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Nonlinear interaction between ultrafast Kelvin waves and the diurnal tide over a Brazilian equatorial station

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Abstract

In this study, we investigate the occurrence and characteristics of nonlinear interactions between ultrafast Kelvin waves (UFKWs) and the diurnal tide over the Brazilian equatorial region, using one year of neutral wind measurements from an all-sky meteor radar at São João do Cariri (7.4°S, 36.5°W). Six UFKW events were identified through wavelet analysis. During these intervals, **signatures consistent with nonlinear interactions were detected**, including modulation of the diurnal tide amplitude at UFKW periods and the presence of **secondary waves at frequencies consistent with the sum and difference of the UFKW and diurnal tide frequencies and** with amplitudes **between** 5-15 m/s. Secondary waves also exhibited upward propagation and vertical wavelengths of 26-58 km. **Such relatively long vertical wavelengths are favorable for vertical propagation into the lower thermosphere.** Comparisons between observed and theoretical vertical wavelengths revealed partial agreement with nonlinear interaction theory, indicating the importance of local atmospheric conditions. These results indicate that UFKWs play a significant role in short-term tidal variability and could contribute to vertical coupling processes in the equatorial atmosphere.

Introduction

The atmosphere can support a wide range of motions across various time and spatial scales. Many of these motions are periodic and can be understood as wave phenomena. Waves play a fundamental role in atmospheric dynamics, transporting energy and momentum throughout the atmosphere. Key components of the atmospheric wave spectrum include atmospheric tides, gravity waves, and planetary-scale waves, all of which contribute to the overall wavelike motion in the atmosphere. These waves can be considered primary waves. As they propagate, they may interact with other, producing additional waves that can propagate independently through the atmosphere. This dynamic process adds further complexity to the atmospheric wave spectrum.

Nonlinear interactions are characterized by the generation of secondary waves whose frequencies and wavenumbers correspond to the sum and difference of the frequencies and wavenumbers of the primary waves, as well as by the modulation of the amplitude of one primary wave at the period of the other. In the mesosphere and lower thermosphere (MLT) region, experimental evidence of nonlinear interactions between tides and planetary-scale

waves have been reported since the 1980s (e.g. Manson et al., 1982), which reported the modulation of the semidiurnal tide at periods of approximately 5 days. Studies by Teitelbaum (1989) and Teitelbaum and Vial (1991) provided theoretical support and shed light on the observations. Since then, numerous investigations based on both observations and numerical simulations have been conducted to characterize and understand the dynamical process that take place in the nonlinear interactions between tides and planetary-scale waves (e.g. Pancheva & Mitchell., 2004; Alves et al., 2012; Huang et al., 2013; Nystrom et al., 2018; He et al., 2024).

Nonlinear interactions participate and influence various atmospheric processes. They can induce short-term variability of tidal wave components, which could potentially affect the whole atmospheric dynamics. Nonlinear interactions also take part in atmospheric phenomena such as sudden stratospheric warmings (e.g., Chau et al., 2012; Mitra et al., 2023). Additionally, nonlinear interactions are one of the pathways to the coupling between the neutral and ionized atmosphere (e.g., Gan et al., 2017; Yamazaki et al., 2020; Forbes et al., 2021; Ma et al., 2022; Li et al., 2023). More recently, nonlinear interactions between atmospheric waves have been used to interpret a variety of periodic signals observed in atmospheric parameters (Qin et al., 2021; Mitra et al., 2024). For instance, during the 2019 minor Antarctic sudden stratospheric warming Eswaraiah et al., (2020) and Wang et al. (2021) observed a westward-propagating quasi-10-day wave (Q10DW) with zonal wavenumber one exhibiting symmetry about the equator, which deviates from theoretical expectations. They proposed that nonlinear wave–wave interactions may have excited Q10DWs with a range of wavenumbers, potentially accounting for the observed discrepancies with the theoretical framework.

Restricted to equatorial and low-latitude regions, Kelvin waves are zonally eastward-propagating waves that contribute to the planetary-scale wave spectrum. They occur in three distinct period bands: 15–20 days, 7–10 days, and 3–4 days and are referred to as slow, fast, and ultrafast Kelvin waves, respectively (Wallace and Kousky, 1968; Hirota, 1978; Salby et al., 1984). Ultrafast Kelvin waves (UFKWs) present longer vertical wavelengths, enabling them to propagate above the mesopause (Forbes, 2000). The nonlinear interaction between UFKW and atmospheric tides has been investigated through observations and numerical simulations. England et al. (2012) presented observational evidence of nonlinear interaction between ultrafast Kelvin waves (UFKWs) and the diurnal tide. Egito et al. (2018) also provided evidence of such interaction, including the generation of a ~1.3-day secondary wave, modulation of the diurnal tide amplitude, and associated variability in MLT airglow emissions. They further investigated the characteristics of the 1.3-day secondary wave and found that it propagates upward with a vertical wavelength of approximately 44 km, which is sufficiently long to penetrate into the E-region dynamo. Subsequently, Egito et al. (2020) reported a persistent 1.3-day oscillation in both ionospheric F region parameters virtual height ($h'F$) and the critical frequency (f_oF_2), attributing it to modulation of the E-region dynamo wind system by the secondary wave, which highlights the role of nonlinear interactions in driving day-to-day ionospheric variability. Nystrom et al., (2018) investigated the nonlinear interactions between Kelvin waves with distinct periods and zonal wave numbers with migrating and nonmigrating diurnal tides based on numerical simulations with the thermosphere-ionosphere-mesosphere

electrodynamics general circulation model (TIME-GCM) from National Center for Atmospheric Research (NCAR). They found a spectrum of fifteen secondary waves generated by nonlinear interactions highlighting that nonlinear wave-wave interactions could significantly modify the way that the lower atmosphere couples with the ionosphere. Additionally, investigating the vertical structure of the secondary waves, they pointed out the discrepancy between the predicted and observed vertical structure of the secondary waves in their simulations.

