements, obtained over C. Paulista (from December 2001 to July 2006 and from September 2007 to October 2008) and over Cariri (from August 2004 to January 2009), the data series were subjected to band-pass filters with cutoff periods appropriate to the study.

In order to investigate the characteristics and vertical structures of the planetary waves, the amplitude and phase were determined by harmonic analysis, using sliding windows stepped by 1 day.

3 Results and discussions

3.1 Spectral analysis

To reveal the dominant periodicities of the oscillations present in the zonal and the meridional wind components, a wavelet spectral analysis was applied for all data winds obtained at the altitude of 90 km over Cariri and C. Paulista. For each year of data a wavelet was computed, considering additional data at the beginning and end of the data series to avoid edge effects, when possible. The spectra obtained were used to form the annual averaged Morlet wavelet transform spectrum. To illustrate our results, Fig. 1 displays the annual averaged Morlet wavelet transform spectrum for both wind components. The Cariri annual averaged spectrum was performed using the 4.4 years wind series database (August 2004–January 2009) and the C. Paulista annual average spectrum was performed using 5.3 years wind data (December 2001–July 2006 and September 2007–November 2008).

From the wavelet power spectra plots, it is possible to see that zonal wind exhibited peaks related with QTDW, mainly during January–February, at both sites. There are peaks near 6–7 days in the zonal wind wavelets during April–May, from late August to mid-October and a strong peak around November, 16 days at both sites. Here it should be noted that the 6–7 day activities at Cariri were stronger than at C. Paulista. The zonal wavelet spectra exhibit energy for periods around 16 days at both sites during May–August. The presence of peaks in periods near 16 days also can be seen during March–April in the zonal winds over C. Paulista, and during January–February and September–December at Cariri. The zonal spectra still show energy in the range of 3–5 days during early March and mid-November at both sites, and weak events from June to August at Cariri. The presence of the power spectra in the 3–5 day period range only in the zonal wind component can to be associated to the ultra fast Kelvin wave (UFKW), mainly in the equatorial region.

The wavelet power spectra for meridional wind component are characterized by the presence of strong energy for a period of nearly 2 days at both sites, mainly during January–February, however, activities with weak energy also can be seen throughout the year. Note that 2-day activities in the meridional wind component are longer lasting at Cariri than C. Paulista.

The presence of these periodic peaks in the spectra of the horizontal winds is well known and has been investigated over time. However, some planetary wave characteristics, obtained from meteor radar measurements, may provide new insights to improve the understanding of the MLT region dynamics in the Southern Hemisphere. Thus, we will focus our attention on the seasonality of the 2, 6–7 and 16 day oscillations.

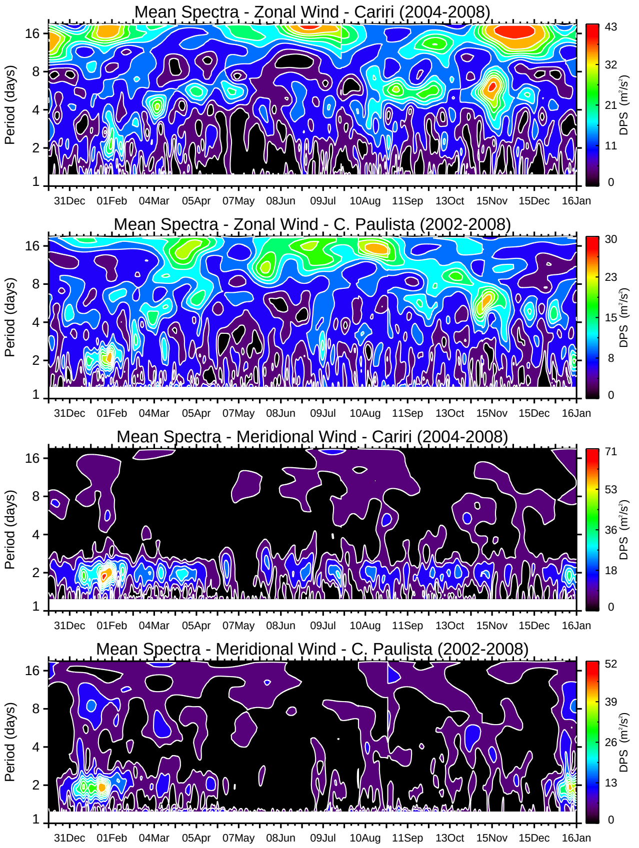

Figure 1. Annual averaged Morlet wavelet transform spectrum for zonal and meridional winds at 90 km over Cariri for the years 2004 to 2008 and C. Paulista for the years 2002 to 2008.

3.2 Quasi-two-day wave amplitudes

To investigate QTDW time evolution, the horizontal winds at the two sites were subjected to a band-pass filter with cutoff periods of 1.5 and 2.5 days, centered on 2 days, since QTDW period changes particularly from 1.6 to 2.5 days (from 40 to 60 h) and is close to 2 days in the Southern Hemisphere (e.g., Craig and Elford, 1981; Lima et al., 2004).

Figure 2 shows the zonal- and meridional- filtered winds over Cariri (blue doted line) and C. Paulista (solid black line), at 90 km. The filtered winds are characterized by amplification bursts concentrated in the January and February months for all years, in both components at the two sites. Amplifications can also be observed during other times of the year, such as March and April and in the second half of the year, and are more evident in Cariri winds.

To investigate variability of the QTDW vertical structures over the two sites, the amplitude and phase from the seven height gates data series were estimated in a least-mean-square sense by harmonic analysis technique. The analysis was carried out for 6-day sliding window stepped by 1 day.

