The 3-4 day Ultra-Fast Kelvin wave (UFKW) induced airglow and MLT wind variability and its possible interaction with diurnal tide over the Brazilian equatorial region

Fábio Egito*, Universidade Federal do Oeste da Bahia-UFOB
Ricardo A. Buriti, Amauri Fragoso de Medeiros, Universidade Federal da Campina Grande-UFCG.
Hisao Takahashi, Instituto Nacional de Pesquisas Espaciais.

This paper was prepared for presentation during the 15th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 31 July to 3 August, 2017.

Abstract

Airglow and wind measurements from the Brazilian equatorial region have been used to investigate the presence and the effects of the 3-4 day Ultra-Fast Kelvin Wave in the MLT. Airglow data came from a multichannel photometer, which measures the OI5577, O_2b(0-1) and OH(6-2) airglow integrated intensities and the OH rotational temperature. Wind measurements were performed by a meteor radar, which provides zonal and meridional wind between 80 and 100 km altitude. Both instruments are installed at São João do Cariri (7.4°S, 36.5°W) and provided quasi-simultaneous data in 2005. The results show that the 3-4 day oscillations appear intermittently along the year in both airglow and wind. The 3-4 day oscillations compatible with Ultra-fast Kelvin wave were observed simultaneously in both airglow and wind in March, August and October/November. Ultra-fast Kelvin wave induced amplitudes in the airglow overcome 40% in OI5577 and O_2b(0-1) emissions, while in OH(6-2) emission the amplitudes range from 15 to 20%. In the temperature, amplitudes were near 3 K. The presence of the 3-4 day oscillation in the airglow seems to be affected by the local time of the measurements, which occurred particularly in OI5577 emission. It was observed that taking pre-midnight airglow data could hide the presence of 3-4 day oscillation. Such feature is related to the interaction between the Ultra-Fast Kelvin Wave and the diurnal tide, which is indicated by a modulation of the diurnal tide amplitude in the zonal wind at the period of the Ultra-Fast Kelvin Wave.

Introduction

Planetary scale waves along with atmospheric tides strongly influence the large-scale dynamics in the Mesosphere and Lower Thermosphere (MLT) region. In the equatorial MLT many studies have investigated the contribution of such waves to the total dynamics budget of that region. Particularly, the 3-4 day wave, normally associated to the Ultra-Fast Kelvin Wave (UFKW), has been investigated due to its effects on the MLT neutral dynamics and its consequent influence on the ionosphere. The UFKW is the third Kelvin wave mode, in addition to the Slow and Fast Kelvin wave modes. According to the linear theory, Kelvin waves are equatorially trapped waves that propagate eastward and that present only perturbation in the zonal direction (Andrews, 1987). The UKW's are believed to contribute to the well-known Intra-seasonal (ISO), semi-annual (SAO) and quasi-biennial (QBO) oscillations by depositing eastward momentum into the mean flow and, consequently, partially forcing them (Andrews, 1987; Miyoshi and Fujiwara, 2006). Additionally, experimental measurements and numerical modeling have shown the influence of the UFKW in the day-to-day variability of the equatorial ionosphere (Takahashi et al., 2007; Onohara et al., 2011). Forbes (2000) predicted in his dynamical model that the UFKW effects on the composition and temperature should affect the airglow emissions coming from 90 and 110 km altitudes. From ground-based airglow measurements, Takahashi et al. (2002) associated, possibly for the first time, the 3-4 day airglow variability due to an UFKW. After, Lichstein et al. (2002), using the wave field from Forbes (2000) model's in a unidimensional chemistry-dynamical model, demonstrated that 3-4 day oscillations in the airglow reported by Takahashi et al. (2002) were consistent with an UFKW interpretation. Theoretical predictions and observational evidences have shown that the non-linear interaction between tides and planetary scale waves can affect dramatically both neutral and ionized atmosphere dynamics (Teitelbaum and Vial, 1991; Pancheva, 2001; Pedatella and Liu, 2013). Most of these studies address the non-linear interaction between tides and the 2-day, 5-day and 16-day planetary waves. Concerning the UFKW's, England et al. (2012) investigated the non-linear interaction between them and the tides in the MLT and its effects in the ionosphere. Effects of such interactions in the composition, however, have been little studied. Airglow measurements can provide information about the composition and temperature of the MLT and, along with wind measurements, could expand the view of the MLT dynamics. In this paper, we investigated the 3-4 day oscillations associated to UFKW in the MLT airglow and wind. Additionally, we address the interaction between the diurnal tide and UFKW and its effects on the airglow variability.

