Signatures of ultra fast Kelvin waves in the equatorial middle atmosphere and ionosphere

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[1]   In the equatorial atmosphere, oscillations with periods of 3 to 4 days have been observed in the meteor radar zonal wind at Cariri (7.4°S, 36.5°W), in the ionospheric minimum virtual height h'F and the maximum critical frequency foF2 at Fortaleza (3.9°S, 38.4°W), and in the TIMED/SABER satellite temperature data in the stratosphere-mesosphere. Wavelet analyses of these time series reveal that the 3−4-day oscillation was observed for all of these data during the period from March 1 to 11, 2005. From the characteristics of the downward phase propagation (wavelength of ~40 km), longitudinal and latitudinal extension, we conclude that this oscillation must be a 3.5−day Ultra Fast Kelvin (UFK) wave. This is the first report of clear evidence of propagation of a UFK wave from the stratosphere to the ionosphere. The UFK wave could have an important role in the day-to-day variability of the equatorial ionosphere evening uplift. **Citation:** Takahashi, H., et al. (2007), Signatures of ultra fast Kelvin waves in the equatorial middle atmosphere and ionosphere, *Geophys. Res. Lett.*, *34*, L11108, doi:10.1029/2007GL029612.

1. Introduction

[2] The role of planetary scale waves in the Earth's atmosphere has been extensively studied since *Rossby* [1940] reported free propagating waves in the troposphere and stratosphere. It is well known that planetary waves transport momentum and energy on a global scale, not only in a longitudinal sense, but also latitudinal and inter-hemispherical. Their propagation to the middle (30 to 100 km) and upper (above 100 km) atmosphere has been investigated by several observational techniques, both ground based and satellite [e.g., *Lieberman and Riggin*, 1997] and also by

model studies [e.g., *Miyoshi and Hirooka*, 1999]. Concerning planetary waves in the ionosphere and coupling process with the lower atmosphere, *Pancheva and Lysenko* [1988] reported quasi-two-day waves in both mesospheric winds and in the F-region electron density. *Forbes* [1996] suggested that planetary waves potentially account for significant day-to-day variability of the F-region iono- sphere. *Pancheva et al.* [2002] studied the variation of the peak height of the ionospheric F2-layer, with 27-day, 16-day and quasi 2-day periods and suggested that the 16-day period must be related to the semidiurnal tide in the MLT region. In relation to this *Haldoupis et al.* [2004] suggested that interactions between planetary waves and tides in the lower ionosphere could be responsible for E-region vari- ability. The role of planetary waves in the ionosphere and in coupling between the middle atmosphere and ionosphere, however, is still not well known.

[3] In the equatorial and low latitude region, where the Coriolis force is negligible, there exist Kelvin waves, in addition to Rossby normal mode and Rossby gravity waves. Kelvin waves are divided into 3 categories, slow (~16 days), fast (6−7 days) and ultra fast (3−4 days) (hereinafter referred to as UFK). Slow and fast Kelvin waves have been observed in the stratosphere and mesosphere [e.g., *Hirota*, 1979], but because of their relatively short vertical wave- length (10−20 km), they are believed not to propagate above the mesopause. The UFK wave in the stratosphere was first reported by *Salby et al.* [1984]. Due to the long vertical wavelength (>50 km), this wave could penetrate into the mesosphere and even above 100 km. *Forbes* [2000] called attention to this wave.

[4] The purpose of the present work is, therefore, to investigate whether there is a signature of UFK waves in the ionosphere. The presence of UFK waves was confirmed by observing mesospheric winds from 4 different sites separated in longitude and latitude, and TIMED/SABER satellite temperature data. Wavelet analysis was applied to detect a common wave packet in both the ionospheric parameters, foF2 and h'F, and in the mesospheric winds.

2. Observations

[5] A digital ionospheric sounder (DPS-4) is operated at Fortaleza (3.9°S, 38.4°W, Geomag. 2.1°S). This is a wide- band pulsed radar system with 500 W peak power and a precise fast-switching frequency synthesizer, covering the frequency range from 0.5 to 30 MHz. Ionograms are taken at 10-minute intervals. The ionospheric parameters used in the present analysis are the maximum frequency of the F2 layer, foF2, and the minimum virtual height, h'F.

