JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, A11303, doi:10.1029/2012JA018139, 2012

On the linkage of mesospheric planetary waves with those of the lower atmosphere and ionosphere: A case study from Indian low latitudes

K. Niranjan Kumar,[1] A. Taori,[2] S. Sathishkumar,[3] V. Kamalakar,[4] R. Ghodpage,[5]
S. Gurubaran,[3] P. T. Patil,[5] S. V. B. Rao,[4] and A. K. Patra[2]

Received 18 July 2012; revised 27 August 2012; accepted 18 September 2012; published 3 November 2012.

[1] In this paper we study the planetary-scale wave features using concurrent observations of mesospheric wind and temperature, ionospheric *h'F*, and tropospheric wind from Tirunelveli, Gadanki, and Kolhapur, all located in the Indian low latitudes, made during February 2009. Our investigations reveal that 3 to 5 day periodicity, characterized as ultrafast Kelvin (UFK) waves, was persistent throughout the atmosphere during this period. These waves show clear signatures of upward wave propagation from troposphere to the upper mesosphere, linking the ionosphere through a clear correlation between mesospheric winds and *h'F* variations. We also note that the amplitude of this wave decreased as we moved away from the equator. These results are the first of their kind from Indian sector, portraying the vertical as well as latitudinal characteristics of the 3 to 5 day UFK waves simultaneously from the troposphere to the ionosphere.

Citation: Niranjan Kumar, K., A. Taori, S. Sathishkumar, V. Kamalakar, R. Ghodpage, S. Gurubaran, P. T. Patil, S. V. B. Rao, and A. K. Patra (2012), On the linkage of mesospheric planetary waves with those of the lower atmosphere and ionosphere: A case study from Indian low latitudes, *J. Geophys. Res.*, *117*, A11303, doi:10.1029/2012JA018139.

1. Introduction

[2] The coupling of Earth's atmosphere, vertically, from the troposphere to the middle atmosphere-thermosphere/ionosphere through dynamical processes is important for understanding the momentum and energy flow. The lower atmosphere is understood to be the source of broad spectrum of waves (planetary waves, tides, gravity waves) [*Beer*, 1974]. These waves propagate upward into the mesosphere and lower thermosphere (MLT) region and also play a crucial role in the processes occurring at the ionospheric *E* and *F* regions [e.g., *Abdu et al.*, 2006; *Lastovicka*, 2006; *Takahashi et al.*, 2007; *Fagundes et al.*, 2009; *Goncharenko et al.*, 2010; *Taori et al.*, 2010]. The equatorial planetary waves have been classified as Kelvin waves and Rossby-gravity waves based on their periods, wave number and propagation direction [*Matsuno*, 1966]. These waves are believed to be excited by oscillations in the large-scale convective heating pattern in the equatorial troposphere [e.g., *Holton*, 2004]. Rossby-gravity waves propagates westward and the periods typically 1 to 5 days based on their zonal wave number. Kelvin waves, however, propagates eastward and are a source of eastward momentum in the middle atmosphere [*Sato and Dunkerton*, 1997]. A distinguished characteristic of Kelvin waves is that they do not have meridional perturbation velocity and are often observed in the zonal wind and temperature perturbations. Observational reports indicated that Kelvin waves span a wide range of periodicity. For example, the "slow" Kelvin waves with periods in the range of 15–20 days, having the vertical wavelength of around 10 km, are characterized by wave number 1 [*Wallace and Kousky*, 1968]. From rocket experiments, "fast" Kelvin waves with periods in the range of 6–7 days, having the vertical wavelength of ~20 km with zonal wave number 1 are also detected in the upper stratosphere [*Hirota*, 1978]. Measurements from LIMS/Nimbus-7 stratosphere-mesosphere measurements led to the discovery of another class of Kelvin waves called the "ultra-fast" Kelvin (here after, UFK) waves [*Salby*, 1984]. The UFK waves have wavelengths greater than 20 km and periods ranging from 2 to 6 days. The long vertical wavelengths and shorter periods make UFK waves capable of reaching the MLT region altitudes. Hence these waves are considered important for neutral-ion coupling [e.g., *Forbes*, 2000].

[3] A number of studies reported the characteristics of UFK waves in the MLT region using the meteor and MF radars [*Riggin et al.*, 1997; *Yoshida et al.*, 1999; *Pancheva et al.*, 2004; *Lima et al.*, 2008]. The principal role of UFK waves in the middle atmosphere is in driving the intraseasonal oscillations (ISO) into the MLT region. Several studies reported the existence of ISO in the MLT region [*Eckermann*

---

[1] Divecha Centre for Climate Change, Indian Institute of Science, Bangalore, India.
[2] National Atmospheric Research Laboratory, Gadanki, India.
[3] Equatorial Geophysical Research Laboratory, Tirunelveli, India.
[4] Sri Venkateswara University, Tirupati, India.
[5] Radar Observatory, Indian Institute of Geomagnetism, Shivaji University, Kolhapur, India.

Corresponding author: K. N. Kumar, Divecha Centre for Climate Change, Indian Institute of Science, Bangalore 560012, India. (niranjan@caos.iisc.ernet.in)

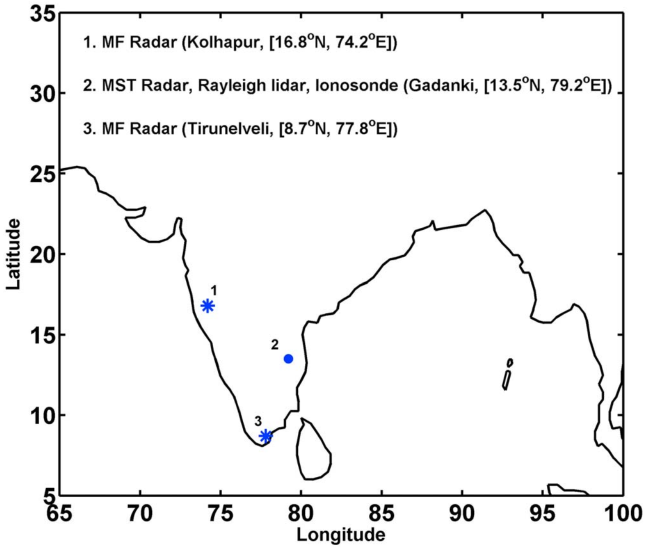

Figure 1. Map showing the location of instruments used in the present study. The asterisk shows the MF radar sites. The solid circle shows the location of MST radar, ionosonde, and Rayleigh lidar.

et al., 1997; *Isoda et al.*, 2004]. However, it is also suggested that the MLT ISO may not be due to direct propagation from lower atmosphere. Subsequent reports have shown the involvement of diurnal tides (migrating and nonmigrating), intraseasonally modulated gravity waves and UFKs in the generation of ISO in the MLT region [*Eckermann et al.*, 1997; *Lieberman et al.*, 2003; *Miyoshi and Fujiwara*, 2006]. Some reports, however, show the direct propagation of ISO up to stratosphere [e.g., *Ziemke and Stanford*, 1991; *Niranjankumar et al.*, 2011]. Nevertheless, the UFKs are the primary driving forces of ISO in the MLT region due to their long vertical wavelengths and their interaction with the background winds can lead to generation of ISO in the MLT winds [*Miyoshi and Fujiwara*, 2006].

