JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D07109, doi:10.1029/2006JD007962, 2007

On the tropospheric origin of Mesosphere Lower Thermosphere region intraseasonal wind variability

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Received 24 August 2006; revised 21 November 2006; accepted 21 December 2006; published 12 April 2007.

[1] Continuous medium frequency radar observations of mesosphere lower thermosphere (MLT) region winds during February 2004–May 2005 (486 days) over Tirunelveli (8.7°N, 77.8°E) revealed intraseasonal oscillations (ISOs) in the 82- to 94-km height region. Two distinct oscillations with periods 50–70 and 20–40 days are noticed predominantly in zonal winds. As it is well established that these oscillations are nonstationary and localized in time, wavelet analysis has been employed to study the time evolution of these oscillations. The analysis showed that 50- to 70-day oscillation peaks during June-October and 20- to 40-day oscillation peaks during January-March in the MLT region. To trace back the origin of these oscillations, the tropospheric ISO has been studied for the same period using outgoing long-wave radiation (OLR) observations. The OLR, which is the proxy for convective activity in the lower atmosphere, around the radar site 5–10°N, 70–80°E is used for the present analysis. The wavelet analysis of OLR showed the 50- to 70-day oscillation peaking at the same time as in the MLT region. The shorter period oscillation (20–40 days), which showed its peak during January-March in the MLT region, is not observed in the OLR data during these months. However, the analysis of water vapor, which is the prime candidate for excitation of tides, showed the 20- to 40-day oscillation during the same time as in the MLT region. In the present study, the lower atmospheric convective activity through gravity wave excitation and water vapor through tidal forcing are accounted for the observed ISO in the MLT region. The significance of present results lies in showing the highly coherent oscillations in OLR and MLT region zonal winds. The coupling between the lower and middle atmospheric ISO is extensively discussed in the light of existing mechanisms.

Citation: Kumar, K. K., T. M. Antonita, G. Ramkumar, V. Deepa, S. Gurubaran, and R. Rajaram (2007), On the tropospheric origin of Mesosphere Lower Thermosphere region intraseasonal wind variability, *J. Geophys. Res.*, *112*, D07109, doi:10.1029/2006JD007962.

1. Introduction

[2] Owing to the importance of dynamics of mesosphere lower thermosphere (MLT) region, many observations have been carried out across the globe to explore this part of the atmosphere. Ground-based radars, rockets, and satellite observations were extensively used to understand the various physical processes in this region. Among all these, ground-based medium frequency (MF) and meteor radar observations of MLT from different geographical locations significantly contributed to the present understanding of dynamics and energetics of this region of the atmosphere [*Vincent*, 1984; *Meek et al.*, 1985a, 1985b; *Vincent and Fritts*, 1987; *Manson et al.*, 1991, 1999, 2002; *Vincent and Lesicar*, 1991; *Manson and Meek*, 1993; *Thayaparan et al.*, 1995a, 1995b; *Rajaram and Gurubaran*, 1998; *Gurubaran and Rajaram*, 1999]. In the earlier phase of these studies, height profiles of tidal amplitudes and phases were treated extensively, and in the later phase, the interest was shifted to tidal forcing mechanisms and its variability at different timescales. In recent years, MLT region wind variability at intraseasonal scale became a cynosure in the field of middle atmospheric dynamics.

[3] *Eckermann and Vincent* [1994] reported intraseasonal oscillations (ISO) in equatorial MLT winds from the Christmas Island (2°N, 157°W) MF radar observations. Since then, there has been considerable interest in the middle atmospheric community to trace back the origin of these oscillations to the lower atmosphere. *Eckermann et al.* [1997] proposed many possibilities of observed MLT region ISO and concluded that the intraseasonal cycles in tropospheric convection produce observed intraseasonal variations in the intensity of gravity waves and nonmigrating diurnal tides impinging upon the mesosphere. According to these authors, this intraseasonally modulated wave activity induces similar periodicities in the zonal MLT flow. *Lieberman* [1998] studied the ISO in the zonally averaged zonal wind