Methodology

The airglow intensities have been measured in Brazilian equatorial region at São João do Cariri (7.4°S, 36.5°W) observatory (hereafter Cariri Observatory) by a multichannel photometer, denominated MULTI-3. The MULTI-3 uses tilting interference filters to select the airglow wavelengths to be measured. The five interference filters enable to measure airglow integrated intensities of the atomic oxygen green (OI557.7nm) and red (OI630.0nm) lines, the molecular oxygen O_2b(0-1), the Meinel OH(6-2) band and the sodium NaD (589.0nm) line. Additionally, from the OH and O_2b(0-1) spectra rotational temperatures are inferred. For more details about the instrument calibration and additional characteristics see Takahashi et al. (2002). Airglow measurements take place only during the nighttime and usually occur during 13 nights centered on new moon period. For this study we have analyzed the OI557.7nm (hereafter OI5577), $O_2b(0\text{-}1)$ (hereafter O2) and OH(6-2) (hereafter OH) emissions and OH(6-2) rotational temperature (hereafter TOH) measured during 2005. For analysis purposes, we consider only months with at least 8 nights of observations. Additionally, each night must have at least 3 hours of continuous data. The Table 1 shows the number of nights for each month in 2005 with observations that have met the previous established criteria.

Table 1 – Number of nights per month with airglow observations in 2005.

	J	F	M	A	M	J	J	A	S	O	N	D
2005	8	-	13	13	9	-	9	9	-	14	11	-

Neutral wind components are derived by using measurements performed by the meteor radar also installed at Cariri observatory. The radar operates at 35.24 MHz frequency and uses one transmitter antenna and an array of five receiving ones. The radar transmits pulses of 12 kW peak power, which are partially back reflected by the ionized trail produced during meteor ablation. From reflected echoes, zonal and meridional wind components are retrieved. In this study, we calculated the zonal and meridional winds at 82, 85, 88, 91, 94 and 98 km altitudes at each two hours. Except for technical issues, the radar can operate continuously and provide data 24 hours per day.

To search for 3-4 day periodic variations in the airglow we have applied the Lomb-Scargle periodogram (hereafter LS periodogram), which is suitable to search for periodic variations in non-regularly sampled data as the airglow. The airglow time series corresponding to a total period of observation is build up by putting in sequence all the nights with measurements. After, the mean intensity for the corresponding month is subtracted from the original time series and then LS periodogram is calculated for the residuals. This procedure is performed for each emission and for each month with observations. Figure 1 shows an example of the OH intensity measured between October 26th and November 8th in 2005 and its corresponding LS periodogram. Each group of data corresponds to one night of observation.

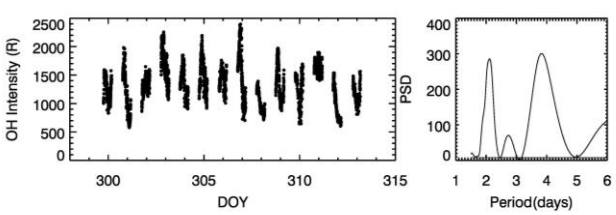

Figure 1 – Example of the nightly OH airglow intensity between October 26th and November 8th in 2005 (left) and the corresponding Lomb-Scargle spectrum (right).

Results

Airglow and wind spectral analysis

Airglow and rotational temperature time series have been analyzed by applying LS periodogram as described in the previous section. Figure 2 shows the normalized LS spectra of OI5577, $O_2b(0\text{-}1)$ and OH(6-2) emissions and OH temperature for all month with observations in 2005. For each parameter, all monthly LS spectra have been grouped to produce a 2-dimension plot in order to provide an entire year perspective view. In this case, the spectrum of each month is exhibited without the blank space corresponding to the interval in which there is no observations due to Moon phase. The blank spaces correspond to the months without observations. Vertical axis represents the frequency in cycles per day, covering a period range from 1.5 to 7 days. Power Spectral Density (PSD) higher than 0.4 indicates a confidence level of 95% and black line contours indicates spectral peaks in the periodogram. Horizontal black lines delimit the period range from 3 to 4 days. The spectra indicate the presence of periodic variations in the airglow and rotational temperature at frequencies corresponding to periods around 2 days, 3-4 days and 5-7 days, which are observed simultaneously in more than one parameter along the year. Such periodic variations in the MLT are usually associated to planetary scale waves. The 3-4 day oscillation, commonly associated to the Ultra-Fast Kelvin, Wave (UFKW) will be the focus of this study.