[4] The involvement of planetary waves (2–30 day) in coupling the thermosphere and ionosphere is also a subject of interest. These waves are believed to be responsible for the substantial part of modulation of the *E* region wind-driven dynamo [e.g., *Parish et al.*, 1994, *Voiculescu et al.*, 2000; *Phanikumar et al.*, 2009]. In this regard, UFKs are one of the important sources for the existence of day-to-day variability in the ionosphere. *Takahashi et al.* [2007] observed 3–4 day oscillations in the MLT wind fields and in the *F* region parameters (foF2 and *h'F*2) using ground-based and ionosonde measurements. They attributed that the observed oscillations are due to upward propagating UFK waves from the stratosphere. Kelvin waves are expected to have a Gaussian type latitudinal structure in their amplitude, in the absence of mean wind shear, with maximum amplitudes near the equator and the amplitudes decay exponentially. Recently the UFK wave signatures at ionospheric altitudes are reported even from midlatitudes [*Liu et al.*, 2012]. In general, UFK waves are assumed to be trapped to ±30°, however, their study shows the signatures as high as 40°N. This gives an impression that the latitudinal characteristics of the UFK waves are far more complex and needs more data from low-latitude middle atmosphere.

[5] In this regard, present study investigates the signatures of UFK waves and their latitudinal characteristics over Indian sector with the help of simultaneous multi-instrument measurements extending from troposphere to the ionosphere during February 2009. We examine the characteristics of UFK waves in the MLT region using two MF radars located at Tirunelveli (8.7°N, 77.8°E) and Kolhapur (16.8°N, 74.2°E). During the same period we utilize the tropospheric winds (from mesosphere-stratosphere-troposphere (MST) radar), middle atmospheric temperature (from Rayleigh lidar) and base height of the *F* region of ionosphere (from Ionosonde) data recorded over Gadanki (13.5°N, 79.2°E). Apart from these ground based observations we also make use of the TIMED/SABER satellite measurements as additional support.

2. Data Description

[6] The present study makes use of observations from ground-based instruments such as MF Radars, MST Radar, Rayleigh lidar and ionosonde operated simultaneously in the month of February 2009. The MF radars give the horizontal wind information in the MLT region whereas the MST radar provides wind information in the troposphere. The Rayleigh lidar also have been used for the present study to obtain the middle atmospheric temperature variability. In order to see the ionospheric variability we have also used the ionosonde operated during the observational period. The locations of these instruments are indicated in Figure 1.

2.1. MF Radar at Tirunelveli (8.7°N, 77.8°E) and Kolhapur (16.8°N, 74.2°E)

[7] The Medium Frequency (MF) radars over Tirunelveli and Kolhapur are near identical and operate at 1.98 MHz with a peak transmitter power of 25 kW. The radar operates as a spaced-antenna system [*Vincent*, 1986], relying on coherent echo signals from middle atmosphere ionization. The interpulse period is 12.5 ms during the day and 25 ms during the night. The MF radar makes use of the spaced antenna technique, and samples the horizontal winds in the 70 to 98 km altitude at every 2 km altitude. Full correlation analysis [*Briggs*, 1984] has been carried out to deduce the wind components following standard procedures. Detailed descriptions of the radar system are discussed elsewhere [*Rajaram and Gurubaran*, 1998]. We utilize the wind measurements from both locations obtained during 1–28 February 2009 to study the planetary wave signatures.

2.2. MST Radar at Gadanki (13.5°N, 79.2°E)

[8] The MST Radar located at Gadanki is a phased-array Doppler radar operating at a carrier frequency of 53 MHz with an average power aperture product of 7×10^8 Wm^2.The radar consists of 1024 pairs of crossed Yagi-Uda antenna elements arranged in 32 × 32 matrix over an area of 132 m × 132 m. The radar having a beam width of 3°, gain of 36 dB and a side lobe of −20 dB, can be tilted 20° in steps of 1° from zenith in the north-south and east-west planes. More details of radar system and technical specifications can be found in *Rao et al.* [1995]. For the present study, a continuous observation of the horizontal wind velocities measured by MST radar at Gadanki from 7 to 28 February 2009. The radar was operated daily around 12:00 UT (universal time)

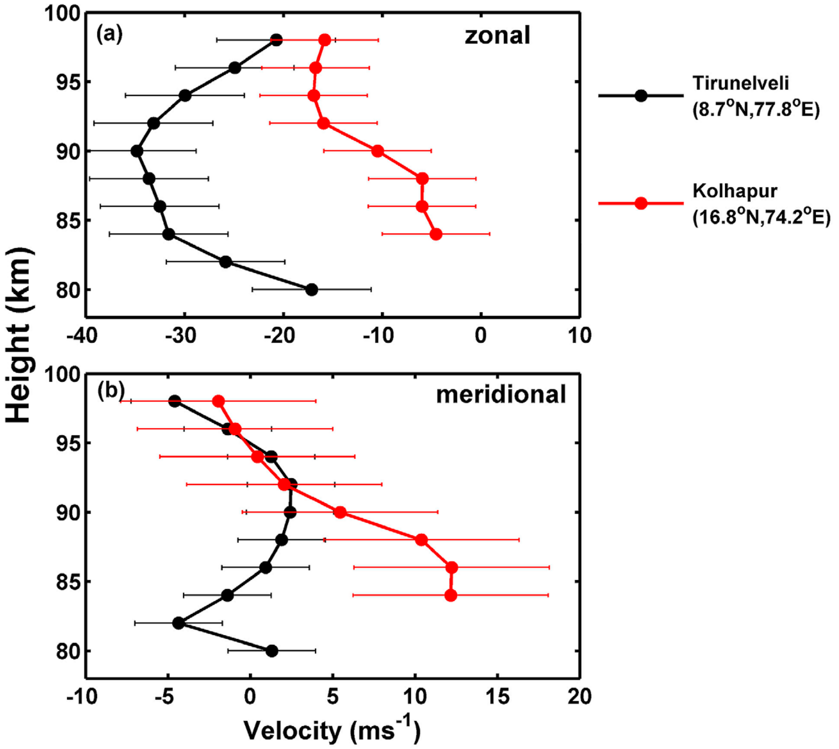

Figure 2. (a) Mean zonal winds in the month of February 2009 using MF radar located at Tirunelveli (black) and Kolhapur (red) in the altitude range of 82–98 km. (b) Same as Figure 2a but for meridional winds.

for about 15 min to 1 h in the six beam mode. The radar beam was titled 10° in the east, west, north, and south directions along with two zenith beams with two orthogonal polarizations, Zx and Zy. We have averaged around twenty profiles, with an altitude resolution of 150 m, in 1 h to get one height profile for a day; i.e., around 12:00 UT.

2.3. Rayleigh Lidar at Gadanki (13.5°N, 79.2°E)

[9] The lidar system located at Gadanki is equipped with a Nd-YAG pulsed laser at 532 nm with energy of about 550 mJ, operating at a pulse repetition rate of 50 Hz and pulse width of 7 ns. The estimation of temperature profile from Rayleigh lidar are derived with the help of downward integration onion peel method where temperature values are obtained by seeding the model temperature and pressure values at ~100 km. Details of the lidar system and the method of temperature retrieval are discussed elsewhere [*Siva Kumar et al.*, 2003]. In present study we have used the temperature profiles in 30–70 km altitude range, with an altitude resolution of 300 m, from 12 to 26 February 2009, during which we have a daily continuous nighttime measurements for more than 4 h.

2.4. Ionosonde at Gadanki (13.5°N, 79.2°E)

[10] The ionospheric parameters viz. base height and *F* region critical frequency (i.e., *h'F* and foF_2) over Gadanki are obtained with the help of a digital ionosonde (KEL make, model IPS42). The ionosonde was routinely operated during the period of current investigation; i.e., January–March 2009, with a temporal resolution of 15 min.

[11] To support our observations we also makes use of temperature measurements from TIMED/SABER satellite data in the month of February 2009 for a latitude and longitude grid of 10°N–20°N and 70°E–80°E, respectively.