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data in the MLT using Upper Atmospheric Research Satellite–High-Resolution Doppler Imager (UARS/HRDI) data. The ISO was found to extend between ±20° latitude from the equator. Subsequent studies at midlatitudes by *Pancheva et al.* [2003] also found ISO variability in MLT winds. For the record, intraseasonal variability in midlatitude winds is hardly unexpected given the large role of stratospheric warmings and associated mesospheric cooling responses in polar winter middle atmosphere meteorology. In the midlatitude, the observed oscillations were slightly greater than (∼75 days) usual tropospheric ISO (30–60 days). Pancheva et al. concluded that the observed 75-day variability in gravity wave activity and tidal amplitudes does not originate in the troposphere, but may be imposed in situ in the mesosphere. In a recent study, observations from the three equatorial radar sites, Jakarta (6°S, 107°E), Pontianak (0°N, 109°E), and Christmas Island, were compared by *Isoda et al.* [2004] to investigate possible differences in the zonal wind ISO as a function of latitude and longitude. Their results suggested the diurnal tide involvement in the generation of the ISO of the zonal mean flow in the MLT region. They also suggested that the generation of nonmigrating tides is modulated at the ISO period in the lower atmosphere, and these nonmigrating tides propagate to the MLT region. Then, the breaking/dissipating tides modulate the zonal mean wind in this region. In contrast to *Eckermann et al.*, *Isoda et al.* did not observe the modulation of gravity wave activity in the MLT region at intraseasonal scales. However, the latter study stated that the role of gravity wave could not be ruled out. Thus there are contrasting observations from the different geographical locations. All these studies tried to relate the ISO in the lower atmospheric convection and the observed MLT wind variability. In another recent study, *Lieberman et al.* [2003] proposed that the tropical tropospheric variability may be communicated to the diurnal tide and possibly to the middle atmosphere by means of water vapor heating. These authors reevaluated the significance of water vapor heating as a source of variability for nonmigrating tides. Using a general circulation model, *Miyoshi and Fujiwara* [2006] studied the excitation mechanism of intraseasonal oscillation of the zonal mean zonal wind in the equatorial MLT. Their results showed that wave-mean flow interaction with ultrafast Kelvin waves [*Yoshida et al.*, 1999] and diurnal tides is important for driving the intraseasonal oscillation. The authors also showed that not only the migrating diurnal tide but also the nonmigrating diurnal tide plays an important role in excitation of the intraseasonal oscillation.

[4] Apart from these indirect coupling mechanisms of lower and middle atmosphere, some previous studies have suggested that the ISO Rossby wave may be able to propagate directly into the upper stratosphere (and higher) by first refracting out to midlatitudes, and then refracting back into the equatorial upper stratosphere [*Ziemke and Stanford 1991*]. *Ziemke and Stanford* [1991] are the first to propose this mechanism. Some possible evidence for this was inferred from Indian rocketsonde data from the upper stratosphere [*Nagpal et al.*, 1994; *Kumar and Jain*, 1994].

[5] The key factor of the present study is that all previous MF radar studies of ISOs in the MLT have used data from radars stationed in the Indonesian region or from radars in the Pacific well to the east of Indonesia. The MF radar winds from the current study focus for the first time on the southern Asian region, well to the west of Indonesia. This is important because tropospheric ISO is known to be controlled by fundamentally different dynamics to the east and to the west of the convective super clusters over Indonesia that drives the ISO [*Madden and Julian*, 1994; *Hendon and Salby*, 1994; *Zhang*, 2005]. Thus ISO activity in the MLT to the west of Indonesia may have a fundamentally different dynamical origin and physical explanation to that observed to the east of Indonesia. The central objective of the present study is to show the ISO in the MLT region zonal winds for the first time from this latitude and to discuss its tropospheric origin in the light of existing mechanisms. The significance of the present results lies in showing that the ISOs in lower atmospheric convective activity and water vapor are distinctly different, and both are having their signatures in the observed MLT region ISO. Section 2 describes the database used for the present study including MF radar details, section 3 presents the results, and discussion and concluding remarks are given in section 4.

2. Data Analysis

[6] The MF radar observations of MLT region winds during February 2004–May 2005 over Tirunelveli (8.7°N, 77.8°E) located near the southern tip of India form the basis for the present study. The radar wind observations are averaged everyday to form the time series data of zonal and meridional winds for a total number of 486 days. The MF radar at Tirunelveli was installed by the Indian Institute of Geomagnetism, during the middle of 1992, with assistance from Dr. R. A. Vincent and his group at the University of Adelaide, Australia. The radar system operating at 1.98 MHz is identical to the one placed on Christmas Island by the University of Adelaide. The technical details of this radar system can be found in the work of *Vincent and Lesicar* [1991]. The Tirunelveli MF radar provides winds in the 68- to 98-km region using full correlation analysis. In this study, we focus our attention in the height region of 84–96 km as the data are densely populated here and also the data acceptance rate, determined by the rejection criteria adopted in the method of wind determination, is quite low for altitudes below 84 km during nighttime. Short data gaps were filled using linear interpolation.

[7] To study the lower tropospheric ISO, we used outgoing long-wave radiation (OLR) around the radar site. To evaluate the oscillations in the water vapor, we used the water vapor measurements by the regular radiosondes flown by India Meteorological Department (IMD). As there were no radiosonde measurements at the radar site, the measurements from nearby IMD station at Trivandrum (8.5°N, 77°E) have been used for the present study. The relevance of OLR and water vapor to the present study will be discussed in the next section. Thus time series of MLT region winds, tropospheric water vapor, and OLR are examined to bring out the coherence of ISO in lower and middle atmosphere.