The 3-4 day periodic variations in the airglow and temperature can be identified in more than one parameter in all seasons along the year. They are observed in January, March, July, August and November. Investigations concerning the variability of the 3-4 day induced oscillations in the MLT wind indicate the presence of semiannual variations in their occurrence with intensification around equinoxes (Yoshida et al., 1999; Tsuda et al., 2002; Davis et al., 2012). Additionally, Forbes et al. (2009) showed that UFK exist intermittently during all months of year, but its amplitudes present variability of 20-60 days. Therefore, the present signatures of the 3-4 days oscillations in the airglow are in agreement with the reported activity of the 3-4 day oscillations in the MLT.

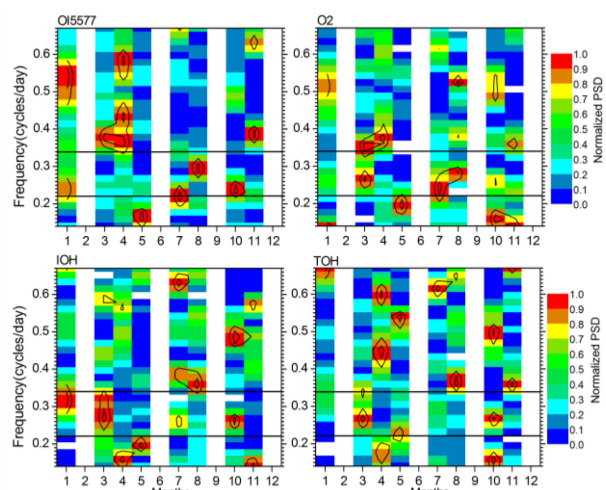

Figure 2 – Monthly normalized Lomb-Scargle periodogram of OI5577 (top-left panel), $O_2b(0\text{-}1)$ (top-right panel) and OH(6-2) (bottom-left panel) emissions and OH (bottom-right panel) temperature.

Periodic oscillations in the MLT zonal and meridional wind at 90 km identified by means of the wavelet transform are shown in the Figure 3. The zonal wind spectrum is marked by periodic oscillations at periods between 3 to 4 days and periods from 5 to 8 days. On the other hand, meridional spectrum is primarily dominated by quasi-2-day oscillations, which are particularly strong during the summer in January, although they are also observed around spring equinox. The white hatched areas delimited by vertical black lines indicate the intervals with simultaneous airglow measurements. From airglow LS periodogram and wind wavelet spectra (Figures 2 and 3, respectively) one can identify common oscillations at periods near 2 days, 3-4 days and 5-7 days in several occasions along the year. Considering the 3-4 day range, common oscillations in the airglow and in the zonal wind can be clearly observed in March (days 60 to 80) and August (days 210 to 230). In these two cases, the airglow observations match entirely with 3-4 day peak in the zonal wind spectrum. On the other hand, the 3-4 day oscillation in the airglow in January (days 2 to 9) does not present such signature either in the zonal or meridional wind spectra. In the cases of the 3-4 day oscillations observed in the airglow in July (days 210 to 225) and October/November (days 300 to 320), the corresponding meridional wind spectrum does not present any similar signature. Nevertheless, the zonal wind exhibits periodic variations close to the 3-4 day range or presents the 3-4 day oscillation very close to the time interval with airglow observations. In this last case, it is possible that the 3-4 day periodicity be present in the zonal wind, but with smaller amplitudes.

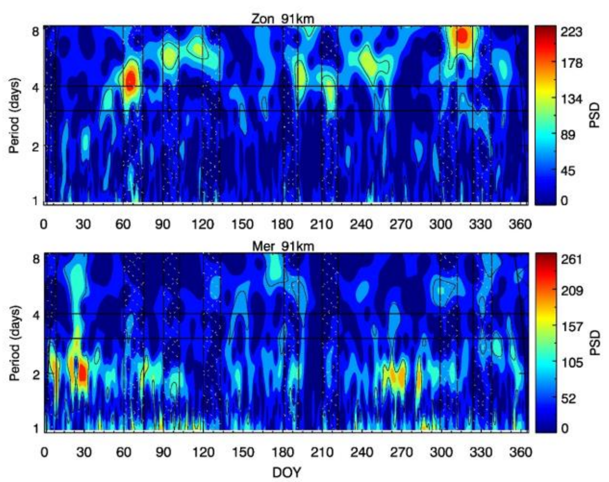

Figure 3 –Wavelet spectra of the zonal (top) and meridional (bottom) wind at 91 km. in 2005.

