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Characteristics of the Quasi-16 Day Wave in the Mesosphere and Lower Thermosphere (MLT): A Review Over an Equatorial Station Thumba (8.5°N, 76.5°E)

Siddarth Shankar Das
Space Physics Laboratory, Vikram Sarabhai Space Centre ISRO-PO, Trivandrum India

1. Introduction

To understand the climate variability and weather prediction in the Earth's atmosphere, measurements of winds, temperature and wave activities are very crucial. The Earth's atmosphere is believed to act as a source and sink for the waves of a broader spectrum with periods from few seconds to years. Generally, the Earth's atmosphere is stably stratified except the planetary boundary layer and thus makes a reasonable assumption for the presence of atmospheric waves. A barotropic atmosphere in a resting basic state is able to support these spectra of waves. These waves move diagonally upward or downward and horizontally. The mean zonal circulation is mainly driven by these atmospheric waves, which are believed to be generated in the troposphere and propagates horizontally and vertically in to the middle and upper atmosphere. These waves transport energy and momentum from one region to another without the transport of material medium thereby impinging the signature of the source region on to the sink region. The waves propagating in Earth's atmosphere are expected to be both anisotropic and dispersive. The anisotropic characteristics of these waves mean that the properties of the waves are not uniform in all the directions. The propagating waves can be characterized by the amplitude and phase, which depends on time and space. When the wave frequency (ω) is depends on the wavelength ($2\pi/k$) then the wave is dispersive. For such waves the group velocity is different from the phase velocity. A better understanding of the vertical coupling by these wave activities will provide a deeper insight into the processes that control the dynamics and energetics of the whole atmosphere.

The atmospheric waves can be classified on the basis of (i) extra tropical modes against equatorially trapped modes, (ii) free mode and forced modes, (iii) external mode and internal modes and (iv) modes that interact with the mean flow through wave dissipation. In middle atmosphere, internal force mode is important due to its generation in the mid-troposphere and propagates vertically into the middle atmosphere. These waves carry forward the information over thousands of kilometer horizontally and tens of kilometers vertically. The three major oscillations in existing in the middle atmosphere (~10-100 km) are gravity waves, atmospheric tides and planetary waves, distinguished mainly by wave periodicity (*Holton*, 1975; *Andrew et al.*,1987). Gravity waves are oscillation with a period between minutes to hours, whose

restoring force is buoyancy; tidal waves are daily oscillations with larger horizontal structures and are excited through direct absorption of sunlight by water vapour in the troposphere and ozone in the stratosphere; planetary waves are disturbances having zonal wavelengths of global scale, often maintained by internal dynamics.

Among these waves and oscillations, the planetary waves play an important role in the dynamics of the mesosphere and lower thermosphere (MLT) region. The quasi 16 day wave is a planetary wave which has period of 16 ± 4 days with westward propagating phase and zonal wave number = 1. This is a global-scale phenomenon of tropospheric origin, and is frequently observed in the MLT region. These oscillations become quite important in the equatorial latitudes as they exhibit unique propagation characteristics (*Salby*, 1984). The characteristics of these planetary scale waves are significantly modified by the energetics and dynamical state prevailing in the MLT region through which they propagate.

The quasi-16 day wave was first reported by *Kingsley et al.* (1978) using meteor wind radar and by now, there are ample of observational evidences of quasi 16 day wave in winds at MLT region using space-borne, ground-based, and in-situ measurements (*Forbes et al.,* 1995; *Espy and Witt*, 1996; *Mitchell et al*., 1999; *Espy et al*., 1997; *Luo et al*., 2002; *Manson et al.,* 2003; *Pant et al.,* 2004; *Jiang et al*., 2005; *Lima et al.,* 2006; *Jacobi et al.,* 2007; *Vineeth et al*., 2007a and 2011; *Das et al*., 2010). There are two proposed mechanisms for the existence of the quasi-16 day wave in the MLT region: (1) a 16 day wave is generated in the winter hemisphere, ducted in the vicinity of equator and then propagates vertically toward the summer pole by following the westerly mean winds, and (2) a 16 day wave is generated by the oscillatory deposition of energy and momentum into the summer mesosphere due to gravity wave breaking, which propagates upward after modulation by a 16 day wave in the summer troposphere and lower stratosphere (*Lima et al*., 2006).

Investigations of quasi 16 day wave are also been carried out on the seasonal characteristics (*Mitchell et al.,* 1999; *Pancheva et al.,* 2004; *Lima et al.,* 2006; *Das et al*., 2010). *Jacobi et al*. (2007) have established the phase relation between wind and temperature of quasi 16 day wave in MLT region over mid-latitude. Simultaneous observation of these planetary waves at two different locations is also reported by *Luo et al*. (2002) and the authors have established a phase relation between them using medium frequency (MF) radar. *Manson et al*. (2003) have shown the modulation of gravity waves by planetary waves of 2 and 16 day periodicity using MF radar network over North American Pacific region. *Luo et al.* (2001) have suggested that the solar activity can also modulate the existing planetary waves or even trigger wave like perturbations through changing radiation fluxes in the MLT region. Earlier studies have shown that these planetary scale waves can have global scale structure in the mesopause region (e.g. *Miyoshi*, 1999). Over equatorial station Thumba (8.5^{o}N, 76.5^{o}E), *Reddi and Ramkumar* (1995) and *Das* et al. (2010) have shown the presence of quasi 16 day wave in mesospheric winds and temperature. *Pant et al.* (2004) have shown the evidence of direct solar control of these planetary waves in mesospheric temperature using multi-wavelength day glow photometer and MF radar. *Vineeth et al.* (2007a and 2011) have shown that quasi 16 day wave in mesopause temperature and equatorial electrojet. However, most of the previous studies have investigated the seasonal variations of 16 day planetary wave and their characteristics in winds over mid-latitude MLT region and very few studies are carried out over lower latitudes, especially using mesospheric temperature and wind simultaneously. Moreover, the propagation characteristics of these planetary waves above 80 km are not well understood.