[8] We have chosen wavelet analysis to study the time evolution of ISO. Wavelet analysis is becoming a common tool for analyzing localized variations of power within a time series. By decomposing a time series into time-frequency space, one is able to determine both the dominant modes of variability and how those modes vary in time. A complete

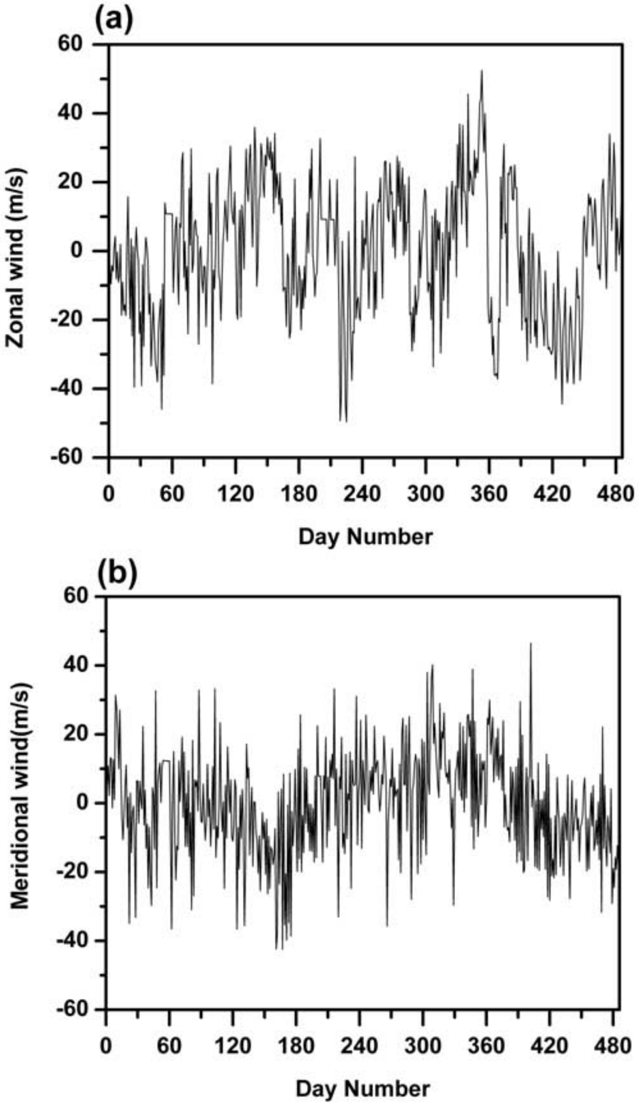

Figure 1. Time series of (a) zonal and (b) meridional wind at 84 km (the first and last tick marks in the *x* axis represent 1 February 2004 and 31 May 2005, respectively).

description of geophysical applications can be found in the work of *Foufoula-Georgiou and Kumar* [1995], while a theoretical treatment of wavelet analysis is given in the study of *Daubechies* [1992]. The wavelets are by construction very localized functions being able to resolve frequency transitions during short time periods. For the present study, we use Morlet wavelet function as mother wavelet. Localization of signal characteristics in time and frequency domains can be accomplished very efficiently with this wavelet function.

3. Results and Discussion

[9] The continuous MF radar observations of MLT region zonal and meridional winds for a total number of 486 days at 84 km are shown in (Figures 1a) and (1b), respectively. The first and last tick marks in the *x* axis represent 1 February 2004 and 31 May 2005, respectively. These figures show that the zonal winds exhibit pronounced intraseasonal variability as compared to the meridional winds. To exactly know the periodicity and the time of occurrence of ISO, the time series of zonal and meridional winds are subjected to wavelet analysis. (Figures 2a) and (2b) show the output of wavelet analysis applied to the time series data shown in (Figures 1a) and (1b), respectively. The *x* axis of (Figures 2a) and (2b) shows the day number, and the *y* axis shows the time periods of the observed oscillations. The *y* axis is limited to 10–100 days to highlight the ISO. The solid lines shown in the wavelet spectra correspond to the "cone of influence." The cone of influence is the region of the wavelet spectrum in which edge effects become important and is defined here as the e-folding time for the autocorrelation of wavelet power at each scale. This e-folding time is chosen so that the wavelet power for a discontinuity at the edge drops by a factor e^{-2} and ensures that the edge effects are negligible beyond this point. The periods within these solid lines are free from edge effects, and we will concentrate on only those oscillations that are

