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Longitudinal variability in intraseasonal oscillation in the tropical mesosphere and lower thermosphere region

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[1] Simultaneous observations of mean zonal wind at 88 km obtained by the meteor radars at Cariri (7.4°S, 36.5°W) and Ascension Island (7.9°S, 14.4°W) and two medium-frequency radars at Tirunelveli (8.7°N, 77.8°E) and Pamuengpeuk (7.7°S, 107.7°E) have been used to investigate the influence of the intraseasonal variations in the lower tropospheric convective activity associated with the Madden-Julian oscillation on the longitudinal behavior of intraseasonal oscillations (ISO) of the zonal winds in the equatorial mesosphere and lower thermosphere (MLT). The ISO activity in the lower tropospheric convective activity is examined by employing outgoing long-wave radiation (OLR) as a proxy for deep convective activity occurring in the tropical lower atmosphere. The longitudinal and temporal variabilities of the ISO amplitudes in MLT zonal winds are explained in terms of the intraseasonal variabilities in the convective activity. We have also employed daily zonal wind data provided by the United Kingdom Meteorological Office (MetO) to examine the ISO activity in zonal winds at 25 pressure levels from the surface to 0.1 hPa (60 km height) over the respective radar locations.

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1. Introduction

[2] The circulation of the equatorial middle atmosphere is known to be dominated by a quasi-biennial oscillation (QBO) and a semiannual oscillation (SAO). At heights below 35 km, the winds are dominated by the QBO, while above 35 km, by the SAO [*Ebdon*, 1960; *Reed et al.*, 1961; *Baldwin et al.*, 2001]. The SAO has maximum amplitudes near the stratopause (~50 km) and mesopause (~85 km), with minimum near 65 km, and the stratospheric SAO (SSAO) is in antiphase with the mesospheric SAO (MSAO) [*Hirota*, 1978; *Hamilton*, 1982; *Garcia et al.*, 1997]. The QBO and SAO are centered at or near the equator, and their cycles start first at upper levels and then descend steadily with time. Descending wind regimes are usually a characteristic of a circulation driven primarily by waves propagating from below. It has been suggested that upward coupling of energy and momentum by waves generated in regions of intense tropospheric convection is expected to be important for determining the state of the equatorial middle atmosphere. Convectively generated waves such as Kelvin, Rossby-gravity and gravity waves play a crucial role in driving the QBO in the lower stratosphere and the SSAO [*Lindzen and Holton*, 1968; *Dunkerton*, 1979; *Dunkerton*, 1997; *Garcia*, 2000], whereas Kelvin waves and gravity waves are considered to be important for driving the MSAO [*Hirota*, 1978; *Dunkerton*, 1982].

[3] The equatorial mesosphere and lower thermosphere (MLT) region zonal winds are characterized by long-term variations such as the annual oscillation (AO) and the semiannual oscillation (SAO) [e.g., *Vincent*, 1993]. In addition, the SAO amplitudes show biennial variations [e.g., *Burrage et al.*, 1996]. Wind oscillations caused by the ultrafast Kelvin waves (UFK) with 3–4 day period and quasi 2-, 5-, and 16-day wind oscillations have also been investigated [*Tsutsumi et al.*, 1996; *Riggin et al.*, 1997; *Kovalam et al.*, 1999; *Yoshida et al.*, 1999; *Isoda et al.*, 2002; *Sridharan et al.*, 2003; *Mota Lima et al.*, 2008]. Besides these oscillations, the MLT zonal winds also undergo variations, in periods ranging from 20 to 100 days, which have been termed as the intraseasonal oscillation (ISO), first reported by *Eckermann and Vincent* [1994] from Christmas Island (2°N, 150°W). *Eckermann et al.* [1997] further investigated the ISO using long-term (1990–1995) observations by medium-frequency (MF) radar made at Christmas Island. Periodicities of about 25, 40, 60 days

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were observed not only in the zonal wind, but also in the amplitude variations of gravity waves and diurnal tidal amplitudes.

[4] In the equatorial troposphere, intraseasonal variability is a dominant feature of convective anomalies. Intraseasonal variabilities in the zonal wind velocity and tropical rainfall are observed and are mostly confined in the region between the Indian Ocean and the western and central Pacific [*Madden and Julian*, 1971; *Zhang*, 2005]. The Madden-Julian oscillation (MJO) of this kind is characterized by large-scale convective anomalies that develop over the tropical Indian Ocean and propagate slowly eastward over the maritime continent to the western Pacific [*Madden and Julian*, 1972], slowly decay over central Pacific and vanish over the eastern Pacific. Individual MJO events last typically between 30 and 60 days. Large-scale pressure and circulation anomalies develop with the convective anomalies and can be interpreted as a moist equatorial Kelvin-Rossby wave response in the tropics [*Hendon and Salby*, 1994; *Matthews*, 2000]. The MJO can be considered as a mixed Kelvin and Rossby wave near the source region and an eastward propagating Kelvin wave radiating away from the source region [*Madden and Julian*, 1994]. The MJO attenuates rapidly above the tropopause [*Madden and Julian*, 1971].The studies of rocket and radiosonde data from tropical Indian stations showed that the wind variabilities in the intraseasonal time period are diminished above tropopause and reintensified at the upper stratospheric heights [*Nagpal and Raghavarao*, 1991; *Nagpal et al.*, 1994; *Kumar and Jain*, 1994]. *Nagpal and Raghavarao* [1991] and *Nagpal et al.* [1994] argued that the Rossby waves of time period in the intraseasonal time scale could propagate into the tropical atmosphere from midlatitudes, whereas *Kumar and Jain* [1994] suggested that the Rossby waves associated with the MJO might leak into the upper stratosphere from tropical troposphere via vertical propagation. *Ziemke and Stanford* [1991] observed strong ISO activity at in daily global geopotential height data from British Meteorological Office analyses in a longitude zone near India which they associated with tropical Rossby waves that refracted to mid latitudes then back to tropical latitudes near the stratopause.

[5] *Eckermann et al.* [1997] reported that the ISO periods observed in the zonal winds of the MLT region are similar to the MJO periods and suggested that the intraseasonal cycles in the tropospheric convection associated with the MJO cannot propagate directly into the MLT region because of their slow phase velocity but modulate the intensity of the upward propagating gravity waves and nonmigrating diurnal tides and that these induce intraseasonal variations in the MLT region zonal winds through wave induced driving of the mean flow (when they either dissipate or break).

[6] *Lieberman* [1998] studied the ISO in the zonally averaged zonal winds in the altitude range 65–100 km using Upper Atmospheric Research Satellite–High Resolution Doppler Imager (UARS/HRDI) data. The maximum amplitudes of the ISO were observed at 95 km and 75 km height, with a local minimum at around 80 km. The ISO was found to be present between ±20° latitude from the equator and these ISO features moved downward in time and exhibited equatorial symmetry with the maximum at the equator.

[7] 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] in order to investigate possible differences in the zonal wind ISO as a function of latitude and longitude. Their results suggest that the generation of nonmigrating tides is modulated at the ISO period in the lower atmosphere, and these modulated nonmigrating tides propagate to the MLT region. Then the breaking/dissipating tides modulate the zonal mean wind in this region. Their correlative analysis suggests that though the ISO in the diurnal tide correlates well with the ISO in zonal wind, the ISO in the gravity waves does not. However, this study did not rule out the role of gravity waves in causing the ISO in zonal wind.

[8] Using a general circulation model, *Miyoshi and Fujiwara* [2006] studied the excitation mechanism of the ISO of the zonal mean zonal wind in the equatorial MLT. Their results showed that the wave-mean flow interaction involving ultrafast Kelvin waves [*Yoshida et al.*, 1999] and diurnal tides (both migrating and nonmigrating) is important for driving the ISO.

[9] *Kumar et al.* [2007] reported ISO activity in zonal winds over Tirunelveli for the observational period, February 2004 to May 2005. They observed similar ISO activities in the time scale of 50–70 days that peaked at the same time in OLR at 75°E, averaged over 5°N–10°N latitude, as well as in MLT zonal winds, whereas shorter-period ISO (20–40 days) in the MLT zonal wind coincided with that in the tropospheric water vapor. However, long-term data obtained from a longitudinally distributed network of radars is required to confirm the relation between the ISO in lower tropospheric convective activity and the ISO in mesospheric zonal wind.

[10] Recently, using long-term data (1993 to 2006) obtained from the MF radar at Tirunelveli, *Sridharan et al.* [2007] studied the long-term variability of ISO in MLT zonal winds and its relation to MJO in the troposphere. They show that the ISO in both MLT zonal winds and tropospheric convective activity reveal biennial variability. Their observations could establish that larger ISO amplitudes coincided with strong westward winds.

[11] The above-mentioned few studies on the ISO activity in the stratosphere and lower mesosphere were confined to Indian region only. Whether the upper stratospheric and lower mesospheric (USLM) ISO is a mean-wind vacillation or a forced planetary wave response or both is not clear. Most of the observational studies of ISO activity in the equatorial MLT were pursued using MF (Christmas Island, Pontianak, Tirunelveli) and meteor radar (Jakarta) data from regions where the MJO was usually strong (convectively active region (60°E to 210°E)). The nature of ISO activity over a convectively quiescent region has not been reported. Most of the questions regarding the longitudinal and vertical behavior of the ISO and its response to the local convective activity remain unanswered.