3. Results and Discussions

[12] In order to identify whether planetary wave activity was persistent during February 2009, we first identify the UFK signatures in mesospheric winds and characterize them. Then we investigate the UFK signatures in ionospheric parameters. We show that UFK signatures were also persistent in mesospheric temperatures. To make the UFK propagation complete, at last we show the upward propagating planetary wave signatures in tropospheric winds.

3.1. Planetary Wave Signatures in Mesospheric Winds

[13] To elaborate the background wind conditions at mesospheric altitudes, we average the full February month wind data obtained from Tirunelveli and Kolhapur, which are shown in Figure 2. We note that the mean zonal winds are westward in the altitude range 80–98 km. The magnitude of the westward winds, however, over Kolhapur are smaller compared to the one noted over Tirunelveli. The mean meridional wind over Tirunelveli show northward flow which reveals a transequatorial flow during the winter months which was earlier reported by *Rajaram and Gurubaran* [1998]. However, the meridional winds at Kolhapur show southward winds till 90 km from where above they become northward. It is evident from Figure 2a that once the eastward propagating waves (e.g., Kelvin waves) reach the mesospheric

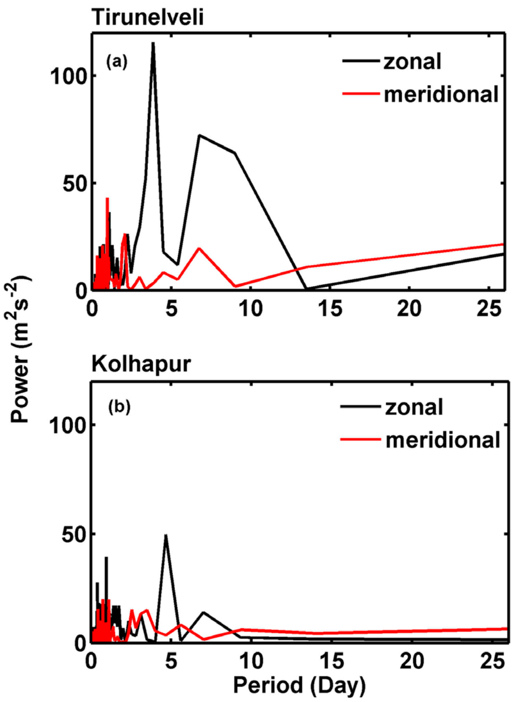

Figure 3. (a) Fourier power spectrum of zonal and meridional winds from Tirunelveli MF radar averaged between 82 and 90 km. (b) Same as Figure 3a but for Kolhapur MF radar.

heights they can propagate to higher heights as they will be least affected by the background wind filtering.

[14] We know that MLT region variability is overwhelmed with small-scale gravity waves to large-scale planetary waves. Therefore, to identify the presence of planetary wave modulations in the MLT region during the observational period, we applied the Fourier transform to the daily mean winds after the removal of diurnal components obtained from the hourly mean horizontal winds. Figure 3 shows the power spectrum of zonal and meridional winds averaged between 80 and 98 km during the observational period of February 2009. Interestingly, the spectrum shows wave periods in between 2.5 and 5.5 days to occur at both locations, i.e., Tirunelveli and Kolhapur. It also shows that meridional component of these waves is negligible compared to the zonal components. This provides us the first confirmation that the modulation in zonal winds is associated with the UFK waves. Moreover the Figure 3 also shows that the amplitude of planetary wave decreases with latitude which is consistent with the signatures of UFK wave. We note that the spectral power of UFK is reduced by more than half over Kolhapur compared to the power noted over Tirunelveli. Note that the power of UFK wave is ~115 m^{-2} s^{-2} in Tirunelveli zonal winds, whereas it is ~50 m^{-2} s^{-2} over Kolhapur. Although the Fourier analysis of wind data indicates the presence of a certain period/frequency, but do not localize the frequency information. However, the planetary-scale wave activity shows nonstationary characteristics, namely particular wave modes can occur in bursts of small duration [*Salby*, 1984]. In that sense the wavelet analysis allows us to extract the time-frequency information. Hence we apply a wavelet analysis to the MLT winds to see the localization of UFK wave signatures. The method of wavelet analysis is adopted from *Torrence and Compo* [1998]. Figure 4 shows the Morlet wavelet based analysis of the MLT winds averaged for the altitude range 80–98 km during February 2009. The wavelet spectrum also shows prominent modulation of MLT winds at 3 and 5 day wave periods, almost all the time during the observational period at the two locations. Also the power of the UFK waves (3–5 day) reduces as we move away from equator (Tirunelveli to Kolhapur). Also there is one stronger peak between 5 and 10 days in Figure 4a, which we have also noted in the Fourier analysis. However, the present study focuses on the oscillations with periods 3–5 day which are known to be associated with UFK waves.

[15] Above results provide evidence that UFK waves were present in the MLT zonal winds in both, equatorial (Tirunelveli) and low-latitude (Kolhapur) locations. In order to see the vertical propagation characteristics of the UFK waves, we used the harmonic analysis using least squares fitting for the zonal component between 3 and 5 days, with an increment of 0.2 days during February 2009 (28 days) on the mesospheric winds. The vertical profiles of the obtained phase of these oscillations are shown in Figure 5 together with the standard deviation. It is evident that the phase decreases with height indicating the wave energy to propagate upward. From the vertical phase propagation in zonal wind (i.e., rate of change of phase with respect to height), the vertical wavelengths are estimated to be 58 ± 5 km, 27 ± 0.5 km for Tirunelveli and Kolhapur data, respectively. In the light that the vertical wavelength of UFK waves is highly sensitive to the background winds [*Forbes*, 2000], the variation of vertical wavelength from Tirunelveli to Kolhapur suggests that the waves might have underwent a Doppler shift in the presence of higher mean winds which is clearly

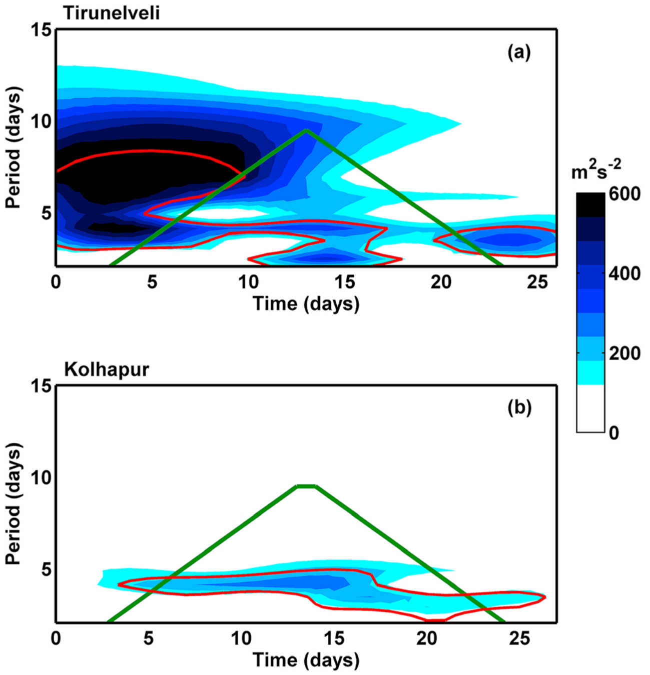

Figure 4. Wavelet (Morlet) power spectrum of daily mean zonal winds in February 2009 over (a) Tirunelveli and (b) Kolhapur averaged between 82 and 98 km.