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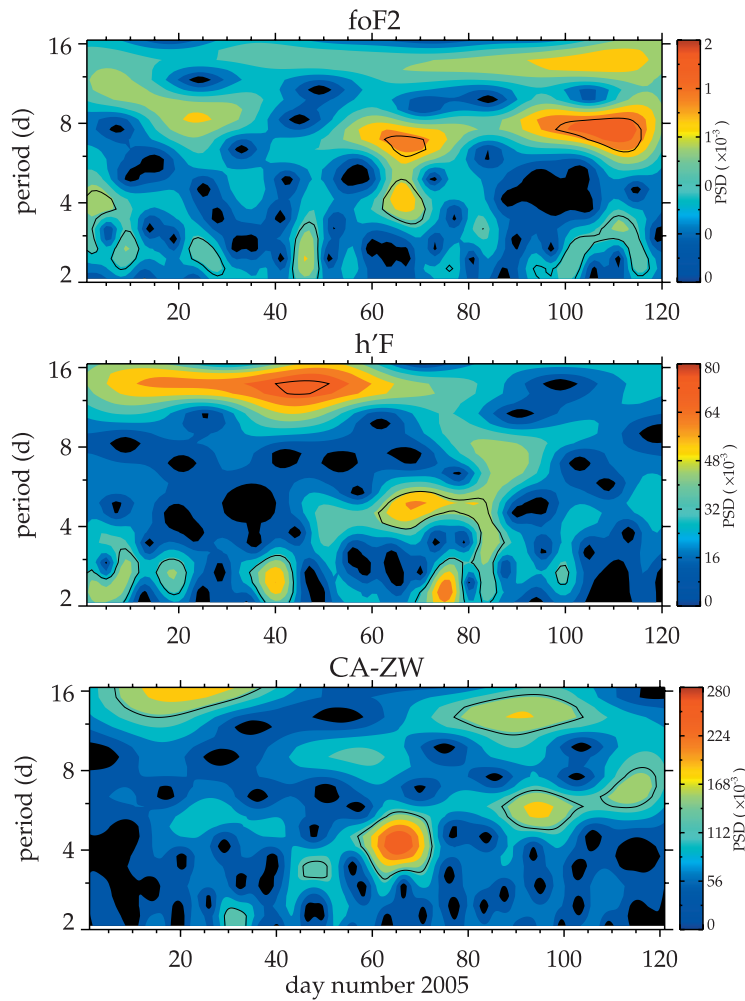
Figure 1. Wavelet analysis of (top) ionospheric foF2, (middle) h'F observed at Fortaleza, and (bottom) mesospheric zonal wind at 90 km observed at Cariri during the period from January 1 to April 30, 2005.

SkiYmet meteor radars are operated at São João do Cariri (7.4°S, 36.5°W), hereafter Cariri, Cachoeira Paulista (22.7°S, 45.0°W) and Santa Maria (29.7°S, 53.7°W). The Brazil SkiYmets are pulsed radars operating at 35.2 MHz with an interferometric receiver antenna array. The zonal and meridional winds are estimated in one hour time bins for 7 (4-km thick) atmospheric layers, with a height overlap of 1 km between adjacent layers. The SkiYmet radar at Ascension Island (7.9°S, 14.4°W), hereafter Ascension, operates at a frequency of 43.5 MHz. A description of the data processing for this radar has been presented elsewhere [*Pancheva et al.*, 2004].

[6] The TIMED satellite has been in operation since 2002 and the SABER (Sounding of the Atmosphere by Broadband Emission Radiometer) instrument observes atmospheric temperature from 10 to 130 km altitude [*Russell et al.*, 1999]. In this study the level 2B kinetic temperature data from 30 to 100 km, are used. The precision of measurement is about 1 K below 80 km and 2 K above 80 km.