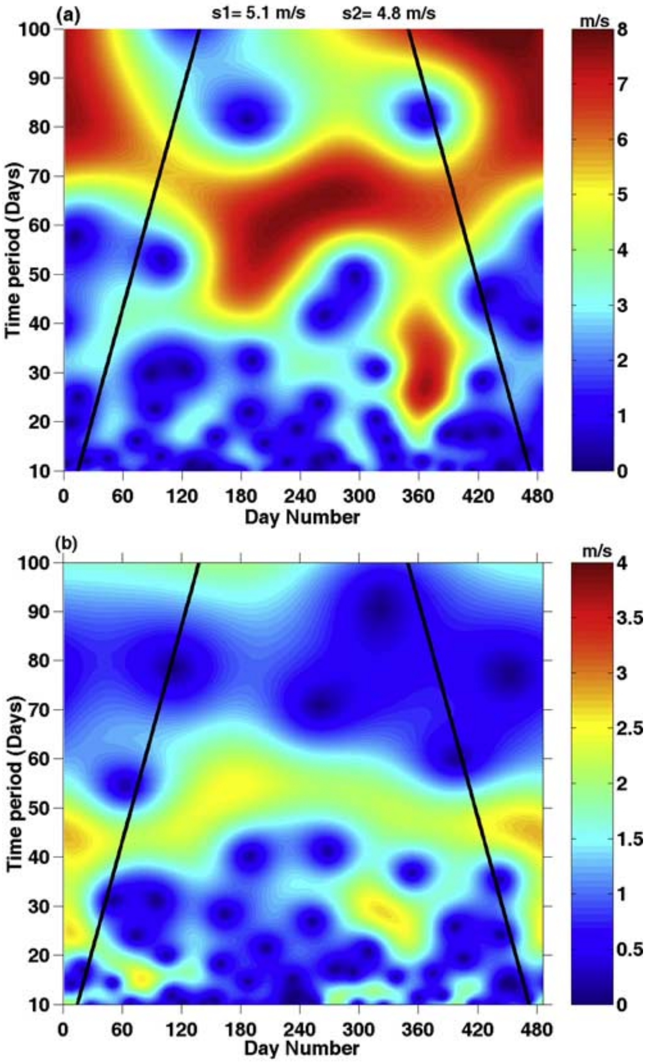

Figure 2. Wavelet spectra of (a) zonal and (b) meridional wind at 84 km (s1 and s2 indicate the 95% confidence level amplitudes for 50- to 70- and 20- to 40-day oscillations, respectively).

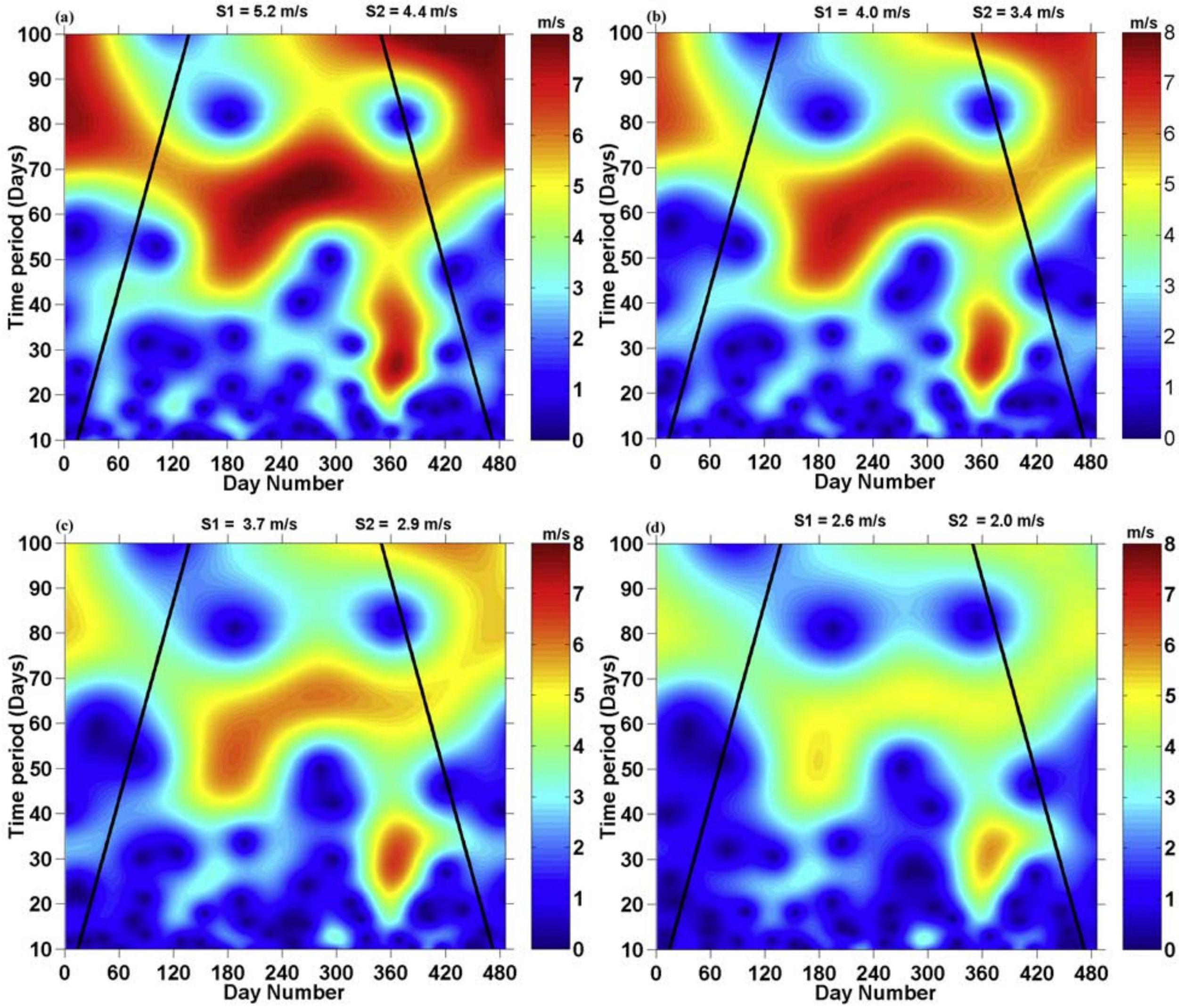

Figure 3. Wavelet spectra of zonal wind at (a) 86 km, (b) 88 km, (c) 90 km, and (d) 92 km (s1 and s2 indicate the same as in Figure 2).

