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# 3-4 day Kelvin waves observed in the MLT region at 7.4º S, Brazil

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## Resumen

Mediciones de vientos obtenidas con un radar de meteoros operando en São João do Cariri-PB (7.4° S, 36.5° O), Brasil, durante el año 2005, se han usado para estudiar las características de las ondas ultra rápidas Kelvin en la región de la mesopausa y la termosfera inferior. Un análisis de los datos, por la técnica de transformadas de wavelet, revela la ocurrencia de oscilaciones con periodos de 3 a 4 días en ese año. Parámetros observados fueron usados para confirmar si las oscilaciones de 3 a 4 días satisfacen la relación de dispersión para ondas Kelvin. Los resultados muestran que solamente las oscilaciones ocurridas (presentes) en los meses de febrero-marzo y mayo-junio (denominados primero y segundo eventos), son compatibles con ondas propagantes Kelvin ultra rápidas con un número de onda zonal s=1. En ambos eventos, la amplitud del viento zonal alcanzó valores máximos de 25 m/s y 20 m/s, respectivamente. La progresión vertical de la fase muestra una fase descendiente, compatible con una propagación de la energía de onda subiendo y una longitud de onda vertical de aproximadamente 40 km para ambos eventos.

**Palabras clave:** Ondas Kelvin, atmósfera superior, aeronomía, dinámica de la atmósfera, radar de meteoros.

## Abstract

Meteor wind measurements obtained from São João do Cariri-PB (7.4° S, 36.5° W), Brazil, during 2005, have been used to examine the ultra-fast Kelvin wave characteristics in the mesopause and lower thermosphere region. The hourly winds were subjected to wavelet analysis and the results revealed the presence of 3-4 day oscillation in four episodes along the year. The observed parameters were used to check if the 3-4 days oscillations satisfy the dispersion relation for Kelvin waves. The results showed that only the oscillations that occurred in February-March and May-June (first and second events), are compatible with equatorial ultra-fast Kelvin wave propagation, with zonal wave number s=1. During these two events, the zonal wind amplitudes reached maximum values of 25 m/s and 20 m/s respectively. The vertical phase structure showed descending phase, compatible with ascending wave energy, and vertical wavelengths of about 40 km were found for both events.

**Key words:** Kelvin Waves, upper atmosphere, aeronomy, atmospheric dynamics, meteor radar.

## Introduction

From linear theory, a barotropic atmosphere in a resting basic state is able to support a broad spectrum of waves with periods ranging from few seconds to years. The mean zonal circulation is mainly driven by atmospheric waves, which are believed to be generated in the troposphere and propagate horizontally and vertically to the upper atmosphere, under suitable conditions (Andrews *et al.*, 1987).

The three major types of oscillations in the middle atmosphere are gravity waves, atmospheric tides and planetary waves, distinguished mainly by wave frequency. Gravity waves are oscillations with periods of the order of minutes to hours and small horizontal scale, whose restoring mechanism is buoyancy. Atmospheric tides are daily oscillations with larger horizontal structure and are primarily excited by direct absorption of sunlight by water vapor in the troposphere and ozone in the upper stratosphere and lower mesosphere. Planetary waves are disturbances having zonal wavelengths of global scale. Free traveling planetary waves can take the form of Rossby modes as westward propagating 5- and 16-day waves, mixed Rossby-Gravity as westward propagating 2-day waves, or Kelvin modes as eastward propagating 3.5-day waves.

In the equatorial region, owing to the small Coriolis effect, atmospheric waves acquire a character different from wave motions observed in the middle and high latitudes allowing the propagation of some distinct wave modes such as Kelvin and mixed Rossby-gravity waves, which are latitudinally confined near the equator

(Matsuno, 1966). Equatorial Rossby-gravity waves with zonal wavenumber 4 and period near 5 days were observed from radiosonde data by Yanai and Maruyama (1966). Planetary waves also can account for day-to-day variability of the F-region ionosphere. Takahashi *et al.* (2007) reported signatures of ultra fast Kelvin wave in the equatorial ionosphere, and suggest that this wave could affect the post-sunset **ExB** uplifting of the F-layer by wave-induced changes in the E-region and/or the lower thermospheric neutral wind.