[7] For the present study, the first four months of 2005, from January 1 (day 1) to April 30 (day 120) are used. Cariri and Ascension are located in the same latitudinal zone but

longitudinally separated by 2400 km, which makes it possible to observe phase differences in the temporal variation between the two sites. The three meteor radars in South America, located from 7°, 23° and 29°S, make it possible to investigate latitudinal effects. The longitudinal distance between the Fortaleza ionosonde and the Cariri meteor radar is about 430 km, negligible for our purpose.

3. Results

[8] The equatorial ionosphere electron density profile changes drastically just after sunset. The F-layer is uplifted because of the F-region dynamo effect. In order to see the uplifting and its day to day variability, we chose a fixed local time of 20:00 LT (23:00 UT), when h'F generally reaches its maximum height. The h'F time series shows significant day to day variations within a range of 220 to 350 km. On the other hand foF2 has a large diurnal variation due to ionization during the daytime and F region dynamo effects during the night time. F-region plasma depletions also affect foF2. Therefore, in order to characterize the day to day variability of foF2 we chose a local
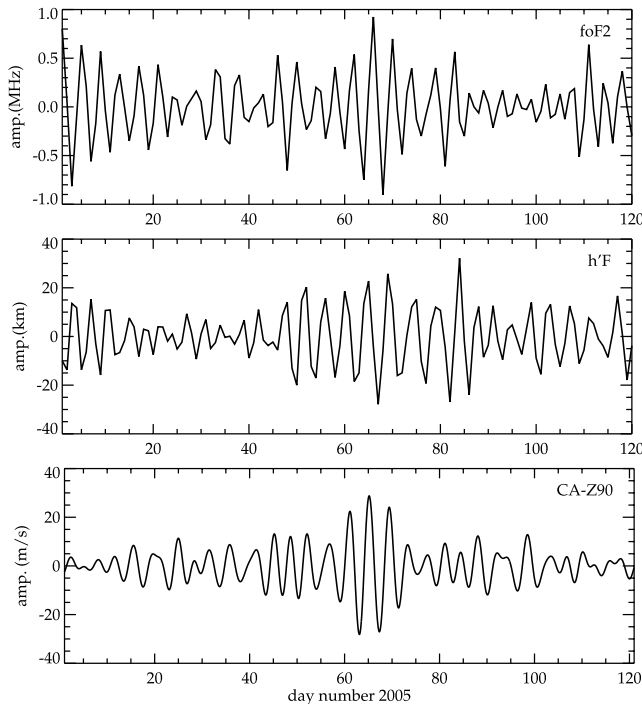
Figure 2. Amplitude and phase of the 4 ± 1-day filtered oscillations of (top) Fortaleza foF2, (middle) h'F, and (bottom) Cariri zonal wind at 90 km during the period from January 1 to April 30, 2005.

time of 19:00 LT (22:00UT) when the F-layer is in its nighttime regime but before the formation of plasma depletions. Under these conditions both h'F and foF2 should be partly related to the E-region dynamo process.

[9] In order to characterize periodic oscillations, with periods longer than 1 day, a wavelet spectral analysis was applied to the time series of the ionospheric foF2, h'F and 90-km mesospheric zonal wind. In Figure 1 are shown Morlet wavelet power spectra for foF2, h'F and zonal wind, for periods from 2 to 16 days as a function of day of the year. Since there is only one sample per day for the foF2 and h'F time series, the spectrum cuts off for periods of less than 2 days. The full line circled areas indicate a significance level higher than 90% in the spectral power density. Several kinds of wave packet with periods between 3 and 16 days can be seen. Among them a common periodic oscillation with a period of around 4 days can be seen for the three time series, lasting about 12 days, from day number 60 (March 1) (hereafter day 60) to day 75 (March 16). In order to show the amplitude and phase of oscillation a band-pass filter with a width of 2 days, centered on 4 days, was applied to the time series. The results are shown in Figure 2. The wind shows the maximum amplitude of 25−30 m/s centered on day 66. The wave packet lasted only about 12 days with 3 crests and then disappeared. A similar oscillatory feature can be seen in foF2 with an amplitude of 0.8 MHz, corresponding to an electron density variation of $\sim 2 \times 10^5$/cm^3. Although the h'F series does not form a clear wave packet, the amplitude of height variation reached 25 km (50 km peak-to-peak) at day 66. It is worth noting that h'F and the wind are almost in phase and there is a

