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Observational evidences of the influences of tropospheric subtropical and midlatitude stratospheric westerly jets on the equatorial stratospheric intraseasonal oscillations

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Abstract:

Using six Global Positioning System (GPS) Radio Occultation (RO) satellites (SAC-C, METOP-A and COSMIC/FORMOSAT-3, CNOFS, GRACE and TerraSAR-X) determined height profiles (1-40 km) of atmospheric temperature over the Indian tropical station of Gadanki and the European Center for Medium Range Weather Forecast (ECMWF) Interim Reanalyses (ERA-Interim) zonal wind and temperature data for four years (2009-2012), the present work reports that the tropospheric Subtropical Westerly Jet (SWJ) and the Midlatitude Stratospheric Westerly Jet (MStWJ) play important roles in controlling differently the vertical propagation of tropical Intra Seasonal Oscillations (ISO) with different period bands from the troposphere up to the stratosphere during Northern winters. In the months of December-May (Northern winter to summer, NWTS) of all these years, there is significant 10-20 day and 20-40 day oscillations in the troposphere up to the height of 13 km and above this it reappears at all heights above 21 km. The 40-80 day oscillation also shows similar characteristics except that it almost disappeared during NWTS months of the year 2010-2011in the stratosphere. The absence of these signals in the intervening heights of ~17-20 km is explained on the basis that these two bands actually propagate from the tropical to subtropical region near the tropopause and then reappears in the tropical stratosphere after refracted by the subtropical westerly jet. The poleward and equatorward propagation of these bands in the troposphere and stratosphere respectively are found using the ERA-interim data. Further the two longer period bands of ISO show strong

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quasi-biennial oscillation in the lower atmosphere with opposite phases (when one band shows maximum the other one shows minimum in a particular year) between these two bands. It is also observed that the phase of the tropical stratospheric Quasi Biennial Oscillation (QBO) has significant control on the strength of the Mid latitude stratospheric westerly jet (MStWJ) that in turn controls the refraction of the tropical tropospheric longer (40-80 days, Longer period ISO; LISO) but not the smaller periods of ISO (SISO) back to the tropical stratosphere. In accordance with earlier theoretical modelling studies, the westerly phase of the lower stratospheric QBO occurred during NWTS months of 2010-2011 over the Indian longitudinal sector causes severe disruption of the MStWJ at 30 km height. This disruption caused the prevention of refraction back again to the tropical stratosphere of significant tropospheric LISO that arrived from the tropics through the tropopause. Further, in these four years, it is observed no direct vertical propagation of tropical tropospheric ISO to the stratosphere. The interannual variations in the tropical stratospheric LISO are related strongly to the phase of the equatorial lower stratospheric QBO in zonal wind and the strength of the MStWJ.

Keywords: ISO in temperature and zonal wind; GPS RO and ERA-interim data; tropical tropospheric and stratospheric temperature and winds; seasonal characteristics of MJO

Introduction

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Using the wind velocities measured by a medium frequency radar over the Christmas island, it has been reported the existence of Intra seasonal oscillations (ISOs) with peaks near the periods of ~ 60 days, 35 - 40 days and 22 - 25 days in the equatorial Mesosphere and Lower Thermosphere (MLT) region winds (Eckermann and Vincent, 1994; Eckermann et al., 1997). It is also reported similar periodicities in gravity-wave and diurnal-tide amplitudes in the MLT region (Eckermann et al., 1997). It was suggested that the 30 - 60 day Madden-Julian oscillation manifested in the tropical tropospheric convection (Madden and Julian, 1971, 1994) and a

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separate 20 - 25 day oscillation over the western pacific (Hartmann et al., 1992) can modulate the gravity wave and diurnal-tidal intensities at ISO periods. These modulated waves and tides then propagate upwards to the MLT region and create similar periodicities in the wave-induced zonal mean flow of the MLT region. Using observations of the winds from HRDI (High Resolution Doppler Imager), Lieberman (1998) showed that the ISO in the MLT zonal winds is wave-driven. Rao et al. (2009) considered radar observations of MLT region dynamics in different longitudinal sectors and found that ISO amplitudes have significant longitude variation, suggesting a close connection to the vigor of convective activity in the underlying troposphere. Earlier, it is reported that the upper mesospheric (based on an empirical analysis of measurements with the High Resolution Doppler Imager (HRDI) on the Upper Atmospheric Research Satellite (UARS) spacecraft) intra seasonal oscillations (2-4 months periodicity) in the meridional winds are associated with similar oscillations occurring in temperature (Microwave Limb Sounder (MLS) of UARS data) near the stratospheric height of ~55 km (Huang and Reber, 2003; Huang et al., 2005). Recently, Rokade et al. (2012) showed, using medium frequency radar data in the Indian tropical stations of Tirunelveli and Kolhapur, the intraseasonal oscillation (ISO) in the mesospheric winds are correlated well with ISO in the outgoing longwave radiation, indicating that the mesospheric ISOs are inherently related to the ISOs in the tropospheric convective activities (say Madden Julian Oscillation).

It is also reported the biennial variations of ISO in the zonal winds and diurnal tide amplitude in the mesosphere (Isoda et al., 2004). Further, Isoda et al. (2004) reported that gravity wave variances at ISO periods and the ISO in the zonal wind are not correlated in the MLT region. They suggested that dissipating non-migrating diurnal tide modulated at the ISO period is

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the source of ISO in the MLT region zonal wind. . Using UARS/HRDI zonal wind data Lieberman [1998] studied the characteristics of ISO in the MLT region during December 1991 - March 1995.. Peak ISO amplitude of about 20 m/s was found at 95 km and 75 km in the latitudes of ±20° around the equator, with a local minimum at around 80 km. By using a GCM, Miyoshi and Fujiwara (2003) showed variations in the migrating diurnal tide amplitudes with periods of 12 and 25 days in the heights from 20 to 300 km, implyingdynamical coupling between the lower and upper atmospheres.

The important characteristic of the Madden Julian Oscillation (MJO) in the tropical troposphere is that it attenuates rapidly above the tropopause (Madden and Julian, 1971). This was corroborated by studies of rocket and radiosonde data from the Indian tropical stations (Nagpal and Raghavarao, 1991; Nagpal et al., 1994; Kumar and Jain, 1994). Using rocket wind data from Indian stations spanning 8.5° - 21.5°N, the reintensification of the MJO in the upper stratosphere was reported by Nagpal and Raghavarao (1991), Nagpal et al. (1994) and Kumar and Jain (1994). The occurrence of nearly equal amounts of intra seasonal activity in both the zonal and meridional winds led them to conclude that its characteristics are different from that of Kelvin waves, and associated the activity with Rossby waves. Further it was argued that these Rossby waves would have propagated into the tropical upper stratosphere through mid latitudes (Nagpal and Raghavarao, 1991; Nagpal et al., 1994). However, Kumar and Jain (1994) suggested that the waves would have leaked into the upper stratosphere from the tropical troposphere via direct vertical propagation because the MJO contains a significant Rossby-wave component, particularly in forcing zones near India (Hendon and Salby, 1994). Mote et al. (2000) showed signatures of tropical intraseasonal oscillation in the upper tropospheric moisture and dynamical fields in the heights of 100-200 hPa levels with complicated characteristics near the 100 hPa level. For the first time on a global scale, their analysis demonstrates that the response of the 100-hPa level water vapor to the Tropical Intra seasonal oscillation (TIO) is out of phase with that at 215 and 147 hPa levels. They also found that while the convectively active phase moistens the upper troposphere, the tropopause region becomes dryer. Madden and Julian (1972) observed significant MJO in temperature near 100 hPa level. Mote et al. (1998) noted a 30- to 60-day spectral peak in water vapor measured by Microwave Limb Sounder (MLS). The sharp attenuation of the TIO signal in the lower stratosphere was noted also by Mote et al. (2000). Further it was observed that the spectral power of water vapor variations in the 30- to 70- day band drops by an order of magnitude between 100 and 68 hPa (Mote et al., 1998).

It is interesting to note some other aspects of the ISO. It is found that ISO period of 60–80-days is present not only in the atmospheric dynamical parameters but also in the fluxes of solar ultra violet (UV) rays and ozone concentration (Zhou et al., 1997). Moreover, the intraseasonal oscillations are found not only in the equatorial stratosphere but also over the Antarctica during Austral winters. Based on the Met Office stratospheric assimilated data and the TOMS total ozone, Huang and Weng (2002) reported that Stratospheric Antarctic Intraseasonal Oscillation (SAIO) (30-day oscillation) occurs (within 60E – 120E) with deep vertical structure extending from the upper troposphere to the upper stratosphere. They found that the amplitude increases rapidly with height below 5 hPa and decreases slowly with height above and the vertical shows westward-tilting with increasing height below 5 hPa and a more barotropic structure above. The calculated vertical and meridional wavelengths are about 80 km and 13,343

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km respectively, and the scale height is 7 km, mostly westward propagating. Further, they suggested that the topographically forced planetary wave propagates upward in a baroclinic atmosphere and only those waves with largest zonal scale can propagate deep into the upper stratosphere because of the Charney-Drazin criterion (Charney and Drazin, 1961; Karoly and Hoskins, 1982).