Understanding the occurrence of nonlinear interactions could shed light on the short-term variability of the coupled mesosphere thermosphere ionosphere system. In this study, we investigate the occurrence of nonlinear interaction between UFKW and tides, and describe the characteristics of the secondary waves generated through this interaction.

Data and Analysis

This study analyzes neutral wind measurements in the MLT over the Brazilian equatorial region, carried out by an all-sky meteor radar operating at São João do Cariri (7.4° S, 36.5° W) for the year of 2020. The radar measures neutral winds based on the reflection of Doppler-shifted echoes produced by meteor trails at altitudes between approximately 80 and 100 km. The radar transmits pulsed signals that are reflected by ionized meteor trails, which are carried by the neutral wind and are assumed to drift at the same velocity. From the Doppler-shifted echoes, it is possible to retrieve the zonal and meridional components of the neutral wind. The meteor radar at Cariri consists of one transmitting antenna and five receiving antennas. It transmits a 35.24 MHz signal with a peak power of 12 kW. Meteor echoes are grouped in altitude and time bins to infer wind components. The zonal and meridional wind components are calculated every hour at six different altitudes (82, 85, 88, 91, 94, and 98 km). To analyze the wind we applied the wavelet transform (Torrence and Compo, 1998); Lomb-Scargle periodogram (Lomb, 1976; Scargle, 1982) and harmonic analysis.

Results

UFKWs appear as transient features in the wind field, lasting only a few cycles. In contrast, tides are prominent atmospheric features that, although variable, persist in the wind field. In the equatorial MLT region, the diurnal tide is dominant. To investigate possible nonlinear interactions between UFKWs and tides, we first identified the presence of UFKWs using wavelet spectral analysis. We applied the Morlet wavelet transform (Torrence and Compo, 1998), which is suitable for identifying transient periodic signals, such as those left by UFKWs in the neutral wind. **Figure 1 shows the wavelet power spectrum of the zonal wind (upper panel) and meridional wind (lower panel) at 91 km (left panels) and 94 km (right panels) altitude.** Black contour lines indicate regions where the signal's confidence level exceeds 90%. Horizontal dashed lines at 2.8 and 4.5 days indicate the period range associated with UFKWs. The wavelet analysis reveals several periodic variations in the zonal wind in the UFKW period range. At least six events (DOY 1–10, 60–75, 90–100, 215–230, 240–260 and 280–290) can be observed throughout the year, showing peaks in spectral energy in the zonal wind that can be associated with UFKWs. These bursts of UFKW last between 10 and 20 days, allowing them to leave its signature over at least two cycles. Wavelet spectra at other altitudes (not shown here) also exhibit a similar distribution of spectral energy associated with UFKWs. The UFKW

signatures are observed during all seasons. The seasonal distribution of UFKWs described here is similar to that found in other studies (e.g., Lima et al., 2008). Conversely, as expected for UFKWs, no such strong signatures appear in the meridional wind, which is dominated by shorter period oscillations such as quasi-two-day oscillations.

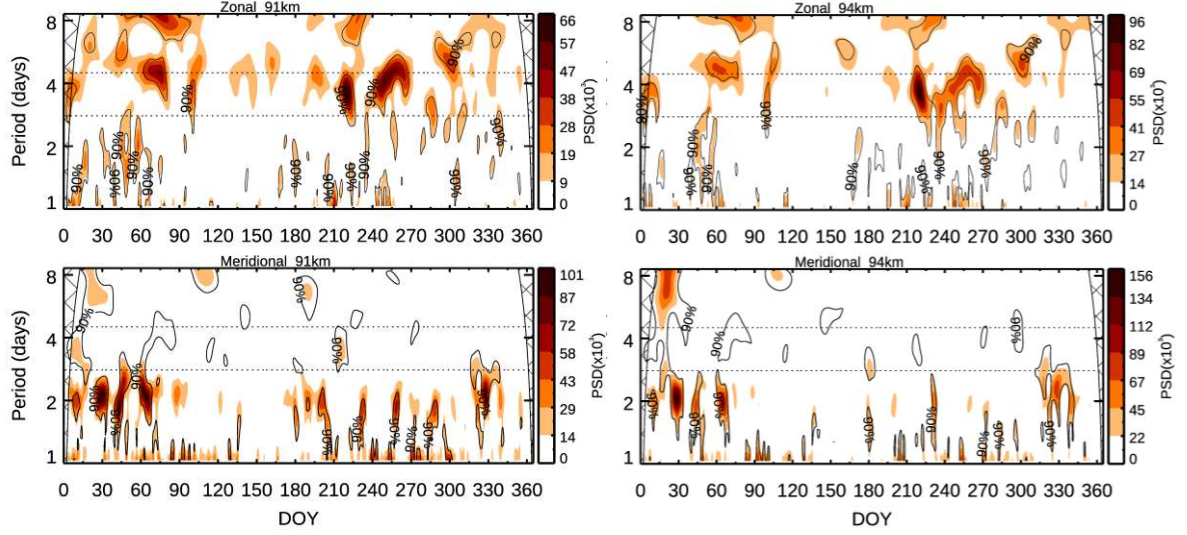


Figure 1- Wavelet power spectrum of the zonal (top) and meridional (bottom) wind at 91 km (left panels) and 94 km (right panels).

A single ground station does not provide information about the horizontal structure of the wave, but measurements of the wind at six vertical layers permit the determination of vertical profiles of amplitude and phase. From the vertical phase profile, one can infer propagation direction and vertical wavelength. To examine these features of the UFKW signatures, we performed a harmonic analysis to obtain vertical profiles of amplitude and phase. Using the least squares method, we fitted the following harmonic function to the data.

$$y(t) = y_o + A \cos\left(\frac{2\pi(t-\phi)}{T}\right) \quad (1),$$

in which y_o is the mean wind, A is the wave amplitude, t is the time, T is the UFKW period and ϕ is the phase in the same units as t .

