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Variability of the lunar semidiurnal tidal amplitudes in the ionosphere over Brazil

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Abstract. The variability in the amplitudes of the lunar semidiurnal tide was investigated using maps of Total Electron Content over Brazil from January 2011 to December 2014. Long period variability showed that the annual variation is always present in all investigated magnetic latitudes and it represents the main component of the temporal variability. Semiannual and intraseasonal (∼120 days) oscillations were the second and third components, respectively, but they presented significant temporal and spatial variation without a well-defined pattern. Among the short period oscillations in the amplitude of the lunar tide, the most pronounced ones were concentrated between 7-11 days. These oscillations were stronger around the equinoxes, in special between September and November in almost all latitudes. In some years, as in 2013 and 2014, for instance, they appeared with large power spectral density in the winter hemisphere. There was also observed evidence of antisymetry in the amplitudes maxima and minima of the 7-11 days oscillation with respect to the magnetic equator. These characteristics are compatible with normal mode westward propagating quasi 10 days planetary wave with horizontal wavenumber equal to 1. Besides, using data from a meteor radar located at low latitudes in Brazil for November 2013, when the amplitude of the 7-11 days oscillation was strong, it was possible to identify the presence of quasi 10 days oscillation in the both zonal and meridional component of the horizontal winds. These results suggest a possible coupling process by modulation of the lunar semidiurnal tidal amplitudes that allows the propagation of the 7-11 days waves into the thermosphere-ionosphere system.

1 Introduction

Planetary waves are produced by large-scale perturbations in the atmosphere that can have horizontal wavelength up to 40.000 km around the equator. Those waves can have periods which vary from a couple days to weeks. Planetary waves are responsible for most of the temporal and spatial variation in the stratosphere and they also contribute substantially to the variability of the mesosphere and lower thermosphere (MLT). Basically, planetary waves have been classified in three types: (1) quasistationary midlatitude Rossby waves, (2) normal modes and (3) equatorial waves.

Quasistationary Rossby waves are important to the midlatitude dynamics because they can largely influence the atmospheric fields as wind and temperature and are responsible for the distribution of the Ozone and other trace gases. Rossby normal modes, also known as free modes are predicted by the theory as oscillatory solutions of the Laplace's tidal equation without

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forcing. The Laplace's theory is constructed over an isothermal and non-damping atmosphere, thus, the real conditions of the real atmosphere can produces normal modes with some similarities to the theoretical ones. The class of planetary waves which occur near the equator and the most commonly observed in the MLT region are the Kelvin waves, which are classified as low Kelvin waves (periods of $\sim$ 16 days), fast Kelvin waves (periods of 6-7 days) and ultrafast Kelvin waves (periods of 3-4) days.

Dissipative processes in the atmosphere act significantly in the upward propagation of planetary waves producing a pronounced damping above 100 km altitude. Among several mechanisms, the cooling by emission of heat and interaction with small-scale waves have been pointed out as the most important dissipative processes (e.g., Smith and Perlwitz, 2015, and references therein). However, large number of studies in the last decades have shown evidence for oscillations with periods of planetary-waves in the thermosphere (e.g., Forbes, 1996; Pancheva and Laštovička, 1998; Pancheva et al., 2002; Laštovička, 2006; Abdu et al., 2006, 2015; Jonah et al., 2015; Gan et al., 2015; Mo and Zhang, 2020, and references threin). Understanding how planetary waves can penetrate into the thermosphere-ionosphere system have raised up as one of the current most important topic of research in the atmospheric layer's coupling. Recent works have given some insights in this topic (e.g., Forbes et al., 2014; Gasperini et al., 2017), but further observation and investigations are necessary in order to understanding this coupling.

The lunar semidiurnal tide with period of $\sim$12.424 solar hours is the most important Moon's oscillation for the atmosphere in terms of amplitudes. Although the generation of the lunar semidiurnal tides comes from the lower levels of the atmosphere due to the Moon's gravitational attraction and interaction with vertical motion of the oceans and solid Earth, it can propagate into the thermosphere with less influence of the dissipative process. As the source of the lunar tide is well known, variation associated to the sources are predictable. Then, it can be used as an important trace to observe changes in the atmosphere as it propagate vertically. Furthermore, modulation of the lunar semidiurnal tidal amplitudes by planetary waves can be used to explain the presence of these waves in the thermosphere-ionosphere system, which is the main purpose of the present work. Additionally, variability of long period in the lunar semidiurnal tidal amplitudes is also investigated.

Data from a Global Navigation Satellite System (GNSS) network over Brazil was used to calculate the amplitudes and phases of the lunar semidiurnal tide in the Total Electron Content (TEC) of the ionosphere from 2011 to 2014 (Paulino et al., 2017). In the present work, the temporal variability of the lunar semidiurnal tidal amplitudes was extensively investigated showing long and short period oscillations.

2 Analysis and results

2.1 Filtering

Further description of the methodology to calculate the TEC maps was provided by Takahashi et al. (2016). TEC maps have also been used to calculate the amplitude and phases of the lunar semidiurnal tide from 2011 to 2014 over Brazil (Paulino et al., 2017). In the present study, the variability due to low and high frequencies in the lunar semidiurnal tide amplitudes observed in those TEC maps is investigated in details.

Figure 1 shows the filtering process in the amplitudes of the lunar semidiurnal tide calculated at 10^o S (magnetic).