[12] Simultaneous data obtained from the network of radars situated at the low-latitude sites, Tiruneveli (TIR) (8.7°N, 77.8°E), Pameungpeuk (7.7°S, 107.7°E) (PPK), Cariri (CAR) (7.4°S, 36.5°W) and Ascension Island (ASC) (7.9°S, 14.4°W), during the period from June 2004 to December 2005 are made use of in this work to study the longitudinal nature of the ISO of the zonal winds in the equatorial MLT region and its relation to the intraseasonal variability of convective activity associated with the MJO in

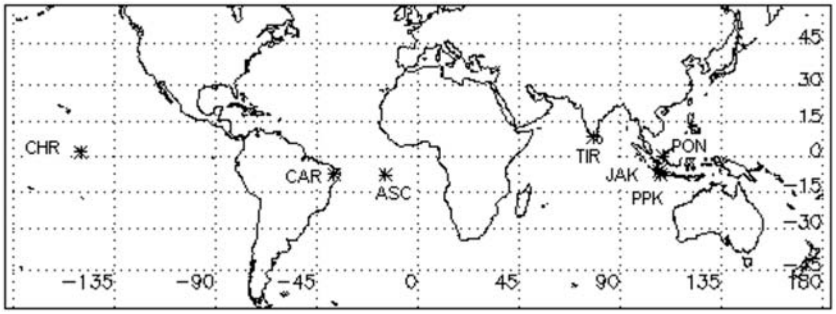

Figure 1. Locations of the meteor and MF radars used in this study, Cariri (CAR), Ascension Island (ASC), Tirunelveli (TIR), and Pameungpeuk (PPK), and the locations of other radars, Jakarta (JAK), Pontianak (PON), and Christmas Island (CHR), whose data were used for the earlier ISO studies in MLT region (represented by asterisks). Different latitudes and longitudes are represented by horizontal and vertical lines, respectively.

the troposphere. The zonal wind data provided by the United Kingdom Meteorological Office (MetO or Met Office) are used in this work to study the ISO at stratospheric and lower mesospheric altitudes.

2. Data

[13] Figure 1 is a map showing the locations of the radars used for the present study and the locations of other radars (Christmas Island, Pontianak and Jakarta) whose data were used for the earlier ISO studies. The MF radar at Tirunelveli is operating at 1.98 MHz frequency. It measures winds using the spaced antenna technique in the 68–98 height range during daytime and from 70 km during nighttime. The data acceptance rate is relatively high at heights above 84 km with largest acceptance rate is around 88 km. Winds are recorded every 2 min at 2 km height intervals (for further details, see *Vincent and Lesicar* [1991]). The MF radar at Pameungpeuk is operating at the frequency of 2.008 MHz. The antenna array, consisting of three antennas arranged in an equilateral triangle, is used for both transmission and reception. The radar uses spaced antenna technique to sample winds in the height region 70–98 km at every 2 km intervals. The data acceptance rate is high above 80 km with the highest data rate around 88 km. The meteor radars at Cariri and Ascension Island are commercially produced SKiYMET all-sky systems. The SKiYMET Meteor radar at Cariri operates at 35.24 MHz and uses five-receiver antennae forming an interferometric array. The meteor positions are obtained from the relative phase of the echoes at the multiple antennas together with the echo range. The radial velocity is determined from the Doppler shift and the horizontal winds are estimated in 1-h 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. The SKiYMET Meteor radar at Ascension Island operates at frequency near 43.5 MHz and uses a similar antenna configuration as with the other SKiYMET systems. Routine data analysis yields hourly spaced values of the horizontal winds in six independent height intervals centered on heights of 81, 84.5, 87.5, 90.5, 93.5 and 97 km and a maximum data rate around 90 km. Technical and acquisition details for the meteor radars are given by *Hocking and Thayaparan* [1997] and *Hocking et al.* [2001]. The MF spaced antenna technique and the meteor method both provide reliable means for synoptic studies of neutral air motions and the zonal mean winds are measured with a higher degree of consistency between the two techniques in the height range 85–94 km at time scales of greater than 12 h [*Hocking and Thayaparan*, 1997].

[14] To study the nature of the ISO activity in the lower tropospheric convection, we used outgoing long-wave radiation (OLR) data (obtained from the National Oceanic and Atmospheric Administration–National Centers for Environmental Prediction (NOAA-NCEP)) as a proxy for deep tropical convection [*Hendon and Woodberry*, 1993]. The OLR data are indicators of cloud top heights. Very high and cold clouds (low OLR) at tropical latitudes are presumed to be associated with deep convection.

[15] The zonal wind data provided by the United Kingdom Meteorological Office (MetO data) are used to examine the ISO activity in zonal wind at 25 pressure levels from the surface up to 0.1 hPa (∼0–60 km). The MetO data are results of assimilation of measurements such as satellite, radiosondes, and aircraft data into a numerical forecasting model of the stratosphere and troposphere. The numerical forecasting model, the so-called Unified Model, is based on a set of primitive equations and incorporates several physical parameterizations. A description of the original data assimilation system is given by *Swinbank and O'Neill* [1994] and the new 3D-variational system is described by *Lorenc et al.* [2000]. The model produces realistic stratospheric circulations [*Swinbank et al.*, 1998]. After a GW parameterization [*Warner and McIntyre*, 1999] was introduced during the year 2000, such features as the quasi-biennial oscillation and semiannual oscillation [*Scaife et al.*, 2000] also emerged. Intercomparisons of different climatological data sets for the middle atmosphere revealed uncertainties and problem areas [*Randel et al.*, 2004]. The rough estimates of the errors in the analyzed fields (for temperature and wind) are 1K and 6 m/s at low heights and the errors are predicted to be larger at high latitudes and at the uppermost levels. The Met Office data have been used by many researchers to study various dynamical phenomena including planetary waves [*Fedulina et al.*, 2004, *Chshyolkova et al.*, 2006], inertial circulation [*Orsolini et al.*, 1997], and sudden stratospheric warmings [*Manney et al.*, 1994; *Cho et al.*, 2004; *Shepherd et al.*, 2007; *Pancheva et al.*, 2008]. The daily data fields have global

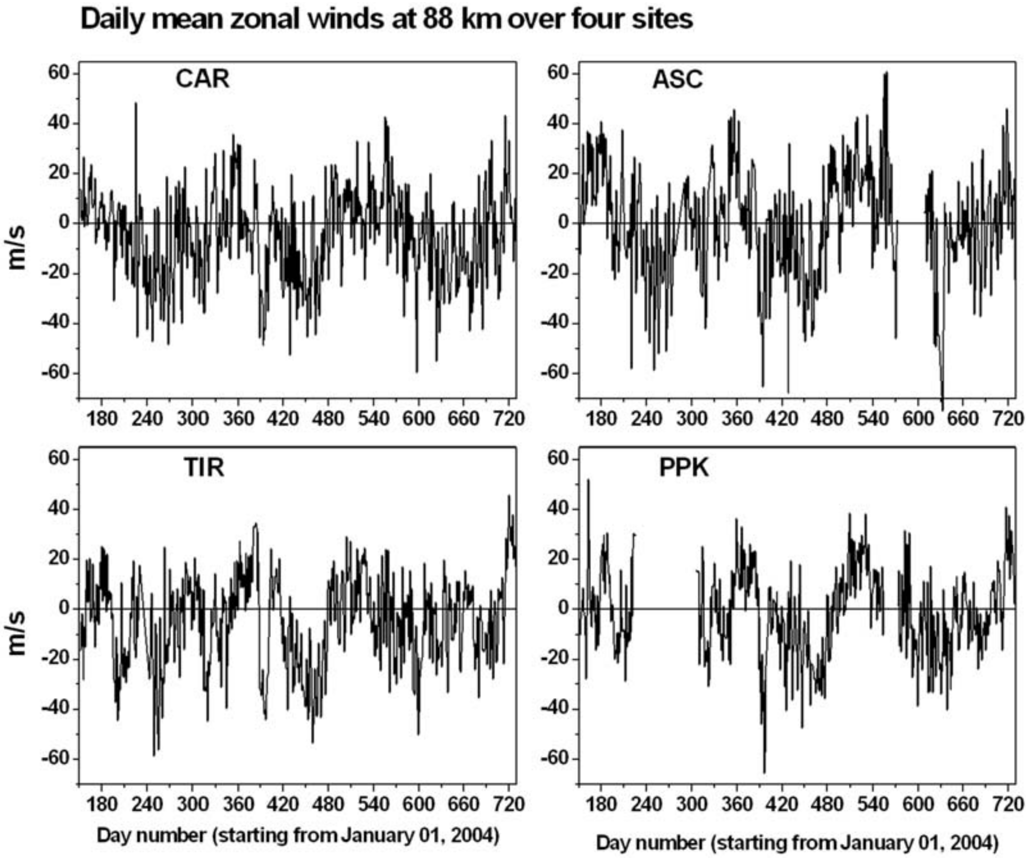

Figure 2. Time series of daily mean zonal winds at 88 km altitude over (top left) Cariri, (top right) Ascension Island, (bottom left) Tirunelveli, and (bottom right) Pameungpeuk for the observational period 1 June 2004 to 31 December 2005.

coverage with 2.5° and 3.75° steps in latitude and longitude, respectively. The data proved to be very useful in understanding tropospheric/stratospheric dynamical processes.

3. Results and Discussion

3.1. Behavior of the ISO in Zonal Wind at 88 km Height

[16] The time series of daily mean zonal winds determined from the observations made by the four radars at a height of 88 km for the period of June 2004 to December 2005 is shown in Figure 2. The quality of data is very poor during the observation periods, with day numbers in the range 224–308 and 555–572 at PPK and days 573–602 at ASC and we have shown gaps for those particular periods. The data acceptance rate is relatively high at heights above 84 km, with largest acceptance rate at around 88 km for both the MF radars at TIR and PPK. The meteor radars at CAR and ASC measure winds at 80–100 km height, with the maximum data rate around 90 km. Moreover, the MF and meteor radars measure the zonal mean winds with higher degree of consistency in the 85–94 km height range. In this work, we have chosen to consider the daily mean zonal winds at 88 km for studying the ISO.