In order to investigate additional features of the 3-4 day oscillations in the wind the Figure 4 shows the filtered zonal and meridional winds at 88, 94 and 98 km altitudes, which correspond approximately to the nominal altitude peaks of OH, O2b(0-1) and OI5577 emissions. Cut off frequencies correspond to periods from 2.8 to 4.2 days. The hatched areas delimited by vertical black lines indicate interval with airglow observations. The filtered zonal and meridional wind exhibit bursts of amplitude intensification along the year. In spite of being observed in both components, amplitude intensifications are higher in the zonal wind and reach up to 20 m/s. Comparing with the wavelet analysis, one can see that most of the signatures of the 3-4 day oscillations identified there (Figure 3) can be observed in the filtered wind, especially in the zonal component.

Considering the intervals with airglow measurements (hatched areas) and those in which 3-4 days oscillations have been identified (Jan, Mar, Jul, Aug and October), significant amplitudes (at least 10 m/s) are observed in the zonal and meridional wind. In the case of January, significant amplitudes are observed in the meridional wind at 94 and 98 km, while in the zonal component the amplitudes are much lower. Looking at March, the zonal wind present high amplitudes in the 3-4 day band in all altitudes and reach 20 m/s at 94 km. Although the amplitudes in the meridional wind are not negligible, they are lower than in the zonal one. Considering the interval with 3-4 day oscillation in the airglow in July, it is interesting to note that amplitudes in the zonal and meridional wind during this time interval are somewhat complementary. In the beginning of airglow observations, amplitudes are higher in the meridional wind in all altitudes, while in the zonal wind amplitudes are much lower. On the other hand, at end of the airglow observations, as the amplitudes in the meridional wind become lower, in the zonal wind they increase and reach magnitudes around 10 m/s at all altitudes. In the case of the 3-4 day oscillations identified in August and in October in the airglow, wind variability is characterized by significant amplitudes in the zonal wind, while amplitudes in the meridional wind are lower.

As predicted by the linear theory, Kelvin waves are expected to present perturbations only in the zonal direction. The 3-4 days oscillations in the MLT are usually associated to the high phase speed Ultra-Fast Kelvin waves. Analyzing the common events of 3-4 day oscillations in the airglow and wind depicted above under the point of view of zonal and meridional wind perturbations, it is possible to see that the cases of March, August and October/November are compatible with UFKW's as their amplitudes in the zonal wind are higher than in the meridional one. The case of July presents mixed characteristics. The amplitude of the 3-4 day oscillation alternates its magnitude in the zonal and meridional wind during the airglow observations. What could explain this feature is that the 3-4 day oscillation in the beginning of the airglow observation is not a UFK and at the end of it, an UFK penetrates in the MLT, consequently the zonal wind amplitude increase around day 190. Finally, the 3-4 day oscillation identified in the airglow in January seems not to be caused by UFKW because the perturbations appears only in the meridional wind. A possible explanation for the 3-4 day wave activity in the meridional wind component in the equatorial MLT was pointed out by Younger and Mitchell (2006). They investigated the wind field variability in the MLT at Ascension Island (8ºS, 14°W) and observed a relatively high activity of the 3-4 day wave in the meridional wind. They suggested the presence of mixed Rossby-gravity waves and long period inertia-gravity waves as a possible explanation for such feature. As Ascension Island latitude is almost same latitude as Cariri, it may be possible that the 3-4 day oscillation observed in the airglow in January and July were due to mixed Rossby-gravity waves or long period inertia-gravity waves.