The main aim of the present study is that to show how different bands of ISO (10-20 days, 20-40 days and 40-80 days) propagate to the tropical stratosphere from below in the troposphere through the subtropical jet over the Indian region. oscillation Analysing Microwave Sounding Unit (MSU4) and Stratospheric Sounding Unit (SSU) temperature data sets, Ziemke and Stanford (1990) found that there is no direct vertical propagation of 1-2 month signals in the equatorial stratosphere. Further, Ziemke and Stanford (1991), Niranjan Kumar et al. (2011) and Guharay et al. (2014) have clearly shown that the tropical stratospheric ISO is a result of vertical propagation of ISO from the lower troposphere to tropopause from where it gets refracted to mid latitudes. The presence of the subtropical westerly jet allows the equatorial ISO to get refracted both vertically and laterally towards again to the equatorial region. The focus of the present study is to show the strong and direct link between the interannual modulation of the tropical stratospheric ISO and the interannual variation of the strength of different ISO bands in the troposphere Using six GPSRO satellites determined vertical profiles of temperature in the heights of 6-40 km over the Indian tropical station of Gadanki and the ERA-interim reanalyses temperature as well as the zonal winds in the whole tropical-high latitude regions, the present work attempts to establish the concept that strong subtropical westerly jet allows the easier subsequent propagation of the refracted tropical tropospheric ISO back to the equatorial

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stratosphere for the years 2009-2012. It is natural to get interested to know that when some atmospheric physical phenomena (say intra seasonal oscillations) are normally explained by available large scale data sets (NCEP-NCAR , ERA-interim, MERRA etc.) what actually happens in a limited regional space that is a small subset of larger domain in which large scale physics (ISO) is happening. After all large scale phenomena can be considered as ensemble average of small scale phenomena occurring in small size regions. One can easily ask whether these large scale phenomena (ISO) can be seen in smaller scale regions like the present case of Gadanki. Further, question arises as to whether an ensemble average of many small-time-scale phenomena (wave-mean flow interaction of gravity waves, tides, Kelvin waves, planetary waves etc. whose periods are within a few to tens of days) or a single large-time-scale phenomena as a whole contributes to the observation of intra seasonal oscillation. The best example here is the persistent tropical stratospheric quasi-biennial oscillation occurring due mainly to wave-mean flow interaction. The present work is the result of these basic questions. However, in order to show that the ISO as a whole propagates poleward near the tropopause and equatorward at higher heights through refraction about the subtropical jet, the present work includes analyses of large ERA-interim data sets of temperature and zonal wind that cover the full latitude zone of 0-30N and the full height of 1-40 km in these years of 2009-2012.

While section 2 describes briefly about the six GPS RO satellites determined height profiles of temperature over Gadanki and the ERA-interim reanalyses temperature and zonal wind data, section 3 gives the detailed observations of the characteristics of ISO in particularly three bands (1) 10-20 day oscillation, (2) 21-40 day oscillation and (3) 41-80 day oscillation in the whole heights of the tropical troposphere and stratosphere. Section 4 provides a detailed

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discussion of the observations and the section 5 gives the summary and conclusion of the present work.

Data and Methodology:

Global Positioning System (GPS) satellites based radio occultation technique has become a powerful remote sensing tool to determine the vertical profiles of atmospheric refractivity, geopotential, temperature, pressure, water vapor, etc. with high accuracy and vertical resolution (0.5 km to 1 km) in the Upper Troposphere -Lower Stratosphere (UTLS) and ionospheric electron density (Kursinski et al., 1997; Rocken et al., 1997; Steiner et al., 1999). Global Positioning System /Meteorology (GPS/Met) successfully demonstrated the applicability of the RO technique for probing the Earth's atmosphere and the provision of accurate data [Ware et al., 1996; Rocken et al., 1997; Steiner et al., 1999]. Information about these GPSRO satellites, namely, SAC-C (for lower atmospheric temperature studies see for e.g. Schmidt et al., 2005), METOP-A and COSMIC/FORMOSAT-3, CNOFS (for lower atmospheric temperature studies see for e.g. Wang et al., 2015), GRACE and TerraSAR-X can be found in these web pages:
https://eoportal.org/web/eoportal/satellite-missions/s/sac-c,
https://eoportal.org/web/eoportal/satellite-missions/m/metop,
https://eoportal.org/web/eoportal/satellite-missions/f/formosat-3,
https://eoportal.org/web/eoportal/satellite-missions/c-missions/cnofs,
https://eoportal.org/web/eoportal/satellite-missions/g/grace,
https://eoportal.org/web/eoportal/satellite-missions/t/terra.
In the present work, we utilized the temperature (wet temperature, wetPrf) information obtained from these six satellites in the whole height region of 6-40 km and for the latitudinal and longitudinal regions of 8^0-18^0N and 75^0-85^0E centered about the Indian tropical station of National Atmospheric Research Laboratory (NARL), Gadanki (13.5°N, 79.2°E) during the years 2009-2012 to determine the vertical propagation characteristics of planetary scale waves and oscillations (10-120 day oscillation). This product wetPrf is based on a 1DVAR retrieval using

dry RO temperatures and ECMWF data (for details see the description on the UCAR data website). Daily height profiles of temperature are constructed for the full year of 2009-2012 over the mentioned coordinates by averaging the temperature values obtained within this region by all the satellites. Small data gaps are linearly interpolated in time (days). All the data presented in the work and the detailed information about these satellites is obtained freely from the website of http://cdaac-www.cosmic.ucar.edu/cdaac/products.html. Since the radio occultation (RO) technique gives the most accurate (~0.05 K in the heights of 8-30 km) measurement of atmospheric dry temperature with high vertical resolution (increasing from ~60 m near the surface to ~1.5 km at 40 km), it is being taken as the bench mark measurement against all other measurements made with radiosonde sensors and satellite based brightness temperature at microwave or infrared frequencies. When we study the characteristics of long period oscillations (say intraseasonal oscillation) in different years, it is essential that there should not be any errors in the measurements as it happens with different types of sensors in radiosondes and different weighting functions of height associated with different frequencies of brightness temperature in the case of satellites. It is to be remembered that RO technique is mission and geography independent (Kuo et al., 2004 and 2005; Ho et al. 2007; He at al., 2009; Ho et al., 2009). Since the sampling errors associated with the present considered geographical grid and the number of measurements available at different times in a day within the grid is significantly less with respect to long period intraseasonal oscillations, they are not shown or discussed here.

For the detailed information on model reanalysis data of ERA-interim reanalysis data one is referred to Dee *et al.* (2011) and the present data at different pressure levels are downloaded from the website http://apps.ecmwf.int/datasets/data/interim_full_daily/?levtype=pl. In the

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present work, Morlet wavelet transform mehod has been employed for the detailed investigation of time evolution characteristics of oscillations with period bands of particularly the 10-20, 21-40 and 40-80 days.A practical step-by-step guide to wavelet analysis with examples time series is provided by Torrence and Compo (1998), including statistical significance testing and cone of influence (COI) for the continuous wavelet transform. The complete knowledge of the wavelet analyses carried out in the present study is guided by Torrence and Compo (1998).

Observations:

Fig. 1 shows day (1 January 2009 to 31 December 2012, x axes) vs. period of oscillation (days, y axes) contour plots of Morlet wavelet transform (Torrence and Compo, 1998) power spectrum of temperature (K^2) determined with the help of the six above mentioned GPS RO satellites. Actual power of the spectra is equal to the variance of the time series multiplied by 2 to the power of color bar value.

That is

Actual power = Variance$\times 2^c$

where c is the color bar value. Since the power plotted in the figures is in base 2 logarithmic scale negative values are possible.

The bottom to top left six panels show the spectrum for the heights of 6 to 11 km and similarly the right panel for 12-17 km. The thick magenta colored contour lines indicate that the power inside of which is more than 95% confidence level and the thick black curved lines in the ends of the plots indicate the cone of influences associated with wavelet spectra. It may be observed that around the Northern summer month of April in 2009 (first long vertical black grid line covering all the height panels in one side), there is a significant power in the whole band of 16-64 days in the lower height of 6 km. In the next higher height of 7 km, this band got disrupted into a single narrow one centered around 60 days. At 8 km, there are two bands; 8-16 day band and 30-60 day band, and at the higher height of 9 km they are narrow and centered around 16 and 50 days. In the heights of 10-13 km, there is one oscillation significant with period of ~34 days along with one 16-day significant oscillation at 13 km. In the heights of 14-15 km there is only one oscillation centered near 16 days and there is a reappearance of the ~34-day oscillation at 16 km with no oscillations at 17 km. Since this height of 17 km is near the tropical tropopause, it is suspected that the said oscillations would have either dissipated or refracted to higher latitudes because of the normal doubling of the Brunt-Vaisala frequency and strong vertical shear in the horizontal winds near this altitude (Chen and Robinson, 1992).