slight phase shift (1−2 days) between foF2 and h'F. Vertical structure in the 3.5-day filtered wind oscillation from 80 to 100 km of altitude was also calculated for the period of days 60−70. The phase of the maximum of the zonal wind shifted from 99 km to 81 km, showing a downward phase propagation with a vertical wavelength of 39 ± 5 km. This indicates that the oscillation has the characteristics of a wave, with phase propagating downwards and energy upwards. There is an oscillation form in foF2 in the beginning of the year (days 1−20). It must be related to a strong magnetic activity (Kp 5−7) that occurred during this period.

[10] In order to investigate whether the observed ∼4 day oscillation over Cariri and Fortaleza has the characteristics of a planetary scale wave, we examined its vertical, longitudinal and latitudinal extensions. To study the vertical structure, we used the TIMED satellite SABER temperature data (hereafter SABER temperature). In order to find a representative temperature for a given day over Cariri, the temperature profiles during 24 hours in an area of 2000 km^2 centered on Cariri were collected and used to derive an average profile from 30 to 90 km altitude. In this manner at least 10 profiles were used to get a daily mean profile. For the temperature time series for each height, a wavelet spectral analysis was applied. The results for the 30−40 and 80−90 km altitude intervals, corresponding to the stratosphere and mesopause regions, respectively, are shown in Figure 3. The most striking feature is that there is a common oscillation pattern around the 4 day period. In the 30 km height interval, there is a strong oscillatory feature with a period of 4−6 days between days 30 and 70. At 40 km, this oscillation appeared during days 50−75 centered on day 60. Similar features can also be seen in the 80 to 90 km interval between days 60 and 75. It seems that the wave packet is propagating upwards with a velocity of approximately ∼5 km/day. The 3−5 day filtered amplitude of oscillation (not shown here) showed amplitudes of 1−2 K at around 30−40 km and about 5 K at 80 to 90 km, indicating an increase of amplitude with height. As to the longitudinal propagation feature, we chose the SABER temperature at 90 km height with 5 different longitudinal areas in a same latitudinal zone (7°S), South America, Africa, Indonesia and Eastern Pacific (Polynesia) and applied cross wavelet analysis between them. The phase differences between them indicated that the phase propagation is Eastward with the wave number 1 and the phase velocity is around ∼160 m/s. The vertical wavelength over South America region was ∼37 ± 3 km, similar to that obtained from the wind structure.