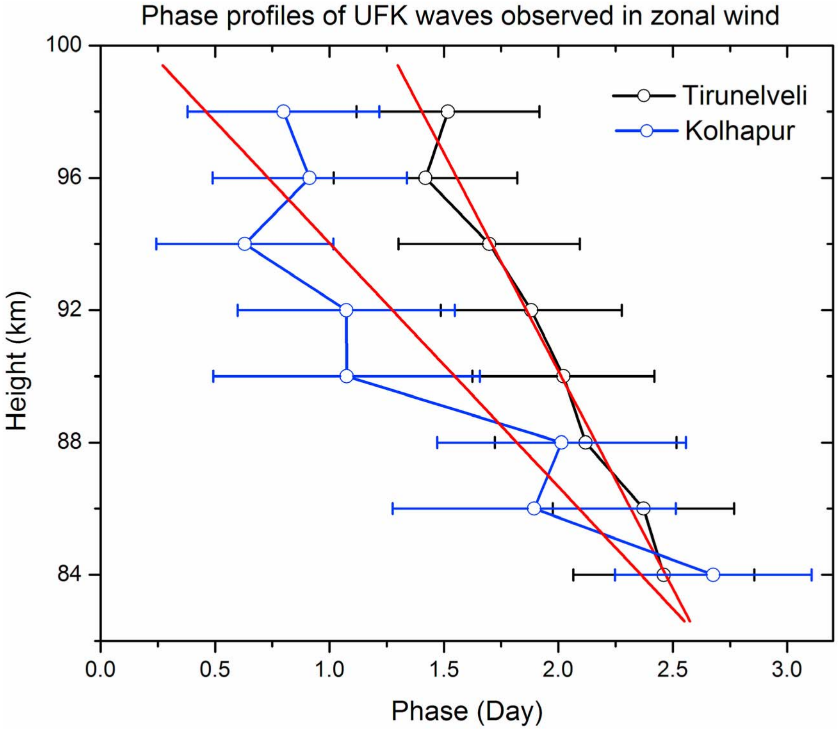

Figure 5. Phase profile computed from harmonic analysis using least squares fitting for zonal winds between 3 and 5 days between 82 and 98 km. Error bars indicate the standard deviations. The straight line is fitted using the least squares method.

noticeable in Figure 2 that Tirunelveli winds were much stronger (westward) than that noted over Kolhapur.

[16] Further, as the observed oscillations are due to Kelvin waves with negligible meridional amplitudes (Figure 3), we can apply the Kelvin wave dispersion relation to determine the zonal wavelength, λ_x, using the following relation [*Holton et al.*, 2001],

$$\lambda_x = T\left[\left(\frac{\lambda_z}{T_N}\right) + \bar{u}\right] \tag{1}$$

where λ_z, vertical wavelength, T_N the period of Brunt-Väisälä frequency, T the wave period and $\bar{u}$ is background zonal wind (above relation has a caveat that it assumes that zonal winds do not vary with longitudes which may not be close to the reality). The Brunt-Väisälä period at 90 km is 400 s, which is estimated from TIMED/SABER temperature data over low-latitude region in the month of February 2009. After substituting these values in the equation (1), the horizontal wavelength of UFK waves at Tirunelveli and Kolhapur are calculated to be 43300 ± 4500 km and 30648 ± 1800 km respectively. The values are close to the 39500 km and 38200 km circumference of circle of latitudes at 9°N and 17°N latitudes respectively. This means that the observed waves are planetary-scale ultrafast Kelvin wave of zonal wave number 1. We also estimated the vertical group velocity using the Kelvin dispersion relation [*Holton et al.*, 2001]

$$\overset{(z)}{Cg} = \frac{\partial\omega}{\partial m} = \mp{}^{Nk}\!/_{m^2} \tag{2}$$

Substituting the values for the horizontal wave number (k) and vertical wave number (m) and Brunt-Väisälä frequency (N), we found that the vertical group velocity of the UFK waves is 16.8 ± 1.2 km d^{-1}.

[17] When we compare of observations with the UFK wave signatures reported elsewhere, the ~3 days wave periods with vertical wavelength about 49 km in MLT zonal wind fields are reported by *Pancheva et al.* [2004]. Using simultaneous observations from two radars located at Jakarta (6.4°S, 107.6°E) and Christmas Island (1.9°N, 157.3°W), *Riggin et al.* [1997] also found a 3.2 Kelvin day period with wave number 1. The radar observations of UFK waves near equatorial radar sites have shown that the zonal wind amplitudes to be in the range 10–30 ms^{-1} at upper mesospheric altitudes. Apart from the ground based observations, UFK waves have also been characterized by the satellite observations. Measurements from upper atmospheric research satellite (UARS) provided evidences of UFKs with periods of the order of 3–6 days with zonal wave numbers 1 and 2 [*Canziani et al.*, 1994; *Lieberman and Riggin*, 1997]. Using the TIMED/SABER satellite *Garcia et al.* [2005] showed the UFK waves in the MLT region having the amplitude of 4 K with average vertical wavelength ~40 km. Using the meteor wind radar at Ascension Island (8°S, 14°W) and Aura MLS satellite, *Davis et al.* [2011] characterized the UFK waves in the MLT region during 2005–2010. The UFK with zonal wave number 1 waves are found at periods 2.5–4.5 days with average vertical wavelength of 44 km. It is also found a good agreement is found between observations and Kyushu-general circulation model (GCM). In addition to the observational reports stated above numerical simulation studies also showed the existence and vertical propagation of UFK

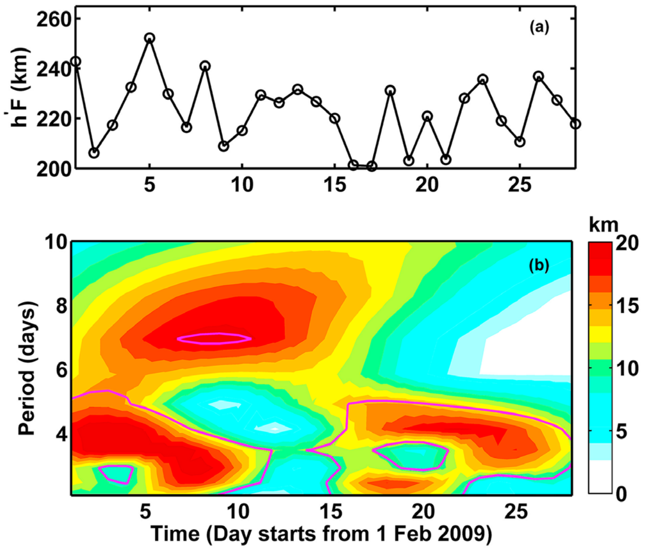

Figure 6. (a) Time series of ionospheric *h'F* observed at Gadanki in the month of February 2009. (b) Wavelet analysis for the time series of *h'F* shown in Figure 6a.

waves into the MLT region [e.g., *Forbes*, 2000; *Ricciardulli and Garcia*, 2000; *Miyoshi and Fujiwara*, 2006; *Chen and Miyahara*, 2012]. Using the Global Scale Wave Model (GSWM) simulations, *Forbes* [2000] predicted the penetration of UFK waves into the MLT region and that suggested that these waves produce an eastward acceleration of 10 $\mathrm{ms^{-1}\ d^{-1}}$. It was also noted that the vertical wavelength of UFK waves are highly sensitive to the Doppler shifting due to background winds. In a further report, *Miyoshi and Fujiwara* [2006] showed that the UFK waves could propagate upward from troposphere to lower thermosphere with duration of 10–60 days. Recently, *Chen and Miyahara* [2012], shown the UFK waves in the Kyushu-GCM model. It was found that UFK waves existed in 15–20 km and 30–60 km altitude range and zonal accelerations caused due to wave dissipation are in the range 8 and −0.5 $\mathrm{ms^{-1}\ d^{-1}}$. Hence the UFK waves characteristics obtained in this study are also similar to those of previous reports as stated above. Our observed values of 3–5 day UFK wave, therefore, are in general agreement with the above mentioned observations. In the present study, we also show the latitudinal variation.