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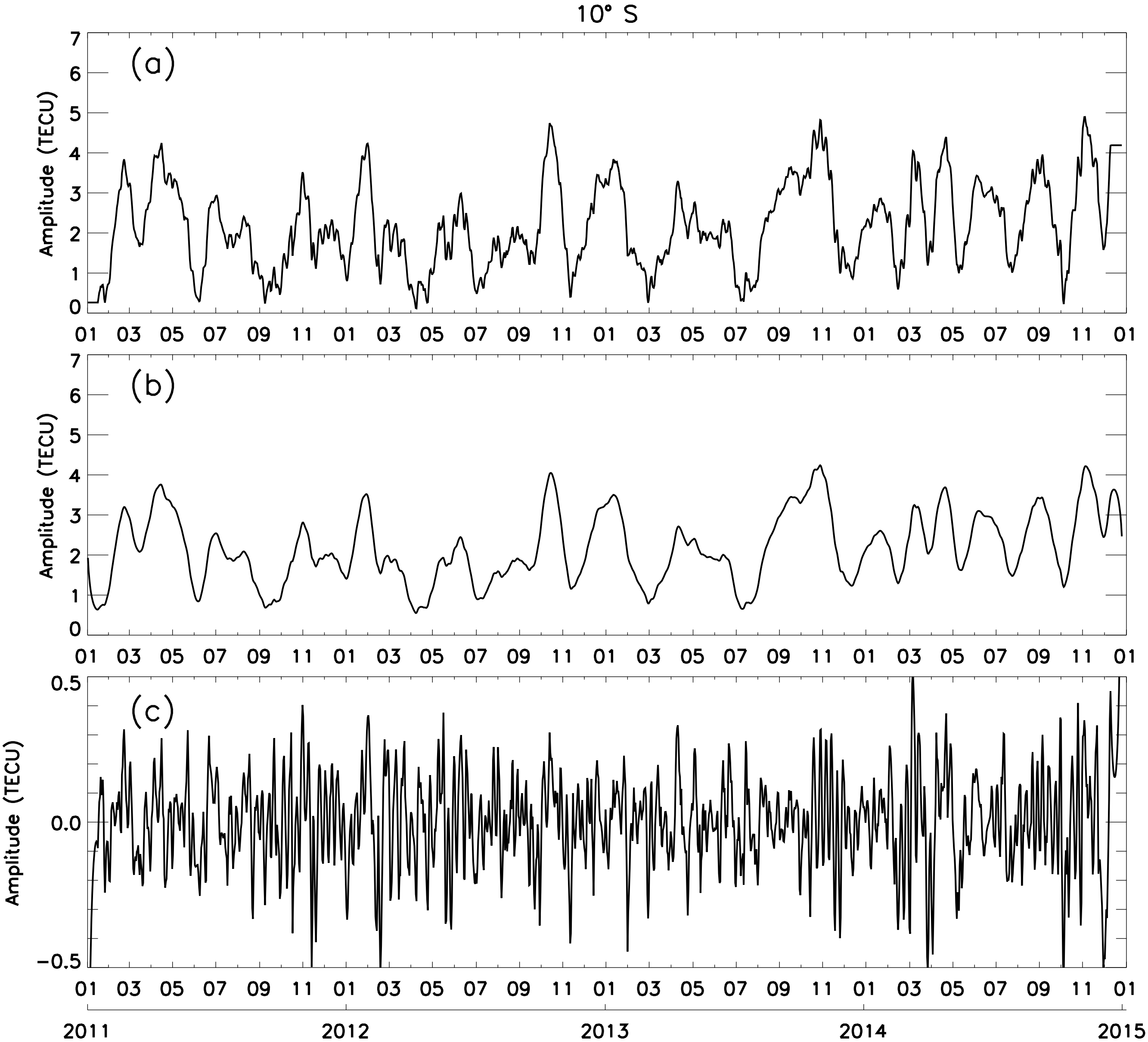

Figure 1. (a) Amplitudes of the lunar semidiurnal tide from 2011 to 2014 calculated at 10^o S (magnetic latitude). (b) Low frequencies calculated using a Butterworth kernel filter from amplitudes of panel (a). (c) Same as Figure (b), but for high frequencies.

Figure 1(a) shows the raw amplitudes in TEC units from 2011 to 2014. One can see that there are low and high frequency oscillations in the amplitudes retrieved from the TEC. Figure 1(b) shows the filtered amplitudes considering periods greater than 30 days and Figure 1(c) shows the high frequencies greater than 1/30 days^{-1}. This filtering process was done using Butterworth Kernel low pass filter of order 1. Mathematically this filter can be written as:

$$filter = \frac{1}{\sqrt{1-\left(\frac{\Omega}{\Omega_c}\right)^{2n}}} \quad (1)$$

where Ω is the frequency, Ω_c is the cutoff frequency and n is the order.

2.2 Seasonal and intraseasonal variability

Considering the filtered amplitudes for periods longer than 30 days, a spectral analysis was done and the results are shown in Figure 2. Lomb-Scargle periodogram (Lomb, 1976; Scargle, 1982) was calculated using the filtered amplitudes from 2011 to 2014 for the magnetic latitudes 10^o N, 0, 10^o S and 20^o S.

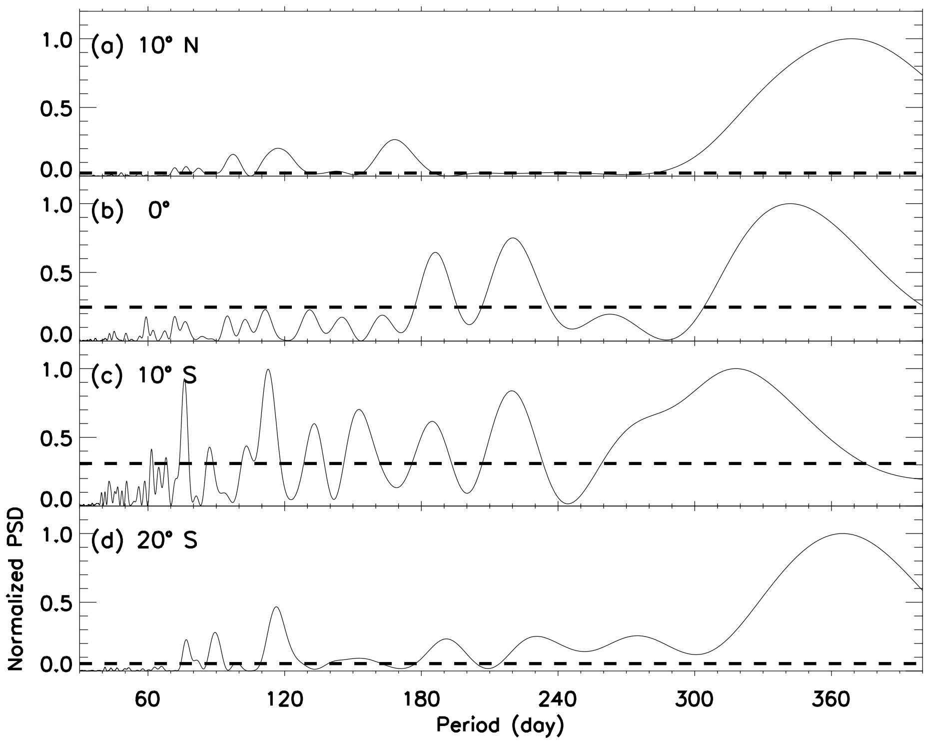

Figure 2. Lomb-Scargle periodogram for (a) 10^o N, (b) 0^o, (c) 10^o S and (d) 20^o S. The horizontal dashed lines represent the confidence level of 99%, i.e., false alarm probability of 0.01.

Figure 2(a) shows strong power density spectrum (PSD) associated to annual variation and semiannual variation. One can observe that there is a third peak around 120 days, i.e., intraseasonal variation. Similar patterns to what is observed at 10^o N can also be observed at 10^o S (Figure 2(c)) and 20^o S (Figure 2(d)). At 0^o (Figure 2(b)), annual and semiannual variations were strong as well, but the intraseasonal variation was weak compared to the other latitudes. Comparing 10^o N to 10^o S, it is clear that there are more significant peak of oscillation in the South, indicating that the long oscillations are not symmetrical with respect to the magnetic equator.

In order to investigate when the periodicities shown in Figure 2 appear more frequently in the dataset, a wavelet analysis was performed and the results are shown in Figure 3 with the respective magnetic latitudes. These wavelet charts were calculated based on the methodology of Torrence and Compo (1998).

Figure 3 shows that the annual variation is always present in the amplitude of the lunar tide. Figure 3(a) shows that the semiannual variation was present in the two first years and the intraseasonal variation appear more pronounced in the beginning of 2013 and 2014.