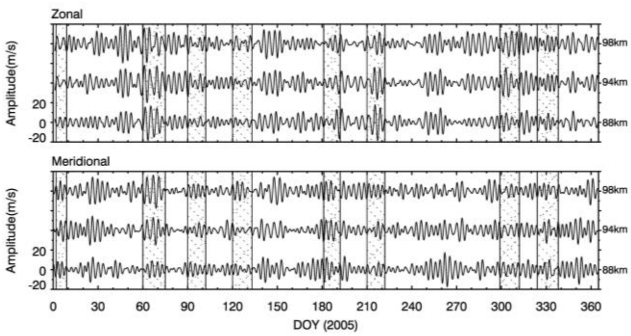

Figure 4 –Filtered zonal and meridional wind at 88, 94 and 98 km with cutoff periods from 2.8 to 4.5 days.

Vertical structure

To provide additional evidence for the UFK wave interpretation of the common 3-4 day oscillation in the airglow and wind we investigate the vertical structure of such oscillations in the zonal wind. From harmonic analysis, we have extracted out the amplitudes and phases of the 3-4 day oscillation in the zonal wind observed in March, August and October. The results are shown on Figure 4. The number on the top indicate the time interval (days of year) analyzed. Amplitudes are found to increase from around 10 m/s at 82 km altitude to 28, 21 and 15 m/s at 91 km in events of March, August and October/November, respectively. While in the first two events the amplitudes decrease above this altitude, in the third one the amplitude increases up to 22 m/s at 98 km. All the three events exhibit downward phase propagation, indicating an upward wave and energy flux propagation. From the phase lag among the wind layers, we estimated vertical wavelengths (λ_z) of the 3-4 days oscillations. The values are the following: March (44±4) km, August (62±7) km and October (45±5) km. The vertical wavelengths inferred from wind measurements associated to UFK waves in the MLT range from 35 e 85 km and present typical values around 40 km (Vincent, 1993; Younger and Mitchell, 2006; and Davis et al., 2012). Then our results suggest that the three common 3-4 days oscillation observed in the airglow and wind are consistent with a UFK wave interpretation.

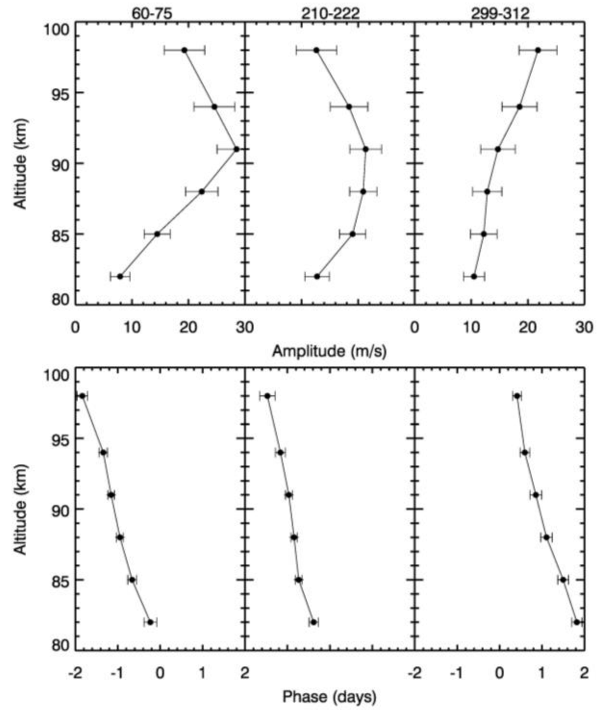

Figure 5 – Vertical amplitude (top panels) and phase profiles (bottom panels) of the 3-4 day oscillations in the zonal wind. Numbers on top panels indicate the day of year.

The Table 2 shows summarize the characteristics of the 3-4 day common oscillations in the airglow and zonal wind observed in March, August and October/November.

Table 2 – Characteristics of 3-4 day oscillations observed simultaneously in the airglow and wind.

Event	Amplitudes					
	OI5577 (%)	O_2 (%)	OH (%)	TOH (K)	wind (m/s)	λ_z (km)
March	-	27	16	3.5K	28	44
August	41	47	-	-	21	62
October	25	18	19	3 K	22	45

Interaction between UFKW and diurnal tide

The 3-4 day oscillation observed in March in the airglow presents some interesting features that are worthy to investigate. From the spectra in the Figure 2, it is possible to infer that the peaks in the LS periodogram correspond to oscillations of about 3.7 days in the OH and O2 emissions and in the TOH. On the other hand, the OI5577 does not present such signature. Instead, it is possible to infer the signature of a 2.7 days oscillation. During this time interval, the 3-4 day oscillation is quite well defined in the wind and presents a vertical structure consistent with an UFKW. Additionally, airglow observations present a good continuity almost without spurious data. The point is for what reason the 3-4 day oscillation does not appear in the OI5577 emission. To investigate this point we performed additional analysis of the simultaneous airglow and wind measurements.