There is a recurrence of the 16-64 day band oscillation at the 6 km height around April in all other years also (3rd, 5th and 7th long vertical black grid lines crossing all the height panels in one side). However, the band becomes narrower and weaker with the following years 2010-2012; 30-60 day oscillation in 2010, 40-60-day band in 2011, 50-60 day band in 2012 (insignificant). The gradual weakening of this band (16-64 day oscillation) with years gives a hint that there may be multi-year oscillation components in this lower height of 6 km. A comparison of the vertical structure (7-17 km) of this band among all these years indicate that it is almost not present in the years 2010 and 2011 but it is strong again in 2012, indicating interannual variation characterics of this oscillation band in the tropical troposphere. One interesting thing to be noted here is that the same set of oscillation bands and the structure of vertical profiles as observed during the Northern summer month of April is observed also during the Northern winter months centered around December but in the heights of 7-16 km. In summary, this band of oscillation (16-64 days) peaked in their significance and is seen clearly during both the Northern summer and winter months of April and December respectively in the upper tropospheric heights of 15-16 km, which are normally just below the tropopause height of 17 km where they are not found. As a contrast, in all the years except 2012 there is a significant ~50 day oscillation (~90 day oscillation in 2011) at the tropopause height of 17 km during the Indian summer monsoon period of June-September. Further at this height of 17 km, there is also ~10-32 day (few narrow bands within this broad band) oscillation during this period in all the years.

In the lower stratospheric heights of 18-20 km (Fig. 2 is same as Fig. 1 except for the heights of 18-29 km), there are no significant oscillations in any season of any year. Above that in all the higher heights (21 km - 29 km), it is noted strong ~50 day oscillation (varying from 40 to 120 days with mostly near 50 days in the years 2010-2012 but near 120 days in 2009) during the months of December-May (between two nearby long vertical black grid lines passing through all height panels in one side) in all the years. It is interesting to note here that during this period of December-May, this oscillation is present in all the other heights also from 30 to 40 km (Fig. 3 is same as Fig. 2 except for the heights of 30-40 km) in all the years except 2011. In order to show the insignificant LISO in the year 2011, Figs. 4a and 4b show the height profiles (1-32 km) of 40-80 band filtered daily (12GMT data) ERA-interim reanalysis temperature (top panel) and

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zonal wind velocity respectively at 13N and 80E for the years 2009-2012. It may be easily identified that both the temperature and zonal wind shows distinctly enhanced 40-80 day band oscillation in the heights of 18-32 km for the wind and 21-32 km for the temperature (top panel of Fig. 4) during the months of November-May in all the years. The year 2011 is clearly distinct as the amplitude of this signal (40-80 day band) is significantly weaker in both the wind and temperature compared to other years. Further, the clear downward propagation of the phase in the zonal wind (bottom panel of Fig. 4) indicates that the source of this band of oscillation is located below 19 km in the lower atmosphere. This band of 40-80 days clearly shows quasi-biennial modulation with activity in 2010 and 2012 but weak in 2009 and 2011.

Contrastingly, the 21-40 day band oscillation is significantly strong in the year 2011 in both the temperature (Fig. 5a) and zonal wind velocity (Fig. 5b, bottom panel) in the stratospheric heights of 20-32 km. Even though this band also shows quasi-biennial variation with minimum in 2010 and 2012 its phase (minimum or maximum) is opposite to that of the 40-80 day oscillation. The 10-20 day oscillation (Fig. 6) is also distinctly enhanced during the months of December-April in all the years of 2009-2012 without significant quasi-biennial modulation.

Since all these three 10-20 day (Fig. 6), 20-40 day (Fig. 5) and 40-80 day (Fig. 4) band oscillations disappear near the tropopause height of 17-18 km and reappear above 19 km in the whole stratosphere up to 32 km over the tropical region (say the presently considered Indian tropical station of Gadanki), these signals are expected to arrive back to the tropical region after getting refracted by the subtropical westerly jet. To show that these signals propagate from the subtropical region, Figs. 7 and 8 show the time (2009-2012) vs. latitude (0-30N) contour plots of filtered 40-80 day oscillation in the temperature and zonal wind velocity respectively for the heights of 17-32 km. One can easily identify from both the Figs. 7 & 8 that the 40-80 day oscillation in both the temperature and zonal wind velocity shows equatorward (tilting towards the right side of the figure from high to low latidues with increasing time) propagation from the subtropical latidude in the heights of 21-32 km. Near the tropopause height of 17 km, while the zonal wind shows clear poleward propagation (tilting towards the right side with increasing latitude) the temperature shows almost constant phase with latitude. The interesting observation here is that the signal is so weak and that there is no statistically significant 40-80 day oscillation that propagates equatorward in the year 2011. From the observations described above for the Figures 4-8, it is clear that during the months of January-March in 2011 (contrasting to other years) there is no significant 40-80 day oscillation in the lower atmosphere as well as in the stratosphere and there is no equatorward propagation of this oscillation in the stratosphere. However, the other two bands of oscillations (21-40 days and 10-20 days) are present in the stratosphere along with equatorward propagation in the stratosphere. Here we showed only the 20-40 day oscillation in the temperature in Fig. 9, which is similar to Fig. 7 except that it is now 20-40 day oscillation.

To address this issue of not observing the Northern winter-summer time LISO in the year 2011, Fig. 10 shows six hourly ERA-interim reanalysis zonal wind velocity at the 10 mb level (~30 km height) for the winter-summer (WTS) months of January-May during the years 2009-2012. It may be noted that the MStWJ in the year 2011 (Figure 10c) is either displaced to much higher latitudes (above 50°N) or almost disappeared when compared to the other years during

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which the jet was wandering in a wide range of latitudes (20°N - 50°N) in these WTS months. This wandering of the jet is often associated with Arctic Oscillation (AO) which also corresponds to a north-south seesaw of zonal-mean zonal wind between 35°N and 55°N (Thompson and Wallace, 2000). Comparing to the jet shown in the Figure 11c for the lower height of 70 mb level (~ 19 km height), it may be observed that the MStWJ jet at the height of 30 km got almost disappeared in the year 2011. It seems that the jet structure shown in the Figure 10c is almost a polar jet. The disappearance of the MStWJ in the year 2011 would have made the planetary waves propagating from the equator to proceed further to the high latitudes rather than get refracted in the subtropical jet. Since the planetary waves were not refracted towards the tropical region above 30 km, there is no significant LISO in these months of January-March in 2011 in the heights of 30-40 km.

To determine whether the long 50-day oscillation is really a propagating one in the stratosphere, Fig.12 shows the height profiles of least square error determined amplitude (left column), phase (mid column) and period (last column) for three bands of oscillations, namely, (1) 10-20 days, (2) 21-40 days and (3) 41-80 days for three different seasons, namely, (1) January-May (top row), (2) June-August (middle row) and (3) September-December (bottom row) of the year 2009. In the least square error method, it is first filtered out all other suspected major oscillations (say annual, semiannual oscillations along with main planetary waves with periods of 2, 3, 5, 7, 10, 15, 27, 40 and 60 days) by keeping the highest frequency in the mentioned particular band. This remaining signal will be subtracted from the mean of the time series and designate the squared value as error. This will be repeated by changing the chosen

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frequency continuously with particular frequency interval (say one day period) until all the frequencies are covered in the selected band. Finally, the signal with the least error will be selected as dominant frequency in the particular band and all the oscillation parameters like amplitude, phase and period associated with this least square error frequency will be considered as optimum parameters for further interpretations.

The seasons are classified such that many reports indicate that the ISO oscillation occurs in the Northern MLT region mainly during January-May (Guharay et al., 2014). Further, the ISO occurring during the Indian south west monsoon period of June-August has some distinct different characteristics when compared to those occurring in the other seasons. The height profiles of wave characteristics are determined for both the GPSRO satellites determined temperature as well as the ERA-interim reanalyses temperature. It may be observed that the phase of the 41-80 day oscillation (top middle panel of Fig. 12) shows a well defined downward propagation in the heights above 20 km and in the lower heights it shows almost a vertically standing oscillation. One can easily identify that this downward propagation in the higher heights is not present in the other seasons (mid panels of mid and bottom rows of Fig. 12). Same kind of height structure of phase of the 41-80 day oscillation is present in all the other years also; Figs. 13, 14 and 15 for the years 2010, 2011 and 2012 respectively. Gradually increasing in value from about 1 K at 6 km height (top left panel of Fig. 12) to about 3 K near the tropopause height of 17 km, the amplitude of the 41-80 day oscillation in both the GPSRO and ERA-interim data remains almost constant (~3 K) at all the higher heights up to 40 km during January-May 2009 as well as in 2010 (Fig. 13). However, the amplitude got steadily reduced to less than 1K at ~ 36 km from maximum near the tropopause height of ~17 km in 2011 and 2012 (Figs. 14 and 15). The sharp increase in amplitude to about 5 K at 36 km in both these years is worth notable and at present we don't have proper explanation for this enhancement. During the other seasons, the amplitude of this oscillation in both these data reaches a maximum of about 10 K near the tropopause height of 17 km in June-August and about 8 K in September-December. The main reason for the large amplitude in these two seasons is due to the intra-seasonal oscillation in the Walker circulation associated with the Indian south-west and north-east monsoons respectively, which is different from the normal Madden Julian oscillation peaking in amplitude during Northern winters. Since the east-west zonal Walker-circulation closes its circulation near the tropopause heigtht and it is most active during the Indian southwest monsoon period of June-August, the zonal winds show distinct ISO oscillation at this height during this monsoon period. It may be observed further that the amplitude after reaching maximum near the tropopause, it steadily decreases to less than 2 K near the top most height of 40 km and the phases are almost vertical in both these seasons. Similar vertical features of 41-80 day oscillations occurred in all the years of 2009-2012 during two seasons of June-August and September-December.