We fitted Equation (1) to the zonal wind data for the six previously listed events. Figure 2 shows the vertical profiles of amplitude and phase of UFKW signatures in the zonal wind. The colored numbers indicate the day of the year (DOY) interval. The vertical profiles show that amplitude generally increases with altitude below 91 km and decreases above this level in most cases. The largest amplitudes reach approximately 26 m/s, while the smallest are just below 10 m/s. The phase profiles exhibit downward phase propagation across all six events, indicating upward energy propagation. We determine the vertical wavelengths by analyzing the phase lag at different altitudes. This is achieved by fitting a linear function to the data, where the slope represents the vertical phase velocity. Multiplying this velocity by the wave period yields the vertical wavelength. **Uncertainties in the phases obtained from the harmonic analysis and in the linear fitting were propagated to estimate the uncertainties in the vertical wavelengths.** The vertical wavelengths range from 35 to 55 km, aligning with typical values for

UFKW reported in the literature (e.g., Younger and Mitchell, 2006; Lima et al., 2008). This suggests that all six cases are consistent with the presence of UFKWs in the wind field. Table 1 summarizes UFKWs features, showing maximum amplitude, vertical wavelength, observed period, and the DOY interval during which they were observed

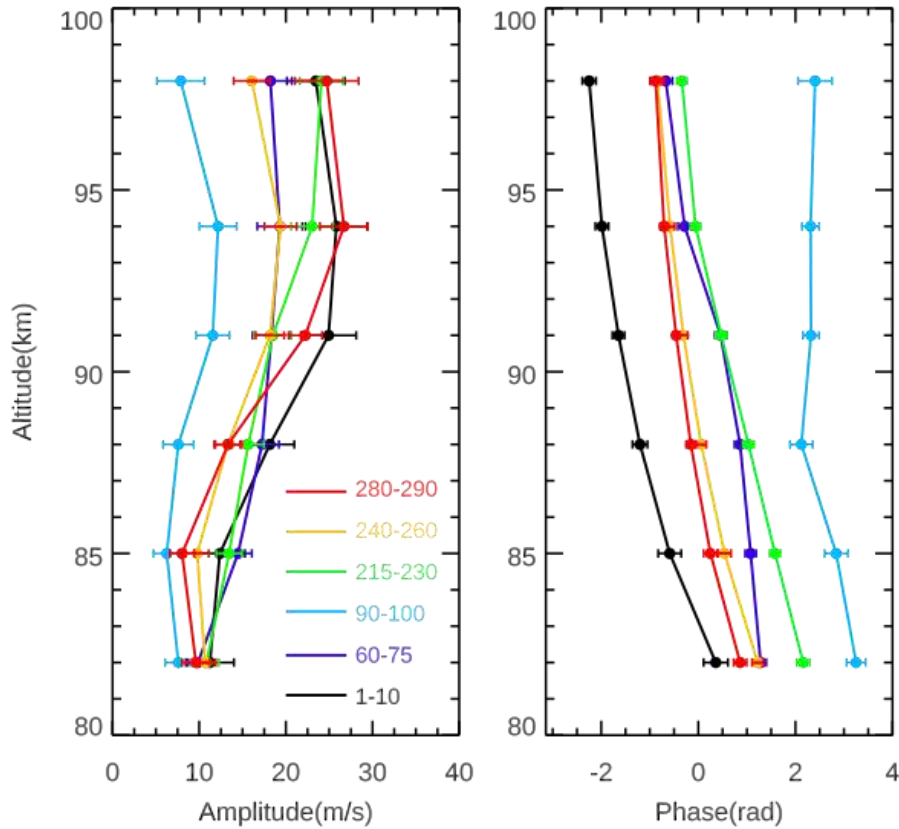


Figure 2 -Vertical structure of amplitude and phase of the UFKW signatures in the zonal wind. Different colors represent different events given by DOY intervals. Phase is expressed in radians to make the comparison at distinct altitudes easier.

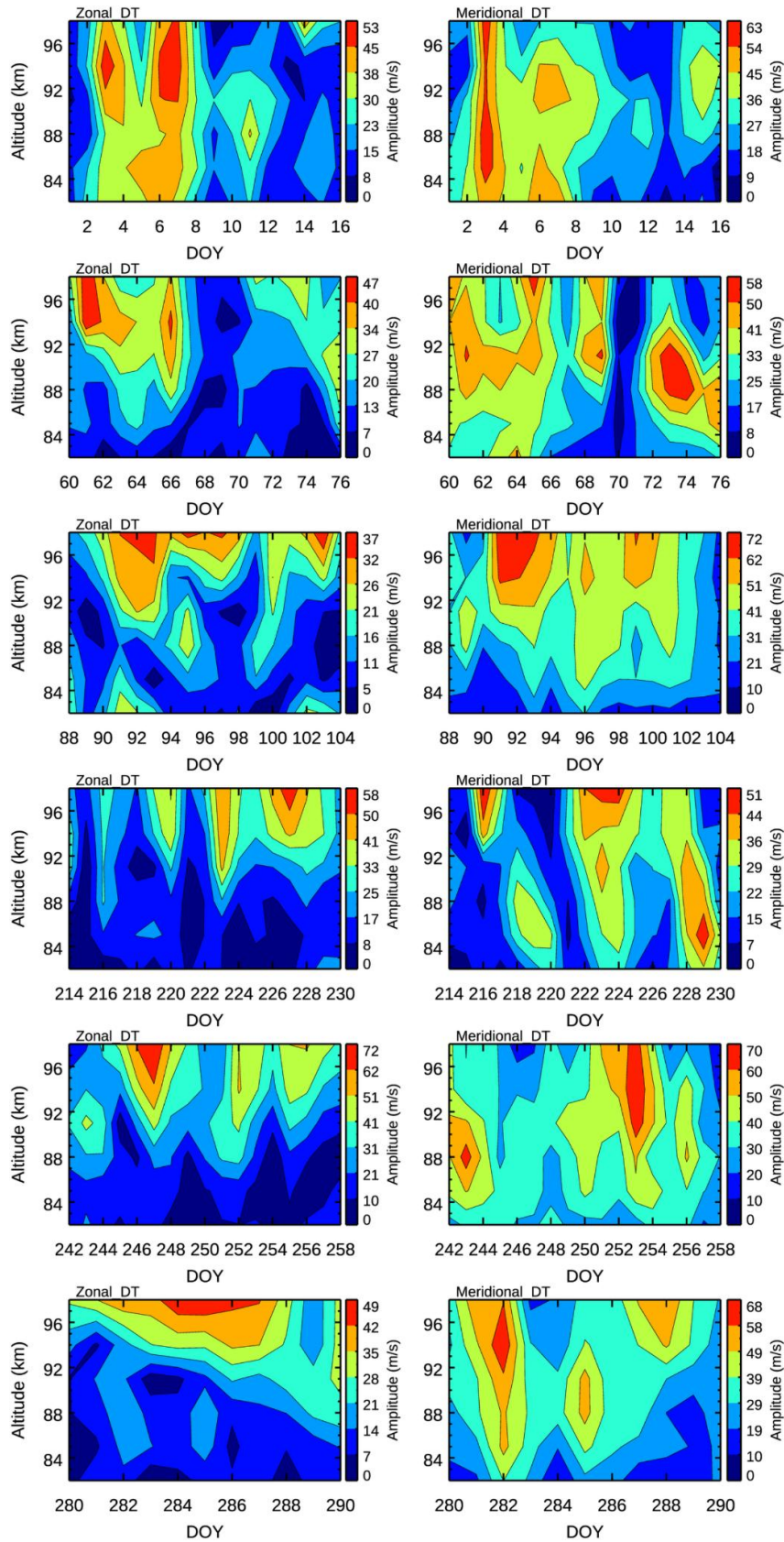
Table 1 -Observed period, maximum amplitude and vertical wavelength of the UFKW signatures in the six events.