The time-height cross section of the amplitudes for each year and mean composite-year QTDW amplitudes observed

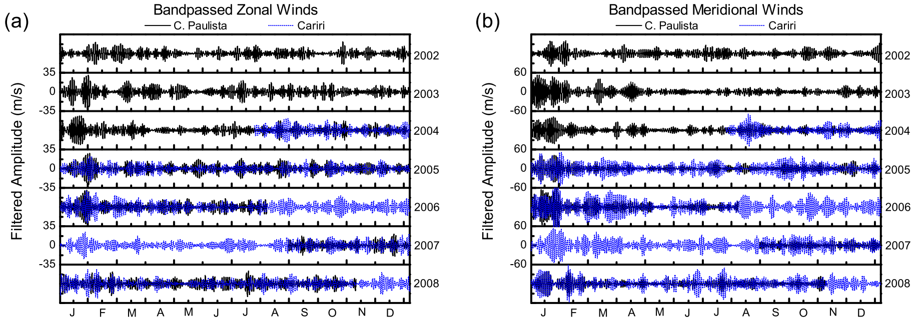

Figure 2. Band-passed hourly **(a)** zonal and **(b)** meridional winds over Cariri (blue doted line), for the years 2004 to 2008, and over C. Paulista (solid black line), for the years 2002 to 2008, at 90 km. The passband limit was 1.5 to 2.5 days, centered on 2 days.

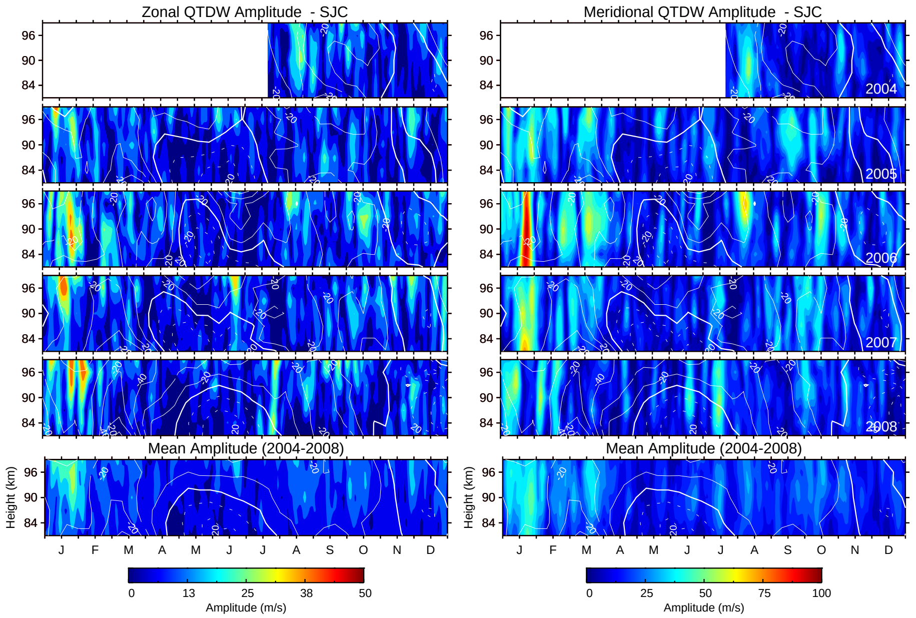

Figure 3. The time-height cross section of the QTDW amplitudes and composite-year QTDW amplitudes over Cariri for zonal (left hand plots) and meridional (right hand plots) components, for the years 2004 to 2008. Monthly mean eastward (dotted) and westward (solid) winds also are plotted as open white contours.

over Cariri and C. Paulista, for zonal (left hand plots) and meridional (right hand plots) components, are presented in Fig. 3 and in Fig. 4 as filled contours, respectively. Additionally, the prevailing zonal winds also are represented, in which the eastward (westward) is indicated by dotted (solid) open white contours. Comparing the prevailing zonal winds observed over Cariri with those observed in C. Paulista it appears that the behaviors are distinct. In general, the prevailing zonal winds over Cariri are negative (westward) throughout most of the year with positive values (eastward) in early summer for all altitudes and from April to July at heights below 96 km. The prevailing zonal winds at C. Paulista are eastward for most of the year except between January and March at heights below 90 km, from April to early August above 90 km and from August to October for the whole range of heights.

From these figures it is possible to see that, in general, the temporal behavior of the QTDW activity confirm those already mentioned from annual averaged spectrum, as illustrated in Fig. 1. As expected, the meridional amplitudes for QTDW are larger than its zonal amplitudes and their strongest amplitudes are registered after austral solstice summer for both sites. During this time the amplitude in the zonal wind component reach maximum values up to 50 m s^{-1} (in 2006 and 2007 over Cariri and in 2006 over C. Paulista), for heights above 90 km at both sites. The meridional amplitudes are strongest for heights below 94 km over Cariri, reaching maximum values up to 100 m s^{-1}, in 2006, whereas for C. Paulista the maximum values of about 75 m s^{-1} were reached in the layer centered on 90 km, in 2003 and 2006. It should also be noted that meridional amplifications for periods near 2-day are allocated in January–February at