Kelvin waves are large-scale eastward-propagating waves and are thought to be forced by convective heating processes in the tropical troposphere (Holton, 1972; Salby and Garcia, 1987). The presence of equatorial Kelvin waves in the middle atmosphere was first identified by Wallace and Kousky (1968). They observed oscillations with 15-20 day period in the lower stratosphere, known as slow Kelvin waves, characterized by wavenumber 1, with an eastward phase speed of 20-40 m/s and vertical wavelength of about 10 km. From rocket experiments, fast Kelvin waves with period near 6-7 days, a phase speed of 50-80 m/s, zonal wavenumber 1 and vertical wavelength of about 20 km were detected in the upper stratosphere (Hirota, 1978). An ultra-fast Kelvin wave with period near 3-4 days was observed in the mesosphere region by measurements via satellite (Salby *et al.*, 1984). These are eastward propagating waves with zonal wavenumbers 1 and 2, phase speed near 120 m/s and with vertical wavelength of about 40 km.

The existence of the stratospheric quasi-biennial oscillation (QBO) is believed to be partly due to the vertical eastward momentum transport by Kelvin waves (Andrews *et al.*, 1987), however, Dunkerton (1997) concluded that additional momentum flux must be provided by gravity waves. The semiannual oscillation (SAO) is also mainly driven by gravity waves, but, Kelvin waves contribute to its eastward phase (Dunkerton, 1982).

In the present paper we examine the ultra-fast Kelvin wave characteristics in the mesosphere and lower thermosphere (MLT) at São João do Cariri-PB, from meteor wind measurements obtained during the year of 2005.

## Meteor wind data and method of analysis

The wind data used in this paper were obtained from meteor radar measurements at São João do Cariri-PB (7.4°S, 36.5°W) during 2005. The system (SKiYMET Meteor Radar System) transmits pulses at 35.24 MHz and uses five receiver antennae forming an interferometric array. Meteor position is obtained from the relative phase of the echoes at the multiple antennas together with the echo range. Radial velocity is determined from the Doppler shift. The horizontal winds were estimated in 1-hour time bins and in seven height intervals of 4 km thickness each, centered in the 81, 84, 87, 90, 93, 96, and 99 km altitudes, with a height overlap of 0.5 km.

In general, the planetary scale wave activity displays non-stationary characteristics, namely, particular wave modes can occur in bursts of limited duration (Salby, 1984). Hence, it is necessary to use a method that detects and identifies signals with transient information content or non-stationary properties. One method of analysis of non-stationary wind fluctuations is the wavelet transform, which has become a common tool for analyzing localized variations of power within a time series (Torrence and Compo, 1998).

To verify the behavior of the 3-4 day oscillation in the time domain we have applied a filter, with a band pass of 2.8-4.2 days, to the time series of the zonal and meridional winds for all 7 height intervals. The amplitude and phase of the 3-4-day wave were obtained by harmonic analysis. The analysis was performed for a sliding 12-day window stepped by one day at a time.

## Results

### *Mean winds*

The averaged zonal and meridional winds observed in the MLT region over S. J. do Cariri during the year 2005 are represented in Figs. 1a, b. Contours intervals are 10 m/s and dark shading denote negative (westward or southward) motions. From Fig. 1a, it is possible to see that the time-altitude structure of the mean zonal wind is characterized by a semiannual oscillation (SAO) with winds that blow westward (negative values) in the whole altitude range from February to mid-April and from the end of July to October. From April to the end of July, the mean zonal wind is eastward (positive values) at altitudes below 96 km, with maximum amplitude at the beginning of June for altitudes below 87 km. For altitudes above 93 km the mean zonal wind is predominantly westward. The mean meridional wind is weak and exhibits an annual cycle with southward winds (negative values) from April to September. During the intervals from January to March and October to December the mean meridional wind is predominantly northward (positive values).