DOY	Period (days)	Maxima amplitudes (m/s)	λ_z (km)
1-10	3.9	25	36 ± 5
60-75	4.3	20	47 ± 6
90-100	3.2	17	55 ± 16
215-230	3.6	21	35 ± 2
240-260	4.2	22	43 ± 6
280-290	3.3	26	44 ± 6

In the context of the nonlinear interaction between tides and planetary-scale waves, the primary evidences of this interaction include the modulation of tidal amplitude at the periods of the planetary waves and the generation of secondary waves with frequencies equal to the

sum and difference of the frequencies of the tides and planetary-scale waves. First, we analyze the variability of the diurnal tide amplitude during UFKW episodes. To extract tidal amplitudes, we applied a windowed harmonic analysis with a two day length window, forwarded by one day. This approach provides a balance between temporal resolution and stability in amplitude estimates. In the harmonic analysis, we included both the diurnal and semidiurnal tidal components, allowing us to capture the contributions of these key tidal modes and to observe how their amplitudes vary during UFKW events. By focusing on amplitude variations, this method enables us to track how UFKWs modulate tidal energy in the atmosphere, highlighting potential wave-tide interactions during active UFKW periods. Although the UFKW is prominent in the zonal wind, there are reports of secondary waves generated by nonlinear interaction between the UFKW and the diurnal tide observed in the meridional wind (England et al., 2012). Therefore, we also included the diurnal tide component in the meridional wind in our analysis. Figure 3 shows the amplitudes of the diurnal tide in the zonal and meridional wind across the six UFKW events, highlighting the short-term variability in diurnal tide amplitude. The diurnal tidal amplitudes consistently exhibit clear modulation at UFKW periods across most of the events in both the zonal and meridional wind. Increases and decreases in amplitude generally coincide well between these components, with a few discrepancies observed in the altitude of the modulation.

During the first event (DOY 1 to 10), the amplitudes exhibit a distinct 4-day periodic variation, especially noticeable above 90 km in the zonal wind and slightly lower in the meridional wind, with pronounced peaks around DOY 3 and 7. This modulation decreases in intensity and shifts to approximately 88 km in both components. In the second event (DOY 60 to 75), two amplitude maxima appear between DOY 61 and 65 at altitudes above 90 km in both the zonal and meridional winds, resulting in a 4-day modulation. In the third event (DOY 90 to 100), the amplitude modulation is less evident; however, periodic intensifications are observed around DOY 92 and 96 at altitudes above 96 km in both components. The fourth (DOY 215-230) and fifth (DOY 240-260) events display similar characteristics, each showing three periodic intensifications, all occurring above 92 km in the zonal wind. In the meridional wind, the diurnal tide amplitudes follow a similar pattern, with enhancements occurring slightly lower in altitude. During the sixth event (DOY 280-290), the diurnal tide amplitude modulation is more prominent in the meridional wind, with enhancements observed around 90 km on days 282 and 285. In the zonal wind, although weak, there is a modulation of the diurnal tide amplitude between 84 and 88 km.



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199 Figure 3. Vertical profiles of amplitude of the diurnal tide in the zonal and meridional wind
 200 during the six events of UFKW. DT stands for diurnal tide.

Another evidence of the nonlinear interaction is the generation of secondary waves with frequencies equal to the sum and difference of the frequencies of the tide and the UFKW. To investigate the presence of secondary waves resulting from the nonlinear interaction between the diurnal tide and UFKW, we performed a spectral analysis using the Lomb-Scargle periodogram during the six UFKW events. Figure 4 presents the periodograms across all altitudes in the zonal and meridional wind. The three black dotted vertical lines highlight the frequencies of the two potential secondary waves (sum frequency at 1.25 cycle per day-cpd hereafter as SW+ and difference frequency at 0.75 cpd hereafter as SW-) as well as the UFKW reference frequency at 0.25 cpd. The diurnal tide frequency is 1 cpd. **Although the observed frequency of the UFKW is not exactly 0.25 cpd and consequently, the sum and difference SW frequencies will not be exactly 1.25 and 0.75 cpd, respectively, we placed these reference lines to make it easier to identify the SW.** The line plots with distinct colors represent the spectrum at different altitudes. The signatures of the UFKW in the zonal wind (along with their absence and/or lower spectral energy in the meridional wind) and the diurnal tide appear consistently as expected. In general, the spectral signatures of the secondary waves are somewhat irregular. Sometimes they appear as SW+, while in other cases they manifest as SW-, and their occurrence varies with altitude.