3.2. Planetary Wave Signatures in Ionospheric Parameters

[18] Planetary waves are one of the important sources of ionospheric oscillations at multiday periodicities. UFKs, in particular, couple the MLT region and ionospheric region either by modulation of the ionospheric electrodynamics or direct propagation of the wave upward into the upper thermosphere. For example, *Forbes* [2000] showed that the UFK waves could propagate upward to the lower thermosphere with zonal wind magnitude of about 10–40 $\mathrm{ms^{-1}}$ and temperature perturbations of about 10–25 K at 100–150 km region A number of studies have shown that planetary waves, gravity waves and tides have their profound effects on the thermosphere-ionosphere system [e.g., *Lastovicka*, 2006; *Rishbeth*, 2006]. There are several reports that review the effects of planetary waves of lower atmospheric origin in the observed parameters of thermosphere-ionosphere system [e.g., *Kazimirovsky et al.*, 2003; *Altadill et al.*, 2004]. A few investigators have also shown the signatures of UFK waves in the ionosphere [e.g., *Takahashi et al.*, 2006, 2007]. As we have seen in Figure 5, that there is an upward propagation of UFK waves till the upper mesosphere, hence, with background wind at mesopause region being westward it is worth investigating if the UFK wave with eastward phases propagate higher to imprint their signatures on the day-to-day ionospheric variability. We utilize the ionosonde observations over Gadanki during February 2009. Understanding the complication of daytime and nighttime ionospheric processes occurring in the *F* region, for example, during day time it is affected by ionization and *F* region dynamo while during the night plasma irregularity processes set in. Hence, to see the day-to-day variation, we choose the base height of *F* region (*h'F*) at fixed local time between 19:00 and 20:00 LT. The day-to-day variability of the *h'F* is shown in Figure 6a. We can see the modulations of the *h'F* in the time series. In order to investigate the oscillations in more detail, Morlet wavelet based analysis was performed on the daily *h'F* data during February 2009 (Figure 6b). The periods which are greater than the 95% significance level (measured by the Chi-square fit) are contoured. The wavelet analysis shows that the spectrum peaks at two periodicities, one between 3 and 5 days, which might be associated with UFK waves and other, at 5–10 days. It is interesting that the 5–10 day oscillation was also observed in the MLT winds over Tirunelveli (Figure 4a) which we believe is also a signature of planetary wave propagation, however as our data are limited for one month duration to specifically to identify 3–5 day wave, we avoid more discussion on 5–10 day wave. Figure 6b shows the spectrum between 3 and 5 days peaks at two times during the observational periods. Also we can observe the spectrum is shifting toward the high-frequency side which might be due to the Doppler shifting because of background winds. It is also noted that there is some phase coherency in the wavelet spectrum of ionospheric *h'F* variation with the MLT winds of Tirunelveli (Figure 4a) in 3–5 day and 5–10 day periodicity band. In order to confirm this, we examined the cross-wavelet transform between the MLT winds from Tirunelveli and *h'F* data (Figure 7). The cross-wavelet power

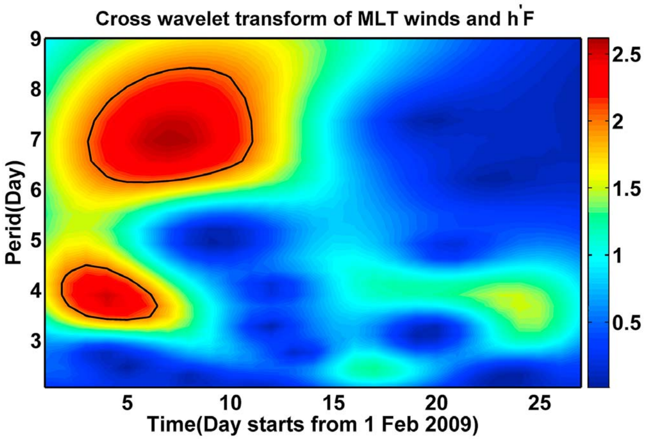

Figure 7. Cross-wavelet power of MLT winds over Tirunelveli and ionospheric *h'F* over Gadanki.

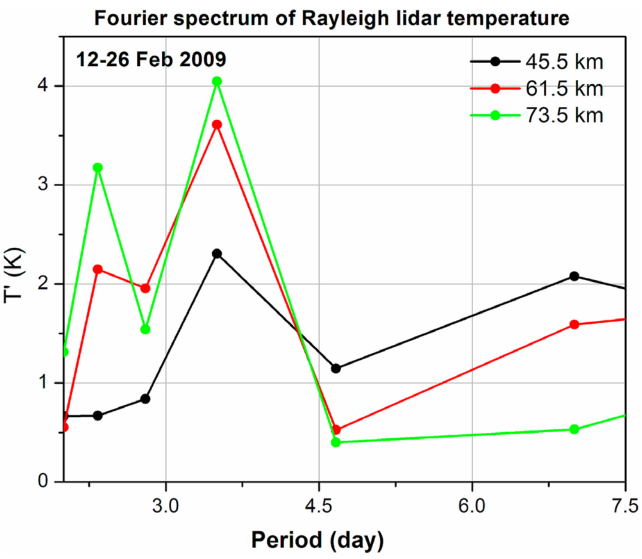

Figure 8. Fourier spectrum of daily nighttime averaged temperature from Rayleigh lidar over Gadanki during 12–26 February 2009 at 45.5, 61.5, and 73.5 km.

tells us the areas of high common power between the two time series [*Grinsted et al.*, 2004]. We can notice the common features of individual wavelet transforms in cross wavelet analysis which maximize at 3–5 and 5–10 day periodicities. This clearly suggests that the UFK waves noted at mesospheric altitudes might have propagated to the ionospheric heights and modulated the *F* region parameters.

3.3. Planetary Wave Signatures in Mesospheric Temperatures

[19] The present study so far has shown that UFK waves noted at mesospheric altitudes have a link with the day-to-day variability of base height of the *F* region of ionosphere. In fact, earlier studies have reported the presence of 3 day variation in the equatorial region extending from stratosphere to ionosphere [*Takahashi et al.*, 2007]. Hence, it is now interesting to see the origin of these UFKs waves in the stratosphere as well as in the troposphere. To see this, we use the Rayleigh lidar temperature data during 12–26 February 2009 over Gadanki. We performed the Fourier analysis on the nightly averaged temperature data at different altitudes. Figure 8 plots the spectrum at altitudes of 45.5 km, 61.5 km and 73.5 km. We clearly note that there is enhancement in the 3–4.5 day period band. Also the amplitude of the wave is increasing with altitude owing to decrease in the density, suggesting no dissipation/saturation of these waves. This provides evidence that the wave has its origin in the lower atmosphere. The temperature measurements from lidar are taken up to ~75 km, hence in order to see the UFK signature still higher heights we make use of the temperature measurements of TIMED/SABER satellite during 1–28 February 2009 over the latitude/longitude of 10°N–20°N/70°E–80°E. We have examined the spectrum associated with daily temperature using the Fourier analysis (Figure 9a). It is noticed that there is clear signature of 3–5 days waves up to 90 km. We also observe a 5–10 day wave which was noted also in mesospheric winds over Tirunelveli and *h'F.* The phase profile of the 3.8 day wave is shown in Figure 9b. The phase profile clearly indicates the upward propagation of energy into height heights. Hence, the TIMED/SABER satellite data also support our observations of UFK waves and that these waves are propagating upward in the MLT region.