[11] As to the longitudinal and latitudinal extensions of the 4-day oscillation in the meteor winds for Cariri, Ascension, Cachoeira Paulista and Santa Maria, Figure 4 shows the 3−5 day filtered spectrum of the 4 sites. It is clear to see that the 4-day oscillation, its phase and amplitude, is almost identical for Cariri and Ascension. No significant phase lag between the two sites was found due to the short distance between them. If we compare Cariri with Cachoeira Paulista, the phase is also almost the same but the amplitude of oscillation at Cachoeira Paulista is about a half that at Cariri. The amplitude at Santa Maria is negligible. This latitudinal decrease of amplitude suggests us that this could be a wave trapped in the equatorial region. A similar 4-day wave was
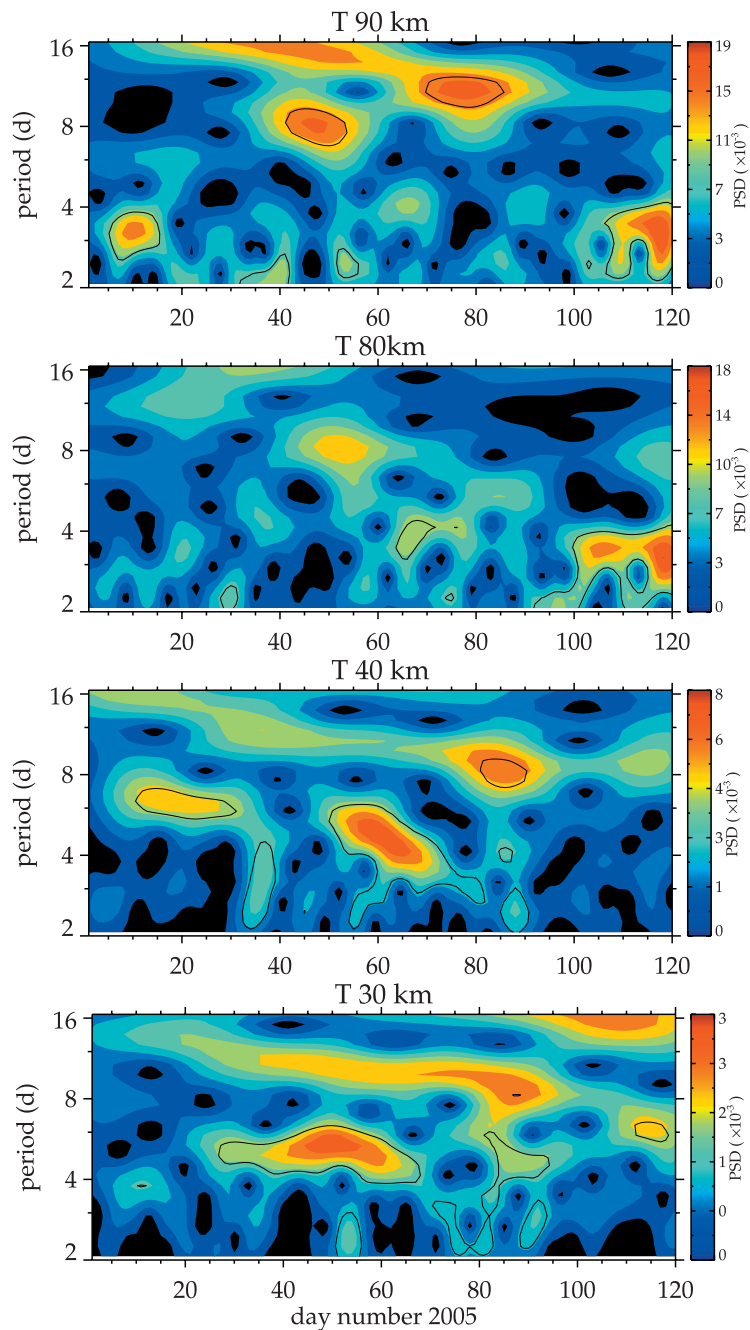
Figure 3. Wavelet analysis of the temperature field from 30, 40, 80, and 90 km over the Cariri region observed by TIMED/SABER during the period from January 1 to April 30, 2005.

observed between days 205 and 215 (July 24–August 3) for the ionospheric parameters, mesospheric wind and SABER Temperatures. It is interesting to note that this period is almost the same as that observed in 2004 (days 220–230) [*Takahashi et al.*, 2006]. As for the meridional winds at Cariri, we note that there is no 3–4-day oscillation, although there is some 2-day oscillation in the beginning of the year.