[17] It is apparent from Figure 2 that the winds at each site track each other reasonably closely. The mesospheric semiannual oscillation (MSAO) is clearly evident over all the sites, with westward flow during the equinoxes and eastward flow during the solstices. Wind variabilities in intraseasonal time scale are also apparent. In order to examine the dominant periods of time variations of the zonal winds in the intraseasonal time scale, a spectral analysis of zonal winds at 88 km was performed whose results are shown in Figures 3a–3c. From the whole data set, three data segments have been chosen corresponding to different time intervals, namely, days 152–407 (1 June 2004 to 15 February 2005) (256 data points), days 408–535 (16 February 2005 to 21 June 2005) (128 data points) and days 603–730 (26 August 2005 to 31 December 2005) (128 data points), and a fast Fourier transform (FFT) is applied to the each data segment to check the presence dominant periodicities in different time intervals. The 95% confidence levels for all stations are shown as well. To test the statistical significance of the spectral amplitude (R_k), we have used a method in which the probability 'p' that the ratio $R_k^2/\sum R_k^2$ exceeds a parameter 'g' is given by $p = [m\,(1-g)^{m-1} + \text{higher-order terms}]$ (here, $\sum R_k^2 = 2/N \sum (X_i - X_{mean})^2$), the summation on the left-hand side runs from k = 1 to m and that on the right-hand side runs from i = 1, N, the number of points; m = N/2. The error introduced in neglecting the higher-order terms is only 0.1% for p = 0.05 (95% confidence level). Therefore, the parameter g (for p = 0.05) can be calculated from the relationship, $p = m(1-g)^{m-1}$. The parameter g_k is given by $g_k = R_k^2/\{2/N \sum (X_i - X_{mean})^2\}$. If $g_k > g_p = 0.05$ (for 95% confidence level), the amplitude is 95% significant.

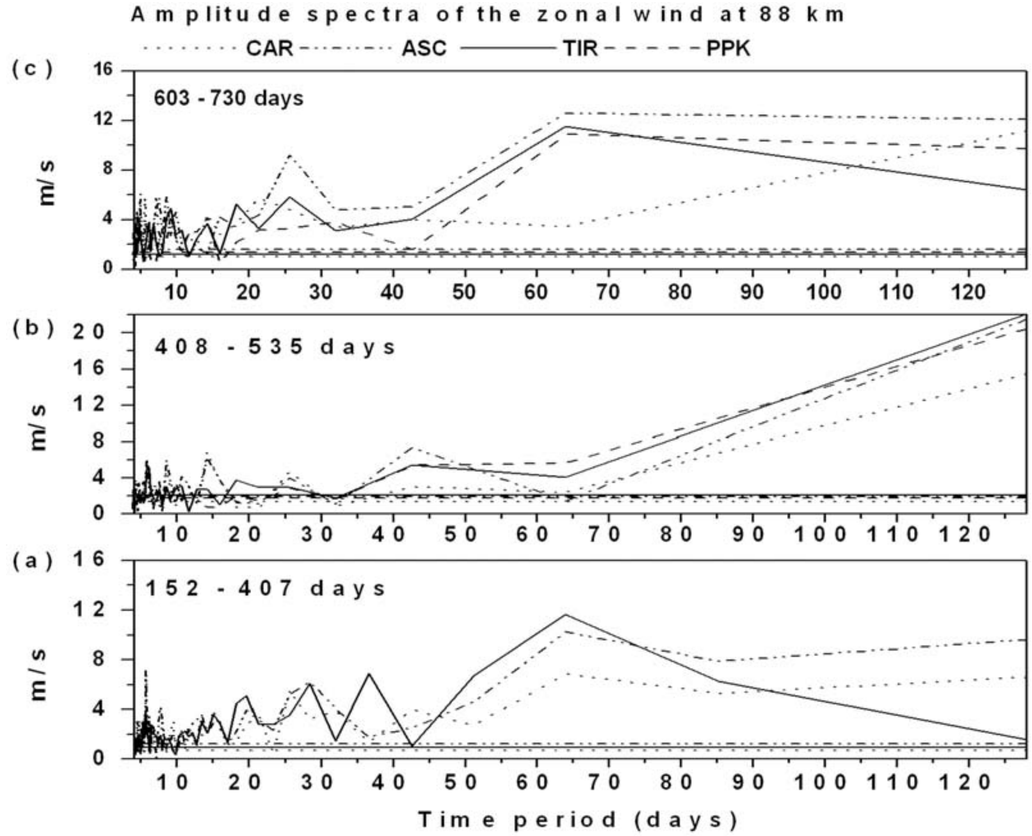

Figure 3. Amplitude spectra of the daily zonal winds at 88 km over four sites for the three time intervals (a) 152–407 days, (b) 408–535 days, and (c) 603–730 days. The horizontal lines represent the 95% confidence levels.

[18] As our main interest is to study intraseasonal oscillations, we now focus on the oscillations in the period range 20–100 days. During the time interval 152–407 days (Figure 3a), a dominant peak is observed around day number 65 and peaks at other days around 25–28 and 20 are also observed over the three stations CAR, ASC and TIR. A peak around 37 days is also observed over TIR. The 65-day oscillation is very strong over TIR and is some what weak over CAR during this interval. As there is a major gap (days 224–308) in PPK data during this interval, spectra for PPK are not shown in Figure 3a. During the interval 408–535 days (Figure 3b), oscillations with the time period around 42 days are dominant over all the stations and a weak oscillation of time period around 26 days is also observed. During the interval 603–730 days (Figure 3c), again a dominant peak is observed around the 65 days and a peak around 25 days is also evident. From Figures 3a–3c, it can be noticed that that the ISO activity with time period around 65 days is quite strong during the time intervals 152–407 days and 608–730 days, whereas a 42-day activity is dominant during the interval 408–535 days.

[19] By applying a filter with band pass of 20–100 days, fluctuations in the period range 20–100 days in the daily mean zonal winds at 88 km height were extracted and are shown in Figure 4. The results from this exercise reveal the similarity of ISO variations over the four sites during most of the times except on a few occasions. As can be seen in Figure 4, during the observational period days 152–320 (June 2004 to October 2004), the ISO activity in the 60–70 day period band is dominant at TIR and PPK (largest amplitudes of around 20 m/s), whereas it is relatively weak at ASC (largest amplitudes in the range 10–15 m/s) and at CAR (largest amplitude in the range 5–10 m/s). At the same time, the observation period days 320–620 (November 2004 to September 2005) is dominated by a weak 25–45 day ISO activity at all sites and for the period 620 to 730 (September 2005 to December 2005) 60–70 day activity is dominant over TIR and PPK. The ISO activity at MLT heights is relatively more prominent over TIR as compared to other stations during most of the time in all time periods. It should be noted that during the observational period with day numbers in the range 360–420, when the zonal winds exhibit 20–30 day variability, a strong westward peak (with more than 30 m/s amplitude) is observed around day number 395 over all four sites.

[20] We have calculated cross-correlation functions (CCF) for the ISO of the zonal wind between different radar locations. In Figures 5a–5c, the cross-correlation function between the ISO at different locations have been shown for the three time periods 150–223 days, 309–550 days, and 603–730 days. The reason for selecting these time segments is that the zonal wind data are continuous without any major gaps at all the four locations during these periods. From Figure 5a, it can be observed that the ISO over TIR and PPK are highly coherent with the maximum CCF value around 0.80 and lag in phase of about 1 day compared to ISO over the remaining locations during the period 150–223 days. During the period

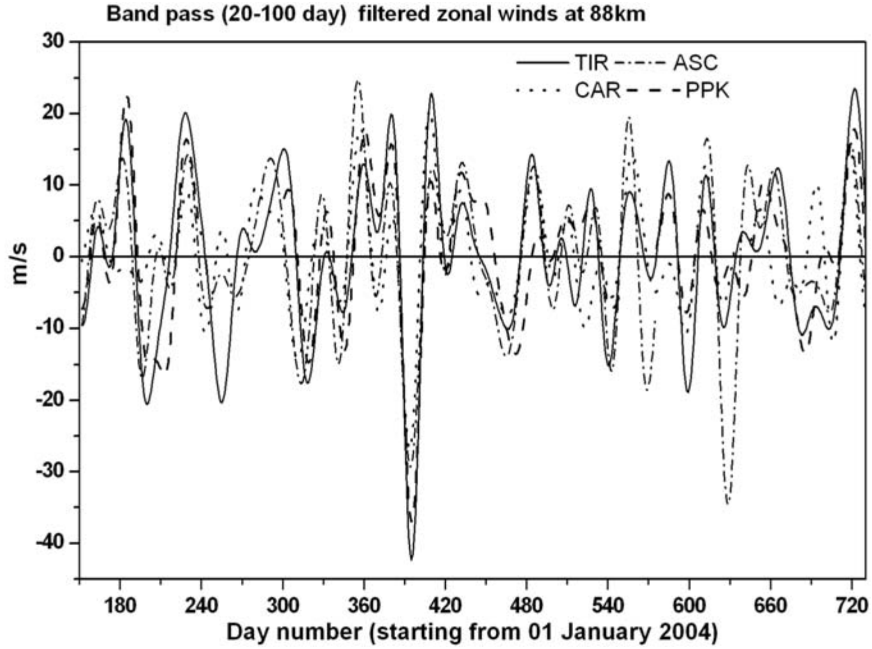

Figure 4. Band-pass (20–100 days) filtered daily zonal winds at 88 km observed at Cariri, Ascension Island, Tirunelveli, and Pameungpeuk for the observational period 1 June 2004 to 31 December 2005.