Figure 3(b) (magnetic equator) shows that the semiannual variation were strong in the end of 2012 and beginning of 2013 with outspread of this peak to over 200 days. Figure 2(b) shows also this behavior in the Lomb-Scargle chart.

Figure 3(c) shows that the semiannual oscillation in the amplitude of the lunar tide becomes stronger than the annual in the second half of 2013. It is important to observe that the intraseasonal oscillation was present in the amplitude of the lunar tide from 2011 to March 2013 and became very strong at the end of this time range, compared to the other latitudes and times.

Figure 3(d) shows that the intraseasonal oscillation appeared in 2013 and 2014 and, at this magnetic latitude, the semiannual oscillation was weaker than the intraseasonal.

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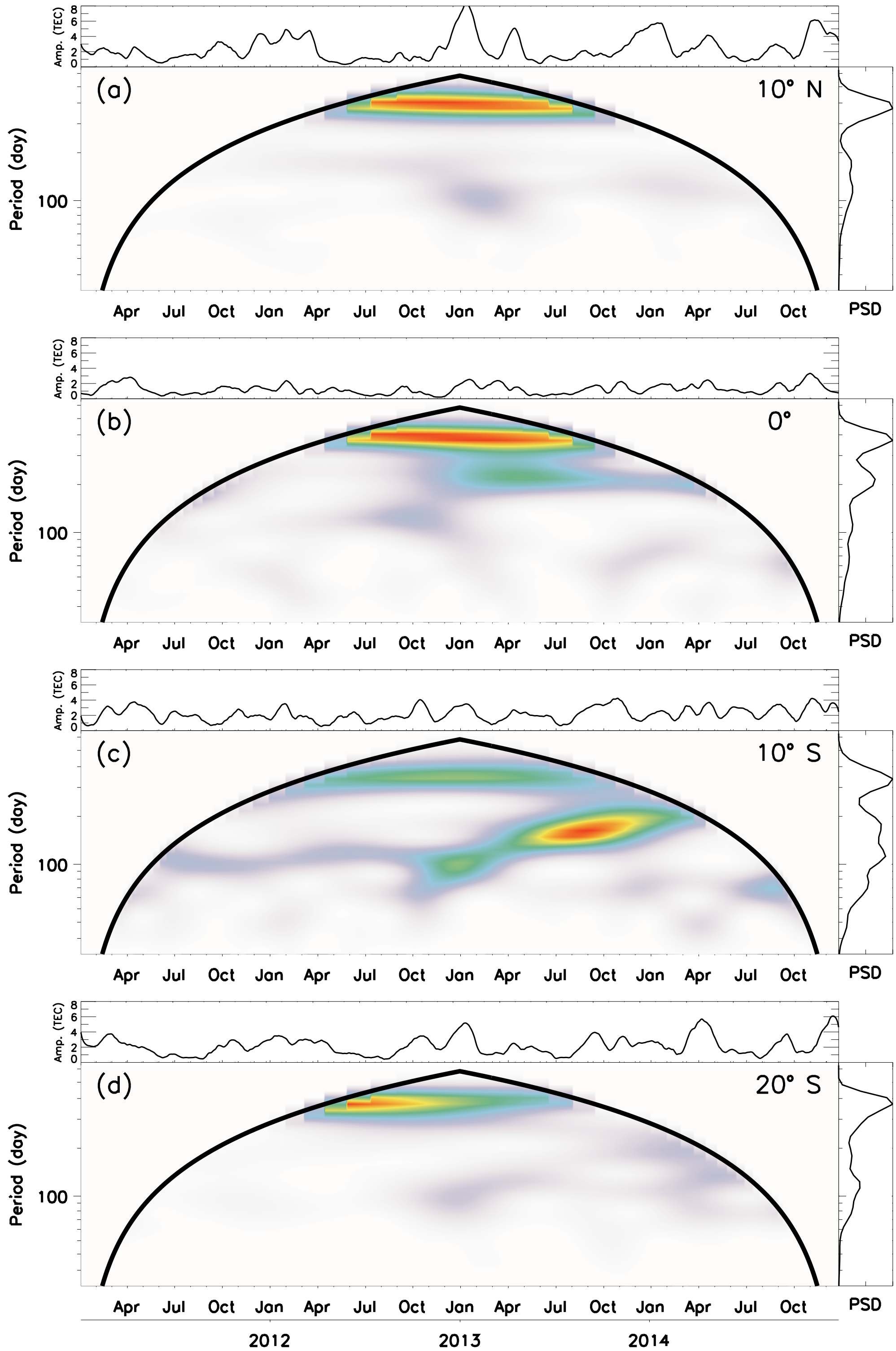

Figure 3. Wavelet analysis for (a) 10^o N, (b) 0^o, (c) 10^o S and (d) 20^o S. The black lines in the contours represent the cone of influence.

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2.3 Short period oscillations

The short period oscillations observed in the amplitudes of the lunar tide were the main focus of this work, primarily, because these oscillations can be associated to the planetary waves revealing important aspects in the atmosphere-ionosphere coupling from below.

Figure 4 shows the Lomb-Scargle periodogram for the same latitudes as in Figure 2, but considering only periods shorter than 30 days. These periodograms were calculated using the high frequencies in the amplitudes of the lunar semidiurnal tide as exemplified in Figure 1(c). Figure 4(a) to 4(d), which represent the magnetic latitudes from 10^o N to 20^o S, show significant periodicities from 7 to 12 days, when the time range from 2011 to 2014 is used. Hereafter, we are going to refer to these oscillations as quasi 8 days (Q8D) oscillation, although sometimes they can be either shorter or longer than 8 days. Similar assumption has been used by Ahlquist (1982). Please, note that other long periods were also observed above the significance levels, but they were not so pronounced like the Q8D oscillation as it is going to be shown ahead.