4. Discussions

[12] The observed evidence, ~4 day period, vertical phase propagation, longitudinal extension, and equatorial trapping, suggest that the observed wave might be a 3.5-day UFK wave generated in the troposphere and propagating upward. Signatures of the UFK wave at mesospheric heights were first reported by *Vincent* [1993] and later by *Lieberman and Riggin* [1997] and most recently by *Pancheva et al.* [2004]. *Takahashi et al.* [2006] showed simultaneous 3.5-day oscillations in the mesospheric zonal wind and ionospheric h'F and suggested that a UFK wave was present in the ionosphere. In the present work we find vertical and latitudinal extensions that agree with the characteristics of the UFK wave. *Forbes* [2000] predicted penetration of this wave into the ionosphere. Because of their long vertical wavelength (>40 km), these waves could
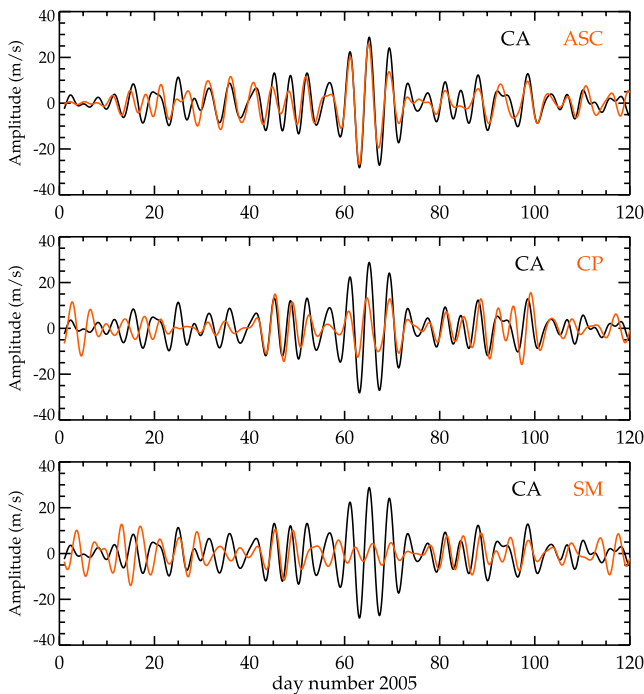
Figure 4. Amplitude and phase of 4 ± 1-day filtered harmonic spectrum: (top) comparison of meteor radar zonal winds at 90 km between Cariri (CA) (7.4°S) and Ascension (ASC) (7.9°S), (middle) Cariri and Cachoeira Paulista (CP) (22.7°S), and (bottom) Cariri and Santa Maria (SM) (29.7°S) during the period from January 1 to April 30, 2005.

reach the lower thermosphere (100–150 km). Recently *Miyoshi and Fujiwara* [2006] showed, in their general circulation model, that the UFK wave could propagate upward to the lower thermosphere with the duration of 10–60 days, i.e., 2 to 15 cycles. They also demonstrated vertical extension (up to 120 km) and latitudinal extension greater than 40 degrees. Our present results coincide with their model, except for the latitudinal extension. From our observations, the UFK wave almost disappears at 29°S. Between days 60 and 70, there was a moderate magnetic activity with Kp from 3 to 5. Wavelet analysis of the Ap index showed ∼8–10-day oscillation during this period, but no ∼4 day oscillation occurred. The observed 8-day oscillation in foF2 (Figure 2) could be related to this activity. During the second evidence of 4-day oscillation, days 205–215 (mentioned in the previous section), there was a magnetically quiet period.

[13] The presence of 3–4-day modulation of the day-to-day variability in both h'F and foF2 suggests that the UFK wave could penetrate into the ionosphere. If the Kelvin wave reaches E-region heights (100 to 120 km) it could modulate the local wind system resulting in modulation of the E-field that maps to the F-region. The E layer integrated conductivity longitudinal gradient at sunset, which controls the intensity of the prereversal electric field can be modulated by E region winds as shown by *Abdu et al.* [2006]. If the wave penetrates even higher, to 150 to 200 km, it could directly modulate the lower thermosphere zonal wind speed, resulting in direct modulation of the F-region dynamo.

From the present analysis, however, it is difficult to conclude which process is responsible.

5. Conclusion

[14] On the basis of meteor radar wind measurement from 4 different longitude and latitude sites, all in the South America and Atlantic ocean zone, we could identify the propagation of a UFK wave during the period March 1 to 16, 2005. The SABER temperatures also showed the presence of a UFK wave propagating from 30 to 90 km height. The observed wave amplitude of the zonal wind at 90 km height was 28±3 m/s and that of the temperature was around 4 ± 1 K. During the same period the ionospheric F layer h'F also showed ∼4-day oscillations, with an amplitude of 23 ± 3 km, and the critical frequency, foF2, also showed the same oscillatory pattern with an amplitude of 0.8 ± 0.1 MHz. These facts strongly suggest that the UFK wave propagates from the troposphere to the ionosphere. The UFK wave could affect the post-sunset **ExB** uplifting of the F-layer via wave-induced changes in the E-region and/or the lower thermospheric neutral wind.

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