Regarding other period bands of 10-20 day and 21-40 day oscillations, it may be noted that the amplitudes are within 1 K in all the heights of 6-40 km and in all the seasons of the years 2009-2012. Exception is that during the summer monsoon period of June-August, the 21-40 day oscillation shows increase in amplitude from ~0.5 K at 6 km to ~3 K at 12 km and above that height up to 40 km the amplitude is oscillating between 0.5 K and 3 K. In 2009, while the model (ERA-interim) shows the steady increase in amplitude up to about 3 K at 12 km, the observation value is within 1 K but the reverse is true in 2010. However in 2011, both the model and observation show the increasing trend but in 2012 both the values are within 0.5 K up to the height of 12 km. In 2009, the oscillatory nature of the 21-40 day oscillation in the higher heights of 20-40 km is visible in both the values but with higher frequency in the observational value. The phase of the observed 21-40 day oscillation has some interesting characteristics that during January-May in 2009 (top mid panel of Fig. 12) it shows a downward propagation from 10 km up to the tropopause height and above that up to the top most height of 40 km it shows clear sinusoidal oscillation with vertical wavelength of ~4 km. However, the model phase shows clear downward propagation in the whole height range of 6-40 km during this period. In the other seasons of 2009, even though both the phases are matching but they are vertically standing in nature in almost all the height range. The characteristics are different in 2010 and 2011, in that both the model and observational phases show upward propagation in the heights of 20-40 km and downward propagation in the lower heights of January-May and during the other two seasons they are oscillatory in nature in all the heights. In 2012, both the model and observational phases show oscillatory character with upward propagation in the higher heights and downward propagation in the lower heights during January-May. During June-August, while the observation shows vertically standing wave characteristics the model shows oscillatory characteristics in all the height ranges. However during September-December, both the phases show upward propagation in the higher heights but vertically standing wave characteristics in the lower heights of 6-20 km.

From the vertical phase structures of both the observed as well as model (ERA-interim) 11-20 day oscillation in January-May of 2009 (top mid panel of Fig. 12), it may be ascertained that the wave propagated up to the tropopause and above that it remained stationary, indicating that this wave would have either dissipated or refracted near the tropopause height. It is almost

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vertically stationary in all the heights in the other two seasons. During January-May of 2010 (Fig. 13), it shows (both the model and observations almost agree each other) downward phase propagation in almost all the heights, indicating that the 11-20 day oscillation propagated without any hindrance from the lower atmosphere to upper stratosphere. However in the other two seasons, they are either stationary or fluctuating randomly with height in the whole troposphere and stratosphere. Similar is true in all the seasons of the year 2011. However in 2012, the phase shows downward propagation with some fluctuations in all the heights during the January-May and June-August months but during September-December it shows upward propagation in the heights higher above 25 km.

Discussion

It is known that the stratospheric and tropospheric circulations are coupled during Northern winters through dynamical linking of the mean stratospheric background flows with the upward propagating planetary scale waves generated in the troposphere [Charney and Drazin, 1961; Matsuno, 1970; Randel, 1987; Perlwitz and Graf, 1995]. The present work attempts to explain this dynamical coupling mechanism of the equatorial stratosphere in terms of long period oscillations like intra seasonal oscillations generated in the tropical lower atmosphere and the subtropical westerly jet occurring normally during the Northern winter. Using six GPS RO satellites determined temperature during 2009-2012, it is observed in the present work the presence of intraseasonal oscillation in all the seasons of all the years with periods varying in the range of ~10-100 days in the whole troposphere over the Indian tropical station of Gadanki.

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Above the troposphere, in the first few kilometers of height in the lower stratosphere there is no signature of any long period wave activity in any of the seasons of these years. It is worth to recall here from the report by Chen and Robinson (1992), using a three-dimensional linear time-dependent primitive equation model, that vertical propagation of wave activity into the stratosphere is very sensitive to the vertical shear of the zonal winds and the vertical gradient of buoyancy frequency near the tropopause. Since normally the Brunt-Vaisala frequency gets almost doubled near the tropical tropopause, it is almost impossible for long period oscillations to penetrate through the tropopause in the tropical region. The present observation of reappearance of the LISO (~50 day oscillation) above 20 km and up to the topmost height of 41 km during the NWTS periods of January-May in all the years except 2011 gives us an interesting case study of investigating what would have controlled the stratospheric LISO from being present in the tropical region during 2011. The present observation of January-May upper stratospheric LISO is in accordance with the meteor radar observations of ISO (40-70 day oscillation) in zonal wind in the South American equatorial station São João do Cariri (7.4°S, 36.5°W) MLT region by Guharay et al. (2014). They observed good correlation between the MLT region ISO in zonal wind and the lower tropospheric outgoing longwave radiation (proxy for convection), total columnar water vapor (proxy for tides) and zonal wind. Their observation of downward propagation of peak amplitude of ISO in the MLT region indicates the role of upward propagating wave contribution to the generation of ISO. It can be noted that the familiar Madden Julian oscillation is an example of intraseasonal oscillation which can be interpreted as mixed Kelvin and Rossby waves near the source region and an eastward propagating Kelvin wave away from the source (Madden and Julian, 1994). Guharay et al. (2014) believed that the origin of the MLT region ISO can be traced to the eastward propagation of lower tropospheric

Madden Julian oscillation originating below 4 km from the Indian and western and central Pacific oceans (Madden and Julian, 1971). However, using radar wind observations over Jakarta (6°S, 107°E), Pontianak (0°N, 109°E) and Christmas Island, Isoda et al. (2004) inferred that the mesospheric ISO cannot be associated with propagating disturbances and that it is a variation of the zonal mean flow. Their observation of ISO modulated zonal wind and diurnal tide in the MLT region implies an appreciable contribution of the diurnal tide originating from the lower troposphere. The biennial variability found by them in the ISO amplitude of the zonal wind and zonal amplitude of the diurnal tide has some accordance with present observations. Over the Indian tropical station of Gadanki (13.5°N, 79.4°E), Guharay et al. (2012) reported the existence of a dominant ISO in the period range of 20 to 100 days with intermittent behavior in the troposphere, insignificant amplitude in the stratosphere, and consistent variability in the mesosphere.

In the present study, from the vertical phase structure of the 41-80 day oscillation, it is observed clear downward phase propagation in all the higher heights of 21-41 km, indicating that the source of this oscillation lies below 21 km. This signal either would have come directly from the troposphere or would have been refracted from higher latitudes. The present observation of no signals in the intervening height range of 18-21 km but the presence of statistically significant signals in the lower heights indicate that the direct vertical propagation of the ISO signal from the troposphere to stratosphere needs to be ruled out. In this scenario, the source of the tropical stratospheric ISO should be related either to the higher latitude regions or to the indirect vertical propagation of tropical tropospheric ISO through higher latitudes. The later hypothesis is a viable process because of the presence of the subtropical westerly jet wandering in the mid latitudes due to the global scale Rossby waves (Thompson and Wallace, 2000). In support of this argument, in the Southern Hemisphere Indonesian sector, Ziemke and Stanford (1991) showed an evidence of temperature fluctuations in the troposphere propagating initially quasi-horizontally towards higher latitudes along the bottom of the tropopause to near 35°S. The stratospheric winter westerlies located around this latitude allow vertical propagation of the 1-2 month perturbations up to the middle stratosphere where the wave train arches equatorward and upward to the stratopause. After twenty years of this observation in the Southern Hemisphere, Niranjan Kumar et al. (2011) reported a similar event for the Northern Hemisphere by using the MST radar measured over the Indian tropical station of Gadanki and ECMWF reanalyses winds. By noticing the phase of the ISO in the horizontal winds, they found that the ISO propagated upward from the lower troposphere up to near the tropopause, where it got sharply attenuated. The ECMWF data showed that the ISO was refracted to the subtropical latitudes, through the tropical tropopause, from where it got radiated upward into the stratosphere. Again by studying the phase propagation characteristics of the ISO, it is shown that ISO arched back toward the tropical latitudes and propagated to the mesospheric region.

The arguments of Ziemke and Stanford (1991) and Niranjan Kumar et al. (2011) support very well the present observation of the tropical stratospheric ISO in the NWTS periods of the years 2009, 2010 and 2012 as well as the absence of it in 2011. From the Figures 10 (10 mb, 30 km) and 11 (70 mb, 19 km), it is clear that the MStWJ present in the height of 19 km is totally disappeared in the height of 30 km. Up to this height from 23 km, the LISO signal with period of about 40 days is present during January-May in 2011 and above this height the signal disappeared in all the heights up to the present highest height of 40 km. This would suggest that the appearance of the tropical stratospheric LISO strongly depends on the presence of the strong NWTS period MStWJ. The presence of the downward phase propagation (top mid panel of Fig. 14) but the less significant power (Fig.3) of the 41-80 day oscillation in 2011 indicates that the refraction of the tropical tropospheric LISO from the subtropical jet is not totally disappeared but it is partially refracted leading to less significant power in the refracted signal. Another interesting physical process that controls the characteristics of wave propagation between the tropics and subtropics is the phase of the tropical stratospheric quasi-biennial oscillation. It can be noted from Fig.10c that the anomalous year 2011 witnessed westerly phase while the rest of the all the other years witnessed easterly phase of QBO in zonal wind at ~30 km height. Modeling studies have confirmed the influences of QBO phases on the lateral and vertical propagation of planetary scale waves between the equator and high latitudes as the phases can modulate the propagation characteristics of waveguides (O'Sullivan and Young, 1992; Niwano and Takahashi, 1998; Chen and Huang, 1999). For example, reports claim that easterly phase of equatorial QBO can lead to more disturbance of the northern polar vortex and disruption of the vortex by sudden stratospheric warmings (Holton and Tan, 1980). From the examination of 16 years of Northern Hemispheric geopotential height data, they showed that the monthly mean polar vortex strength up to 10 hPa was positively correlated with the equatorial zonal wind at 50 hPa. In winters, when the phase of the QBO is easterly then there is a possibility that the vortex becomes weaker and more disturbed than during summers.