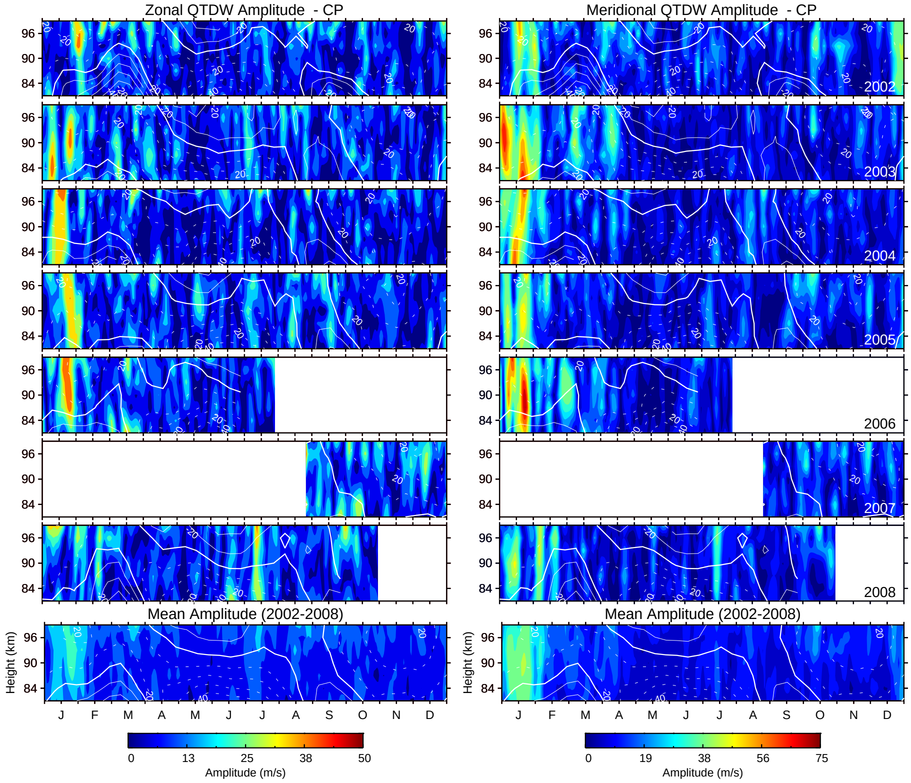

Figure 4. The time-height cross section of the QTDW amplitudes and composite-year QTDW amplitudes over C. Paulista for zonal (left hand plots) and meridional (right hand plots) components, for the years 2002 to 2008. Monthly mean eastward (dotted) and westward (solid) winds also are plotted as open white contours.

C. Paulista, whereas over Cariri the amplifications remain until the beginning of April.

The presence of the amplifications for periods near 2-day can also be seen during austral winter and spring seasons for zonal and meridional components over both sites. The zonal QTDW amplitudes are more intense for heights above 90 km with presence in the time interval from mid-June to December at Cariri and from July to October at C. Paulista. The meridional component also exhibits amplifications for periods near 2 days during austral winter and spring seasons, in which the amplitudes are more intense above 90 km at both sites, however, the mean amplitudes over C. Paulista are weaker than at Cariri.

Additional information can be obtained from the QTDW phase vertical structure. Thus, the phase lag obtained by harmonic analysis were used to estimate the QTDW vertical wavelength and its vertical propagation direction. The QTDW phase vertical structure (not shown here) in the meridional winds are descending, which implies a upward propagation of energy in all events analyzed at both sites. In general, the meridional QTDW vertical wavelengths over C. Paulista were larger than those at Cariri. During the strongest events (January–February) the estimated vertical wavelengths (λ_z) were about 65 and 40 km over C. Paulista and Cariri, respectively. Values of $\lambda_z \sim 40$ km were obtained from meridional winds over C. Paulista during equinoxes, whilst over Cariri values of $\lambda_z \sim 30$ km were found. In winter time, C. Paulista presents $\lambda_z \sim 45$ km and Cariri $\lambda_z \sim 35$ km. The vertical wavelengths from zonal winds were also estimated, however they will not be discussed here due to poor reliability, since the phases are difficult to resolve for lower amplitudes.

As seen above, the QTDW amplitudes presents interannual variability during the time in which they are more intense, namely in January–February, wherein the amplitudes are more intense in 2006 at Cariri and in 2003 and 2006 at C. Paulista, just when very large sudden stratospheric warming (SSW) events were registered. Inter-annual variability also can be seen during the July–October time interval, mainly for meridional component at Cariri. The influence of the SSW on MLT tropical dynamics have been investigated by McCormack et al. (2009) and Lima et al. (2012). They have suggested that the strongest westward lower-mesospheric jet observed during summer 2006 contributed to an QTDW rapid amplification by nonlinear interaction mechanisms. It is notable from the Fig. 3, that during January–February 2006 the MLT zonal prevailing wind reversal over Cariri occurred later than in the other summers, suggesting that the MLT zonal wind dynamics had been impacted by interhemispheric penetration of energy from the winter hemisphere during this strong SSW event (Lima et al., 2012). However, the prevailing zonal wind over C. Paulista appears not to have been affected during 2003 and 2006 SSW events.

From the results it is also clear that the QTDW presents a seasonal cycle in the meteor winds, with the strongest amplitudes occurring after the solstice to late austral summer for the zonal component and after the solstice to early austral autumn for meridional component at two sites. Episodes of weaker amplifications are observed during the second half of the year. The minima activity were observed in April–June and in November–December, at both sites.

The QTDW seasonal behavior at low latitudes, with intensification in the summer, has been observed in both hemispheres (Lima et al., 2004; Pancheva, 2006). However, in the equatorial region, QTDW amplifications have also been observed during summer and winter (Harris and Vincent, 1993; Palo and Avery, 1996; Gurubaran et al., 2001).

To explain the seasonal QTDW amplification, Salby and Callaghan (2001) performed numerical studies to investigate the relationship between the normal and unstable modes. According to their results, the intensification of the QTDW during solstice months is due to energy transference from the mean flow to the wave, which occurs at the unstable region and then disperses globally into the Rossby-gravity modal structure. Rojas and Norton (2007) proposed that seasonal amplification of the QTDW arises from the interaction of the global-scale Rossby-gravity mode with a local mode, which is locally excited by instabilities associated with the reversed potential vorticity gradients caused by the summer westward jet in the upper stratosphere and lower mesosphere.