within the cone. The preliminary observation of these wavelet spectra reveals that the intraseasonal oscillations are more dominant in zonal winds as compared to meridional, consistent with MLTISO winds in the central Pacific presented by *Eckermann et al.* [1997]. So we will focus our attention only on zonal wind ISO. The striking feature observed in the zonal wind wavelet spectrum is the oscillations with time period 50–70 days during the months of June-October 2004 (day numbers 120–270). One more interesting feature, which can be observed from this spectrum, is the strengthening of 20- to 40-day oscillations during January-March 2005 (day numbers 330–420). To confirm the significance of observed 50- to 70- and 20- to 40-day oscillations, the chi-square test is carried out. It is assumed that the time series has a mean power spectrum; if a peak in the wavelet power spectrum is significantly above this background spectrum, then it can be assumed to be a true feature with a certain percent confidence [*Torrence and Compo*, 1998]. The 95% confidence level is estimated for both the observed oscillations and is shown in (Figure 2a) as s1 and s2. From the values of s1 and s2, it can be seen that the observed peaks of 50- to 70- and 20- to 40-day oscillations are well above the 95% confidence level. To check the consistency of these observed features, spectral analysis has been carried out in the entire 82- to 98-km height region with 2-km height resolution. (Figures 3a–3d) show the wavelet spectra of zonal winds at 86, 88, 90, and 92 km, respectively. These plots confirm two things: first, the consistency of the observed ISO in the MLT region with height, and the applicability of the wavelet analysis to study the time evolution of the ISO. It is interesting to note the highly coherent oscillations in the entire observational height domain. Now our next task is to trace the origin of this MLTISO.

[10] Earlier studies on MLTISO attributed the observed features to the ISO in tropospheric convective activity as discussed in section 1. In the present study, we use OLR as a proxy for the tropospheric convective activity. The OLR data provided by the National Ocean and Atmospheric Administration (NOAA) over the latitudes 5°–10°N are averaged at three longitudes 70°, 75°, and 80°E. The OLR data have been taken at three different longitudes to show the

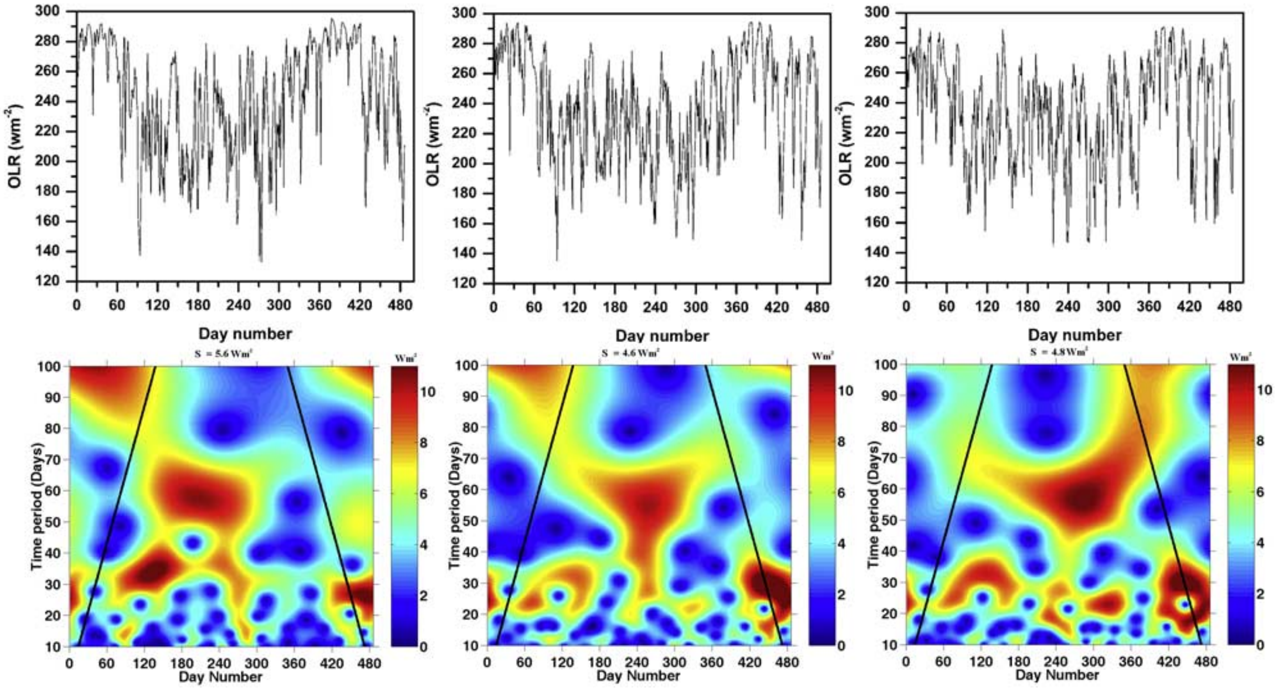

Figure 4. Top panel: Time series of OLR during February 2004–May 2005 at 70°, 75°, and 80°E longitudes (averaged over 5–10°N latitude). Bottom panel: Wavelet spectra of OLR shown in the top panel (S indicates the 95% confidence level amplitude for 50- to 60-day oscillations).