309–554 days (Figure 5b), the ISO between CAR and ASC is highly coherent with the maximum CCR value 0.67 and no lag in phase compared to ISO between other locations. During the period 603–730 days (Figure 5c), the ISO between ASC and TIR is highly coherent with the maximum CCR value 0.85 and lag in phase of about 1 day compared to ISO between other locations. The common feature observed in Figures 5a–5c is that the ISO between TIR-PPK (0.68), ASC-TIR (0.66), ASC-PPK (0.58) and CAR-ASC (0.57) are relatively more coherent and the ISO between CAR-TIR (0.43) and CAR-PPK (0.4) are some what less coherent (the values within brackets indicate the

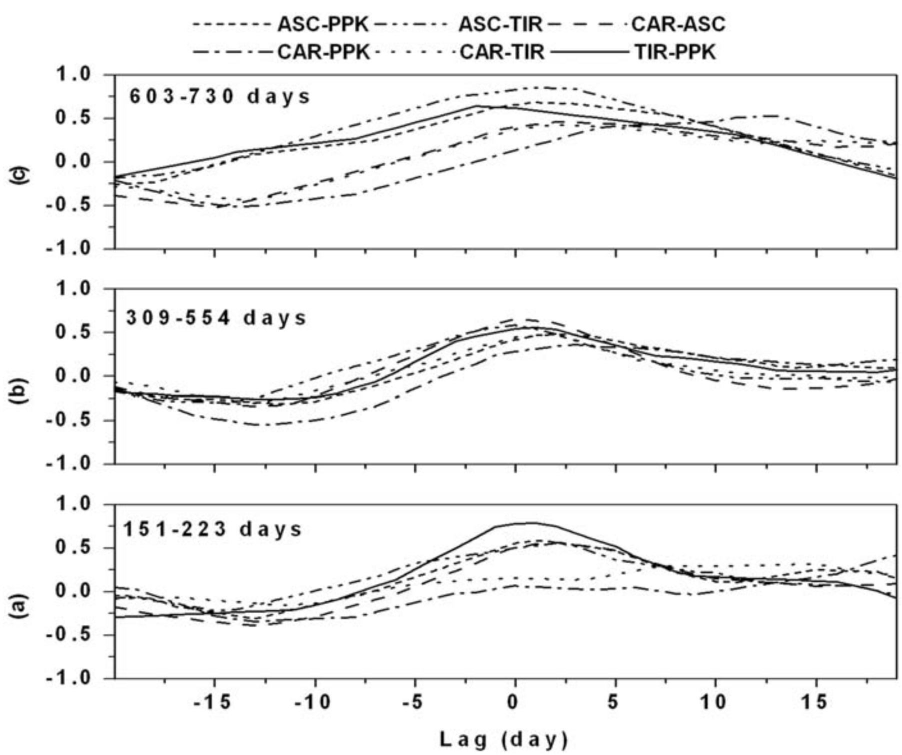

Figure 5. Cross-correlation functions (CCF, vertical axis) between different stations for the ISO of the zonal wind in three different time periods (a) 151–223 days (b) 309–554 days (c) 603–730 days.

Table 1. Cross-Correlation Coefficients for the ISO of the Zonal Wind Between Different Stations

	Observational Period	Maximum CCF	Lag[a] (days)
CAR-ASC	150–240 days	0.57	2
	320–540 days	0.67	0
	620–730 days	0.46	2
ASC-TIR	150–240 days	0.57	2
	320–540 days	0.58	0
	620–730 days	0.85	1
TIR-PPK	150–240 days	0.80	1
	320–540 days	0.59	1
	620–730 days	0.64	−2

[a]Positive lag indicates the first station proceeds.

mean of maximum CCF values for the three time periods). Further, the ISO activity is considerably coherent (with lag in phase near to 0 days for different time periods) between the four radar sites during the period 320–540. During the remaining observational periods 150–223 and 603–730 (during which strong 6–70 day ISO activity is observed over TIR and PPK), the ISO activity shows relatively less coherence in phase (with lag in phase is far from 0 days) between the four sites.

[21] The ISO activity observed in the HRDI zonal mean zonal winds at MLT region [*Lieberman*, 1998] was not in the form of planetary waves and it was suggested by the author that the MLT ISO is not a zonally propagating wave and can be viewed as a wave driven phenomenon. By employing cross correlation analysis of the mesospheric ISO between three radar sites (Pontianak, Jakarta and Christmas Island), *Isoda et al.* [2004] also showed that the mesospheric ISO does not behave like a zonally propagating wave, and they suggested that it can be considered as a vacillation in the zonal mean flow. In order to confirm whether the ISO observed over the four locations show any zonally propagating wave structure or not, we have compared the maximum CCF values and the corresponding time lags between CAR-ASC, ASC-TIR and TIR-PPK. Table 1 shows the maximum CCF values and corresponding time lags between CAR-ASC, ASC-TIR and TIR-PPK. The comparison of ISO phase lags between the four longitudinally separated radar sites in the present work also indicates that the lags in phase are very small regardless of their longitudinal separation, and the ISO phase lags between different sites do not clearly represent a propagating wave of any wave number from 1 to 4. Therefore, one can infer that the mesospheric ISO does not show any zonally propagating wave structure. Rather, oscillations of this kind, perhaps, represent variations in the zonal mean flow. In this work, our aim is to examine whether the longitudinal and temporal variabilities of mesospheric ISO are related to the longitudinal and temporal variabilities of tropospheric convective activity.

[22] Figure 6 shows the height-time contours of the ISO amplitudes (20–100 day filtered zonal winds) of the zonal winds over TIR and PPK. The height-time contours in the Figure 6 are tilted slightly downward with increasing time indicating the downward phase progression of the ISO with time. Earlier studies on ISO [*Isoda et al.*, 2004; *Lieberman*, 1998] in zonal winds at MLT region also revealed the downward phase progression of the ISO in the MLT region.

3.2. ISO in the Lower Tropospheric Convective Activity

[23] Figure 7 depicts the time-longitude behavior of OLR averaged over 10°N–10°S. OLR values less than 190 W/m^2 represent deep convective activity. The deep and broad convective clusters are present mainly over the 70°E–180°E longitude sector and relatively weak convective activity is observed around 20°E and 300°E regions and the remaining regions are convectively quiescent. The

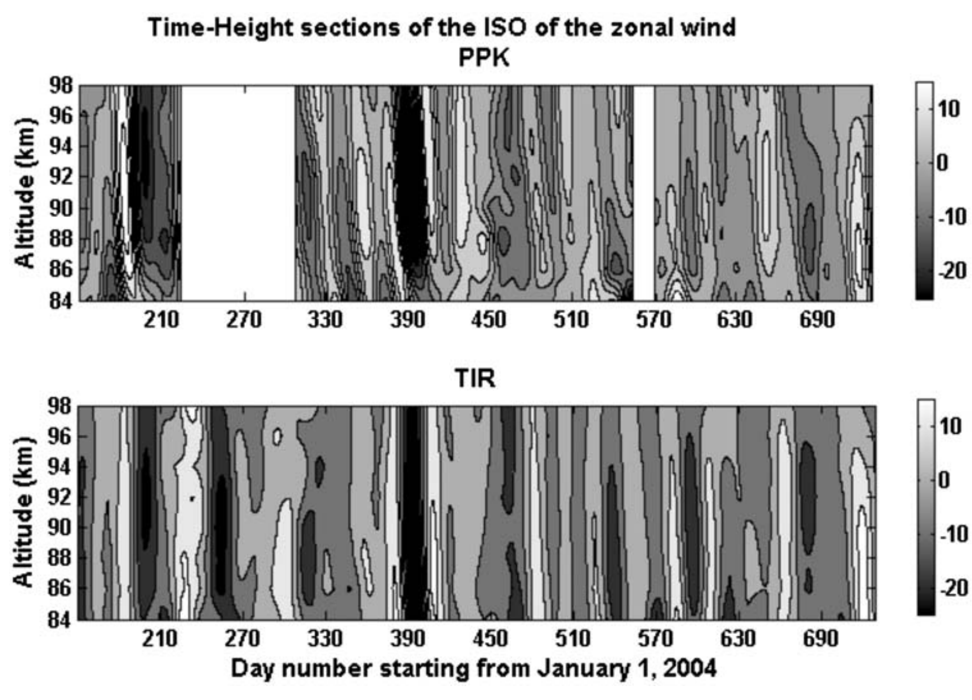

Figure 6. Time-height sections of the ISO of the zonal winds (m/s) over (bottom) Tirunelveli and (top) Pameungpeuk for the observational period 1 June 2004 to 31 December 2005.

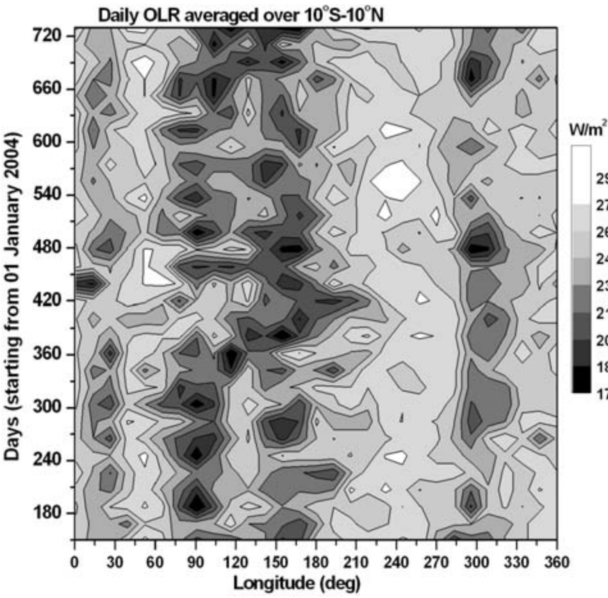

Figure 7. Time-longitude cross sections of the OLR (W/m^2) averaged over 10°N–10°S for the observational period 1 June 2004 to 31 December 2005.

contours over the 70°E–180°E longitude sector tilt slightly toward the right or toward the left during certain times with increasing or decreasing longitude indicating an eastward or a westward motion of the convective clusters.