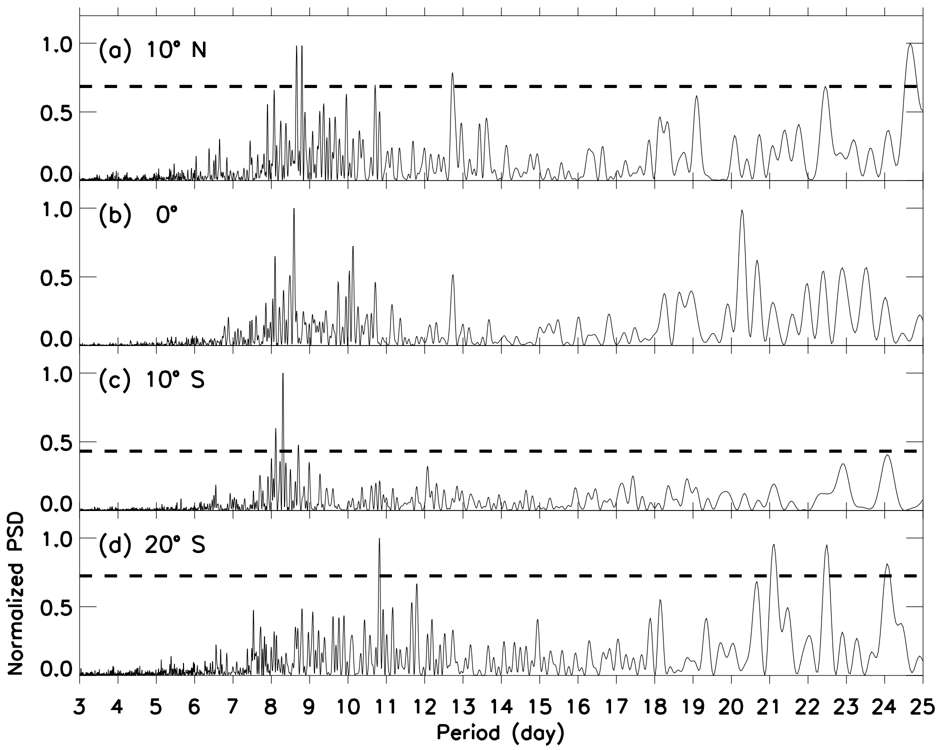

Figure 4. Same as Figure 2, but considering only periods shorter than 25 days. Note that at 0^o all periodicities were below of the confidence level since the amplitudes were smaller compared to the other latitudes.

In order to see the temporal evolution of the short period oscillation in the amplitudes of the lunar semidiurnal tide, wavelet analysis was performed for each year of observation and the results are shown in Figures 5, 6, 7 and 8. One can observe that the dominant oscillation is the Q8D along the whole period of observation. Some particularities are also observed in each year, mainly regarding the epoch of the year in which the Q8D wave is stronger.

Figure 5 shows the wavelet results for the amplitudes of the lunar semidiurnal tide in 2011. The Q8D was stronger from September to November in almost all latitudes. There was a secondary peak of this oscillation from the middle February up to April, except at 10^o S.

Figure 6 shows the results for 2012. Again the Q8D oscillation was the most important oscillation, but it appeared more frequently along the year, in special, out of the magnetic equator. One different aspect was the Q8D strong in February at 10^o N and in May at 10^o S.

In 2013 (Figure 7), the strength of the Q8D oscillation was more concentrated in few months. At 10^o N, the Q8D oscillation had more power spectral density in January and February. At 0^o and 10^o S, the oscillation appeared with more intensity from latter October to December. At 20^o S there were two peaks of the Q8D oscillation in April and May.

Figure 8 shows the power spectral density contour for 2014. One can observed a regular behavior of the Q8D oscillation with two peaks around the equinox months.

An important result revealed from the observations is that the Q8D oscillation is always present in the equinox months. From September to November in almost all latitudes and years it was the dominant oscillation. One can also observe, that the Q8D oscillation appear strong during the winter in 2012 and 2013.

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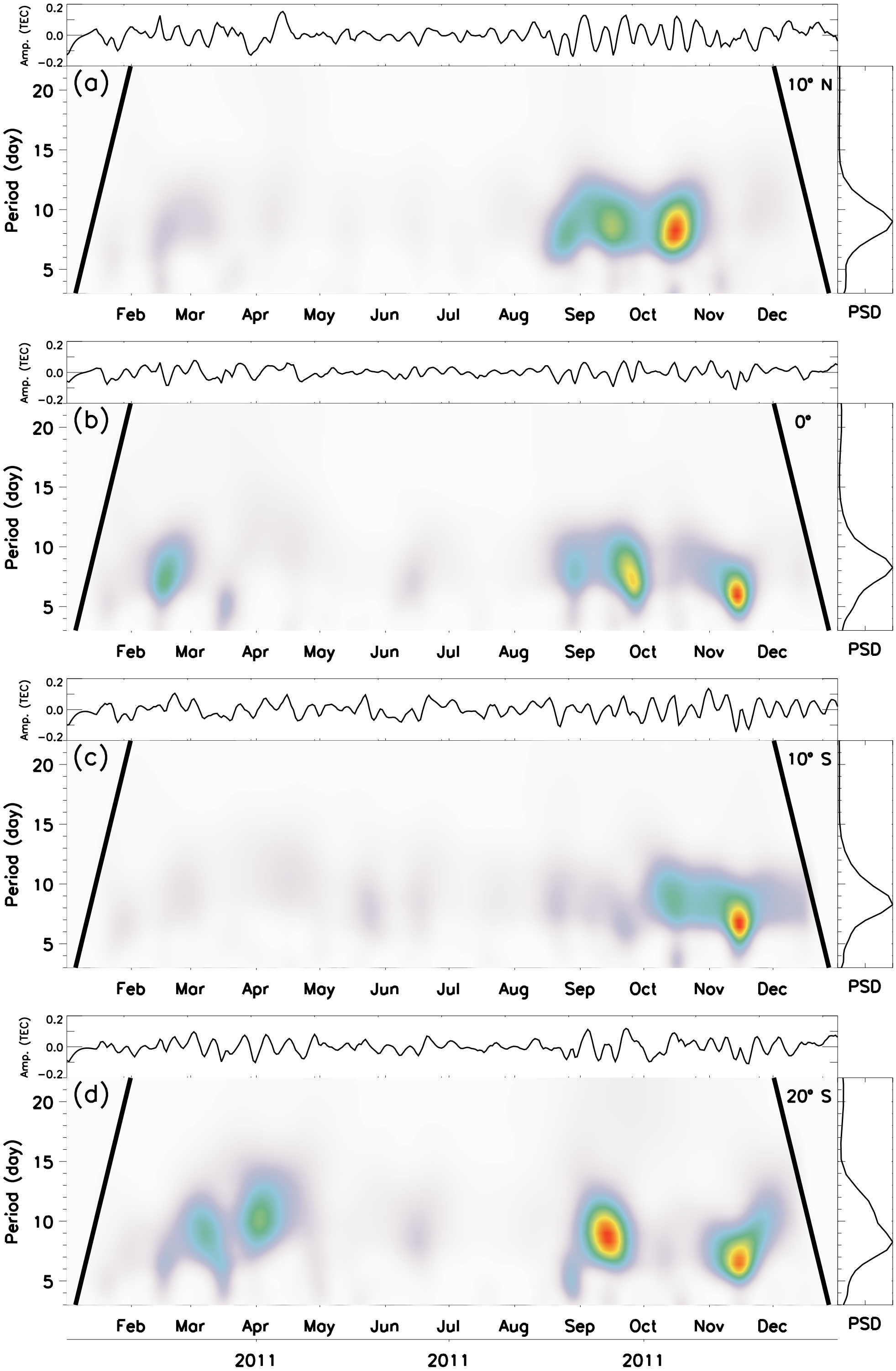

Figure 5. Same as Figure 3, but considering only periods shorter than 25 days during 2011.