horizontal propagation of the ISO. Top panel of Figure 4 shows the time series of OLR during February 2004–May 2005 at three above-mentioned longitudes. From these plots, it is evident that the OLR shows low values during June-September (day numbers 120–240) owing to the southwest monsoon prevailing over these longitudes. Next, we subject these time series data to wavelet analysis to note the periodicities present in the OLR. Bottom panel of Figure 4 shows the wavelet spectra of OLR data at three different longitudes. All the three spectra show the presence of ISO with periodicities 50–60 days. It also can be noted that the observed peaks in 50–60 days are well above 95% confidence level. One more interesting feature observed in these spectra is the eastward propagation of 50- to 60-day oscillation. This feature can be seen by comparing the position of maximum activity of 50- to 60-day oscillations in the wavelet spectra at the three longitudes. However, the ISO in the lower atmosphere is very well established phenomenon over tropics. *Hartmann and Michelson* [1989] analyzed 70 years of daily rainfall data from thousands of sites in India, and they characterized strong ISO variability in precipitation. Subsequent work has clarified the role of ISO in modulating convective rainfall patterns over India, particularly the summer monsoon, using further refined data analysis and modeling [*Krishnamurthy and Shukla*, 2000; *Goswami et al.*, 2003]. The ISO peak in OLR during June-October 2004 (day numbers 120–270) in Figure 4 and its eastward propagation are entirely consistent with the current understanding of tropospheric ISO over India. However, in terms of circulation anomalies, finer scale propagating OLR and precipitation anomalies, the situation near India is not so straightforward. In fact, the slow Kelvin wave response that characterizes the slow eastward movement of the ISO is a far-field response. In the near-field forcing regions in and around India and the maritime continent, the response is characterized by a Kelvin wave propagating to the east and Rossby waves propagating to the west [*Hendon and Salby*, 1994]. These latter westward moving Rossby waves are particularly important in and around India, since the ISO near-field forcing often begins in the Indian Ocean and slowly migrates toward Indonesia, potentially spinning off Rossby waves that propagate short distances westward over India. Evidences for such waves in the troposphere and stratosphere in the Indian sector were provided by *Ziemke and Stanford* [1991] and also were seen in earlier Indian rocket data [*Nagpal et al.*, 1994; *Kumar and Jain*, 1994].

[11] To compare the lower atmospheric ISO (50–60 days) with MLTISO, the wavelet spectra shown in Figure 4 are compared with those shown in Figure 3. These spectra do show the similarities between the tropospheric and MLTISO. The OLR spectra are shown at three longitudes, whereas MLT wind spectra are shown over single longitude. It appears from these spectra that the MLTISO shows the average picture of the tropospheric ISO shown at three longitudes. In other words, the MLT region shows response for lower atmospheric convective activity spread over wide range, which is expected. However, a burst of oscillations in the MLT zonal winds having 20- to 40-day periodicity during January-March 2005(day numbers 330–420) is not observed in the OLR spectral analysis. To date, no study focused attention to verify the oscillations in the lower atmospheric water vapor and to correlate it with MLT region ISO. A recent seminal study by *Lieberman et al.* [2003] comprehensively showed the importance of water vapor heating in understanding the tidal forcing, which in turn influences the middle atmospheric dynamics.

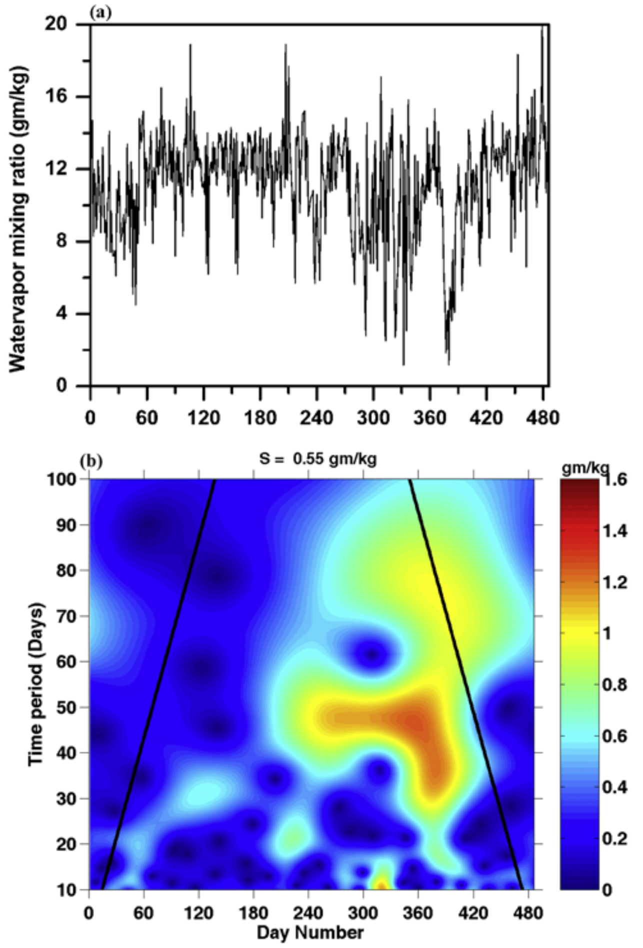

Figure 5. Time series of (a) water vapor mixing ratio and (b) wavelet spectrum of water vapor mixing ratio (S indicates the 95% confidence level amplitude for 20- to 40-day oscillations).