3.4. Planetary Wave Signatures in Tropospheric Winds

[20] To further notice the origin of the 3–5 day waves, we use the simultaneous observations from MST radar during February 2009 (continuous wind measurements were available from 7 to 28 February 2009). The MST radar horizontal wind measurements are shown in Figure 10. We notice that there exists large day-to-day variability in the horizontal

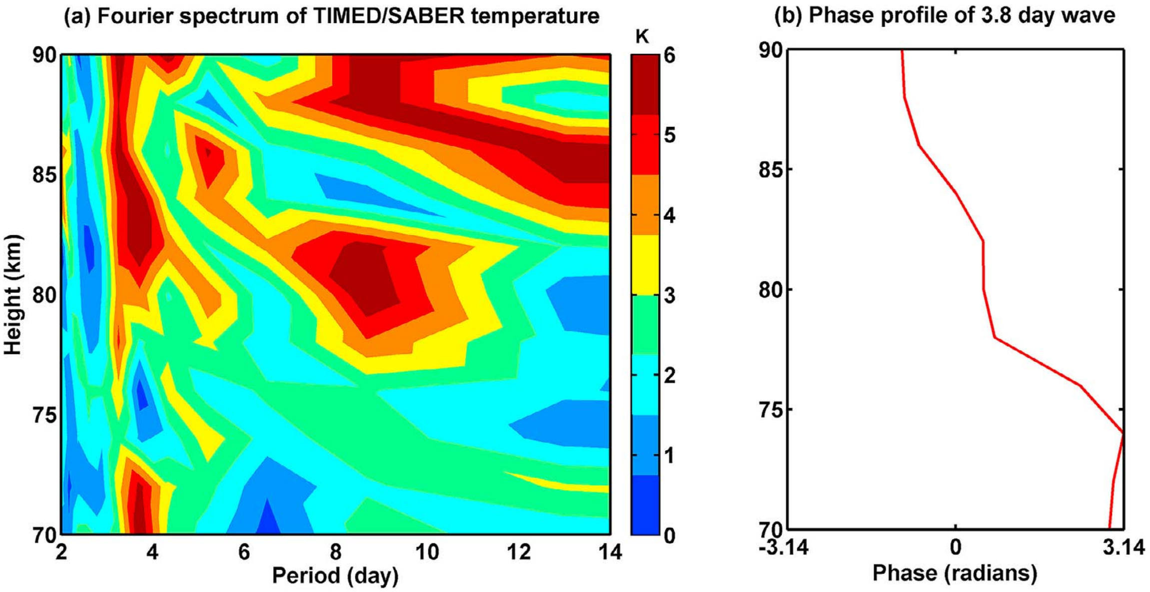

Figure 9. (a) Fourier spectrum of daily temperature in February 2009 observed from TIMED/SABER satellite over Gadanki between 70 and 90 km. (b) Phase profile of 3.8 day wave in temperature.

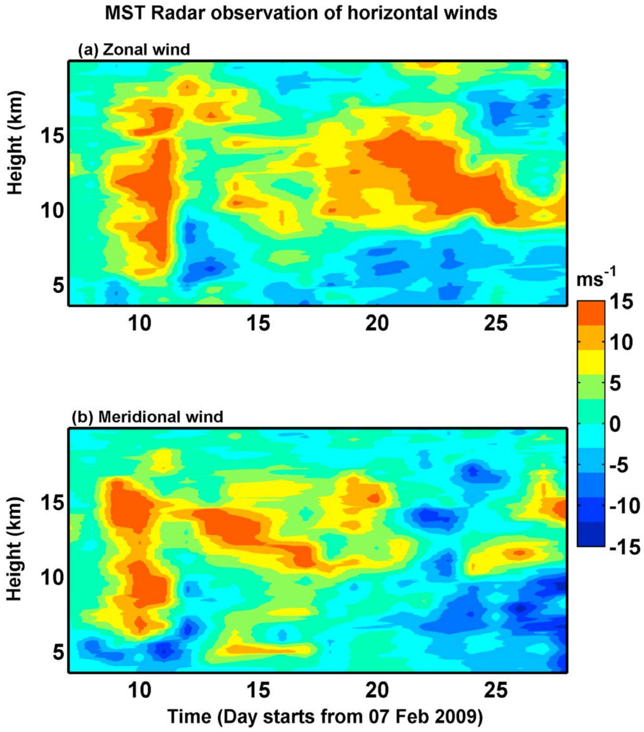

Figure 10. Time-height section of MST radar (a) zonal and (b) meridional winds during 7–28 February 2009 observed over Gadanki.

winds. The lower troposphere is mainly dominated by the westward winds but the middle and upper troposphere show eastward winds. It can be noticed from the Figure 10 that there exist some oscillations with periods of about 3–5 days. Especially, the zonal winds show the descending phase with height, which might be associated with the waves that are propagating upward. In order to see those, we performed the Fourier analysis on the zonal and meridional winds in the middle troposphere, i.e., between 9 km and 14 km. Figure 11a shows the spectrum associated with the horizontal winds. The spectrum shows the zonal winds are clearly modulated by 3–5 days periods with peak at ~4.4 day. We also note that the meridional wind spectra peaks near the 3.6 day. This peak might be associated with the Rossby-gravity waves which are also generated in tropical atmosphere [*Sasi and Deepa*, 2001]. But we can clearly notice that the spectral power ~4.4 day in meridional winds is drops to zero. Since the Kelvin waves are linearly polarized and this gives us strong impression that the spectrum ~4.4 day in zonal component is associated with Kelvin wave. The phase propagation of the wave is shown in Figure 11b, which shows that the wave is almost stationary in the lower and middle troposphere. However, in the upper troposphere, i.e., above 14 km and in lower stratosphere, the phase decreases with height indicating that the wave energy propagates upward. Note that the background zonal winds in the upper troposphere and lower stratosphere are in westward direction (Figure 10a), which makes these eastward waves to propagate upward easily without critical level filtering.

[21] In a nut shell, our investigations clearly show a signature of UFK waves with periodicity 3–5 day in tropospheric winds and their upward propagation. At stratosphere-mesosphere-thermosphere system, we note similar waves to propagate to higher altitudes in wind as well as temperature fields. Further, under the westward winds conditions at mesospheric altitudes, these waves could have propagated to the ionospheric altitudes, a signature of which was noted as 3–5 day wave periodicity noted in ionospheric *h'F* variability. Further we show that amplitude of this wave over Kolhapur was less than half compared to the wave amplitudes noted over Tirunelveli.