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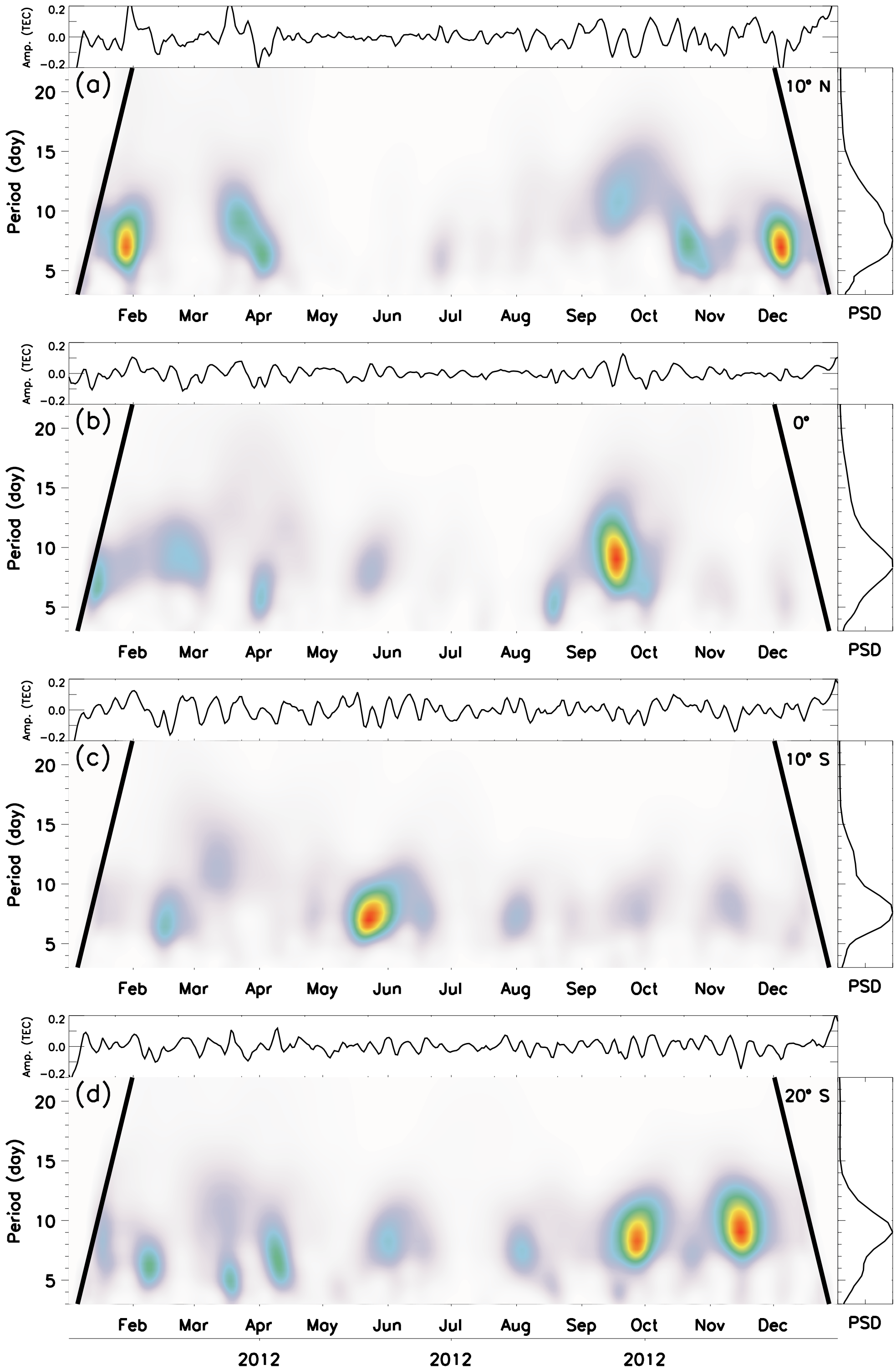

Figure 6. Same as Figure 5 for 2012.

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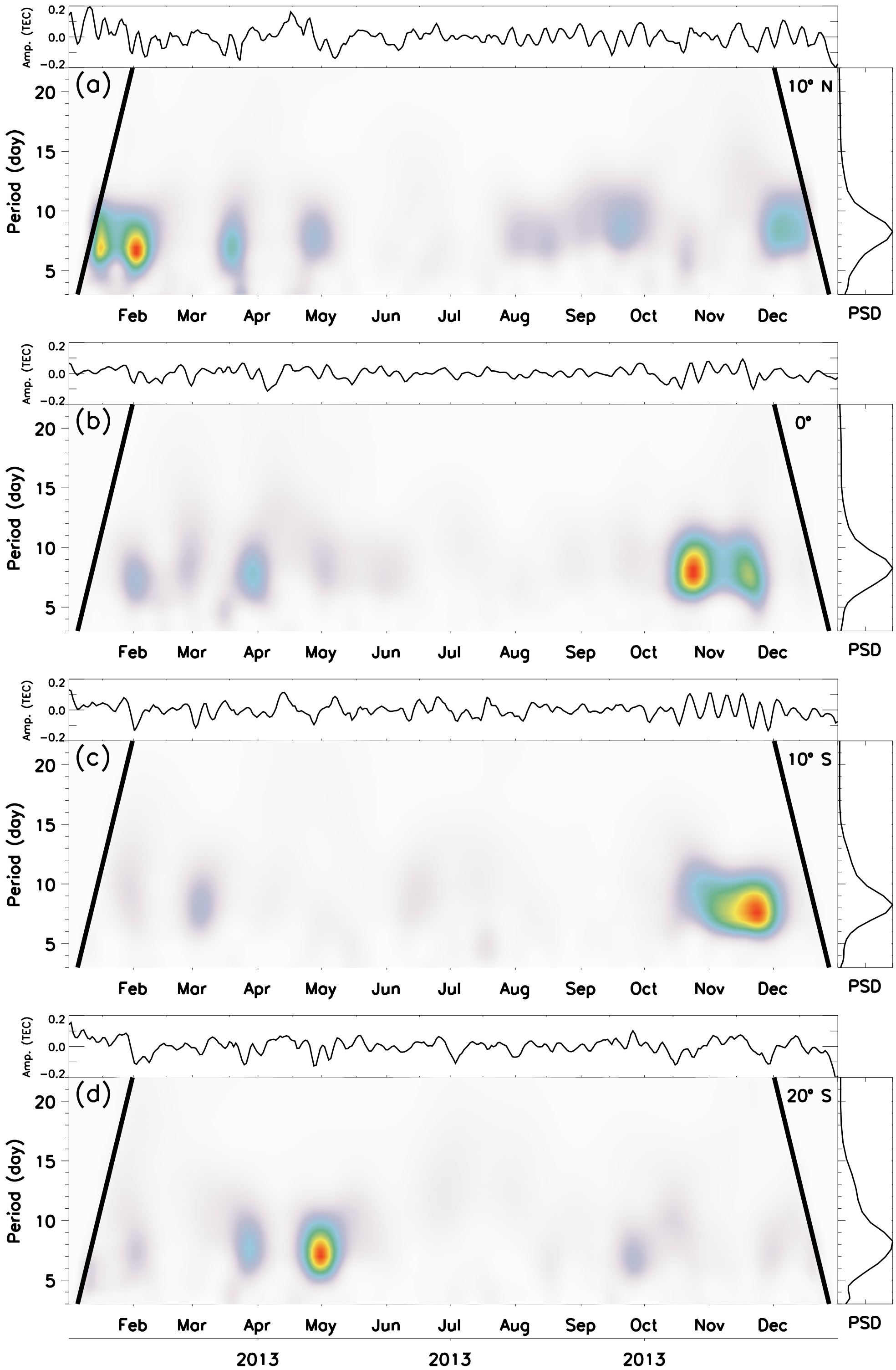

Figure 7. Same as Figure 5 for 2013.