[12] In the present study, we also examined the lower atmospheric water vapor variabilities to see their signatures in the MLT region. The water vapor mixing ratio is estimated from the daily radiosonde observations for the study period and is shown in (Figure 5a). The vertical profile of water vapor mixing ratio is integrated in the height region 0–4 km as most of the water vapor lies in this region of the atmosphere. Again, to know the exact periodicities and their time of occurrence, the time series of water vapor data are subjected to wavelet analysis and is shown in (Figure 5b). The water vapor spectrum shows a very similar burst of 20- to 40-day oscillations during more or less same period (February 2005, around day 360), as observed in MLT region. By examining the spectra of MLT region zonal winds and lower atmospheric water vapor, it can be stated that the oscillations in lower atmospheric water vapor appear to have a signature in the MLT region wind variability. Thus the wavelet analysis showed the signature of both OLR and water vapor oscillations in the MLT region.

[13] To know the phase relation between the observed MLT and lower atmospheric ISO activity, the time history of 50- to 70- and 20- to 40-day oscillations from both the regions are extracted from the wavelet analysis and are shown in (Figures 6a) and (6b), respectively. The time series of OLR (50–70 days) amplitudes at all the three longitudes are plotted together with MLT zonal wind ISO (refer to (Figure 6a)). From this figure, it is evident that the OLR amplitudes at 70°E lags, at 75°E just coincides, and at 80°E leads the MLTISO. At a given time, it seems that the MLTISO shows an average signature of lower atmospheric convective forcing over a wide horizontal extent. The 20- to 40-day oscillation in lower atmospheric water vapor and MLT zonal winds also shows a very good agreement as depicted in (Figure 6b). However, this figure shows that the lower atmospheric 20- to 40-day oscillation leads the MLTISO. It should be remembered that the water vapor observations shown here are from a single station, whereas MLT responds to the oscillations at other longitudes also as mentioned above. Thus very good agreement in the time evolution of amplitudes of lower atmospheric ISO and MLTISO supports the latter's tropospheric origin.

[14] Now let us discuss the possible mechanism through which the lower atmospheric ISO is communicated to MLT region. As discussed in section 1, the most probable

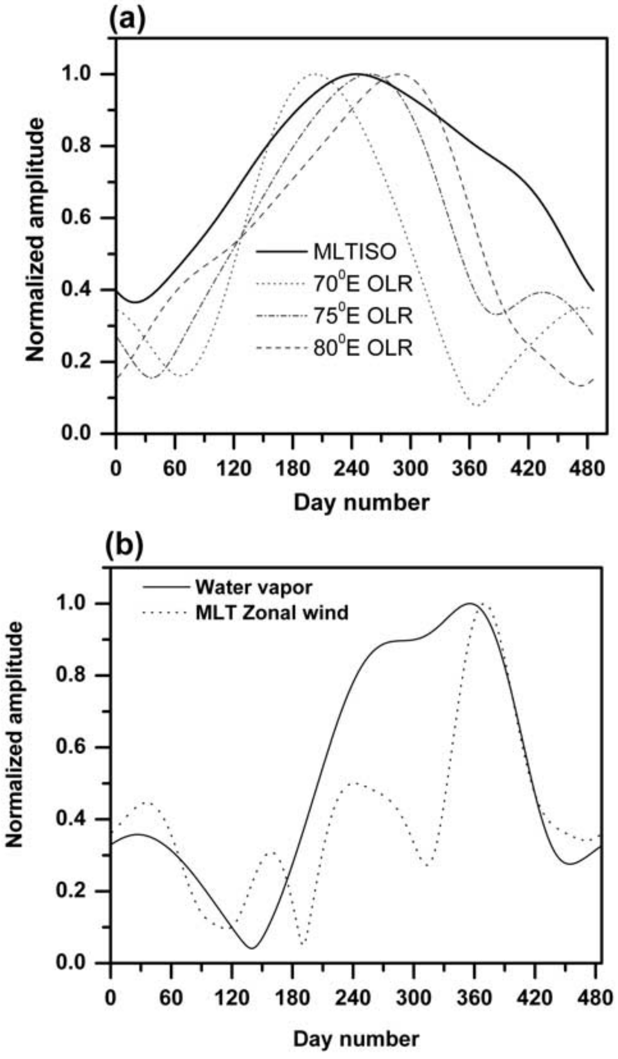

Figure 6. Time evolution of (a) MLTISO (50–70 days) and tropospheric ISO and (b) MLTISO (20–40 days) and water vapor mixing ratio derived from wavelet analysis.