All the airglow LS spectra were obtained using the whole night data. To investigate the absence of the 3-4 day oscillation in the OI5577 emission we have performed additional LS spectral analysis considering not the entire nightly airglow data set. Instead, we take airglow data only within specific time intervals during the night. We did that because it is well established that tides strongly affect the MLT airglow. Tides also present strong nocturnal variation and are known to interact with other waves resulting in changes its characteristics that could affect the resultant airglow variations. Once there is one day gap on 4th March in the airglow data, we take for this particular analysis the data from 5th to 14th March, which present an excellent quality and continuity and it is still long enough to study the 3-4 day oscillations. First we have analyzed the airglow time series build only with data obtained between 18:00h and 00:00h LT. The right panels in the Figure 6 show the LS periodogram of the airglow emissions and OH temperature. At left side of this figure are presented the respective airglow intensities and OH temperature. The red curve represents a fitting corresponding to the 3-4 day harmonic identified in the LS analysis at each parameter. In this case, periodicities in the 3-4 day range exhibit essentially the same features as those observed in the LS spectra obtained with the whole night data (Figure 2), i.e., OH, O2 and OH temperature present approximately 3.5-day oscillations, while OI5577 emission presents a 2.8-day oscillation. Next, we performed the LS spectral analysis of the airglow and OH temperature time series only with the data obtained between 00:00h and 05:00h LT. Figure 7 shows the results. It is interesting to note that in this case the OI5577 emission exhibits a very well-defined 3.5-day oscillation, as well the other two emissions and the OH temperature. In other words, now all emissions and temperature exhibit the same oscillatory pattern and especially in the OI5577 emission, the influence of the 3.5-day wave is most prominent.

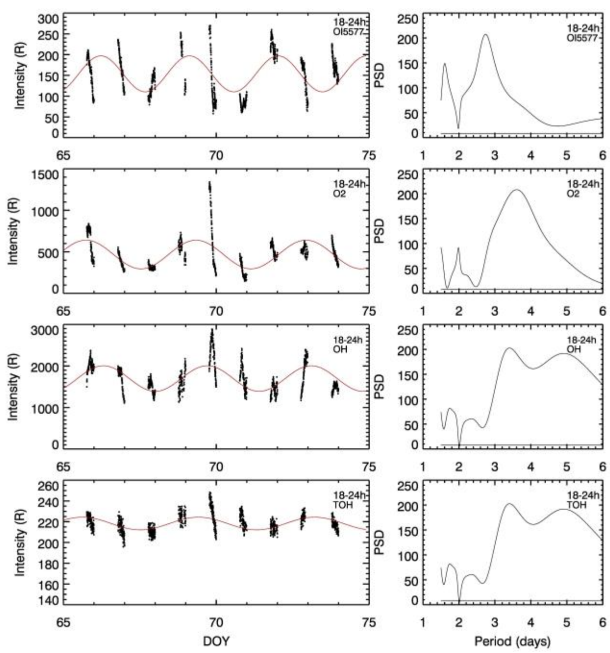

Figure 6 –Lomb-Scargle (LS) spectra (right panels) of the OI5577, O_2(0-1) and OH(6-2) emissions and OH rotational temperature (TOH) calculated with data obtained between 18:00 h and 00:00 h LT, along with its respective time variability from 5th to 14th March 2005 (left panels). The red curve represents a harmonic fitting corresponding to each peak identified in the LS spectra.