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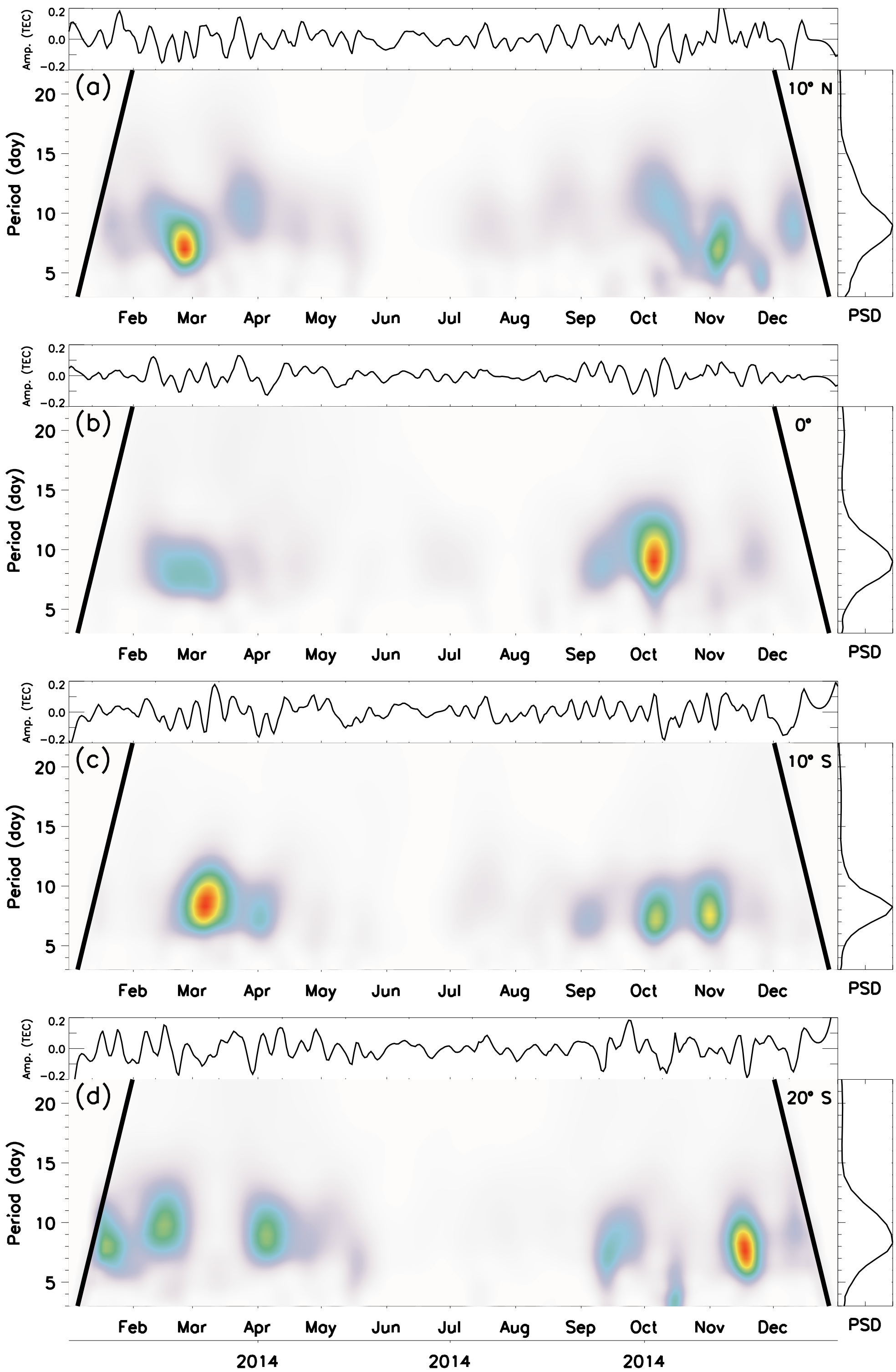

Figure 8. Same as Figure 5 for 2014.

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3 Discussion and summary

It is well known that the lunar semidiurnal tide has a predictable source. Thus, short and long variations observed in the amplitudes must reveal changes in the atmosphere where this tidal component is propagating. For instance, annual and semiannual variation in the amplitudes of the lunar tide has also been observed in the mesosphere and lower thermosphere (MLT) region in the neutral wind (Paulino et al., 2015). Intraseasonal variation has been observed and simulated in some atmospheric fields as well (e.g., Pedatella et al., 2012; Pedatella, 2014). However, more investigation is necessary to the better understanding the reason for those variability.

The results from Figures 2 and 3 show that the annual variation is always present in the amplitudes of the lunar semidiurnal tide in the TEC. At the magnetic equator, the PSD of the annual variation is comparable to the semiannual, for instance. However, far from the equator, the annual variation is stronger. Furthermore, It seems that the annual variation is out of phase at this latitude compared to the annual variation observed in MLT winds (Figure 2, bottom row of Paulino et al., 2015), i.e., the annual variation maximizes around January for all latitudes in the TEC and it maximizes around November in the MLT winds. It reinforces that the lunar tide obey the changes in the atmosphere and the observed variability is not due to changes in the sources, otherwise, we would expect variability almost in phase at different atmospheric levels.

Although the semiannual oscillation raised up as the second peak in the Lomb-Scargle Periodogram (Figure 2) from 2011 to 2014, it appeared sporadically and with more intensity in lower latitudes. In contrast, the TEC observed in Brazil shows a semiannual variation and have maximuma around the equinox during both low and high solar activities (Jonah et al., 2015).

The intraseasonal variation with period around 120 days, in average, was the third peak found in the amplitudes of the semidiurnal tide, it was sporadic at 10^o N, 0^o and 20^o S. At 10^o S, it was present in almost the whole period of observation and stronger than the semiannual oscillation during the first two years of observations. In Paulino et al. (2017), one can see that the intraseasonal oscillation appears evident at magnetic latitudes out of the equator. Maybe the combination of the annual variation with maximum in the austral summer months and semidiurnal variation with maximums around the equinoxes (matching with the TEC maximums) is producing the intraseasonal variation in the amplitudes of the lunar semidiurnal tide.

Figure 1(a) shows roughly a short period oscillation in the amplitudes of the lunar tide which can be observed in all studied latitudes over Brazil. Sometimes, this short oscillation is stronger and sometimes it is very tenuous. It is quite interesting because it was also observed in Paulino et al. (Figure 3 of 2017).

An interesting aspect reveled in this work was the periodicity close to 8 days. Based on the literature, there are two kind of large scale waves with periods close to 8 days: (1) Fast Kelvin wave (e.g., Abdu et al., 2015, and references therein) and (2) Quasi 10 days planetary wave (e.g., Forbes and Zhang, 2015; Yamazaki and Matthias, 2019).