The QTDW vertical wavelength estimated from meridional winds over C. Paulista were longer than those over Cariri. It is known that background winds play an important role in the propagation regime of atmospheric waves, and thus may affect wave parameters. When the QTDW are strongest (January–February) the MLT zonal prevailing winds are westward over Cariri, and are eastward above 86 km over C. Paulista, indicating a shorter λ_z for QTDW propagation in the westward wind. This result is in agreement with those found by Huang et al. (2013) from SABER/TIMED temperatures for solstices in the Southern Hemisphere.

To verify the presence of fluctuations in the QTDW amplitudes, the technique of Lomb–Scargle periodogram was applied to each time series of the amplitudes. The analyses were performed considering the entire series, namely, 4.4 years for Cariri and 5.3 years for C. Paulista. Figure 5 presents the Lomb–Scargle periodograms obtained from amplitudes of the QTDW for the zonal (dotted line) and meridional (solid line) winds obtained over Cariri and C. Paulista for altitudes between 84 and 96 km.

The periodograms for QTDW amplitudes at Cariri are characterized by the presence of power that can be associated with annual and semiannual oscillations in both wind components, thus confirming the annual and semiannual character of the QTDW. The zonal QTDW amplitudes also show energy for a period around 600 days, mainly at 90 and 93 km, while for meridional component weaker energy can be seen for periods longer than 630 days. The periodogram obtained from QTDW amplitudes in the zonal wind component at C. Paulista shows a peak for annual (weak) and semiannual oscillations. For the QTDW amplitudes in the meridional component, the periodogram shows clearly peaks associated with intra-seasonal (90 and 120 days), semiannual and annual oscillations, besides weak energy for period around 560 days.

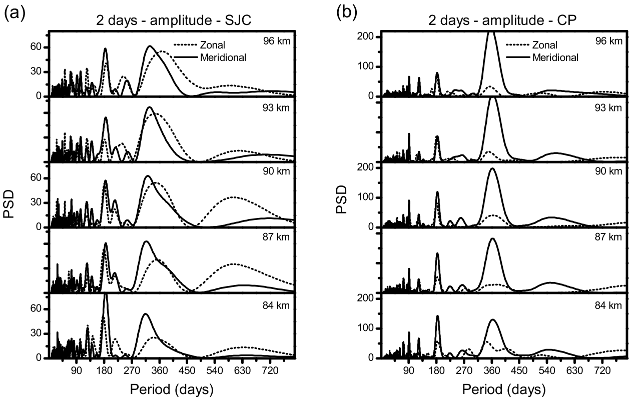

Figure 5. Lomb–Scargle periodograms obtained from amplitudes of the QTDW for the zonal (dotted line) and meridional (solid line) winds obtained over **(a)** Cariri and **(b)** C. Paulista for altitudes between 84 km and 96 km.

The energy for the period larger than 500 days is indicative of a possible modulation of the QTDW amplitudes by the quasi-biennial oscillation (QBO). This fact is probably due to QTDW modulation during the boreal summer (July–August), in which the presence in the winter hemisphere is interpreted as due to interhemispheric leakage. As a consequence, the QTDW would only achieve the latitudes of Cariri and C. Paulista, during boreal summer, in the years when their amplitudes were more intense. By analyzing the temporal behavior of the QTDW amplitudes at Cariri throughout the years (Fig. 3), it is possible to observe that for the July–August months the QTDW amplitudes are more intense for the years when the QBO phases were eastward at 30 hPa. However, such behavior is not evident in the QTDW amplitudes over C. Paulista (Fig. 4). These results are in accordance with those of Sridharan et al. (2003), which found that the variances associated with QTDW during July months were lower during the QBO westward phase (at 30 hPa) and was interpreted that low QTDW activity may be associated with temporal change of QTDW excitation mechanism. Huang et al. (2013) also found that the QTDW show QBO variations, notably in mid-high latitudes.

Studies have suggested that besides the interannual variability, the MLT region also can to be affected by long-term scale variability including the solar cycle influence. A positive correlation between solar effects and MLT QTDW activity has been found by Jacobi (1998). As the data series used in the present study do not cover a long time interval, the solar cycle effect on planetary waves will not be examined.

3.3 6–7 day oscillation amplitudes

As revealed from spectral analysis (Fig. 1), signatures of 6–7 day oscillations are more evident in the zonal wind at both sites, so particular focus shall be given the presence these oscillations only in zonal component. A 4.5–8.5-day band-pass filter centered on 6.5 days has been applied to the data series to isolate the oscillations from zonal winds; the filtered winds for altitude of 90 km are illustrated in Fig. 6. Taking into account the band-passed winds, the 6–7 day oscillations exhibit inter-annual variability displaying larger perturbations from February to early May and from July to early December of each year at both sites. During the time in which there are quasi-simultaneous measurements, larger oscillations at C. Paulista generally correspond to those at Cariri. However, the opposite does not occur. For example, during November, 2004 and from mid-August to September, 2005, larger perturbations are clearly observed in the winds over Cariri, but not over C. Paulista.

To estimate the amplitude and phase values for 6.5-day oscillations a 21-day sliding window stepped by 1 day was used. Figure 7 shows the time-height cross section of the 6.5-day amplitudes for each year and its respective mean composite-year at Cariri (left hand plots) and C. Paulista (right hand plots), for zonal component (as in Fig. 3). Again, the prevailing zonal winds are also represented. It is clearly evident from these plots that 6.5-day exhibits isolated or multiple bursts of amplifications spreading mainly from July to November as well as inter-annual variability, in which the strongest activities were registered from late October to mid-November, around 96 km altitude with maximum values of 28 m s^{-1} over Cariri and around 90 km (22 m s^{-1}) over C. Paulista in the year 2005, and around 87 km in 2006 at Cariri. Moderate amplifications observed in the first half of the year seems to be more frequent in C. Paulista.