[24] It can be noticed clearly in Figure 7 that there is a variation in the convective activity on the intraseasonal time scale over the 75°E–180°E longitude region that is evident without any filtering of OLR data. The highly deep and broadly distributed convective clusters with nearly 65-day variability can be observed during the observation duration 150–360 (the convective centers are separated by nearly 60 days). During the period 360–400, convective clusters move continuously eastward from 90°E longitude to nearly 200°E longitude and later turn westward and undergo westward motion till around day number 420. The continuous motion of the convective clusters during this period (360–420) is faster than the usual eastward motion of the convective clusters associated with the MJO [*Madden and Julian*, 1972; *Zhang*, 2005]. Convective clusters, relatively less deep and less broad, with 25–40 day variability, are observed during the period 450–620. Convective activity is also observed, with 60-day variability, during the period 620–730. In order to know the exact dominant periods of time variations of the OLR in the intraseasonal time scale, the daily OLR data were averaged over the 80°E–100°E and 10°S–10°N region and spectral analysis was performed on the averaged OLR data in the same three time intervals (days 152–407, days 408–535 and days 603–730) for which a spectral analysis was earlier performed on the daily mean zonal wind (Figures 3a–3c) and results are shown in Figures 8a–8c. The 95% confidence levels are also indicated in each of the panels. Besides the peak at 65 days, there is also a peak around 32 days during the time interval days 152–407. A strong ISO activity with 42 days period is observed during the period 408–535 days. During the remaining time interval 603–730 days, peaks around the period 32 day and 65 day are observed. From this exercise, we can infer that the convective activity and its ISO variability over TIR and PPK are quite pronounced, while the convective activity over CAR and ASC is very weak and does not show any ISO. The deep convective activity over the 80°E–100°E and 10°S–10°N region undergoes strong intraseasonal variations with different time periods (65 days, 42 days and 32 days, for example) in different time intervals. Now, we shall proceed to examine the influence of longitudinal variability in convective activity on the longitudinal nature of the ISO in MLT zonal winds by comparing the ISO in OLR with the ISO in zonal winds at 88 km over all the four radar sites.

3.3. Comparison of ISO in Zonal Winds at 88 km Height With ISO in Lower Tropospheric Convective Activity

[25] The results presented in Figures 3a–3c and 8a–8c reveal that the spectra of both zonal wind at 88 km over the three radar sites and OLR averaged over 80°E–100°E and 10°S–10°N region peak at 65 days during the time interval 152–407 days. Similarly, the spectra of both zonal wind over four radar sites and OLR peak at around 42 days during the time interval 408–535 days. During the remaining observational period 603–730 days, OLR spectrum peaks at periods 32 days and 65 days while there is a strong 65 day oscillation in zonal wind at 88 km over all the stations except over CAR and the spectra of zonal wind also peak at 26 days over TIR and ASC, 20 days over CAR and 32 days over PPK. These observations showed that the OLR and the zonal wind at 88 km exhibit similar ISO (especially oscillations at time periods, 65 and 42 days) during different time intervals.

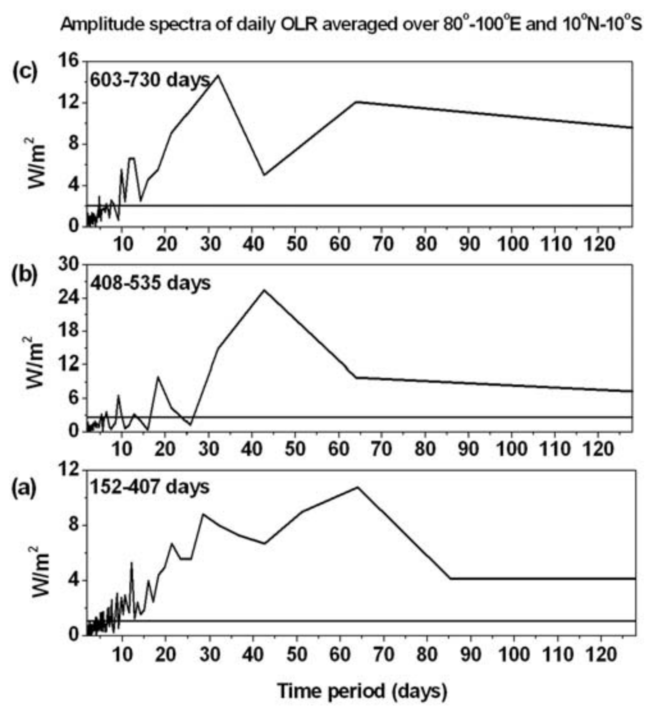

Figure 8. Amplitude spectra of the daily OLR averaged over 80°E–100°E and 10°S–10°N region for the three time intervals (a) 152–407 days, (b) 408–535 days, and (c) 603–730 days. The horizontal lines represent the 95% confidence levels.

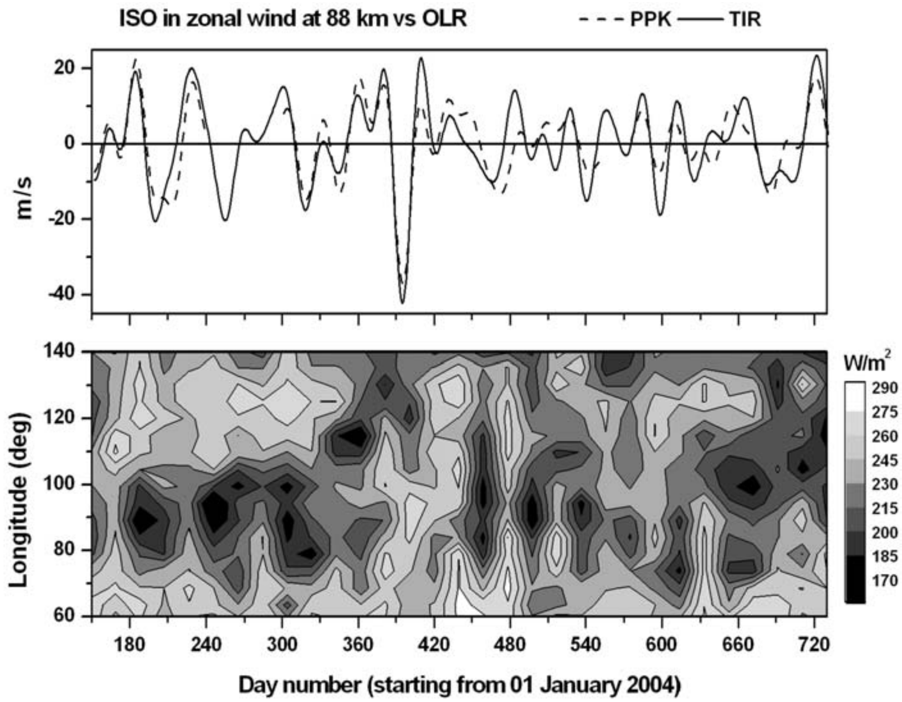

Figure 9. (bottom) OLR (averaged over 10°N–10°S) over 60°E–140°E and (top) ISO in zonal wind at 88 km over Tirunelveli and Pameungpeuk.

[26] In Figure 9 the OLR over 60°E–140°E longitude sector is compared with the ISO in zonal wind at 88 km over TIR and PPK. Both convective activity over the 60°E–100°E region and the zonal wind at 88 km over TIR and PPK undergo similar variations on ISO time scales: 60–70 day variability during the period 150–320 days, 25–45 day variability during 450–630 days and 60–70 day variability during 620–730 days, except during the period 360–420 days when a large transient westward motion was detected at the two radar sites. It appears on the whole that the zonal wind at 88 km over TIR and PPK responds strongly to the ISO in the convective activity over 60°E–100°E. In Figure 10, the OLR over 280°E–360°E longitude sector is compared with the ISO in zonal wind at

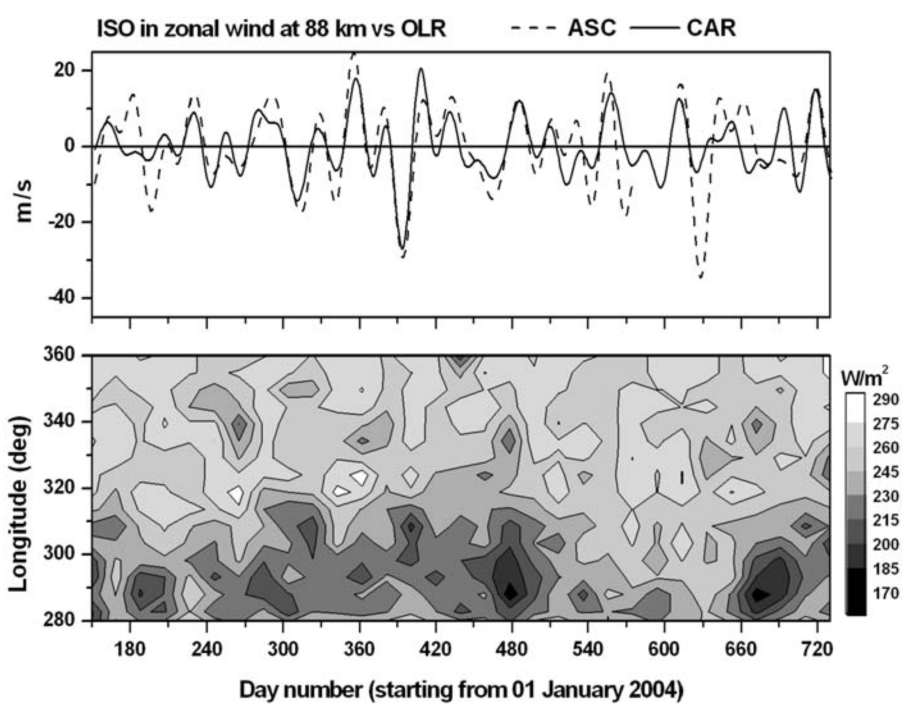

Figure 10. (bottom) OLR (averaged over 10°N–10°S) over 280°E–360°E and (top) ISO in zonal wind at 88 km over Cariri and Ascension Island.