Fast Kelvin waves have been observed with period typically of 6-7 days. It is a kind of wave trapped in the equatorial region which has characteristics of gravity waves, i.e., it obeys the dispersion relation of gravity waves. Fast Kelvin waves are typically observed with large amplitude in the zonal wind and insignificant amplitudes in the meridional one. As the present Q8D oscillation was observed close to the equator as well as at 20^o magnetic latitude, which can be out of the tropic in the west part of Brazil, it is most unlikely that the Fast Kelvin wave is modulating the amplitudes of the lunar semidiurnal tide.

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Some observations have shown that the amplitudes of the Fast Kelvin wave dominate in altitudes below 90 km (e.g., Lieberman and Riggin, 1997). Dhanya et al. (2012) found out periodicities close to 8 days in Equatorial Electro Jet and MLT winds and associated that oscillation to Fast Kelvin wave. Abdu et al. (2015) also observed Q8D oscillation in the vertical drift of F region and spread-F development.

In the past years, the interest in studing the quasi 10 day wave (Q10DW) has been recovered, primarily due to its association with polar Sudden Stratospheric Warmings (SSWs) (Yamazaki and Matthias, 2019; Mo and Zhang, 2020). Another motivation was the long term observation from satellites that allow to investigate seasonality, year to year variation and spatial (latitude x longitude x altitude) dependencies (Forbes and Zhang, 2015; John and Kumar, 2016).

Although the present results concentrate into the oscillations around 8 days in the amplitudes of the semidiurnal lunar tide, these oscillations have characteristics similar to the Q10DWs as pointed out by Forbes and Zhang (2015). For instance, large amplitudes during the equinox months and during the winter in both hemispheres. Another interesting characteristic was the anti-simetry as can be seen in Figure 9, i.e., the amplitudes of the Q8D oscillation is out of phase at the two hemispheres.

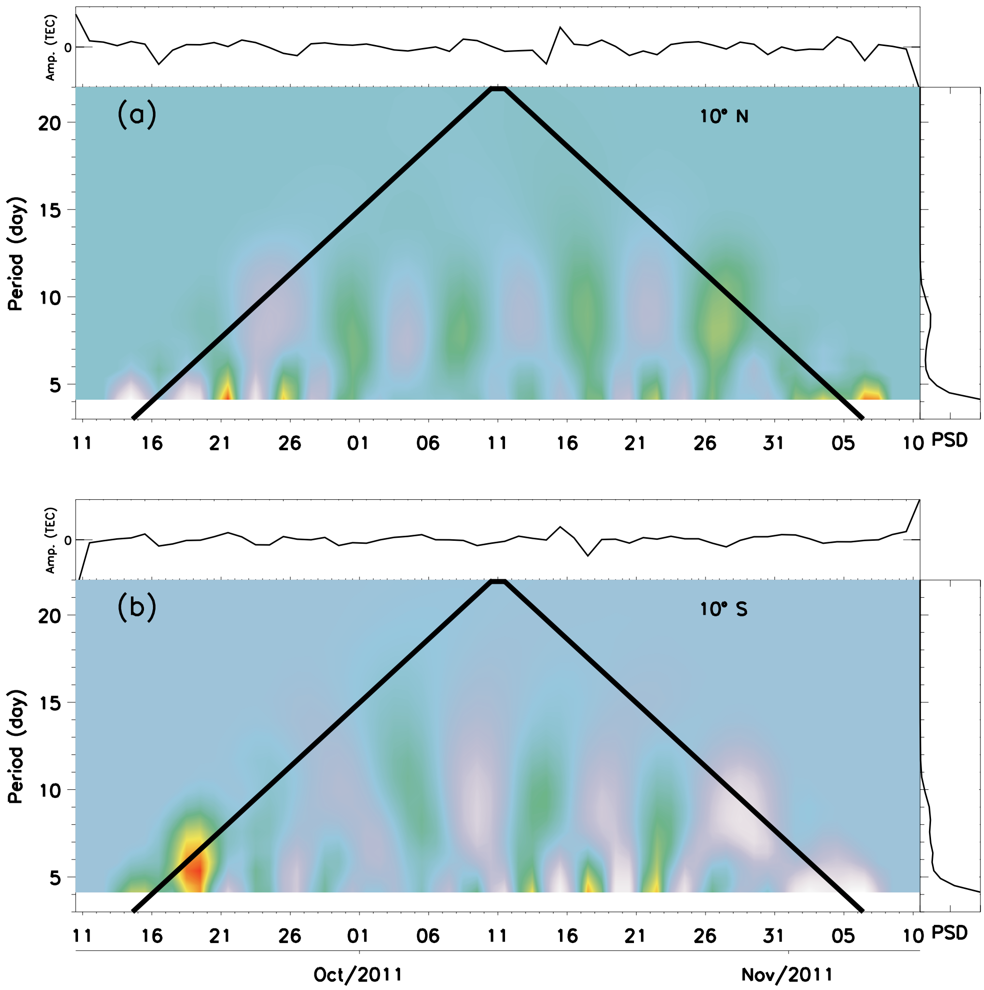

Figure 9. Wavelet phases using data from 10 September to 10 November 2011 for (a) 10^o N and (b) 10^o S.

Observation of wave/oscillation with periods 8-10 days have been made in the thermosphre-ionosphere. For example, Forbes (1996) used data of Medium Frequency radar and magnetometer to show the Q10DW oscillations in the mesopause and low thermosphere region. Pancheva and Laštovička (1998) observed fluctuations of 7-8 days from November to December 1994 during an international Campaign. Abdu et al. (2006) studied variation in the Equatorial Electro Jet (EEJ) and MLT wind and showed the presence of 8-12 days oscillation around the equinox of 1999 in the equatorial region. Jacobi et al. (2007) observed 7-12 days waves in the TEC maps over Europe region. Jonah et al. (2015) have also observed 8-10 days oscillation in TEC over Brazil, primarily around the equinoxes. More recently, comprehensive studies on Q10DW using satellite data presented some important temporal and spatial characteristics of this wave below 110 km altitude (Forbes and Zhang, 2015; John and Kumar, 2016). Additionally, Yamazaki and Matthias (2019) and Mo and Zhang (2020) presented results associating the Q10W to Sudden Stratospheric Warming events.

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It is important to notice that the observations above showed periods varying from 8 to 10 days in both the mesosphere and thermosphere-ionosphere. Forbes and Zhang (2015) showed slight variation (0.4 days) in the period of Q10W (9.7 to 9.9 days) and concluded that the doppler shift produced by the horizontal wind can change the period of the wave. The present study uses amplitudes of the lunar semidiurnal tide in lunar time, i.e., the lunar days is by about 0.036 days longer than solar day. Assuming that the observed oscillation has a period of 8.5 days in lunar time, it corresponds to 8.806 days in solar time. However, this is not enough to explain the discrepancy between the observed period in the lower atmosphere and the present results.