The vertical phase structures are compatible with upward energy propagation, however, a few sporadic events showed ascending phase progression. Unlike the QTDW, the 6.5-day oscillation vertical wavelength estimated from the phase lags obtained at Cariri were larger than those over C. Paulista. Mean values of $\lambda_z \sim 90$ km and $\lambda_z \sim 60$–65 km were estimated in March–April, whereas $\lambda_z \sim 75$–90 km and $\lambda_z \sim 60$ km were registered in October–November at Cariri and C. Paulista, respectively.

The behavior of the 6–7 day oscillation at both sites suggests that this oscillation presents a seasonal cycle with more intense amplifications during August–November and moderated intensities during March–April, which are more frequent at C. Paulista. The seasonal behavior for 6–7 day oscillations with amplifications during the autumn and spring months has been observed from radar measurements (Kishore et al., 2004; Lima et al., 2005; Jiang et al., 2008) as well as from simultaneous measurements by radar and satellite (Lieberman et al., 2003; Riggin et al., 2006). Using SABER/TIMED temperatures, Pancheva et al. (2010) found that 5.5-day Rossby wave amplitudes maximize in March–April and October–November at 40° S in which the late spring amplitudes are stronger than ones during autumn, except in 2003 when an opposite behavior was observed. This peculiarity has not been evidenced in the MLT zonal wind oscillations at C. Paulista during the same time period.

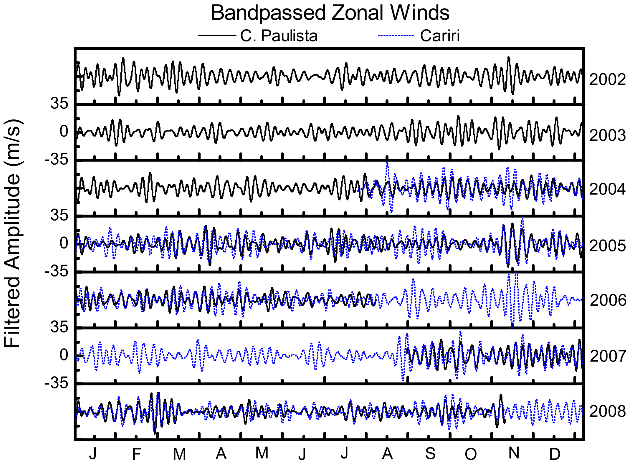

Figure 6. Band-passed hourly zonal winds over Cariri (blue dotted line), for the years 2004 to 2008, and over C. Paulista (solid black line), for the years 2002 to 2008, at 90 km. The passband limit used was 4.5 to 8.5 days, centered on 6.5 days.

Using numerical simulations, Liu et al. (2004) have shown that 6–7 day wave seasonality depends of the waveguide variability, of the barotropic/baroclinic instability conditions, and of the wave critical level. In turn, all these factors are determined by the wind. The simulation results showed that before and after the equinoxes, the condition of the wind favors the propagation and amplification of the 6–7 day wave. However, the MLT zonal background winds are predominantly westward over Cariri and eastward over C. Paulista during the time of the strongest 6.5-day oscillation activities, suggesting that the wave propagation is not affected by background winds in the MLT region.

In their studies, Pancheva et al. (2010) have identified Kelvin 6-day waves in the SABER/TIMED temperatures, with amplification at altitudes near 40–45 km, 75–85 km and 100–105 km, during both equinoxes and June solstice, whose vertical wavelength of 25 km was determined. The presence of 6–7-day oscillations only in the zonal wind in the equatorial region also could be due to eastward fast Kelvin waves. But, the vertical wavelength estimated for 6.5-day oscillation

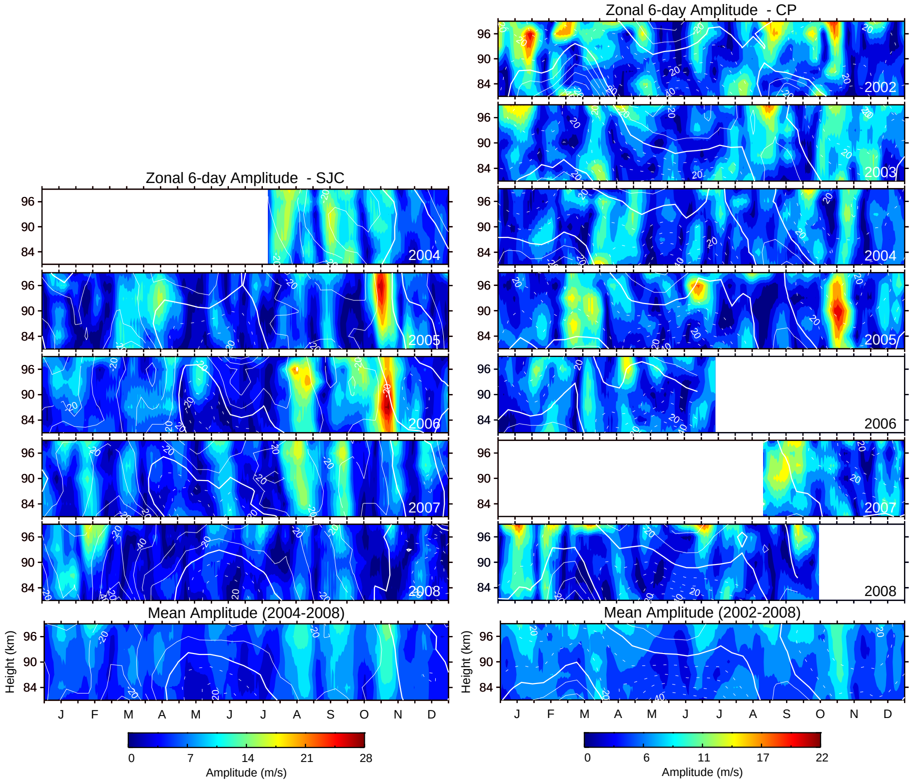

Figure 7. The time-height cross section of the 6–7 day oscillation amplitudes and composite-year 6–7 day amplitudes at Cariri (left hand plots) and over C. Paulista (right hand plots) for zonal component, for the years 2004 to 2008 and 2002 to 2008, respectively. Monthly mean eastward (dotted) and westward (solid) winds also are plotted as open white contours.