In the 1st event (DOY 1-10), the SW+ appears above the confidence level from 88 to 98 km and the SW- is absent in the zonal wind. In the meridional wind, conversely, it is the SW- that appears between 88 and 98 km and there is no signature of the SW+. In the 2nd event (DOY 60-75), the signatures of the SW- show up in the zonal wind only at 94 and 98 km and there is a peak corresponding to the SW+ at 82 km. In meridional wind there are no peaks at the secondary wave frequencies. In the 3rd event (DOY 90-100), there is only a signature of the SW+ in the zonal wind at 82 and 85 km. In the 4th event (DOY 215-230), the signature of the SW- is observed at all altitudes in zonal and meridional wind. Although they are slightly shifted from central frequency, one should notice that the UFKW is not observed at 0.25 cycle-1 frequency and the SW frequencies are not expected to be exactly 1.25 and 0.75 cycle/day. In the 5th event (DOY 240-260), while spectral peaks associated with the SW+ can be observed from 82 to 94 km at least at the significance level, there are no signatures of the SW- in the zonal wind. The meridional wind exhibits similar behavior with SW+ peaks from 85 to 91 km. In the last event (DOY 280-290), one can observe the presence of SW- signatures from 82 to 91 km and the absence of SW+ in the zonal wind. In the meridional wind, it is possible to observe a similar pattern only with the additional presence of SW- signatures at 94 and 98 km.

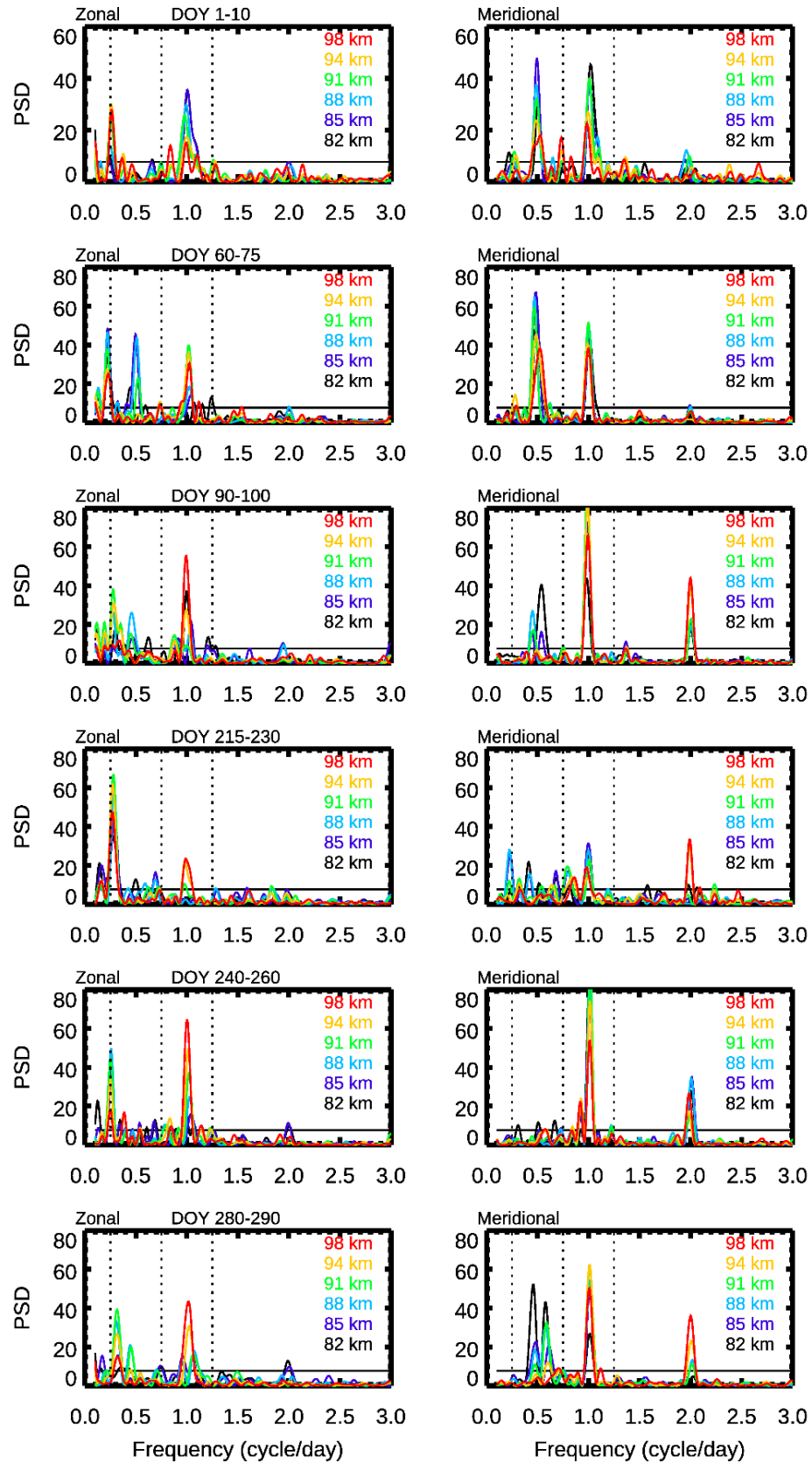


Figure 4- Lomb-Scargle **periodogram** of the zonal (left) and meridional (right) wind at 82, 85, 88, 91, 94 and 98 km altitude during the six UFKW events. **Events are denoted by the DOY interval.**

Besides the UFKW and diurnal tide signatures in the Lomb–Scargle spectra, signatures of the semidiurnal tide and the quasi-2-day wave (Q2DW) are also observed near 2 and 0.5 cpd, respectively, particularly in the meridional wind. Nonlinear interaction between the semidiurnal tide and the UFKW would produce secondary waves with frequencies near 1.75 and 2.25 cpd. Although semidiurnal tidal signatures in the Lomb-Scargle spectra occasionally exceed the confidence level, no significant spectral peaks are observed near these frequencies. This suggests that any nonlinear interaction between the UFKW and the semidiurnal tide was either absent or too weak to produce detectable secondary waves during the analyzed events. Likewise, the observed secondary wave near 0.75 cpd is unlikely to be associated with the Q2DW, whose typical frequency at low latitude regions of the Southern Hemisphere is close to 0.5 cpd (Lima et al., 2004).