Since the year 2011 witnessed easterly phase of equatorial QBO, the disruption of the MStWJ is expected during this year. Noticeable stratospheric (32-36 km, Fig. 3) ISO with period of oscillation centered near 32 days is observed also during the monsoon period of June-August in all the years. Particularly in 2010, the signal is present in all the heights of 30-40 km (Fig. 3) during this monsoon period. This would indicate that the appearance of the ISO in the stratosphere during the Indian summer monsoon period of June-August is controlled by some other mechanisms that are taken as one of the future scopes of the present study.

Summary and conclusions

The present work illustrates clearly the importance of the subtropical westerly jet during northern winters in transporting the tropical tropospheric intraseasonal oscillation (~10-100 day oscillation) to the tropical stratosphere. Since long wavelength tropospheric ISO are refracted along the tropopause because of the almost doubling of the Brunt-Vaisala frequency and vertical shear in zonal winds, it needs some mechanism in the subtropical regions to refract it back again to the tropical stratosphere as well as to higher heights. In this scenario, the subtropical westerly jet was suspected as an important refractant in the reports by Ziemke and Stanford (1991) for the Southern Hemisphere winter) and by Niranjan Kumar et al. (2011) for the Northern Hemisphere winter. Using ERA-Interim reanalyses data, the later has shown explicitly the ISO wave propagation directions between the tropical and subtropical regions of both the troposphere and stratosphere and concluded that the subtropical westerly jet (SWJ) plays a significant role in reflecting back the ISO to the tropical region at higher heights. The interesting question arises is that if the mid latitude stratospheric westerly jet (MStWJ) is weak in strength or disappeared in any of winters then what will happen to the vertical propagation of the tropical tropospheric long period ISO (LISO 40-80 day oscillation) to the stratosphere during these winters. Even though the answer is imminent that the possibility of observing significant ISO in the tropical

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stratosphere is difficult, it needs verification with observations and modeling by comparing the ISO activities in many successive years. Along with that the issue of why the MStWJ to get disrupted in some winters also needs to be addressed. One possible influence to be noted here is the phase of the tropical stratospheric quasi biennial oscillation (Holton and Tan, 1980). From the analyses of four years (2009-2012) of daily temperature measured by six GPS RO satellites (SAC-C, METOP-A and COSMIC/FORMOSAT-3, CNOFS, GRACE and TerraSAR-X) in the heights of 6-40 km over the Indian tropical station of Gadanki, and the ERA-interim reanalyses zonal wind data, the present study shows that during the easterly phase of tropical stratospheric QBO the MStWJ at 10 hPa level (30 km height) got disrupted during the winter-summer (January-May) of 2011. During this time it is noticed also the absence of the tropical stratospheric LISO while it is there in all the other years 2009, 2010 and 2012, indicating that the disruption of the MStWJ led to the refraction of the tropical LISO to the higher latitudes and hence the absence of it in the tropical stratosphere in 2011. The height profiles of significant amplitude and phase of the ISO indicate a clear downward propagation in the tropical stratosphere in these months of January-May of all the years 2009-2012 except for insignificant amplitude in 2011. This would indicate that the ISO propagates upward as waves in the winter stratosphere. Identifying the direct link of tropical stratosphericISO with that in the Mesosphere and Lower Thermosphere (MLT) regionis the future scope of the present work. The scope also includes how the MStWJ controls only the long period ISO (40-80 day oscillation) but not the small period ISO (20-40 day oscillation) in refracting it back to the equatorial region stratosphere thus causing LISO variations in the MLT region.

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Figure captions

Fig. 1. Day (1 January 2009 to 31 December 2012) vs. period (days) Morlet wavelet power spectrum of temperature determined with six GPS RO satellites (SAC-C, METOP-A and COSMIC/FORMOSAT-3, CNOFS, GRACE and TerraSAR-X) in the heights of 6-17 km over the Indian tropical station of Gadanki region (13.5N, 79.2E)

Fig. 2. Same as Fig. 1 but for the heights of 18-27 km

Fig. 3. Same as Fig. 2 but for the heights of 28-40 km

Fig. 4 Time (days from 01 January 2009 to 31 December 2012) vs. height (1-32 km) contour plots of filtered (40-80 days band pass) long period intraseasonal oscillation (LISO) in the ERA-interim (a) temperature (Fig. 4a, top panel) and (b) zonal wind velocity at 13°N and 18°E.

Fig. 5. Same as Fig. 4 but for the 21-40 day oscillation

Fig. 6. Same as Fig. 4 but for the 11-20 day oscillation

Fig.7. Time (days from 01 January 2009 to 31 December 2012) vs. latitude (0-30°N) contour plots of 40-80 day oscillation in the ERA-interim temperature at the heights of 17, 19, 21, 23 and 25 km (left panel) and 27, 28, 29, 30 and 32 km (right panel)

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Fig. 8. Same as Fig. 7 but for the zonal wind velocity

Fig. 9. Same as Fig. 7 but for the 21-40 days band

Fig. 10. Contour plots of six hourly ERA-Interim reanalyses zonal wind velocity at the height of 10 hPa level (30 km) for the period of 01 January to 31 May during four years (2009-2012) for the latitudes of 0N-90N near the longitude of 80E

Fig. 11. Same as Fig. 10 but for the height of 70 hPa level (19 km)

Fig. 12. Height profiles of least sum of square errors determined amplitude (left column), phase (mid column) and period of oscillation (right column) of three bands of oscillations (1) 10-20 day oscillation, (2) 21-40 day oscillation and (3) 41-80 day oscillation in temperature determined by six GPS RO satellites as well as the ERA-Interim reanalyses in the year 2009 for the three ranges of months (1) January-May (top row), (2) June-August (mid row) and (3) September to December (bottom row)

Fig. 13. Same as Fig. 12 but for the year 2010

Fig. 14. Same as Fig. 13 but for the year 2011

Fig. 15. Same as Fig. 14 but for the year 2012.

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Figures 1-15 follows successively in the following pages

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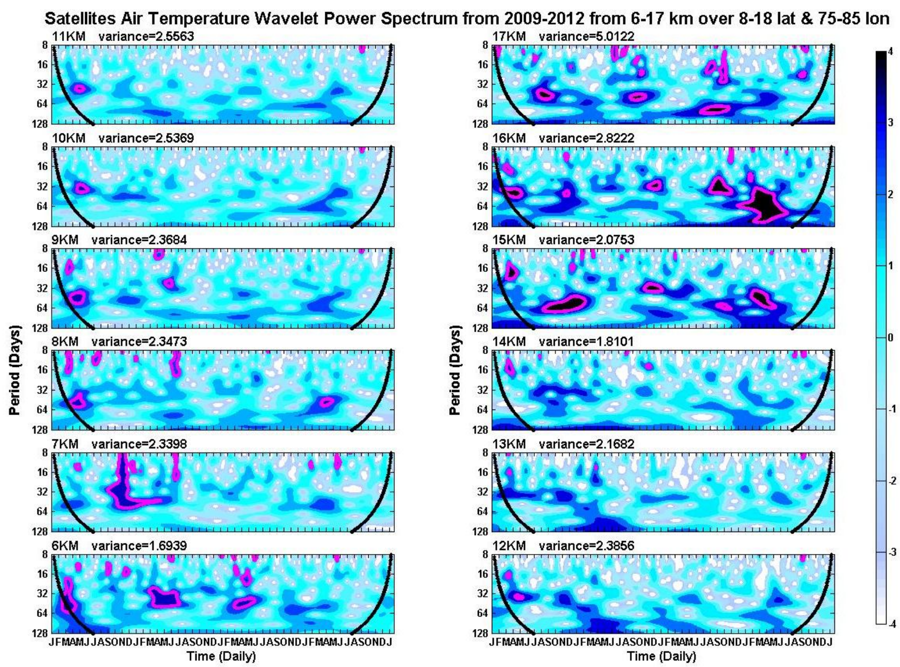

Fig. 1. Day (1 January 2009 to 31 December 2012) vs. period (days) Morlet wavelet power spectrum of temperature determined with six GPS RO satellites (SAC-C, METOP-A and COSMIC/FORMOSAT-3, CNOFS, GRACE and TerraSAR-X) in the heights of 6-17 km over the Indian tropical station of Gadanki region (13.5N, 79.2E)