from MLT zonal winds over Cariri and C. Paulista are largest than those expected for fast Kelvin waves (20 km) and, therefore, in the present analysis it was not possible to capture 6-day perturbation compatible with the equatorial Kelvin wave. The vertical wavelength of 60 km have been reported for 6.5-day waves from equatorial winds (Kovalam et al., 1999) and of 50–60 km from SABER/TIMED temperatures (Pancheva et al., 2010).

Figure 8 shows the Lomb–Scargle periodogram for 6.5-day oscillation zonal amplitudes obtained at Cariri and C. Paulista for altitudes between 84 km and 96 km. The Cariri periodograms are characterized by the presence of peaks associated with the intra-seasonal, semiannual and annual oscillations for all heights, besides peaks around 570 days, mainly at altitudes above 87 km. The periodogram obtained from 6.5-day oscillation amplitudes over C. Paulista exhibits peaks for intra-seasonal, as well as in semiannual periods for altitudes above 84 km, and in annual oscillation for 87 and 90 km heights. The C. Paulista periodogram also displays peaks for periods near 300 days above 87 km, 500 days for 84–93 km altitude range and near 650–720 days above 84 km heights.

By inspecting the behavior of the 6.5-day amplitudes for all years (Fig. 7) it is found that the oscillation manifestations indicate that largest amplitudes at Cariri occur in multiple bursts during the second half of the years, suggesting the intra-seasonal and annual nature this oscillation. The behavior of the 6.5-day amplitudes at C. Paulista exhibits multiple bursts distributed over the years, which also reveal variability in its vertical structure, supporting the periodogram results. The possible QBO effect on 6.5 day waves observed in the wind measurements in both hemispheres have been reported in which the wave showed higher intensity for years when the QBO is weaker, therefore, when QBO phase is westward (Sridharan et al., 2003; Kishore et al., 2004). Pancheva et al. (2010) also have found quasi-5-day Rossby wave modulation due to QBO in which the amplitudes from SABER/TIMED temperature are larger during QBO westward phase. Lima et al. (2005) have reported that 6.5-day oscillation strongest activities at C. Paulista were observed in spring 2000 and 2002, only for westward QBO phase years. However, this feature was not repeated in subsequent years as demonstrated in the present study.

3.4 16-day oscillation amplitudes

The annual behavior of the 16-day oscillations at 90 km are represented in Fig. 9 by the filtered zonal winds, in which a 12–20-day band-pass filter centered on 16 days has

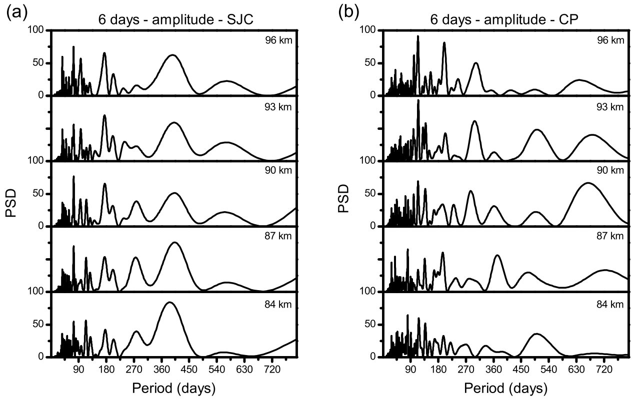

Figure 8. Lomb–Scargle periodograms obtained from amplitudes of the 6.5-day oscillations for the zonal winds obtained over **(a)** Cariri and **(b)** C. Paulista for altitudes between 84 km and 96 km.

been applied to the data series. Analyzing the plots we observe that 16-day oscillations have different behaviors for the two sites. At Cariri the 16-day oscillations are more intense during January–February, June–August and October–December, with inter-annual variability. The 16-day oscillations at C. Paulista are mainly present from May to July presenting amplifications with clear inter-annual variability.

Harmonic analysis has been again performed to estimate the 16-day oscillation amplitudes and phases, using a 48-day window stepped by 1 day. The time-height cross section for 16-day oscillation amplitudes in each year and the mean composite-year over Cariri (left hand plots) and C. Paulista (right hand plots), for zonal component are illustrated in Fig. 10 together with the prevailing zonal winds. The 16-day amplitudes at Cariri are more common from late December to January and from October to November, when it reached a maximum value up to 20 m s^{-1} in 2008 around 96 km height. Bursts are also observed spreading between April and September. The presence of 16-day oscillations over C. Paulista were more frequent from January to July, mainly for the years 2002–2005, clearly presenting inter-annual variability with maximum amplitudes smaller than 20 m s^{-1} in 2005 around 87 km height. It should be noted that in general, large 16-day amplitude at C. Paulista occurs on MLT eastward zonal prevailing wind. However, this feature is not observed for 16-day amplitudes at Cariri.