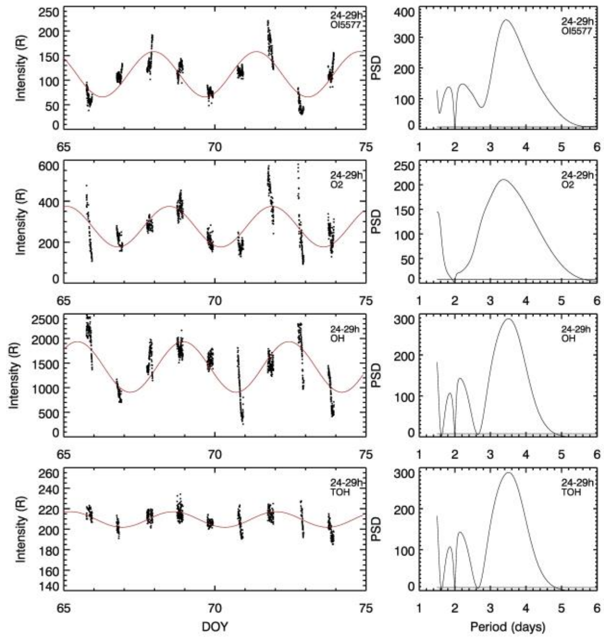

Figure 7- Same as Figure 6, but for the data obtained between 00:00 h and 05:00 h LT.

This result indicates that airglow variability in the scale of days can be affected by the time of acquisition of the data. This feature suggests a possible tidal effect in the emissions. The influence of the solar tides in the airglow is well-known. In the equatorial region, the tidal airglow variability is strong before local midnight, particularly in the OI5577 emission and, after that time, such effects are weaker (Shepherd, 2005). Then tidal variability could be the cause of the absent of the 3-4 day OI5577 emission when considering pre-midnight data. The source of tidal variability includes, among other factors, the interaction with planetary scale waves. When a non-linear interaction between these two waves takes place, the tidal amplitude is normally modulated at the period of the planetary wave. Figure 8 shows the amplitude of the diurnal tide in the zonal (left panel) and meridional (right panel) wind. Both tidal amplitudes exhibit strong variations in time and altitude. From days 60 to 65 the amplitude of the diurnal tide in the zonal wind is weak. From Figure 4 one can notice that amplitude of the 3-4 day wave in the zonal wind is stronger between days 60 and 70, i.e., high amplitudes of the UFKW coincides with low tidal amplitude in the zonal wind. Additionally, the diurnal tide amplitude in the zonal wind presents a clear variability of approximately 4 days, which is stronger above 92 km, indicating a possible interaction between the diurnal tide and the UFKW.

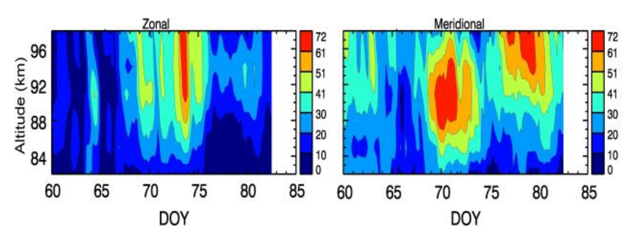

Figure 8 – Diurnal tide amplitude in the zonal (left panel) and meridional (right panel) wind.

The previous results indicate an interaction between the diurnal tide and the UFKW, where the UFKW modulates the amplitude of the diurnal tide. Such modulation is stronger above 92 km. Under this point of view the absent of the 3-4 day oscillation in the OI5577 when taking the whole night and pre-midnight data can be explained as a consequence of the changes in the diurnal tide amplitude due to the presence of the UFKW. Changes in the diurnal tide amplitude also should cause modifications in the airglow variability once the emissions are strongly driven by the diurnal tide before midnight. Moreover, as the changes are stronger above 92 km the OI5577 emission would be expected to be the most affected. On the other hand, when the tidal influence is reduced by taking the airglow data from 00:00h to 05:00h, the effects of the UFKW passage through the emission layers become more evident.

Conclusions

In this study, we have investigated the 3-4 day oscillations in the equatorial MLT airglow and wind. The 3-4 day oscillations appear intermittently along the year in both airglow and wind. They induced amplitudes variations in the airglow that reach over 40% relative to mean intensity in the OI5577 and O_2b(0-1) emissions, while in the OH(6-2) amplitudes range from 15 to 20%. Amplitudes in the zonal wind are maxima around 90 km and their highest magnitudes lay between 22 and 28 m/s. Vertical wavelengths exhibit typical values for UFKW ranging between 44 and 62 km. The 3-4 day oscillations compatible with Ultra-fast Kelvin wave were observed simultaneously in both airglow and wind in March, August and October/November. The UFKW was observed to interact with the diurnal tide by modulating its amplitude. As consequence, the presence of 3-4 day induced oscillations in the airglow could be affected by time of acquisition of the data.

Acknowledgments

We are thankful to Universidade Federal do Oeste da Bahia (UFOB) for supporting our attendance at this congress.

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