88 km over CAR and ASC. The convective activity over CAR (323.5°E longitude) as well as over ASC (345.6°E) is significantly weaker. Though the phases of the ISO in zonal wind at 88 km over CAR and ASC are similar to those observed over TIR and PPK, the amplitudes of the ISO in zonal wind over CAR and ASC are smaller. It may be noted in Figure 10 that the convective activity is not strong and deep convective clusters are observed at few times (around day number 190, 480 and 675, for example) only. The deep convective activity over 280°E–360°E region shows weak ISO activity. During the observational period 150–320, when broad and deep convective clusters with nearly 65-day variability were observed over the 60°E–100° E region, the zonal winds over TIR and PPK also show strong 65-day variability. It seems that the zonal winds over TIR and PPK, as compared with those over CAR and ASC, are influenced more by the 65-day variability of deep convective activity over that region. The larger amplitudes of the ISO observed over TIR and PPK seem to be associated with deep and broad convective clusters.

[27] Referring to Figure 7, the intense convective clusters moved away from the 60°E–100°E region during the period 360–420 (making this region convectively less active) toward east up to 200°E longitude. During the same observational period, the zonal wind at 88 km over TIR and PPK exhibits 20–30 day variability with a strong westward peak (with more than 30 m/s amplitude) around day number 395, as can be seen in Figure 9. This strong westward peak is also seen over CAR and ASC during the same period (Figure 10), but with slightly reduced amplitude. The reason for this transient behavior observed over all four stations around day number 395 is not known.

[28] The following could be a plausible explanation for this longitudinal behavior of the ISO in zonal wind at MLT heights. The zonal winds at tropospheric heights are expected to promptly respond to the local convective perturbations associated with the MJO. As the tropospheric ISO is a large-scale wave disturbance with a small zonal propagation speed, it cannot propagate upward directly into the middle atmosphere. Rather, the MJO is a discrete pulse-like event associated with the variability in deep convection. A spectrum of atmospheric waves is generated in the tropical troposphere owing to deep convection. The intraseasonal cycles in the tropospheric convection associated with the MJO modulate the intensity of the upward propagating gravity waves, nonmigrating diurnal tides and planetary (equatorial) waves, and these generate intraseasonal variations in the MLT region zonal winds through wave induced driving of the mean flow [*Eckermann et al.*, 1997; *Isoda et al.*, 2004; *Miyoshi and Fujiwara*, 2006; *Sridharan et al.*, 2007]. Even though the MJO related convective signals are dominant only over the Indian ocean and western and central Pacific, the waves (especially nonmigrating diurnal tides, planetary and equatorial waves) generated by this deep convective activity are of planetary scale and they could propagate zonally and could show their effect on the zonal mean circulation globally. Any phase delays noticed in the ISO in zonal wind in the upper mesosphere could very well be due to the propagating delays of the waves, as they could be eastward or westward propagating. The measurement sites are not many enough to make any assessment of the propagation direction of the waves participating in driving the ISO. On the other hand, the intensity of those small-scale gravity waves over the convectively active region will be high compared to that over convectively quiescent regions. So, we may expect a relatively stronger ISO activity in zonal wind over convectively active regions as compared to those which are convectively quiescent.

3.4. Behavior of the Stratospheric and Lower Mesospheric ISO as Evident in Met Office Zonal Wind Data Sets

[29] The nature of the ISO activity at MLT heights (above 70 km) and at tropospheric heights is relatively well studied compared to stratospheric and lower mesospheric heights. We employ here the Met Office daily zonal winds to study the behavior of the ISO at 25 vertical pressure levels from 1000 hPa (surface) to 0.1 hPa (around 60 km). In order to compare the ISO activity at 88 km altitude with the ISO at lower heights, we have chosen the Met Office data sets corresponding to those particular latitude and longitude grid positions which are nearest to the respective radar locations for the same period.

[30] By using a band-pass filter with cutoff periods of 20 and 100 days, wind oscillations in the period range 20–100 days in the Met Office zonal wind over the four locations were extracted for all the 25 pressure heights from ground (1000 hPa) to 0.1 hPa (0–60 km). Figure 11 presents the height-time structures of the 20–100 day band-pass filtered Met Office daily zonal winds at the four sites. An inspection of these plots reveals that the ISO activity strengthens above 35 km whereas it is not present below this level over any of the four sites. Though the ISO in zonal wind some times extends from 60 km down to 35 km, it is prominent above 45 km over all the four sites. Amplitudes of the oscillations are on the order of 10–25 m/s above 35 km and less than 5 m/s below 35 km. It can also noticed in Figure 11 that the height-time contours above 35 km level are slightly tilted downward with increasing time. This shows a weak downward phase progression. It was observed in studies of rocket and radiosonde data from the Indian tropical region that the ISO features disappear above tropopause and reintensify at the upper stratospheric heights [*Nagpal and Raghavarao*, 1991; *Nagpal et al.*, 1994; *Kumar and Jain*, 1994]. Different generation mechanisms were proposed for the ISO activity at upper stratosphere and lower mesospheric heights. *Nagpal and Raghavarao* [1991] and *Nagpal et al.* [1994] argued that the Rossby waves in the intraseasonal time scale could propagate into the tropical atmosphere from midlatitudes, whereas *Kumar and Jain* [1994] suggested that the Rossby waves associated with the MJO might leak into the upper stratosphere from tropical troposphere via vertical propagation. One more mechanism is proposed by *Ziemke and Stanford* [1991], wherein the Rossby waves associated with the MJO, propagate into the extratropical upper troposphere and stratosphere from the equatorial troposphere and propagates upward and thereafter refract back into the tropical upper stratospheric region. One more possibility is that the ISO at upper stratospheric and lower mesospheric (USLM) altitudes, similar to the ISO at the MLT heights, could be a manifestation of mean wind variations driven by the breaking/dissipation of the waves generated by the lower tropospheric convection. In that case,

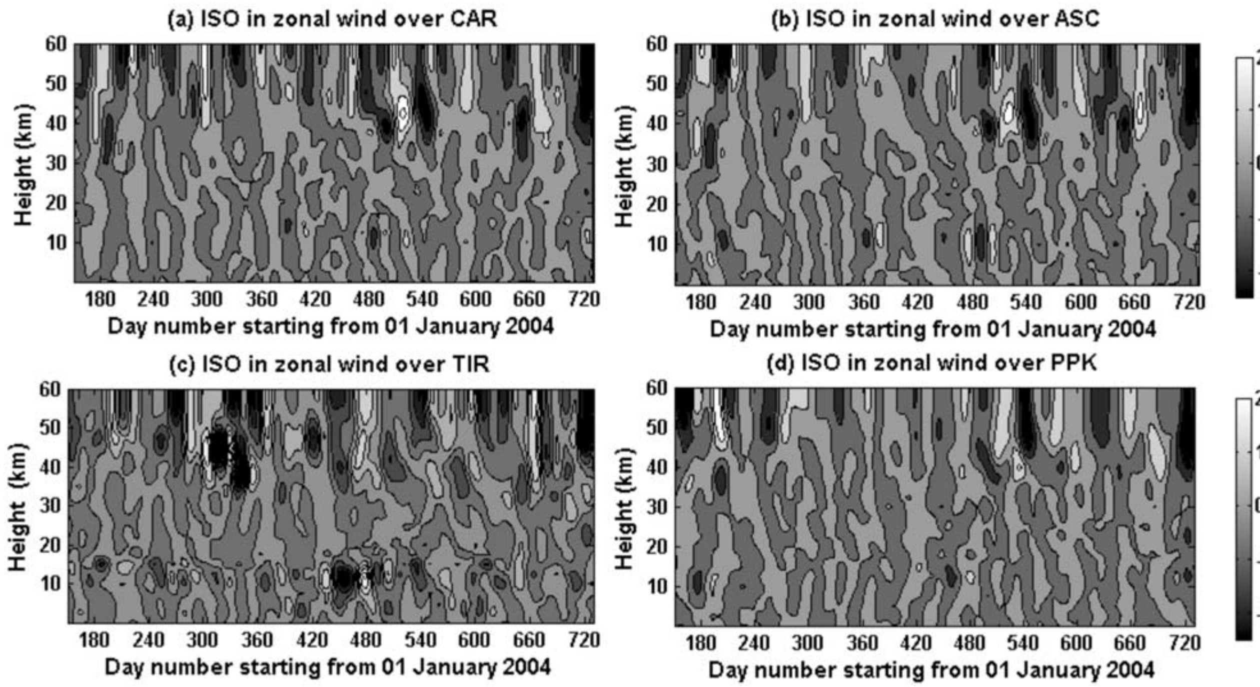

Figure 11. Time-height sections of the ISO of the Met Office zonal winds (m/s) at (a) Cariri, (b) Ascension Island, (c) Tirunelveli, and (d) Pameungpeuk for the observational period 1 June 2004 to 31 December 2005.

it would be important to understand the nature of the ISO at USLM heights and verify whether they show different (opposite phase) behavior like MSAO and SSAO [*Hirota*, 1978; *Hamilton*, 1982; *Garcia et al.*, 1997] or not. The ISO in HRDI zonal mean zonal winds was found to extend continuously from 100 km down to 65 km during certain periods [*Lieberman*, 1998], whereas weak ISO observed in radar zonal winds below 75 km was attributed to degraded instrumental sensitivity at these levels [*Eckermann et al.*, 1997]. Therefore, our observations of the ISO in Met Office zonal winds at upper stratosphere and lower mesosphere altitudes appear to be a possible downward extension of the ISO at higher levels. Now, it is necessary to confirm that whether the ISO observed at stratospheric and lower mesospheric heights is a downward extension of mesospheric ISO which is considered to be a wave driven phenomenon or they are merely planetary-scale waves propagating from troposphere or combination of both components or of different origin. We will examine this aspect in section 3.5 by comparing the phases of the ISO at 88 km altitude with those at 60 km.