4. Concluding Remarks

[22] The present study, for the first time, provides evidence of UFK wave propagation from tropical troposphere to the ionosphere in the Indian low-latitude belt. Using the multi-instruments including two MF radars (one located at Tirunelveli and other at Kolhapur), MST Radar, Rayleigh lidar, Ionosonde located at Gadanki along with the TIMED/SABER satellite temperature measurements, the study illustrates the

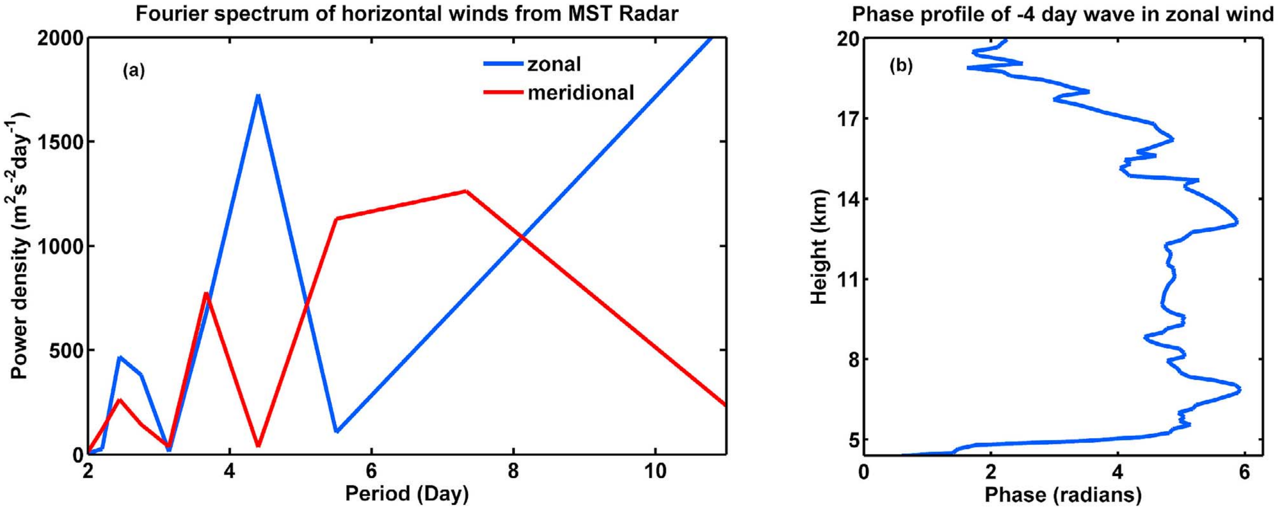

Figure 11. (a) Fourier spectrum of zonal and meridional winds averaged between 9 and 14 km. (b) Phase profile of ~4 day wave in zonal wind.

existence of UFK waves in the zonal wind fields in the MLT region (80–98 km) at both the locations of Tirunelveli and Kolhapur. The power of UFK waves reduced more than half as we move from 8°N to 17°N. The phase propagation of UFK waves in the MLT region was downward from 80 to 98 km, implying the energy associated with these waves to move upward. The estimated vertical wavelengths of the UFK waves are found to be ∼58 km and ∼27 km at Tirunelveli and Kolhapur, respectively and the wave number was found to be one. These waves were also noted in the base height variation of the *F* region (*h'F*). The cross-wavelet spectral analysis reveals high coherence between MLT winds at Tirunelveli and ionospheric *h'F* values at Gadanki, emphasizing that these waves had relevance with the observed day-to-day variability of ionosphere. Further, the Rayleigh lidar and TIMED/SABER observations reveal a downward phase propagation of these waves indicating a coupling between stratosphere-mesosphere-thermosphere through UFK waves. The tropospheric wind measurements also indicate a clear signatures of these waves and their phase show these waves to propagate up to the stratosphere from the troposphere. Thus the present study provides a strong evidence of coupling between different regions of the atmosphere through UFK waves propagating from tropical troposphere to the ionosphere.

[23] **Acknowledgments.** Authors acknowledge the NARL staff for making the Rayleigh lidar and MST radar measurements available for the present study, which is an effort to study the vertical coupling of Earth's atmosphere under NARL SAFAR and CAWSES-II theme-3 programs.

[24] Robert Lysak thanks the reviewers for their assistance in evaluating this paper.

References

Abdu, M. A., P. P. Batista, I. S. Batista, C. G. M. Brum, A. J. Carrasco, and B. W. Reinisch (2006), Planetary wave oscillations in mesospheric winds, equatorial evening prereversal electric field and spread *F*, *Geophys. Res. Lett.*, *33*, L07107, doi:10.1029/2005GL024837.

Altadill, D., E. M. Apostolov, J. Boska, J. Lastovicka, and P. Sauli (2004), Planetary and gravity wave signatures in the *F* region ionosphere with impact to radio propagation predictions and variability, *Ann. Geophys.*, *47*, 1109–1119.

Beer, T. (1974), *Atmospheric Waves*, Adam Hilger, London.

Briggs, B. H. (1984), The analysis of spaced sensor records by correlation techniques, in *Handbook for MAP*, vol. 13, edited by E. A. Vincent, pp. 166–186, Univ. of Ill., Urbana-Champaign.

Canziani, P. O., J. R. Holton, E. Fishbein, L. Froidevaux, and J. W. Waters (1994), Equatorial Kelvin waves: A UARS-MLS view, *J. Atmos. Sci.*, *51*, 3053–3076, doi:10.1175/1520-0469(1994)051<3053:EKWAUM>2.0.CO;2.

Chen, Y.-W., and S. Miyahara (2012), Analysis of fast and ultrafast Kelvin waves simulated by the Kyushu-GCM, *J. Atmos. Sol. Terr. Phys.*, *80*, 1–11, doi:10.1016/j.jastp.2012.02.026.

Davis, R. N., Y.-W. Chen, S. Miyahara, and N. J. Mitchell (2011), The climatology, propagation and excitation of ultra-fast Kelvin waves as observed by meteor radar, Aura MLS, TRMM and in the Kyushu-GCM, *Atmos. Chem. Phys. Diss.*, *11*, 29,479–29,525, doi:10.5194/acpd-11-29479-2011.

Eckermann, S. D., D. K. Rajopadhyaya, and R. A. Vincent (1997), Intraseasonal wind variability in the equatorial mesosphere and lower thermosphere: Long-term observations from the central Pacific, *J. Atmos. Terr. Phys.*, *59*, 603–627, doi:10.1016/S1364-6826(96)00143-5.

Fagundes, P. R., J. A. Bittencourt, J. R. Abalde, Y. Sahai, M. J. A. Bolzan, V. G. Pillat, and W. L. C. Lima (2009), *F* layer postsunset height rise due to electric field prereversal enhancement: 1. Traveling planetary wave ionospheric disturbance effects, *J. Geophys. Res.*, *114*, A12321, doi:10.1029/2009JA014390.

Forbes, J. M. (2000), Wave coupling between the lower and upper atmosphere: Case study of an ultra-fast Kelvin Wave, *J. Atmos. Sol. Terr. Phys.*, *62*, 1603–1621, doi:10.1016/S1364-6826(00)00115-2.

Garcia, R. R., R. Lienerman, J. M. Russell III, and M. G. Mlynczak (2005), Large-scale waves in the mesosphere and lower thermosphere observed by SABER, *J. Atmos. Sci.*, *62*, 4384–4399, doi:10.1175/JAS3612.1.

Goncharenko, L. P., J. L. Chau, H. L. Liu, and A. J. Coster (2010), Unexpected connections between the stratosphere and ionosphere, *Geophys. Res. Lett.*, *37*, L10101, doi:10.1029/2010GL043125.

Grinsted, A., J. C. Moore, and S. Jevrejeva (2004), Application of the cross wavelet transform and wavelet coherence to geophysical time series, *Nonlinear Processes Geophys.*, *11*, 561–566.

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, doi:10.1175/1520-0469(1978)035<0714:EWITUS>2.0.CO;2.

Holton, J. R. (2004), *An Introduction to Dynamic Meteorology*, vol. 88, *Int. Geophys. Ser.*, Academic, San Diego, Calif.

Holton, J. R., M. J. Alexander, and M. T. Boehm (2001), Evidence for short vertical wavelength Kelvin waves in the Department of Energy-Atmospheric Radiation Measurement Nauru99 radiosonde data, *J. Geophys. Res.*, *106*, 20,125–20,129, doi:10.1029/2001JD900108.