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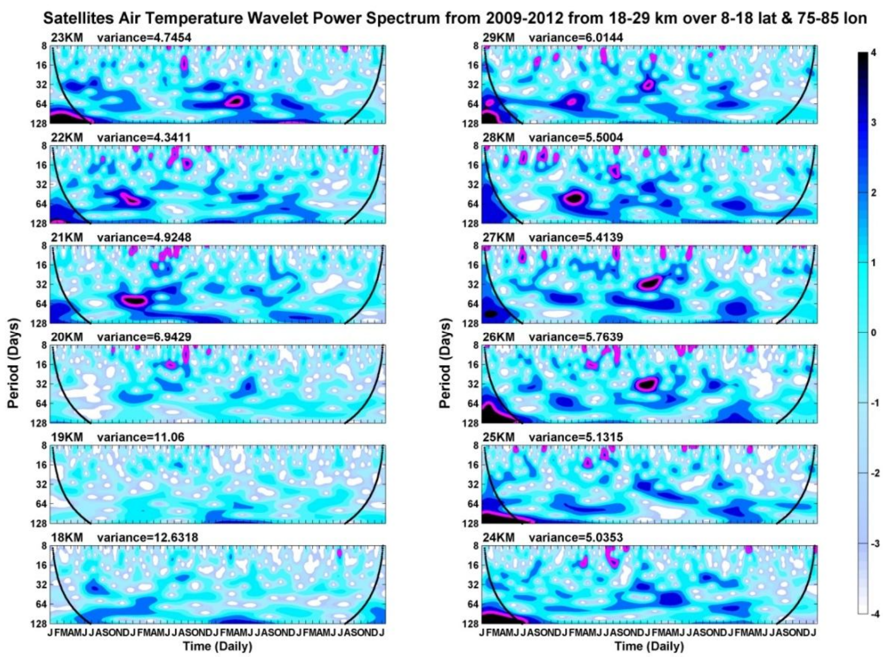

Fig. 2. Same as Fig. 1 but for the heights of 18-27 km

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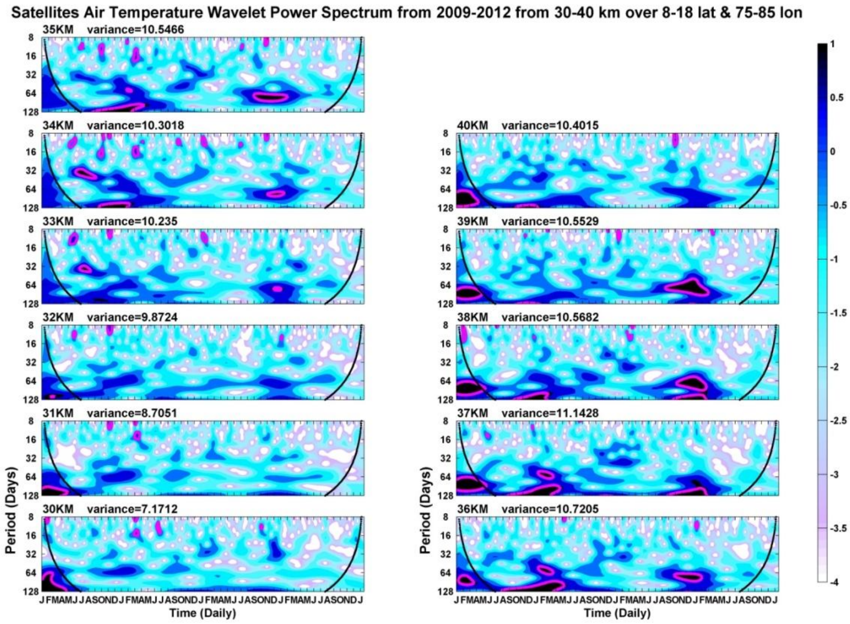

Fig. 3. Same as Fig. 2 but for the heights of 28-40 km

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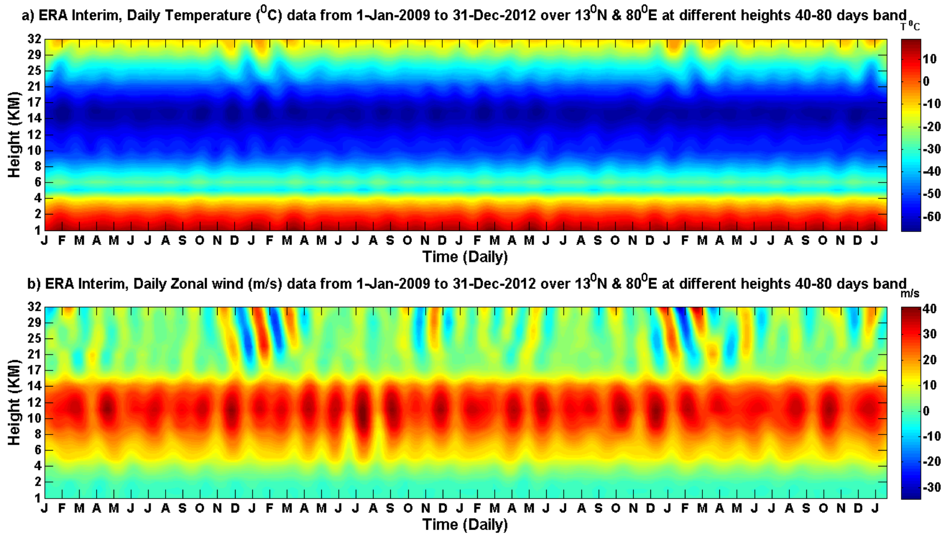

Fig. 4 Time (days from 01 January 2009 to 31 December 2012) vs. height (1-32 km) contour plots of filtered (40-80 days band pass) long period intraseasonal oscillation (LISO) in the ERA-interim (a) temperature (Fig. 4a, top panel) and (b) zonal wind velocity at 13°N and 18°E.

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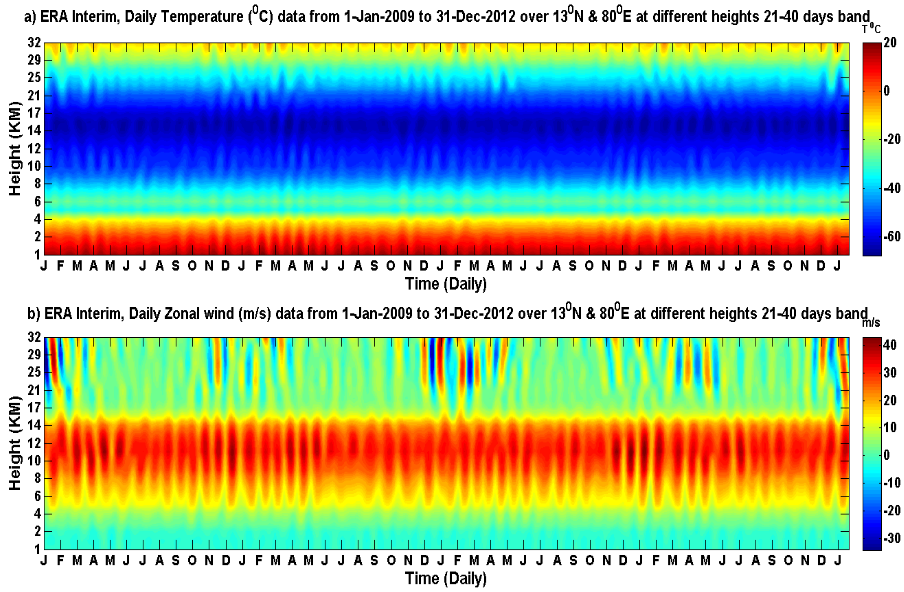

Fig. 5. Same as Fig. 4 but for the 21-40 day oscillation

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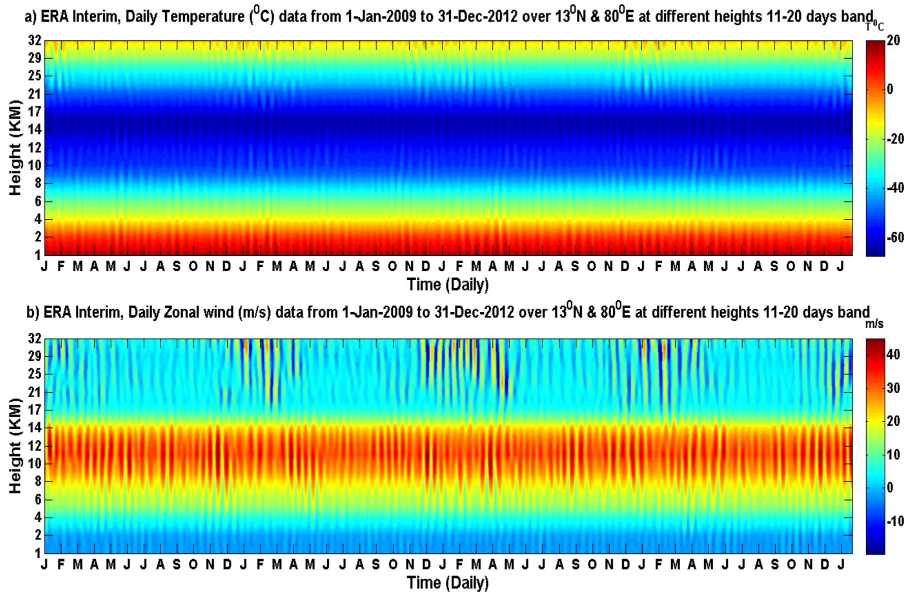