In general, the vertical phase structures of the 16-day oscillations showed upward energy propagation for both sites, except the events registered during October 2005 and from mid-January to February 2008 at Cariri, and in July 2005 at C. Paulista, which presented ascending progression. The vertical wavelength estimated for 16-day oscillations assumed the following mean values $\lambda_z \sim 45$ km (January–February), $\lambda_z \sim 55$ km (April–June), $\lambda_z \sim 80$ km (August–September), and $\lambda_z \sim 50$ km (October–December) at Cariri, whilst at C. Paulista values $\lambda_z \sim 45$–55 km (January–June), and $\lambda_z \sim$ 55–85 km (October–December) were registered.

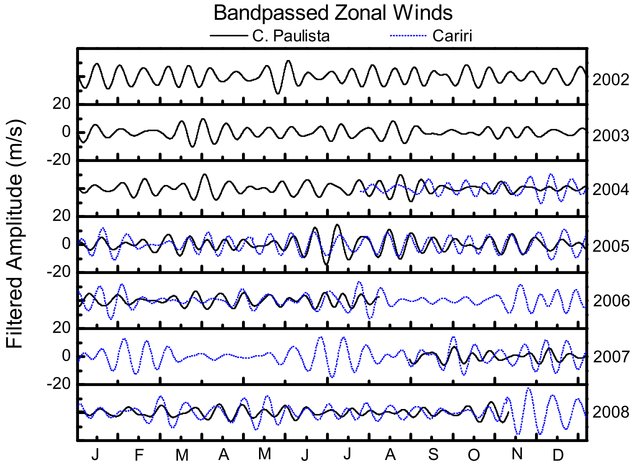

Figure 9. Band-passed hourly zonal winds over Cariri (blue dotted line), for the years 2004 to 2008, and over C. Paulista (solid black line), for the years 2002 to 2008, at 90 km. The passband limits used was 8 to 24 days, centered on 16 days.

From the results, we can observe that at Cariri the 16-day oscillations showed a seasonal cycle with amplitudes more intense from spring to mid-summer and weaker amplitudes from autumn to early winter. The 16-day oscillations over C. Paulista do not show a clear seasonality, but it is possible to see amplifications during winter for all heights and during summer for heights above 94 km.

Studies using measurements obtained by radars in the Northern Hemisphere, reported that the largest amplitudes of the 16-day waves were observed during the boreal winter months. Wave activity was also observed during the summer months (Mitchell et al., 1999; Luo et al., 2002). Using wind measurements obtained in Wuhan (31° N) by meteor radar and in Adelaide (35° S) using MF (Medium Frequency) radar, Jiang et al. (2005) observed that the 16-day waves showed a seasonal cycle in which the maximum amplitude occurred between September and October in the Northern Hemisphere and between July and October in the Southern Hemisphere. As in the present study, Lima et al. (2006) found no clear seasonality in the behavior of the 16-day waves at C. Paulista.

Studies about 16-day waves seasonality in the Northern Hemisphere have revealed that the most intense activity, taking place during the winter months (January to March), is due to vertical wave propagation from lower atmosphere to MLT region (Forbes et al., 1995; Luo et al., 2002). From numerical simulations, the presence of the 16-day wave during the summer months has been attributed to interhemispheric leakage from the winter hemisphere to summer hemisphere (Forbes et al., 1995; Miyoshi, 1999).

From the vertical phase structures it was possible to observe sporadic events with phase progression ascendant, indicating a downward 16-day propagation with a possible source in the upper atmosphere, whose excitation forcing

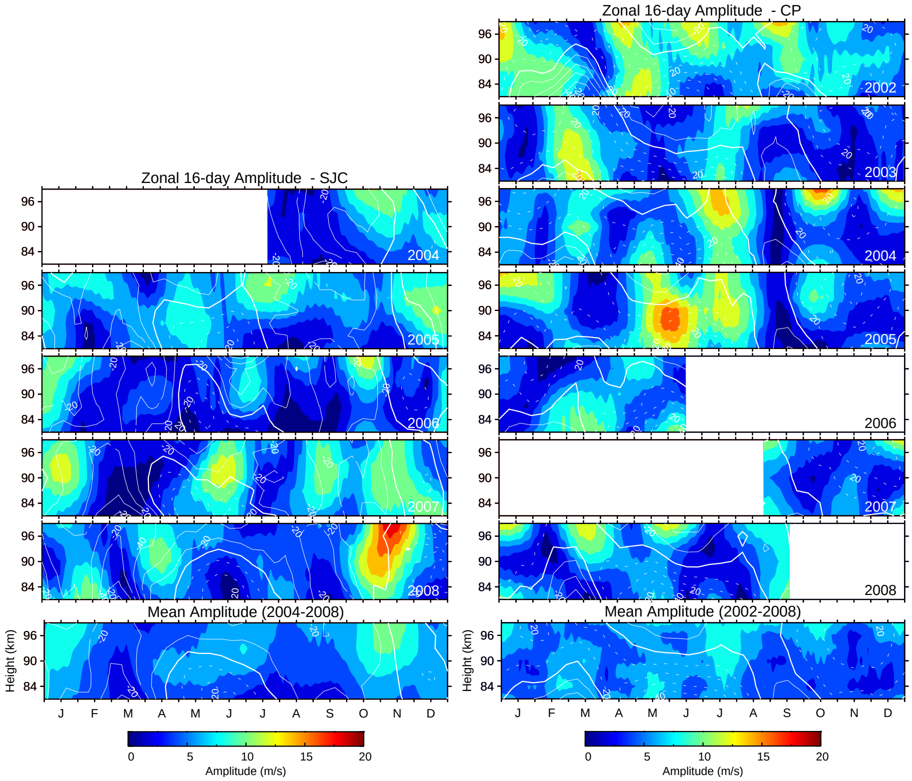

Figure 10. The time-height cross section of the 16 day oscillation amplitudes and composite-year 16 day amplitudes at Cariri (left hand plots) and over C. Paulista (right hand plots) for zonal component, for the years 2004 to 2008 and 2002 to 2008, respectively. Monthly mean eastward (dotted) and westward (solid) winds also are plotted as open white contours.

may have been caused by some instability process in situ. The downward propagating events also can to be attributed to modulation by periodic geomagnetic or solar activity. It is known that atmosphere responds to short-term solar-origin oscillation with periods of ∼27 days as well as of ∼13.5 days. Luo et al. (2001) have found a close relationship between the climatology of the 20–40 day oscillation and 16-day wave, however, other features differ. These oscillations are not considered in this study.