[31] We have also calculated zonal mean zonal winds at different latitudes and altitudes and applied a band-pass filter with cutoff periods of 20 and 100 days to retrieve the fluctuations in the period range from 20 to 100 days. The meridional structure of ISO in Met Office zonal mean zonal winds is shown in Figure 12 at four vertical pressure levels, namely 0.1 hPa (around 60 km), 0.2 hPa (around 55 km), 0.46 hPa (around 50 km) and 1 hPa (around 45 km). It is clearly evident from Figure 12 that at all the four levels the ISO activity is very weak in zonal mean zonal winds except during certain time periods on either side of the equator. In the Northern Hemisphere ISO maxima occur during the period 330–450 days (December 2004 to March 2005) whereas in the Southern Hemisphere, ISO maxima occur during the periods 150–270 days (June 2004 to September 2004) and 510–630 days (June 2005 to September 2005). The hemispheric differences are clearly evident at the four pressure levels and ISO amplitudes peak around the latitude 20°N and 20°S. The maxima of the ISO in MetO zonal mean zonal winds at 45–60 km height range are not symmetric about the equator. It is also observed that the amplitudes of the ISO decrease at the lower heights. The ISO activity in zonal mean zonal wind is very weak below the 1 hPa pressure level (not shown). The ISO maxima in HRDI zonal mean zonal winds at above 70 km exhibit equatorial symmetry during certain periods with the maximum values at the equator [*Lieberman*, 1998] whereas the antisymmetric component that was observed in ISO of the HRDI zonal mean zonal winds during certain periods was attributed to the aliasing of HRDI winds caused by enhanced tidal amplitudes away from the equator (around 25°). Here, may notice that the ISO observed in the MF and meteor radar zonal winds at 88 km does not show any hemispheric differences (Figure 4). Our observation of the antisymmetric behavior of the ISO in Met Office zonal mean zonal winds around the equator indicates that antisymmetric behavior is clearly evident in ISO in the zonal winds at the upper stratosphere and lower mesospheric heights whereas the ISO in the zonal winds at mesosphere and lower thermospheric heights is symmetric about the equator. The actual reasons for this antisymmetric behavior of the ISO in Met Office zonal winds at the upper stratospheric and lower mesospheric heights are currently not known.

[32] One more feature to be noticed in Figures 11 and 12 that the periods of the ISO observed in the zonal mean zonal winds (Figure 12) at the upper stratospheric and lower

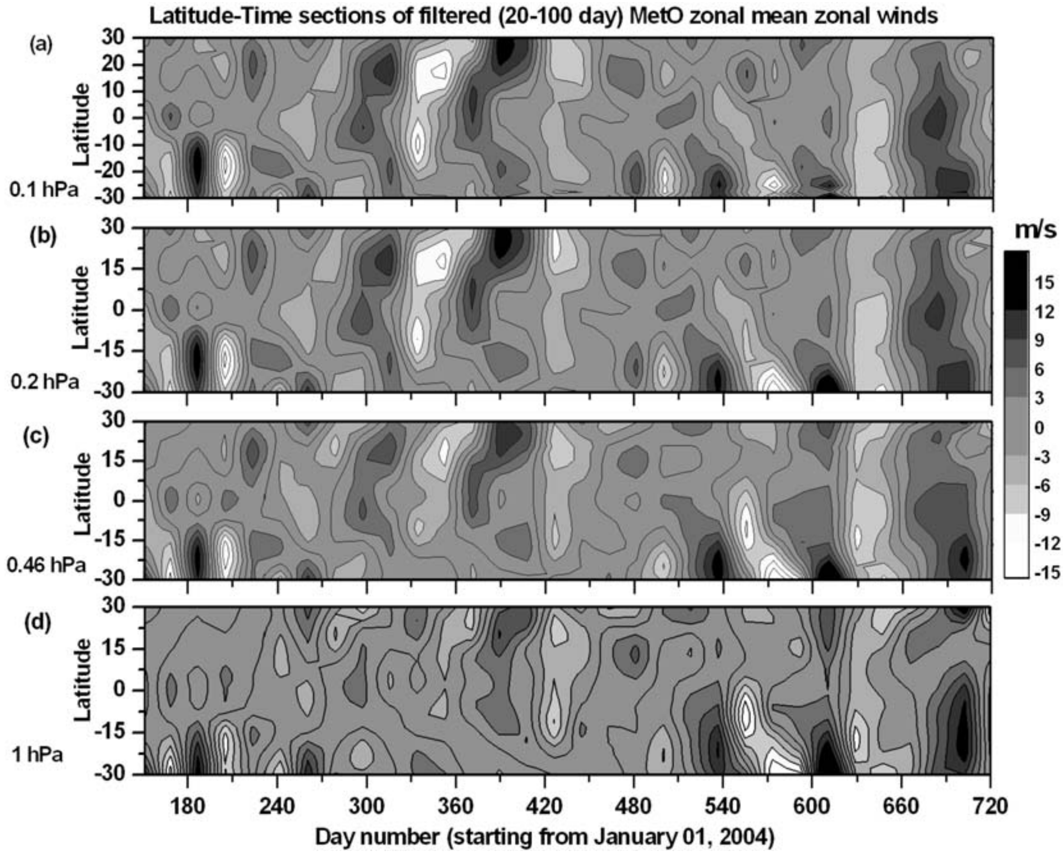

Figure 12. Latitude-time sections of the band-pass filtered Met Office daily zonal mean zonal winds (m/s) at different pressure levels: (a) 0.1 hPa, (b) 0.2 hPa, (c) 0.46 hPa, and (d) 1 hPa.

mesospheric heights seem to be 50–70 days where as the dominant periods of the zonal wind (in Figure 11) over individual locations of the radar sites in the 40–60 km height range seem to be 20–70 days. The variations observed in the zonal mean zonal winds usually refer to either stationary planetary waves or the mean zonal wind variations whereas the variations in the zonal winds at a particular location may contain both the traveling planetary wave components and the mean wind variations (which are considered to be a wave driven phenomenon). So, it seems that the ISO observed in the Met Office zonal winds (Figure 11) over individual locations of the radar sites in the 40–60 km height range contain traveling planetary-scale wave components. There are some observational evidences for propagation of Rossby waves of intraseasonal time scale at least up to stratopause from the Indian region [*Nagpal and Raghavarao*, 1991; *Nagpal et al.*, 1994; *Kumar and Jain*, 1994; *Ziemke and Stanford*, 1991]. We may be able to verify it by studying the planetary wave behavior in the global MetO zonal wind fields. To determine the dominant periods of the planetary waves, we performed two dimensional spectral analysis (which is an analog of the Lomb-Scargle periodogram method based on least square fitting procedure) of the Met Office global zonal winds during the entire observational period and the spectra for the eastward and westward traveling waves with wave number 1 are shown in the Figure 13. A westward propagating wave with a time period of around 28 days is clearly evident over the equatorial region. Eastward propagating waves with periods around 20 days and 28 are also dominant during the observational period as can be noticed in Figure 13. The oscillations with periods of 60 days and above observed in MetO zonal mean zonal winds in Figure 12 are zonal mean responses, whereas the eastward and westward propagating waves observed in Figure 13 are planetary wave components. So, the ISO observed in the MetO zonal winds at USLM heights is a combination of both mean wind variations and planetary wave components.

3.5. Comparison of ISO in Zonal Winds at 88 km Height With the ISO at 0.1 hPa

[33] Figure 14 shows the comparison for the ISO in Met Office zonal winds at 0.1 hPa (~60 km) with the ISO in zonal winds at 88 km for all four sites. The amplitudes of the ISO at 0.1 hPa are smaller than that of the ISO at 88 km and the difference in phase between ISO at 88 km and the ISO at 0.1 hPa is small during the period 360–730 and is somewhat larger during the period 18–360 days over TIR. The amplitudes of the ISO at 0.1 hPa are some what larger than the ISO at 88 km and difference in phase is relatively high either. In case of ASC and PPK, the amplitudes of the ISO at 0.1 hPa are slightly different from that of the ISO at 88 km and difference in phase is also small. The common feature that can be observed from Figure 14 is that the ISO at the lower height shows some similarity with the ISO at 88 km altitude. Though the amplitudes of the ISO at 88 km are different from the ISO amplitudes at 60 km, the eastward and westward phases of the ISO at the two height levels

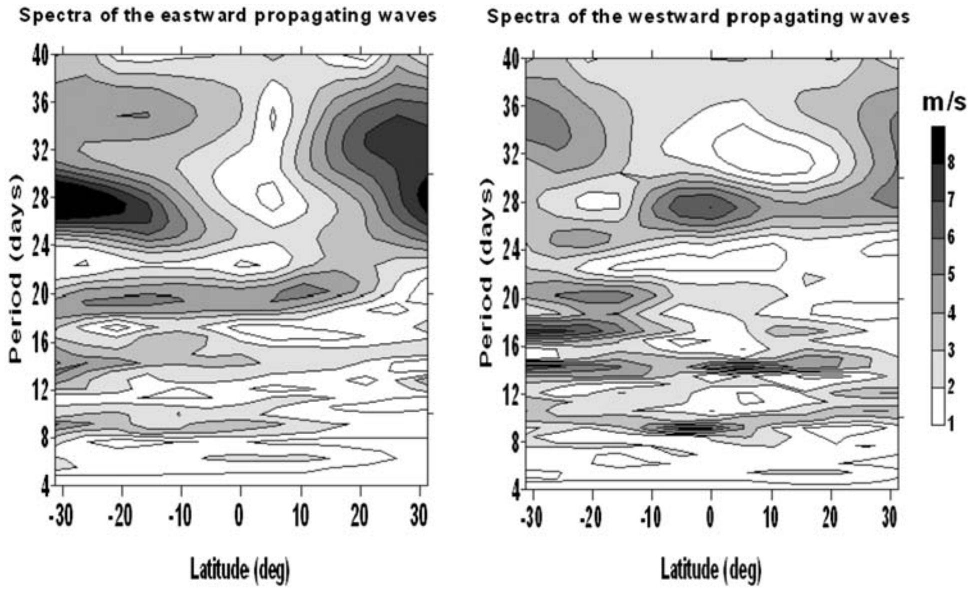

Figure 13. Amplitude spectra of the (left) eastward and (right) westward traveling waves with zonal wave number 1 in Met Office zonal winds (m/s) at pressure level 0.1 hPa for the observational period 1 June 2004 to 31 December 2005.