### *Wavelet analysis*

To reveal the dominant periodicities of the oscillations present in the zonal and the meridional wind components, a wavelet spectral analysis was applied for all seven

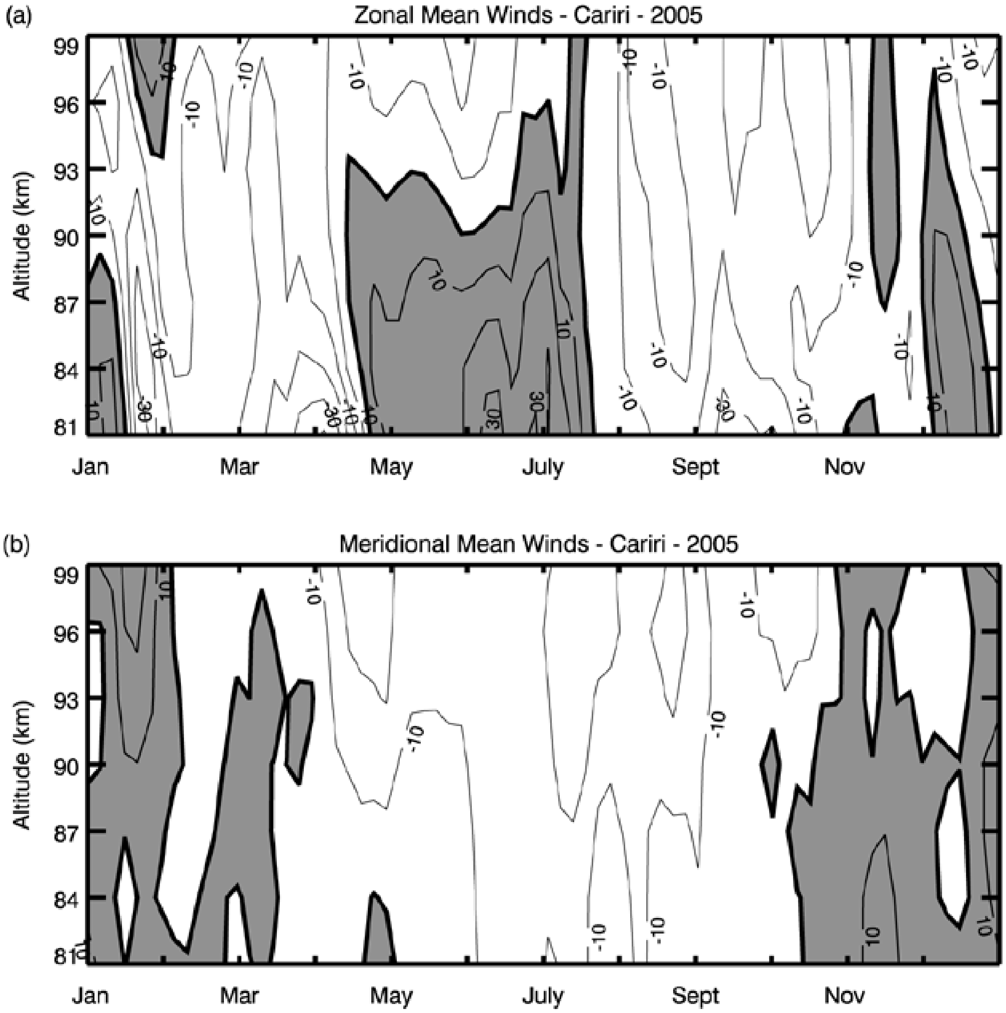

Fig. 1. Time-altitude cross sections of the monthly averaged zonal (a) and meridional (b) wind components observed over S. J. Cariri in the year 2005. Dark shading denote negative (westward or southward) motions. Contours intervals are 10 m/s.

altitude intervals. To illustrate our results, Fig. 2 displays the averaged Morlet wavelet transform spectrum for both wind components in the altitude interval 81-99 km during the year 2005. The averaged spectra were developed from Morlet wavelet results obtained for all altitude intervals, in the period range from 0.5 to 8 days, and satisfactorily exhibit the characteristics observed in the individual spectra.