Isoda, F., T. Tsuda, T. Nakamura, R. A. Vincent, I. M. Reid, E. Achmad, A. Sadewo, and A. Nuryanto (2004), Intraseasonal oscillations of the zonal wind near the mesopause observed with medium-frequency and meteor radars in the tropics, *J. Geophys. Res.*, *109*, D21108, doi:10.1029/2003JD003378.

Kazimirovsky, E., M. Herraiz, and B. A. De la Morena (2003), Effects on the ionosphere due to phenomena below it, *Surv. Geophys.*, *24*, 139–184, doi:10.1023/A:1023206426746.

Lastovicka, J. (2006), Forcing of the ionosphere by waves from below, *J. Atmos. Sol. Terr. Phys.*, *68*, 479–497, doi:10.1016/j.jastp.2005.01.018.

Lieberman, R. S., and D. Riggin (1997), High-resolution Doppler imager observations of Kelvin waves in the equatorial mesosphere and lower thermosphere, *J. Geophys. Res.*, *102*, 26,117–26,130, doi:10.1029/96JD02902.

Lieberman, R. S., D. A. Ortland, and E. S. Yarosh (2003), Climatology and interannual variability of diurnal water vapor heating, *J. Geophys. Res.*, *108*(D3), 4123, doi:10.1029/2002JD002308.

Lima, L. M., E. D. Alves, A. F. Medeiros, R. A. Buriti, P. P. Batista, B. R. Clemesha, and H. Takahashi (2008), 3–4 day Kelvin waves observed in the MLT region at 7.4 degrees S, Brazil, *Geofis. Int.*, *47*, 153–160.

Liu, G., S. L. England, T. J. Immel, K. K. Kumar, G. Ramkumar, and L. P. Goncharenko (2012), Signatures of the 3-day wave in the low-latitude and midlatitude ionosphere during the January 2010 URSI World Day campaign, *J. Geophys. Res.*, *117*, A06305, doi:10.1029/2012JA017588.

Matsuno, T. (1966), Quasi-geostrophic motions in the equatorial area, *J. Meteorol. Soc. Jpn.*, *44*, 25–43.

Miyoshi, Y. and H. Fujiwara (2006), Excitation mechanism of intraseasonal oscillation in the equatorial mesosphere and lower thermosphere, *J. Geophys. Res.*, *111*, D14108, doi:10.1029/2005JD006993.

Niranjankumar, K., T. K. Ramkumar, and M. Krishnaiah (2011), Vertical and lateral propagation characteristics of intraseasonal oscillation from the tropical lower troposphere to upper mesosphere, *J. Geophys. Res.*, *116*, D21112, doi:10.1029/2010JD015283.

Pancheva, D., N. J. Mitchell, and P. T. Younger (2004), Meteor radar observations of atmospheric waves in the equatorial mesosphere/lower thermosphere over Ascension Island, *Ann. Geophys.*, *22*, 387–404, doi:10.5194/angeo-22-387-2004.

Parish, H., J. M. Forbes, and F. Kamalabadi (1994), Planetary wave and solar emission signatures in the equatorial electrojet, *J. Geophys. Res.*, *99*, 355–368, doi:10.1029/93JA02096.

Phanikumar, D. V., A. K. Patra, M. V. Ratnam, and S. Sripathi (2009), Planetary-scale variability in the low-latitude *E* region field-aligned irregularities: First results from Gadanki observations, *J. Geophys. Res.*, *114*, A01301, doi:10.1029/2008JA013564.

Rajaram, R., and S. Gurubaran (1998), Seasonal variabilities of low-latitude mesospheric winds, *Ann. Geophys.*, *16*, 197–204, doi:10.1007/s00585-998-0197-4.

Rao, P. B., A. R. Jain, P. Kishore, P. Balamuralidhar, S. H. Damle, and G. Viswanathan (1995), Indian MST radar: 1. System description and sample vector wind measurements in ST mode, *Radio Sci.*, *30*, 1125–1138, doi:10.1029/95RS00787.

Ricciardulli, L., and R. R. Garcia (2000), The excitation of equatorial waves by deep convection in the NCAR community climate model (CCM3), *J. Atmos. Sci.*, *57*, 3461–3487, doi:10.1175/1520-0469(2000)057<3461:TEOEWB>2.0.CO;2.

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, doi:10.1029/96JD04011.

Rishbeth, H. (2006), *F* region links with the lower atmosphere?, *J. Atmos. Sol. Terr. Phys.*, *68*, 469–478, doi:10.1016/j.jastp.2005.03.017.

Salby, M. L. (1984), Survey of planetary-scale traveling waves: The state of theory and observations, *Rev. Geophys.*, *22*, 209–236, doi:10.1029/RG022i002p00209.

Sasi, M. N., and V. Deepa (2001), Seasonal variation of equatorial wave momentum fluxes at Gadanki (13.5°N, 79.2°E), *Ann. Geophys.*, *19*, 985–990, doi:10.5194/angeo-19-985-2001.

Sato, K., and T. J. Dunkerton (1997), Estimates of momentum flux associated with equatorial Kelvin and gravity waves, *J. Geophys. Res.*, *102*, 26,247–26,261, doi:10.1029/96JD02514.

Siva Kumar, V., P. B. Rao, and M. Krishnaiah (2003), Lidar measurements of stratosphere-mesosphere thermal structure at a low latitude: Comparison with satellite data and models, *J. Geophys. Res.*, *108*(D11), 4342, doi:10.1029/2002JD003029.

Takahashi, H., C. M. Wrasse, D. Pancheva, M. A. Abdu, I. S. Batista, L. M. Lima, P. P. Batista, B. R. Clemesha, and K. Shiokawa (2006), Signatures of 3–6 day planetary waves in the equatorial mesosphere and ionosphere, *Ann. Geophys.*, *24*, 3343–3350, doi:10.5194/angeo-24-3343-2006.

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.

Taori, A., J. J. Makela, and M. Taylor (2010), Mesospheric wave signatures and equatorial plasma bubbles: A case study, *J. Geophys. Res.*, *115*, A06302, doi:10.1029/2009JA015088.

Torrence, C., and G. P. Compo (1998), A practical guide to wavelet analysis, *Bull. Am. Meteorol. Soc.*, *79*, 61–78, doi:10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2.

Vincent, R. A. (1986), *Hardware Requirements: A New Generation Partial Reflection Radar for Studies of the Equatorial Mesosphere*, vol. 20, *MAP Handbook*, Univ. of Ill., Chicago.

Voiculescu, M., C. Haldoupis, D. Pancheva, M. Ignat, K. Schlegel, and S. Shalimov (2000), More evidence for a planetary wave link with midlatitude *E* region coherent back scatter and sporadic *E* layers, *Ann. Geophys.*, *18*, 1182–1196, doi:10.1007/s00585-000-1182-8.

Wallace, J. M., and V. E. Kousky (1968), Observational evidence of Kelvin waves in the tropical stratosphere, *J. Atmos. Sci.*, *25*, 900–907, doi:10.1175/1520-0469(1968)025<0900:OEOKWI>2.0.CO;2.

Yoshida, S., T. Tsuda, A. Shimizu, and T. Nakamura (1999), Seasonal variations of 3.0–3.8 day ultra fast Kelvin waves observed with a meteor wind radar and radiosonde in Indonesia, *Earth Planets Space*, *51*, 675–684.

Ziemke, J. R., and J. L. Stanford (1991), One-to-two month oscillations: Observed high latitude tropospheric and stratospheric response to tropical forcing, *J. Atmos. Sci.*, *48*, 1336–1347, doi:10.1175/1520-0469(1991)048<1336:OTTMOO>2.0.CO;2.