Fig. 6. Same as Fig. 4 but for the 11-20 day oscillation

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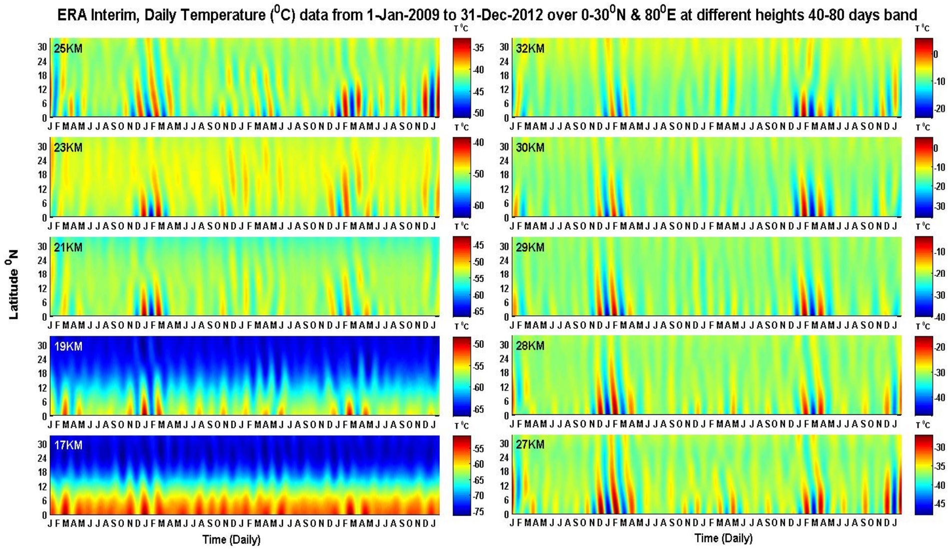

Fig.7. Time (days from 01 January 2009 to 31 December 2012) vs. latitude (0-30°N) contour plots of 40-80 day oscillation in the ERA-interim temperature at the heights of 17, 19, 21, 23 and 25 km (left panel) and 27, 28, 29, 30 and 32 km (right panel)

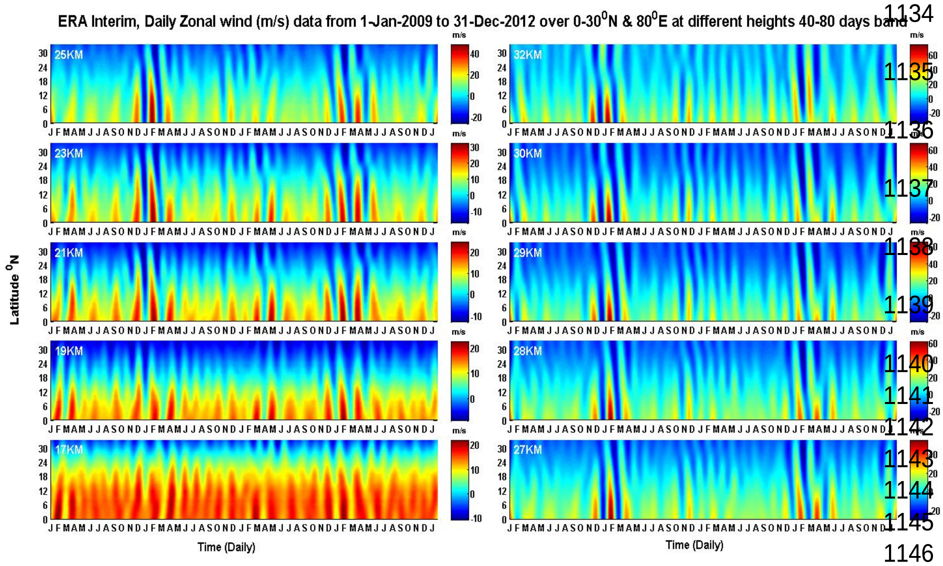

Fig. 8. Same as Fig. 7 but for the zonal wind velocity

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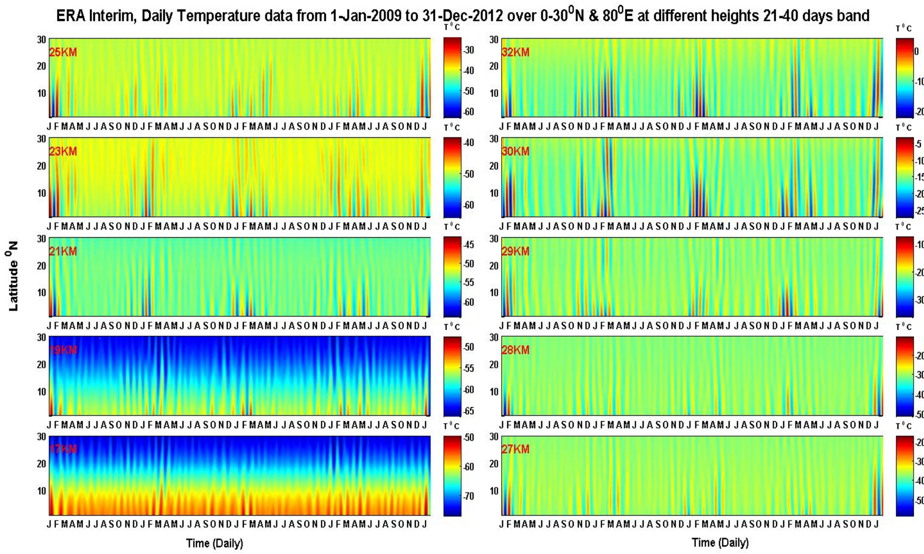

Fig. 9. Same as Fig. 7 but for the 21-40 days band

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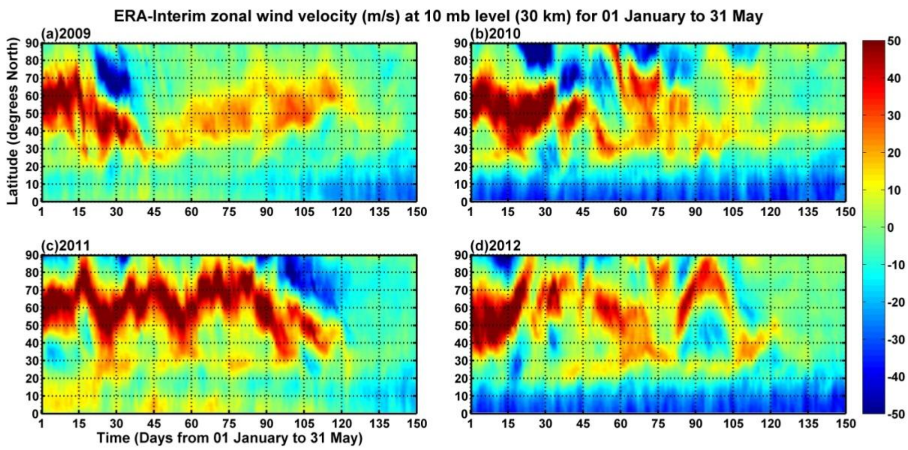

Fig. 10. Contour plots of six hourly ERA-Interim reanalyses zonal wind velocity at the height of 10 hPa level (30 km) for the period of 01 January to 31 May during four years (2009-2012) for the latitudes of 0N-90N near the longitude of 80E

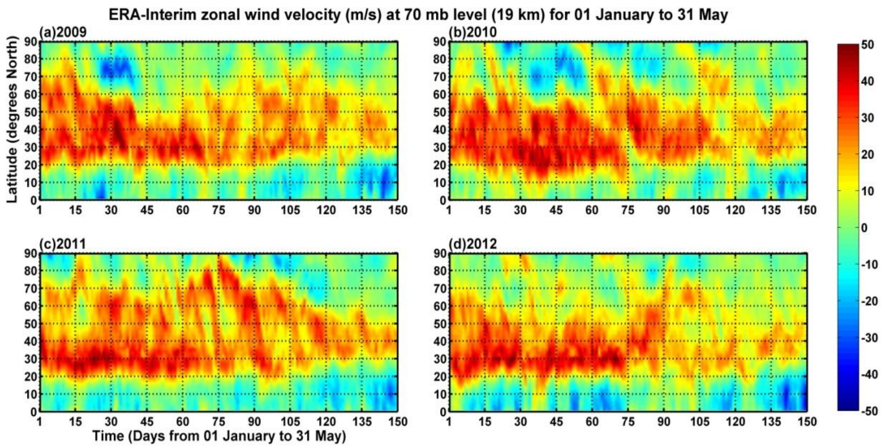

Fig. 11. Same as Fig. 10 but for the height of 70 hPa level (19 km)