Regarding the plots, we can see from Fig. 2(a) that the zonal wind spectra show occasions of energy intensification for the diurnal tide period as well as for quasi-two-day oscillations. However, the zonal wind component is rich in spectral energy associated with 3-4 day, 5 day and 6-7 day oscillations. Spectral energy between 3-4 days period occurs mainly during the time intervals around days 48-78 (17/Feb-19/Mar), 130-160 (9/May-8/Jun), 200-230 (19/July-18/Aug), and 300-330 (27/Oct-26/Nov). From Fig. 2(b), we can observe that the meridional component is characterized by the presence of spectral energy associated with the diurnal tide throughout the year, and strong bursts associated with a quasi-two-day wave, mainly during days 5-40 (05/Jan-09/Feb), 190-200 (09-19/July), and around days 255-285 (12/Sept-12/Oct). Nevertheless, peaks near a 3-4 day period are not appreciable in the meridional wind spectra.

As Kelvin waves are characterized by perturbations in the zonal and vertical winds, with negligible perturbation in the meridional component, we will analyze four episodes in which were observed evidence for 3-4 day oscillations.

### *Band-Pass filtered winds*

Fig. 3 displays hourly zonal and meridional wind components and 3-4-day band-pass filtered winds in three altitude intervals for time segments 48-78 (17/Feb-19/

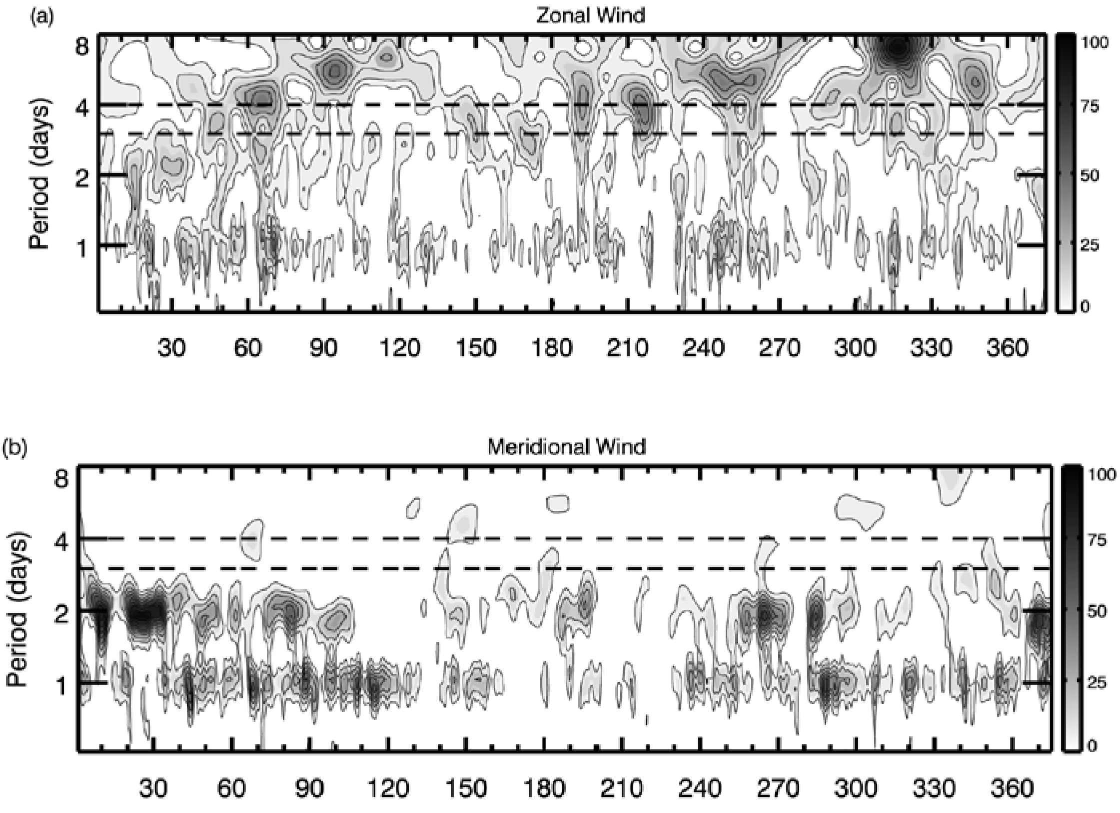

Fig. 2. Averaged (81-99 km) Morlet wavelet transform spectrum results for (a) the zonal (top) and (b) meridional (bottom) winds over São João do Cariri-Brazil. The dotted lines indicate the 3-4 days period range.