occur within a time shift of a few days. This clearly indicates that there is some forcing acting in the intraseasonal time scale at various levels that could cause the vacillations in the mean zonal wind in intraseasonal time scales. Earlier studies suggested that the forcing is due to the upward coupling of energy and momentum by waves generated in the regions of

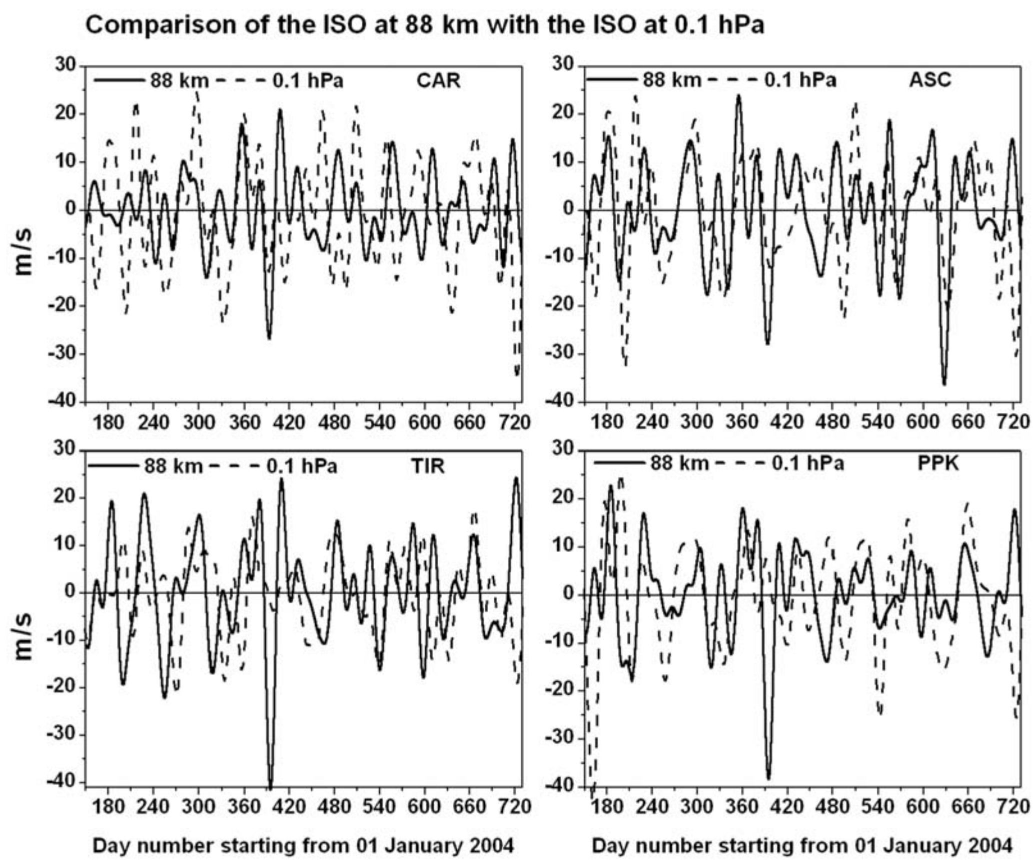

Figure 14. Comparisons of the ISO of the zonal winds at 88 km with the ISO of the Met Office zonal winds at 0.1 hPa (~60 km) over (top left) Cariri, (top right) Ascension Island, (bottom left) Tirunelveli, and (bottom right) Pameungpeuk.

intense tropospheric convection. Waves with slow phase velocities (slow Kelvin wave, Rossby-gravity waves) damp at lower heights while waves with high phase velocities (tides, UFK waves, gravity waves) could propagate up to high altitudes. As convection varies on the intraseasonal scale, the forcing caused by the wave dissipation/breaking varies with similar periods. The nature and amount of forcing at a particular altitude over a particular location depends on the background wind conditions, the strength of the lower tropospheric convective activity and the type and strength of the waves generated by the convective activity and their propagation directions. The atmospheric waves with different phase velocities break/dissipate at different altitudes and could cause similar ISO variations at different altitudes. This could be the reason for the similar ISO at 88 km and at 0.1 hPa during certain periods. The ISO at 60 km has some features similar to those of the ISO at 88 km during certain periods even though the SAO at 88 km is in opposite phase to the SAO at 60 km. This indicates either a possible downward extension of the ISO at upper heights to the lower heights or similar ISO induced by the breaking or dissipation of waves generated by intraseasonally varying lower tropospheric convection. Thus the ISO observed in Met Office zonal winds at USLM region is a wave driven phenomenon.

[34] Much of the wave spectrum propagating from below encounters critical levels at upper rather than lower heights. Therefore, the momentum deposited (or forcing caused) by the wave dissipation/breaking is stronger at upper mesospheric heights as compared to that at lower heights. So, the ISO cycles usually start at around 100 km and extend down to lower heights. The difference in the amount of forcing at different heights could be the reason for the difference in ISO amplitudes at different altitudes.

[35] In the middle atmosphere, the background wind conditions could depend on the phase of the SAO. Usually the SAO is the dominant oscillation in the equatorial middle atmosphere and the stratospheric SAO is in opposite phase to the mesospheric SAO [*Hirota*, 1978; *Hamilton*, 1982; *Garcia et al.*, 1997]. As the SAO is the dominant oscillation in the equatorial middle atmosphere, the response of the zonal wind to forcing caused by the convectively modulated wave dissipation on the intraseasonal time scale might then depend on the phase of the SAO at those altitudes. The study of long-term variability of MLT winds by *Sridharan et al.* [2007] revealed the times of enhancement of the ISO amplitudes in zonal wind coincided with the times of large westward winds and this suggests that the ISO in zonal wind at least partly depends on the phase of the SAO. Even though the MLT zonal wind responds quite promptly to the ISO in the convective activity, the present observations indicate slight enhancement of ISO amplitudes (as seen in Figures 2 and 4) during the westward phase of the MSAO. The dependence of the ISO on the phase of the SSAO at USLM heights is not clearly evident in the Met Office data.

4. Summary and Conclusions

[36] The present work is focused on studying the longitudinal behavior of intraseasonal oscillations of the zonal wind in the low-latitude MLT region, and its relation to the lower tropospheric convective activity, using data on zonal winds obtained by four low latitude radars. The Met Office zonal wind data have also been used to study the ISO at stratospheric and lower mesospheric heights.

[37] The intraseasonal variability in deep convective activity has been observed mainly over the Indian Ocean and western Pacific (75°E–140°E). The two MF radars at TIR (77.8°E) and PPK (107.7°E) are situated in this region, while the two meteor radars at CAR (7.4°S, 36.5°W) and ASC (7.9°S, 14.4°W) are situated in the convectively quiescent region. The zonal winds at 88 km over the four sites exhibit similar ISO in different time period bands (around at 50–70 days and 25–45 days) but stronger over TIR and PPK as compared to CAR and ASC. The convective activity over the longitude sector (60°E–140°E) also exhibits ISO activity ascribed to the MJO in similar time period bands during the same observational periods. The ISO activity in the MLT zonal wind is well correlated with the intraseasonal variability in the tropical convective activity over the Indian Ocean/western Pacific region. Though the ISO in MLT zonal winds are coherent over the all four sites, the ISO activity is relatively weak over the convectively quiescent regions.

[38] The Met Office zonal mean zonal winds in the upper stratosphere and lower mesosphere (in the height range 45–60 km) also showed ISO in similar time period bands. The ISO at these heights exhibits antisymmetric behavior about the equator with maximum amplitudes during winter periods, whereas this behavior is not observed in the ISO in MLT zonal winds. The amplitudes of the ISO at 88 km differ from those found at 60 km. The ISO activity at 60 km is relatively less prominent as compared to that at 88 km. These observations suggest that the ISO at upper levels may propagate down to 45 km altitude during certain times.

[39] Our observations strengthen the earlier inferences [*Eckermann et al.*, 1997; *Isoda et al.*, 2004] that ISO in convective activity associated with MJO induce similar ISO in MLT zonal winds through wave driven forcing. The longitudinal dependence of the ISO at MLT heights, revealing greater amplitudes over regions where the MJO is strong, is a new feature reported in this work. The ISO in the equatorial middle atmospheric zonal wind is a convectively modulated wave driven phenomenon that starts first in the MLT region (at heights close to 100 km) and descends steadily with time down to 45 km.

[40] In order to estimate the role of equatorial waves and tides in the excitation of intraseasonal oscillation of the zonal wind, the intraseasonal variabilities of the waves and tides, and their longitudinal variabilities, need to be studied extensively using long-term data provided by satellites and a network of radars. This will be the subject of our future study.

[41] **Acknowledgments.** We are thankful to the UKMO and the BADC for the access to the data on http://www.badc.rl.ac.uk/data/assim. The daily OLR data were downloaded from the website of NOAA-NCEP climate prediction center.

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