Investigations in other atmospheric fields have shown evidences of 8-10 oscillations with simultaneous periods. Figure 10 shows the horizontal wind at 93 km altitude over Cachoeira Paulista (22.7^{0}S; 45.0^{0}W) during November 2013 measured at 02:00 Universal Time. Further details about the meteor radar and its measurements have been published elsewhere (e.g., Paulino et al., 2012). The temporal evolution of the winds shows some periodic oscillations.

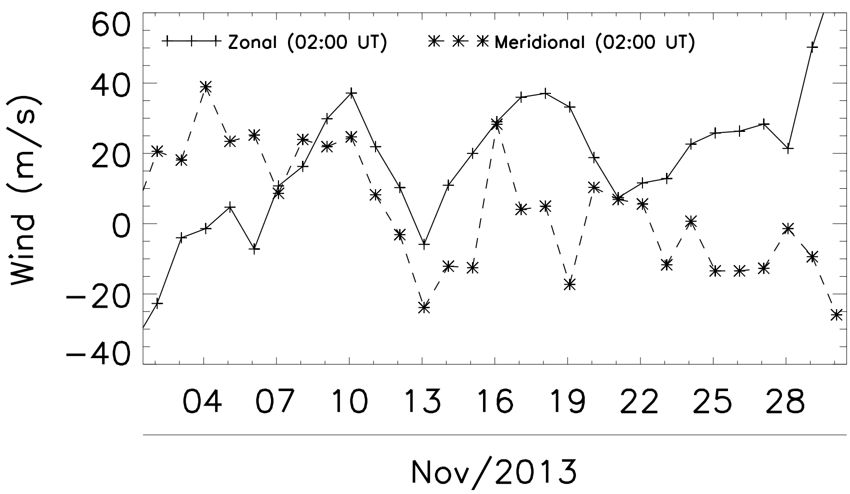

Figure 10. Zonal (solid line) and Meridional (dashed line) wind components at 93 km height over Cachoeira Paulista measured at 02:00 UT during November 2013.

Figure 11 shows the Lomb-Scargle periodogram of the wind including all temporal measurements at 93 km. Quasi 10 days oscillation is shown in both zonal and meridional components of the horizontal wind. In the zonal component the peak of the oscillation was concentrated at 9.7 day, while in the meridional one, the peak was at ∼9 days. The presence of this simultaneous oscillation in the MLT wind strongly suggests that the observed oscillation in the amplitude of the lunar tide might have origin in a coupling with the lower atmosphere.

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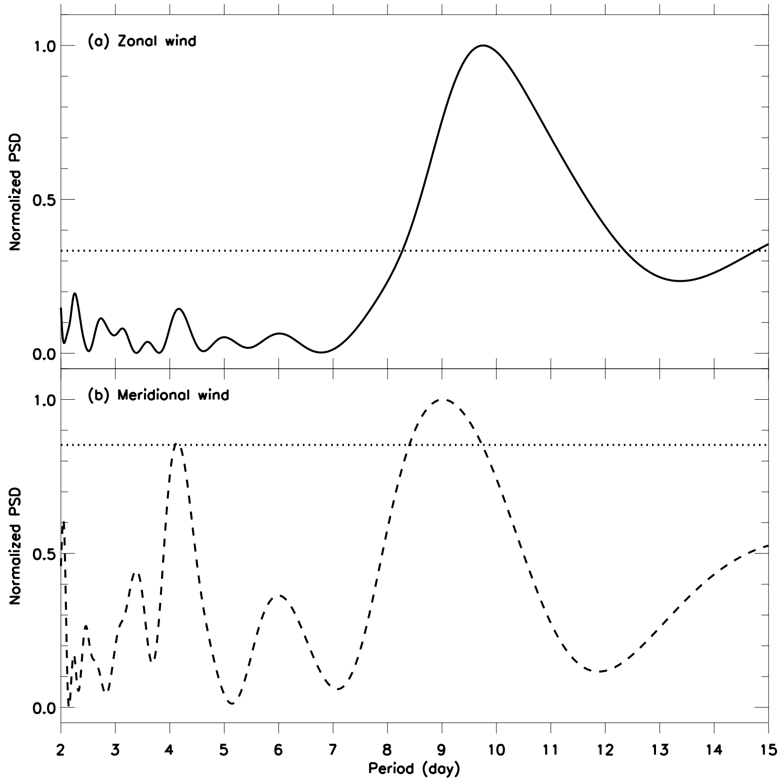

Figure 11. Lomb-Scargle periodogram for (a) zonal and (b) meridional wind during November 2013 at 93 km altitude. Horizontal dotted line represents a significancy level of 95%, i.e., false alarm probability of 0.05.

The main results of this investigation can be summarized as follows:

- There is a strong temporal variability in the amplitudes of the lunar semidiurnal tides calculated in the TEC maps over Brazil from 2011 to 2014;
- Annual variation in the lunar semidiurnal tide is always present in all observed latitudes and it is dominant in lower latitudes;
- Semiannual and intraseasonal (∼120 days) were, respectively, the second and third most important long period oscillation observed in the amplitudes of the lunar tide. However, it was observed a temporal and spatial variability of these oscillations, which allow them to become dominant in a given time interval and latitude range;
- It was observed dominant oscillations between 8-11 days in the amplitudes of the lunar semidiurnal tide with maximums around the equinoxes. In some years, as 2013 and 2014, the peaks occurred in the winter;
- Anti-symmetrical correlation between the Q8D oscillations calculated in conjugate latitudes from September to November 2011 were observed;

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– Coincident measurements of the horizontal wind in low latitudes in the MLT during November 2013 showed quasi 10 days oscillations.

Based on the preset main results to the short period oscillations in the amplitudes of the lunar semidiurnal tide, i.e., the Q8D oscillation, it could be verified that this oscillation has important characteristics of the westward propagating anti-symmetrical normal mode with $s = 1$ with period of quasi 10 days. However, the discrepancy associated to the low period of observation as compared to the Q10DW is an open question that must be further investigated.

According to the theory of planetary waves, the dissipative process into the thermosphere does not allow direct propagation of these wave to high levels. Then, the explanation for observation of planetary waves in the thermosphere-ionosphere have been suggested, basically, based on two possibilities: (1) modulation of the tidal amplitudes, in special, the semidiurnal components which can propagate to higher altitudes into the thermosphere and/or (2) though the theory of dynamo on the electrodynamics of the ionosphere. The present results suggest that the first possibility is more efficient to the propagation of waves with period of 8-11 days.

Data availability. The TEC maps used in this work are available online in the EMBRACE website (http://www2.inpe.br/ climaespacial). Meteor winds can be requested to Dr. Lourivaldo Mota Lima (lourivaldo_mota@yahoo.com.br).

Author contributions. ARP has written the manuscript and performed the analysis in the data base. FSA has worked in the Lomb-Scargle periodograms. IP has revised the manuscript and helped in some analysis of the data. CMW has provided the TEC maps. LML has provided the meteor winds. PPB is responsilbe for the meteor winds and has revised the manuscript. ISB has revised the manuscript.

Competing interests. The authors declare that they do not have competing interests

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