Mar) and 130-160 (9/May-8/Jun). From the graph (a), for the zonal component, it is evident that a 3-4 day wave is present and that the zonal wind is modulated by this wave, mainly during the first time segment, when the 3-4 day oscillation amplitude was more intense. As illustrated in plot (b), the 3-4 day perturbation winds are negligible in the meridional component during both time segments.

The hourly values and respective 3-4-day band-pass filtered winds for both components for time segments 200-230 (19/July-18/Aug) and 300-330 (27/Oct-26/Nov) are illustrated in Fig. 4. Again, as can be seen in plot (a), the hourly zonal wind is modulated by 3-4 day oscillations during both episodes, whereas the meridional wind component does not exhibit appreciable 3-4 day oscillations.

### *Vertical Structure*

The 3-4 day amplitude and phase profiles for the zonal wind component, evaluated by harmonic analysis for time-intervals between days 58 and 70, 140-152, 205-217 and 310-322, can be seen in the Fig. 5. During the first episode (days 58-70) the amplitude increases with height up to 90 km where it reaches a maximum value of about 25 m/s. For the second, third and last episodes, maximum amplitudes of about 20 m/s, 18 m/s and 22 m/s occur at around 99 km, 87 km and 93 km, respectively. The behavior of the phase with height showed descending phase propagation for all four episodes, suggesting upward energy propagation and the vertical wavelengths were estimated to be about 43.8 ± 3.6 km, 42.4 ± 2.8 km, 82.0 ± 6.1 km and 79.8 ± 3.5 km, for the first, second, third and last episodes, respectively.

## Discussion

The fact that the 3-4-day oscillation is significant only in the zonal wind component is an indication that these episodes may be caused by Kelvin waves, but it cannot be considered conclusive evidence. Additional information such as mean winds, vertical structures and theoretical aspects can be used to check if these oscillations satisfy the dispersion relation for atmospheric Kelvin waves, which can be expressed in the follow way,

$$L_x \approx \tau\,[\bar{u} + NL_z/2\pi]$$

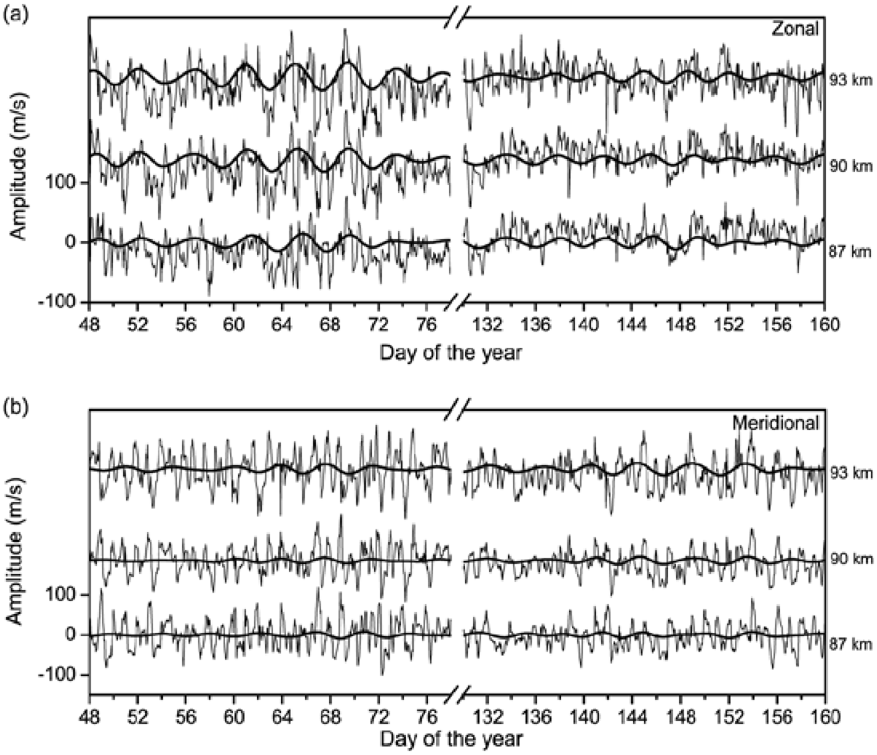

Fig. 3. Hourly zonal (a) and meridional (b) wind components and respective 3-4 days band-pass filtered winds at 87, 90 and 93 altitude intervals over São João do Cariri for day time segments 48-78 and 130-160. The data were filtered by a band-pass filter with cutoff periods of 2.8 and 4.2 days.