As the nonlinear interaction takes place and secondary waves are generated, they can propagate independently and produce their own effects in the atmosphere. To investigate the characteristics of these secondary waves, we performed a harmonic analysis to infer their amplitudes, propagation direction, and vertical wavelengths. We fitted Equation (1) considering the appropriate frequency (SW+ or SW-) to the cases in which the signature of a secondary wave was observed at least at three distinct altitudes. Additionally, we estimate vertical wavelengths only when the vertical phase structure exhibits exclusively upward or downward phase progression.

These criteria are met by the SW+ and SW- observed in the first event (DOY 1-10) in the zonal and meridional wind, respectively, in the fourth event (DOY 215-230) by the SW- in both zonal and meridional wind, in the fifth (DOY 240-260) event by the SW+ in the zonal and meridional wind, and in the sixth event (DOY 280-290) by the SW- in both zonal and meridional wind. Figure 5 shows the amplitudes and phases of the possible secondary waves. Black and red lines denote the zonal and meridional wind components, respectively. Typical amplitudes of both SW+ and SW- range between 5 and 15 m/s, varying with altitude and wind component. Lowest amplitudes occur below 90 km. Vertical phase profiles indicate downward phase propagation, except during the fourth event (DOY 215–230) for the SW- observed in the zonal wind. In this case, there is an inflection point in the phase profile at 91 km, with downward progression above and upward progression below. The downward phase progression in most of the cases suggests secondary waves propagate upward.

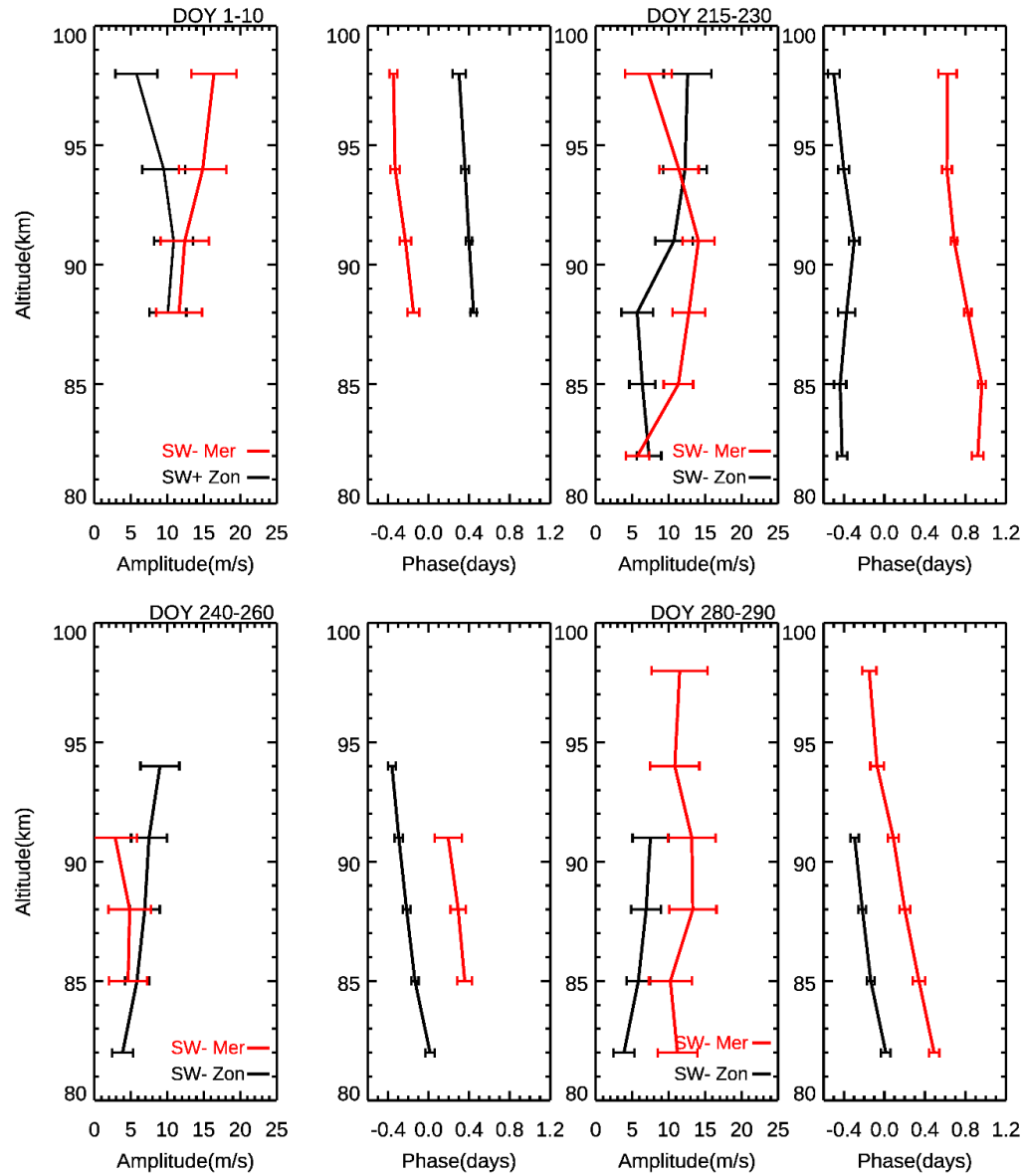


Figure 5-Vertical profile of amplitude and phase of the secondary waves identified at least three distinct altitudes. Black and red lines indicate zonal and meridional wind. **SW+ and SW-** denote sum and difference secondary waves, respectively.

denote sum and difference frequency secondary waves, respectively.