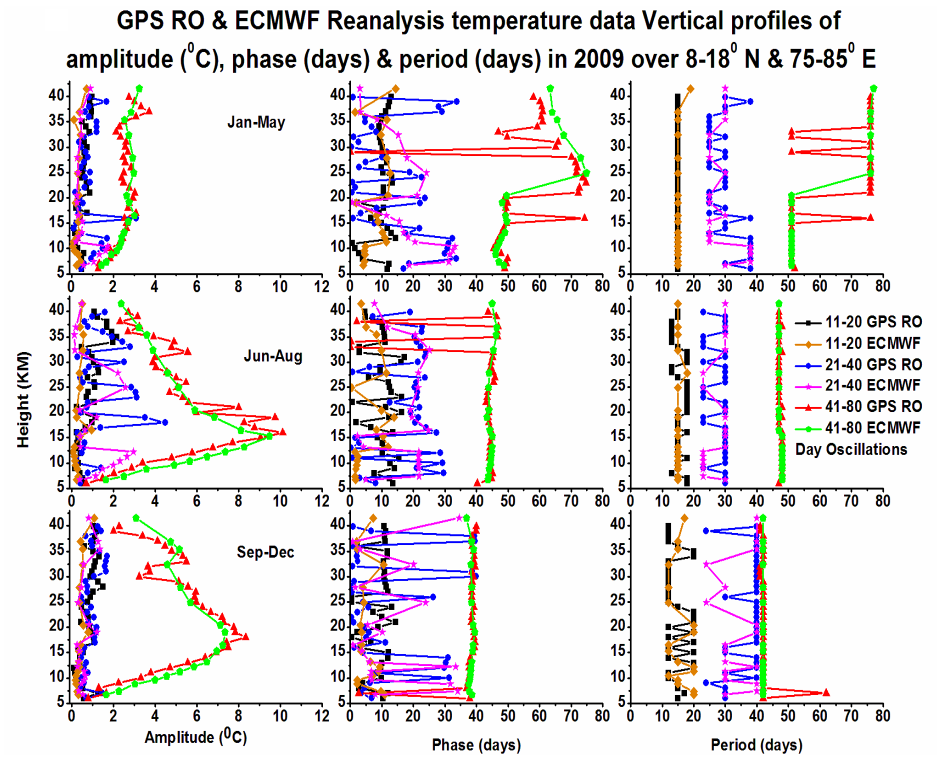

Fig. 12. Height profiles of least sum of square errors determined amplitude (left column), phase (mid column) and period of oscillation (right column) of three bands of oscillations (1) 10-20 day oscillation, (2) 21-40 day oscillation and (3) 41-80 day oscillation in temperature determined by six GPS RO satellites as well as the ERA-Interim reanalyses in the year 2009 for the three ranges of months (1) January-May (top row), (2) June-August (mid row) and (3) September to December (bottom row)

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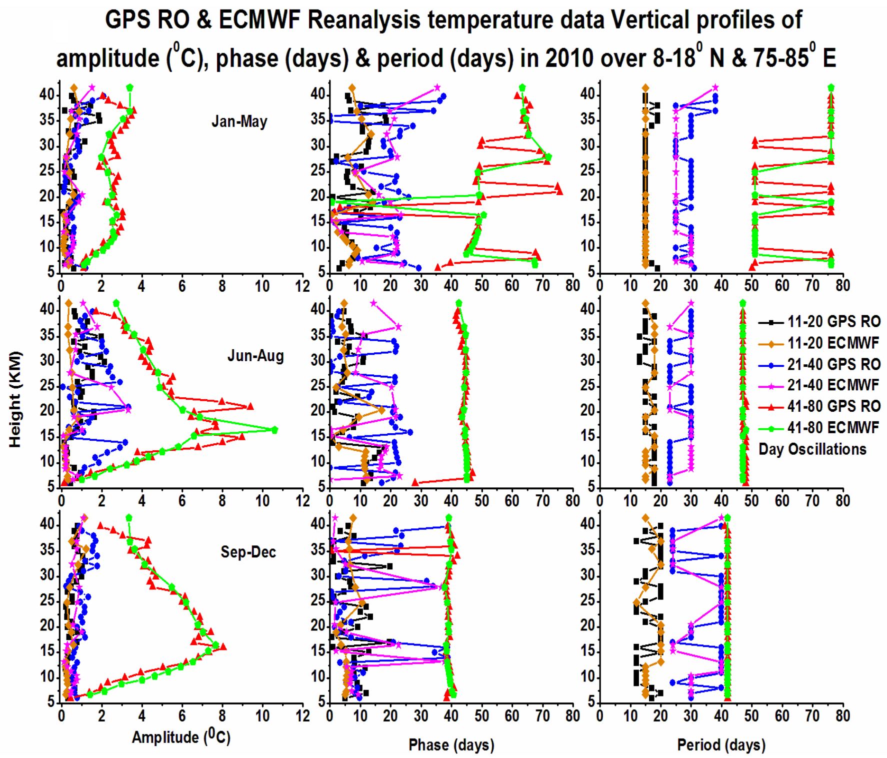

Fig. 13. Same as Fig. 12 but for the year 2010

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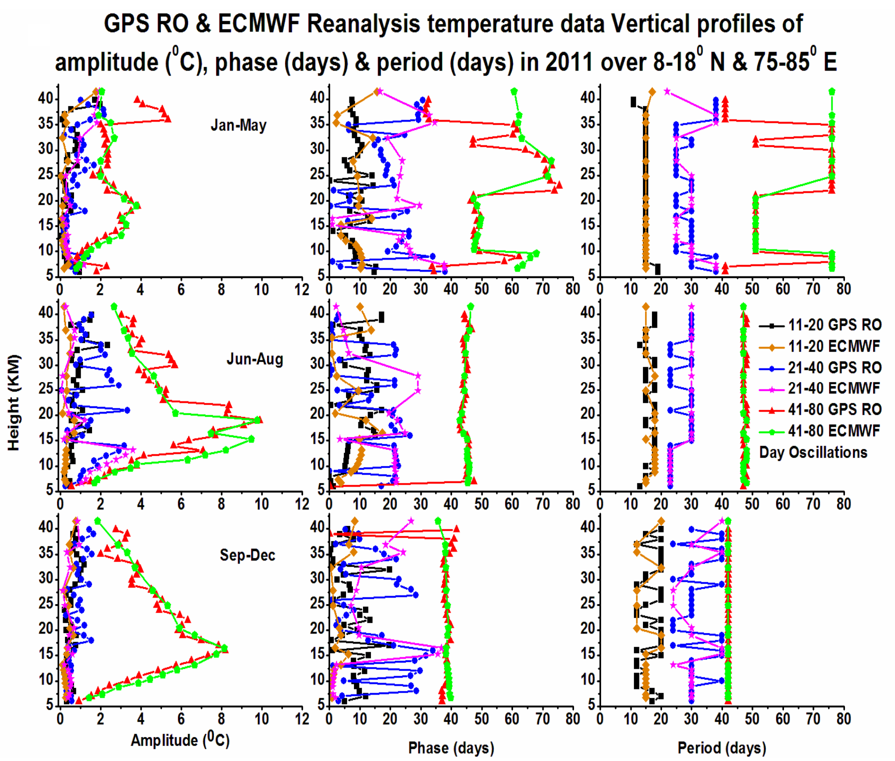

Fig. 14. Same as Fig. 13 but for the year 2011

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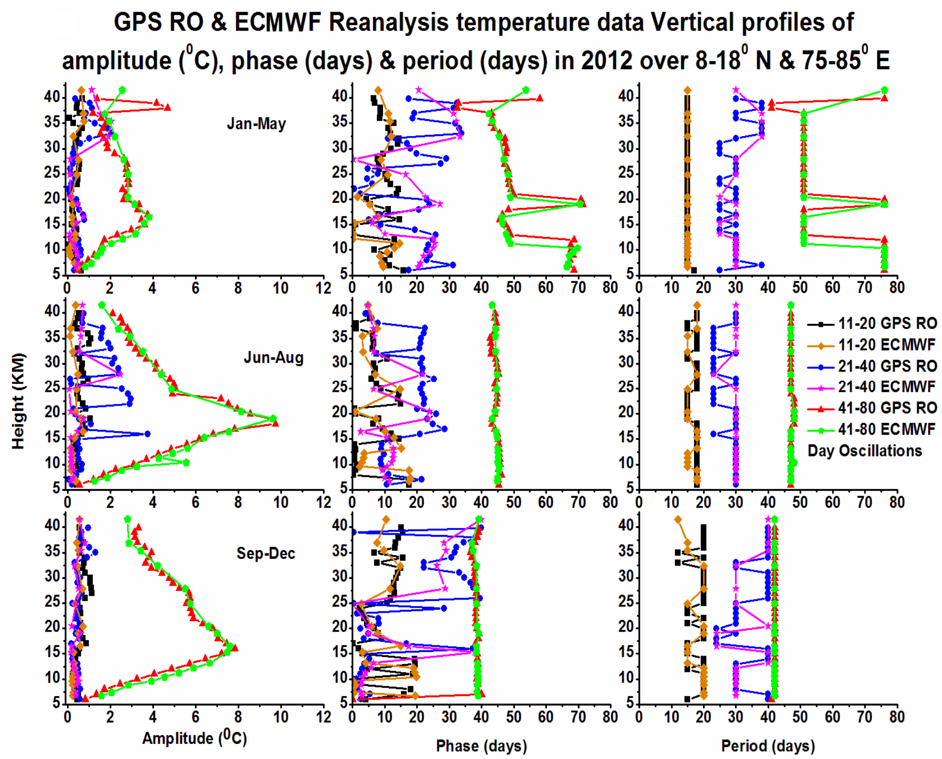

Fig. 15. Same as Fig. 14 but for the year 2012