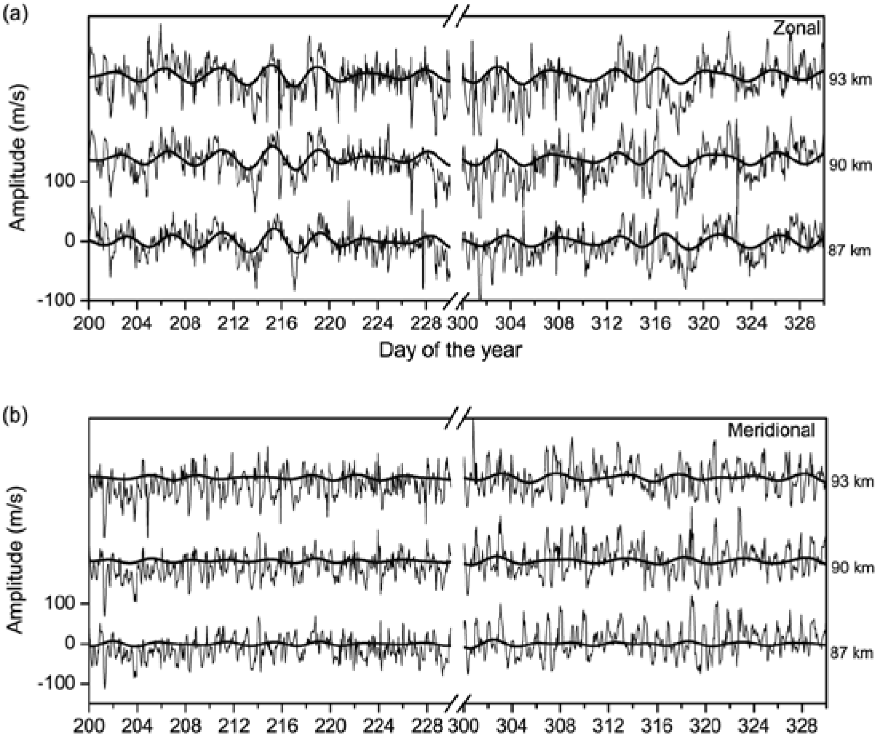

Fig. 4 Hourly zonal (a) and meridional (b) wind components and respective 3-4 days band-pass filtered winds at 87, 90 and 93 altitude intervals over São João do Cariri for day time segments 200-230 and 300-330. The data were filtered by a band-pass filter with cutoff periods of 2.8 and 4.2 days.