The nonlinear theory **also** predicts that the wavenumbers of the secondary waves are also the sum and difference between the wavenumbers of the primary waves, which is described in the equation (2)

$$k_{sw} = k_T \pm k_{PW} \quad (2),$$

in which k_{sw} , k_T and k_{PW} are the vertical wavenumbers of the secondary wave, tide and planetary wave, respectively.

In terms of vertical wavelengths λ , the equation (2) can be expressed as follows:

$$\lambda_{sw} = \lambda_{DT} \lambda_{UFKW} / (\lambda_{UFKW} \pm \lambda_{DT}) \quad (3).$$

We evaluated whether the relationship predicted by equation (3) holds in the present study. The analysis utilized vertical wavelengths of the diurnal tide and the upward propagating Kelvin wave (UFKW), both derived from wind observations. The vertical wavelength of the UFKW was calculated as previously described. For the diurnal tide, we obtained the vertical wavelengths using a composite day analysis restricted to periods of UFKW activity. At each altitude level, a 24-hour composite time series was constructed by averaging wind measurements taken at the same time each day. We fitted a harmonic function as the Equation (1) to the composite time series to derive tidal amplitudes and phases. We considered the diurnal and semidiurnal components. From these, the vertical wavelength was inferred following the same approach as for UFKW, **including uncertainties estimates**. In this context, the theoretical vertical wavelength of the secondary waves refers to that calculated from equation (3), while the observed wavelength corresponds to the value inferred from harmonic analysis of the secondary wave signatures in the wind field. Table 2 presents the vertical wavelengths of the diurnal tide in both the zonal and meridional wind, the UFKWs, and the theoretical and observed vertical wavelength of the secondary waves. For the fourth event (DOY 215–230), as the secondary wave observed in the zonal wind exhibited an inflection point in its phase progression at 91 km, changing from upward to downward, we do not estimate its vertical wavelength. The observed vertical wavelengths of the SW range from 26 to 58 km, whereas theoretical **estimates** exhibit greater variability, spanning 12 to 108 km. Overall, one can observe some discrepancy between the theoretical and observed vertical wavelengths of the SW. In the four events listed in Table 2, a total of eight SW in the zonal and meridional wind components were identified. In the first event (DOY 1-10), both observed and theoretical vertical wavelengths of the SW- and SW+ are very different. The same occurs in the fifth event (DOY 240-260), in which SW+ was observed in the zonal and meridional wind. In two events (DOY 215-230 and DOY 280-290), both observed and theoretical vertical wavelengths agree with each other. In the last event (DOY 280-290), the SW- is observed in both zonal and meridional wind components, however, only the zonal wind theoretical and observed vertical wavelengths agree with each other.

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Table 2- Vertical wavelengths (in km) of the diurnal tide, UFKW and secondary waves in the zonal (z) and meridional (m) wind. **(obs) and (theo) denote the observed and theoretical vertical wavelength of the secondary waves, respectively.**

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DOY	Diurnal Tide (km)	UFKW (km)	SW+(theo)	SW+(obs) km	SW-(theo)	SW-(obs)
1-10	33±2 (z) 27±2 (m)	36±5	17±6 (z)	56±1(z)	108±17(m)	58±14(m)
215-230	18±3 (z) 20±1 (m)	35±2			37±7(z) 47±4(m)	undefined (z) 47±9 (m)
240-260	16±3 (z) 24±4 (m)	43±6	12±3 (z) 15±3 (m)	26±3 (z) 29±3 (m)		

280-290	19±3 (z) 25±1 (m)	44±6			33±7 (z) 58±8 (m)	38±8 (z) 32±2 (m)
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Discussions

The previous results show evidence of the nonlinear interaction between the UFKW and the diurnal tide, which include the modulation of the diurnal tide amplitudes in the zonal and meridional wind at the periods of the UFKW and presence of secondary waves. In the framework of the linear wave theory, wavelike perturbations in the atmospheric fields (e.g. wind, temperature and pressure) are supposed to be small such that the product between perturbations can be neglected. On the other hand, in the context of the nonlinear interaction, products between perturbations are not neglected and the outcome is additional wavelike solutions of the governing equations with frequencies, zonal and vertical wavenumber that are the sum and difference between the frequencies, zonal and vertical wavenumbers of the primary waves. Primary waves are expected to have significant amplitudes for nonlinear interactions to occur. Diurnal tide amplitudes in both zonal and meridional wind are systematically higher than the amplitudes of the UFKW. This might suggest that the UFKW amplitudes play an important role in the nonlinear interaction. Based on MLT meteor wind data over the equatorial region, England et al. (2012) and Egito et al. (2018) reported UFKW amplitudes of 20 m/s and almost 30 m/s, respectively, when nonlinear interaction of this wave with diurnal tide took place. In the present study, evidence of the nonlinear interaction becomes more pronounced when UFKW amplitudes reach and/or surpass 20 m/s. This occurs in most of the events, except in the 3rd event (DOY 90-100). In this event, the UFKW amplitudes stay near 10 m/s, the modulation of the diurnal tide amplitude at the UFKW period is less evident and the presence of SW signatures in the periodogram is incipient, suggesting that, if the nonlinear interaction exists, it is very weak **to be detected. The present observations suggest that stronger evidence of the nonlinear interaction tends to occur when UFKW amplitudes reach approximately 20 m/s or higher.**

In addition to the tidal amplitude modulation, the presence of secondary waves is also indicative of the nonlinear interaction. Once they are generated, they can propagate independently and have their own effects in the atmosphere. Therefore, it is important to investigate and discuss the vertical structure of the secondary waves. The vertical phase structure of the secondary waves indicates upward propagation in almost all cases. Typical values of the observed vertical wavelengths (26 to 58 km) **are relatively large and favorable for vertical propagation into the lower thermosphere** (see Gan et al., 2017).