The vertical wavelength obtained for 16-day oscillations from the downward phase progression for the two sites are in accordance with those estimated by Luo et al. (2000), Luo et al. (2002) and Lima et al. (2006). In their study, Namboothiri et al. (2002) have indicated that the vertical wavelength for 16-day waves registered during winter seems to be larger than in summer months. The present investigation does not show such a feature.

The Lomb–Scargle periodograms of the 16-day oscillation amplitudes for the zonal winds obtained over Cariri and C. Paulista for altitudes between 84 km and 96 km are shown in Fig. 11. In this figure, it is possible to see that the 16-day wave amplitudes at Cariri showed semiannual seasonality, with secondary peaks around 180 days. Clearly the 16-day wave amplitudes showed annual modulation for all heights, with a lower peak at 90 km height. The periodograms for C. Paulista is characterized by the presence of peaks for intra-seasonal periods besides annual modulation, which is mainly observed in altitudes below 93 km.

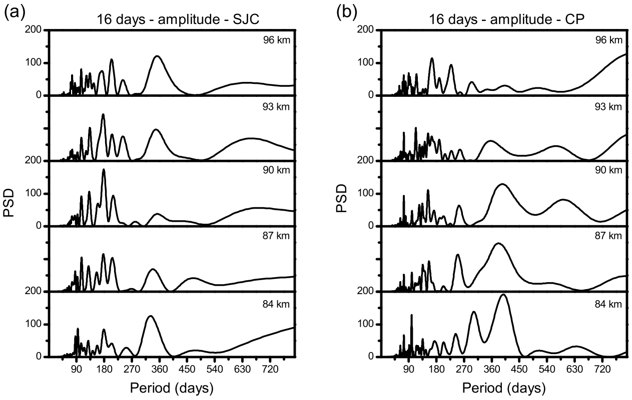

Figure 11. Lomb–Scargle periodograms obtained from amplitudes of the 16-day oscillations for the zonal winds obtained over **(a)** Cariri and **(b)** C. Paulista, for altitudes between 84 km and 96 km.

In accordance with Luo et al. (2002), the seasonal and interannual variability observed from simulation, is partly attributed to QBO. However, Mitchell et al. (1999), using meteor wind measurements obtained in Sheffield in the UK

(53.5° N, 3.9° W), found no evidence of QBO modulation on 16-day oscillations.

As noted, the 16-day wave amplitudes showed different long-term behaviors at Cariri and C. Paulista. Theoretical studies (Forbes et al., 1995; Miyoshi, 1999) and observational (Espy et al., 1997; Luo et al., 2000) showed that the 16-day wave propagation is sensitive to the prevailing wind. Luo et al. (2000) found that 16-day wave at 52° N usually appears during the westward QBO phase. However, Sridharan et al. (2003) recorded the highest 16-day wave amplitudes at 8.7° N during the eastward QBO phase (at 30 hPa).

4 Summary

The hourly winds obtained from meteor radar measurements over Cariri and C. Paulista, Brazil, were used to investigate the dynamics of the MLT region at 7.4° S and 22.7° S. Besides studying the transient character of the planetary waves with periods of 2, 6–7 and 16 days, we have identified the seasonal variations of these oscillation signatures on two sites.

The temporal behavior of the vertical structure of the amplitudes of the oscillations made it possible to develop a climatology of the events with seasonality emphasis. As expected, The QTDW showed a seasonal cycle, with intense amplitudes after the austral summer solstice, and weaker amplitudes after the austral winter solstice, for both sites. The QTDW vertical wavelengths obtained over C. Paulista were longer than those for Cariri. Such behavior has been attributed to differences in wind regimes, in which the shorter vertical wavelength are observed occur on zonal westward winds. A modulation of the QTDW amplitudes by the QBO was observed at Cariri, what is probably due to QTDW modulation during the boreal summer as a result of interhemispheric leakage, that did not reach C. Paulista.

The 6–7 day amplitudes were more intense during August-November, but were less intensity in March-April at both sites. Contrary to QTDW, the vertical wavelengths for 6–7 day wave at Cariri were larger than C. Paulista. The amplitudes of the 6–7 day wave showed intra-seasonal and annual behavior, whereas QBO modulation has not been clearly observed.

The 16-day oscillations showed no clear seasonality in the C. Paulista winds, however, over Cariri these oscillations were more intense from spring until mid-summer and weaker amplitudes were observed from autumn until early austral winter. The vertical wavelength values estimated for 16-day wave are in accordance with those already reported.

Many characteristics of the 2, 6–7 and 16 day planetary scale oscillations which were observed at both sites are compatible with those previously observed in other studies for other sites.

Acknowledgements. The present work was partially supported by the Universidade Estadual da Paraíba, UEPB, and the Conselho Nacional de Desenvolvimento Científico e Tecnológico, CNPq. We are also grateful to the Instituto Nacional de Pesquisas Espaciais (INPE) and the Observatório de Luminescência Atmosférica da Paraíba (OLAP) UFCG for their collaboration and availability of the meteor radar data.

Topical Editor C. Jacobi thanks P. R. Fagundes and one anonymous referee for their help in evaluating this paper.

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