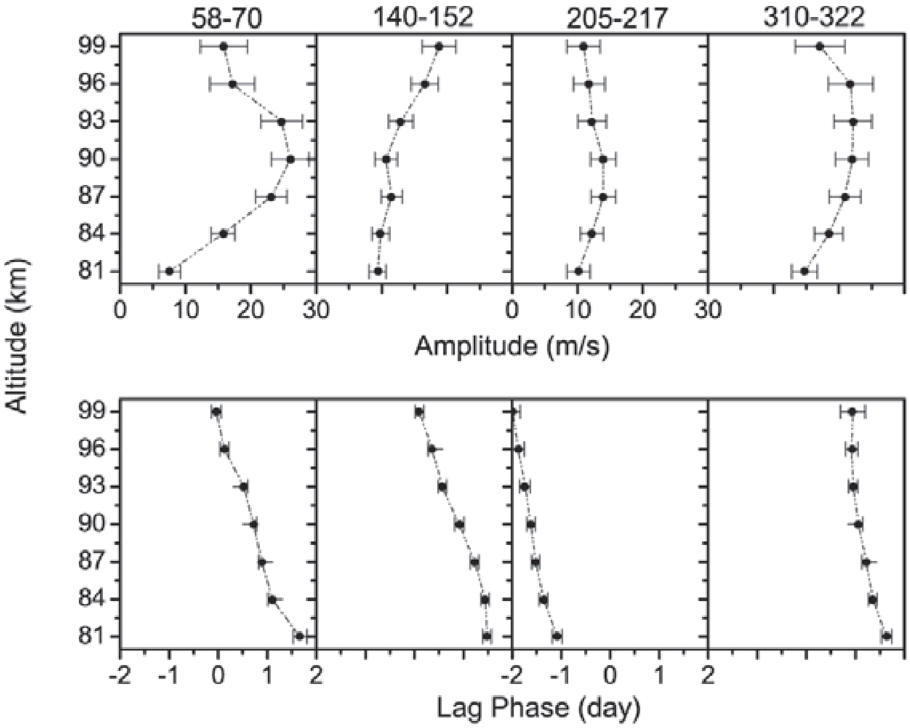

Fig. 5. Vertical profiles of 3-4 day wave zonal amplitude (upper) and lag phase (bottom) as a function of altitude obtained for the time intervals between days 58 and 70, 140-152, 205-217 and 310-322.

where $L_x$ and $L_z$ are zonal and vertical wavelength; $\bar{u}$, N ($\approx 3\times10^{-2}\ s^{-1}$ in the upper mesosphere), and $\tau$ are mean zonal wind, buoyancy frequency, and period, respectively, (Andrews *et al*., 1987). To see if the 3-4 day oscillations observed satisfy the dispersion relation for Kelvin wave, we have assumed that the wave is eastward propagating and used the estimated wave parameters summarized in Table 1.

**Table 1**

Values estimated for 3-4 day wave parameters during the four episodes

| **Episode** | **$\tau$ (days)** | **$A_{max}$ (m/s)** | **$L_z$ (km)** | **$\bar{u}$(m/s)** |
|---|---|---|---|---|
| 1 | 4.0 | 25 | 43.8 ± 3.6 | -15 |
| 2 | 3.6 | 20 | 42.4 ± 2.8 | 10 |
| 3 | 4.0 | 18 | 82.0 ± 6.1 | -10 |
| 4 | 3.5 | 22 | 79.8 ± 3.5 | -10 |

For the first episode, when the magnitude of the mean zonal wind was -15 m/s, the period 4 days, and the vertical wavelength about 44 km, we have a zonal wavelength corresponding to the planetary wave of zonal wave number 1. During the second episode, when the mean zonal wind was 10 m/s, period 3.6 days, and vertical wavelength about 42 km, we have again a wave of zonal wave number 1. However, the vertical wavelengths the third and fourth episodes were estimated to be longer than 75 km, which results zonal wavelength corresponding to zonal wave numbers less than 1.

On the basis of the vertical wavelength, taken together with zonal mean winds and wave periods obtained from observations, and considering the atmospheric Kelvin wave dispersion relation, our results suggest that the 3-4 day oscillations observed during the first and the second episodes can be interpreted as ultra-fast Kelvin waves. Our results for the first and second episodes agree with observations made at Tirunelveli (8.7°N, 77.8°E) for 3.5-day waves, of which zonal amplitudes reached values about 10-15 m/s and the vertical wavelengths were estimated to be from 37 to 57 km (Sridharan *et al*., 2002). Our present data are also in agreement with results from Ascencion Island, which indicated amplitudes near 30 m/s and vertical wavelengths near 47 km (Younger and Mitchell, 2006).

From the present analysis, based on our observations, it was not possible to determine if the 3-4 day oscillations observed during the third and fourth episodes are or not caused by ultra-fast Kelvin waves. There is a limitation to estimate the horizontal wavelength from the estimated vertical wavelength and the dispersion relation. The vertical wavelength could change with background wind (in the presence of wind shear, for example) and it is possible to reach the values greater than 75 km for ultra-fast Kelvin waves (e. g. Riggin *et al.*, 1997). In order to further investigate these cases, additional information such as wave propagation direction, longitudinal and latitudinal structures of the oscillation field would be necessary.

## Conclusions

In this work we have used meteor wind measurements obtained during 2005, at S. J. Cariri, to study 3-4 day Kelvin wave characteristics. From a Morlet wavelet transform it was possible to identify four bursts of 3-4-day spectral energy in the zonal wind during the year. The amplitude of the meridional component of the 3-4 day oscillation was not appreciable during the four episodes, suggesting the possibility of a Kelvin wave.