Possible effects would be the modulation of the wind system of the E region dynamo, which might affect the ionosphere. The modulation of the wind system could yield the modulation of sporadic E layers and vertical ion drifts. Egito et al. (2020) reported a 0.75 cpd (~1.3 day period) upward propagating secondary wave resulting from the nonlinear interaction between an UFKW and the diurnal with relatively long vertical wavelength (~44 km) in the MLT wind system. Corresponding variations at the same period of the SW were observed in the h'F and foF2, indicating possible penetration into the E region dynamo with amplitude sufficiently large to transmit its effects to the F region. Future studies should address in more

detail the effects of the secondary waves in the equatorial ionosphere.

Testing the predictions of the nonlinear theory is important to understand its capability and limitations. **Although we applied equation (3) to predict the vertical wavelengths of the SWs, its comparison with observed vertical wavelengths serves as an additional assessment of the applicability of the simplified theoretical formulation proposed by Teitelbaum and Vial (1991).** In our study, the predictions of the vertical wavelengths using Equation (3) showed partial agreement. In two cases the theoretical and observed vertical wavelengths agree with each other. The use of Equation (3) to predict the vertical wavelengths of the secondary wave produced by nonlinear interactions between tides and planetary scale waves has shown distinct results. Based on MLT wind measurements at Esrange (68°N, 21°E), Pancheva and Mitchell (2004) observed the nonlinear between a 15 and 23-day planetary waves with the semidiurnal tide and found a good agreement between the observed and theoretical vertical wavelengths of the secondary waves produced by the nonlinear interaction. In contrast, based on numerical simulations using the NCAR TIME-GCM, Nystrom et al. (2018) did not achieve any success using Equation (3). In their simulation, they considered the interaction between migrating and nonmigrating diurnal tides and UFKWs with zonal wavenumber 1 and 2, which resulted in a spectrum of a dozen secondary waves. To explain such a discrepant result, Nystrom et al. (2018) stated that Equation (2), which leads to Equation (3), was assumed to be a valid input in the calculation of Teitelbaum and Vial (1991) and did not emerge as a result of the theory or the calculation. They concluded that one cannot assume a priori that wave-wave interactions lead to SW that are well expressed in terms of a single vertical wavelength, or that there is a simple relationship between the vertical wavelengths of secondary and primary waves. To understand such an argument we must look at the papers of Teitelbaum et al., (1989) and Teitelbaum and Vial (1991), which are the framework of the nonlinear interactions involving tides and planetary scale waves.

Teitelbaum et al. (1989) discussed the nonlinear interaction between diurnal (DW1) and semidiurnal (SW2) migrating tides in the generation of the terdiurnal tide. In their model, they obtained the SW by solving the primitive equations, that describe the atmospheric dynamics, forced by second order nonlinear advective terms coming from the solutions of the classical linearized tidal theory, i.e., the forcing is the product of the first order solutions that describe the DW1 and SW2. The outcome was the horizontal and vertical structure of the SWs. In both first and second order solutions, they included latitude and height-dependent mean winds and temperature structures. Teitelbaum and Vial (1991), in their study of the nonlinear interaction between tides and planetary waves, adopted a simpler approach to the problem. They looked at the problem locally, i.e., assumed that nonlinear interaction between the tides and planetary waves exists. Then the relationship between the wavenumbers and frequencies of the primary waves is specified a priori, before solving the second-order nonlinear equations, which are forced by the products of parameters of the primary waves coming from the presence of advective terms in the primitive nonlinear equations. They also **did** not consider mean winds. This simplifies the problem and does not capture important features of the latitudinal and vertical distributions of the SW sources. Nystrom et al. (2018) argued that advective forcing terms that drive SW and their response have very complex latitude-height distributions, and would result in multiple wave modes spanning over a range of vertical wavenumbers, which evolve with altitude due to mean wind and dissipative filtering. Therefore, the discrepancies between observed and theoretical vertical wavelengths in our

study are consistent with the idea that SWs do not necessarily follow a single vertical mode, especially under realistic height-dependent conditions.

Conclusions

Based on a full year of meteor radar observations over the Brazilian equatorial region, six ultrafast Kelvin wave events were identified. During these intervals, modulation of the diurnal tide amplitude at UFKW periods was observed, although with different levels of prominence among the events, and secondary waves at frequencies consistent with the predicted sum and difference frequencies were observed in both zonal and meridional winds. Vertical structure of the secondary waves showed they propagate upward with vertical wavelengths ranging from 26 to 58 km. Such long vertical wavelengths are favorable for vertical propagation into the lower thermosphere. Comparison between observed and theoretical vertical wavelengths revealed partial agreement, suggesting that local atmospheric conditions determine whether classical nonlinear theory can accurately describe secondary wave vertical structure. These findings reinforce the dynamical role of UFKWs in short-term tidal variability and highlight the importance of wave–wave interactions for vertical coupling in the equatorial MLT. Future work should aim to quantify the ionospheric response to these secondary waves and assess the conditions under which nonlinear predictions remain valid.

Data Availability

Meteor radar wind data used in this study is available upon request to the authors.

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540 **Ethics declarations**

541 **Ethics approval and consent to participate**

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543 **Competing interests**

544 The authors have no competing interests with any other groups.

545

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Contributions

547 F. Egito conceptualized the study, performed the data analysis, and wrote the manuscript. F.
 548 Moura contributed to the data analysis and interpretation of the results. R. Buriti was
 549 responsible for the meteor radar operation, contributed to data collection, and assisted in
 550 revising the manuscript. P. P. Batista contributed to the interpretation and discussion of the
 551 results and also participated in the revision of the manuscript.