possibility as reported by *Eckermann et al.* [1997] and *Isoda et al.* [2004] is the modulation of gravity waves and nonmigrating tides generated in the lower atmosphere by the ISO in deep tropical convection. According to their assertion, these waves carry the imprints of ISO and transfer it to the middle atmosphere via wave-mean flow interaction. Their studies also examined the tidal and gravity wave variabilities, which also showed the ISO. *Eckermann et al.* [1997] showed the strong ISO in gravity wave as well as in nonmigrating tidal amplitudes. However, observations reported by *Isoda et al.* [2004] did not show the ISO in gravity wave variances, and they attributed observed ISO in the MLT region to nonmigrating tides rather than gravity waves. Both of these studies considered convective activity as a forcing mechanism for both gravity wave and nonmigrating tides. However, present study for the first time shows the evidence for implication of convective activity as well as water vapor variability at ISO in explaining the observed MLT region ISO. It is well established that water vapor has both migrating and nonmigrating components of tides. The variability in the water vapor will be imprinted on the tidal amplitudes, which will in turn reflect in the MLT region winds. *Lieberman et al.* [2003] discussed the variabilities in the water vapor heating at different timescales, and the present study shows the implications of water vapor variabilities in explaining the MLT region ISO features. Thus the present study emphasizes the consideration of ISO in lower atmospheric water vapor as one of the mechanisms in driving the MLT region ISO apart from the convective activity.

[15] One more possibility of observed MLTISO is the direct propagation of equatorial waves having ISO periods from troposphere to MLT. These possibilities are also extensively discussed by *Eckermann et al.* [1997], and their study concluded that the equatorial waves having ISO periods could not propagate directly into the Pacific MLT region. However, as discussed by *Eckermann et al.* [1997], there is observational evidence for propagation of Rossby waves (Yanai-Maruyama wave) at least up to the stratopause from the Indian region [*Ziemke and Stanford*, 1991; *Nagpal et al.*, 1994; *Kumar and Jain*, 1994]. Thus in terms of a directly radiated dynamical ISO response, the pertinent ISO dynamics near India may be westward Rossby waves, as opposed to the eastward Kelvin wave response which is the only plausible dynamics well to the east in the central Pacific [*Eckermann et al.*, 1997]. This is what makes the current observations particularly interesting, since the local underlying ISO dynamics over India may be fundamentally different than those over the central Pacific. By now, there are two mechanisms by which the Rossby wave reaches the tropical stratopause from the troposphere. One is by refracting to midlatitudes then refract back into the tropical stratopause [*Ziemke and Stanford*, 1991], and another one is direct propagation from troposphere to stratosphere [*Kumar and Jain*, 1994]. By whatever mechanism it reaches at tropical stratopause, the further propagation to MLT region depends on the phase of the stratospheric SAO. The westward phase of SAO filters the Rossby waves, whereas the eastward phase is conducive for their further propagation into the MLT region. In the present study, the stratospheric SAO climatology over Trivandrum (8.5°N, 77°E) shows the westward phase during June-September [*Nagpal and Raghavarao*, 1991], and the MLTISO is observed during June-October in the present study. So Rossby waves will be effectively absorbed near the stratopause itself, and there will be a very little chance for propagating into the MLT region. Thus we rule out the possibility of direct propagation of Rossby waves having ISO periods into the MLT region based on the phase of stratospheric SAO. However, to the date, there are no simultaneous wind measurements from ground to MLT region on continuous basis to study the propagation of Rossby waves from troposphere to MLT. An observational campaign focusing on Rossby wave propagation right from troposphere to MLT region will be very useful to further investigate this issue. On the other hand, the Rossby waves can modulate the intensity of gravity waves passing through the stratopause and can have its signature in the MLT region as discussed by *Eckermann et al.* [1997]. However, the present study suggests that the lower atmospheric convective activity through gravity wave excitation and water vapor through tidal forcing are responsible for the observed ISO in the MLT region wind fields.

4. Concluding Remarks

[16] MF radar observations of MLT region winds revealed the signature of ISO for the first time over this latitude. The wavelet analysis of zonal and meridional wind data showed that the ISO is present predominately in zonal winds. Two distinct oscillations, peaking at different times, are observed in the MLT region zonal winds. The long periods are in the range of 50–70 days, and the shorter ones are in the range of 20–40 days. To trace back the origin of these oscillations, lower atmospheric convective activity and water vapor are examined. Present observations showed beyond doubt that there exists a similar type of oscillations in the lower and middle atmosphere. The 50- to 70-day oscillations in the MLT region showed similarities with lower atmospheric convective activity, whereas the 20- to 40-day oscillations showed similarities with water vapor oscillations. Earlier studies on MLT region ISO attributed the observed ISO features entirely to the convective activity, and the present study demonstrated the implication of lower atmospheric water vapor variability. The present study thus reinforce the work reported by *Lieberman et al.* [2003] on the importance of water vapor heating rate variability in understanding the middle atmosphere dynamics. An attempt was also made to discuss the other possibilities of observed MLTISO in the light of existing mechanisms.

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