From the 3-4-day wave vertical structures obtained by harmonic analysis, we observed maximum amplitudes ranging from 18 m/s to 25 m/s for the zonal wind. The vertical phase profiles showed descending phase for all events in the zonal wind and, the vertical wavelengths were estimated to be about 40 km for the first and second episodes, and about 80 km for the third and fourth episodes.

To see whether the waves are indeed Kelvin waves we have compared the observed vertical wavelengths, zonal mean winds and wave periods with those expected from the dispersion relationships for a Kelvin wave. Our results suggest that only the 3-4 day oscillations observed during the first and the second episodes can be interpreted as ultra-fast Kelvin waves. The wave parameters inferred from observations during these two episodes are in accordance with 3.5 day Kelvin waves observed at Tirunelveli and at Ascension Island. For the third and forth episodes, further investigation using additional data would be necessary to identify the Kelvin waves.

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## Bibliography

Andrews, D. G., J. R. Holton and C. B. Leovy, 1987. Middle atmosphere dynamics. Orlando: Academic press, p. 489.

Dunkerton, T. J., 1982. Theory of the mesopause semiannual oscillation. *J. Atmos. Sci., 39*, 2681-2690.

Dunkerton, T. J., 1997. The role of gravity waves in the quasi-biennial oscillation. *J. Geophys. Res., 102*, 26, 053-26, 076.

Hirota, I., 1978. Equatorial waves in the upper stratosphere and mesosphere in relation to the semiannual oscillation of the zonal wind. *J. Atmos. Sci., 35*, 714-722.

Holton, J. R., 1972. Waves in the equatorial stratosphere generated by tropospheric heat sources. *J. Atmos. Sci., 29*, 368-375.

Matsuno, T., 1966. Quasi-geostrophic motions in the equatorial area. *J. Meteor. Society Japan, 44*, 25-42.

Riggin, D. M., D. C. Fritts, T. Tsuda, T. Nakamura and R. A. Vincent, 1997. Radar observations of a 3-day Kelvin wave in the equatorial mesosphere. *J. Geophys. Res., 102*, 26,141-26,157.

Salby, M. L., 1984. Survey of planetary-scale traveling waves: the state of theory and observations. *Review Geophys. and Space Phys., 22*, 209-236.

Salby, M., D. L. Hartmann, P. L. Bailey and J. C. Gille, 1984. Evidence for equatorial Kelvin modes in Nimbus7 LIMS. *J. Atmos. Sci., 41*, 220-235.

Salby, M. L. and R. R. García, 1987. Transient Response to Localized Episodic Heating in the Tropics. Part I: Excitation and Short-Time Near-Field Behavior. *J. Atmos. Sci., 44*, 458-498.

Shidharan, S., S. Gurubaran and R. Rajaram, 2002. Radar observations of the 3.5-day ultra-fast Kelvin wave in the low-latitude mesopause region. *J. Atmos. Solar Terr. Phys., 64*, 1241-1250.

Takahashi, H., C. M. Wrasse, J. Fechine, D. Pancheva, M. A. Abdu, I. S. Batista, L. M. Lima, P. P. Batista, B. R. Clemesha, N. J. Schuch, K. Shiokawa, D. Gobbi, M. G. Mlynczak and J. M. Russel, 2007. Signatures of ultra fast Kelvin waves in the equatorial middle atmosphere and ionosphere. *Geophys. Res. Lett., 34*, L11108, doi:10.1029/2007GL029612.

Torrence, C. and G. P. Compo, 1998. A practical guide to wavelet analysis. *Bull. Amer. Meteor. Soc., 79,* 61-78.

Wallace, J. M. and V. E. Kousky, 1968. Observational evidence of Kelvin waves in the tropical stratosphere. *J. Atmos. Sci., 25,* 900-907.

Yanai, M. and T. Maruyama, 1966. Stratospheric wave disturbances propagating over the equatorial pacific. *J. Meteor. Society Japan, 44*, 291-294.

Younger, P. T. and N. J. Mitchell, 2006. Waves with period near 3 days in the equatorial mesosphere and lower thermosphere over Ascension Island. *J. Atmos. Solar Terr. Phys., 68*, 369-378.

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