The present study discusses on overall characteristics of the quasi-16 day wave in the MLT region over an Equatorial station Thumba (8.5°N, 76.5°E). Figure 1 shows the geographical location of Thumba. It is envisaged that the present results will contribute to our understanding of the dynamics of the MLT region over low latitudes.

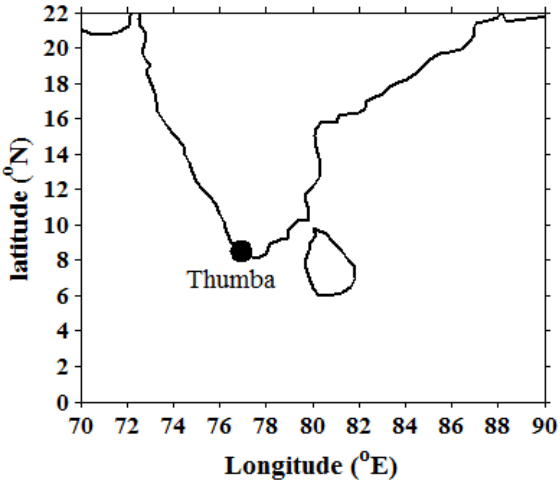

Fig. 1. Map showing the geographical location of the Thumba (8.5°N, 76.5°E), where SKiYMET meteor wind radar is installed.

2. Methodology

The All sky Interferometric meteor wind radar installed at Thumba, commercially named as SKiYMET, operates at 35.25 MHz with a peak power of 40 kW and duty cycle upto 15% to derive the three-dimensional winds and temperature at MLT region (82-98 km), which provides a unique opportunity to study the dynamics of the middle atmosphere. The system has a multi-channel coherent receiver utilizing a meteor detection algorithm to acquire, detect, analyze and display the entrance of meteors. The inbuilt software is used to perform the various calculations in real-time on the detected meteors (*Hocking et al.*, 2001). The winds are derived by observing how the meteor trails drift with time, and the decay time of meteor trails are used to determine the absolute temperature in the height region of 86-90 km (*Das et al.*, 2011). Details of wind derivation can be found in *Hocking et al.* (2001) and the temperature derivation can be found in *Hocking* (1999) and *Das et al.* (2011). The Thumba meteor radar has been operational since June 2004 and still in operational. The data collected from the meteor radar is for ~ 7 years. Figure 2 shows the panoramic view of transmitter/receiver antenna system and in-house transmitter/ receiver system of the radar at Thumba. The specification of Thumba SKiYMET meteor wind radar is given in Table 1.

In principle, hourly mean zonal and meridional winds data can be obtained but for the present study the data used are daily mean at 6-height levels, *viz.*, 82, 85, 88, 91, 94, and 98 km. The wind data derived from SKiYMET radar were well comparable with the MF radar at Tirunelveli (8.7°N, 77.8°E) (*Kumar et al.* 2007a). Daily mean temperature in the height

Parameters	Specification
Frequency	35.25 MHz
Peak power	40 kw (solid state)
Duty cycle	Upto 15 %
Pulse width	13.3 µs
Pulse repetition frequency	2144 Hz
Band width	~ 1.5 MHz
Dynamics range	62-122 dB
Transmitter	4-circular polarized 3-elements Yagi (Cross-elements)
Receiver	5-circular polarized 2-elements Yagi (Cross-elements)

Table 1. Experimental mode of Thumba SKiYMET meteor wind radar.

Fig. 2. Panoramic view of transmitter/receiver antenna system (top panel) and in-house transmitter/receiver system of SKiYMET meteor wind radar at Thumba.

region of 86-90 km, derived from Thumba SKiYMET (*Hocking* 1999; *Das et al*., 2011) radar is fairly comparable with the space borne measurement by Sounding the Atmosphere using Broadband Emission Radiometry (SABER) instrument on board the TIMED satellite and day-glow multi-wavelength photometer in the height range of 86-90 km (*Vineeth et al.,* 2007b; *Kumar* 2007b, *Das et al*., 2011 and reference therein).In the present study, data gaps in both winds and temperature were interpolated with a spline interpolation method. The observed data gaps are very few and they are not affecting the time-series.

3. Results and discussion

- *Seasonal property*

Mesosphere and Lower Thermosphere (MLT) winds were measured over the equatorial station Thumba using SKiYMET meteor wind radar during the period of June 2004 to September 2011, while SKiYMET meteor radar is still in operation. Figure 3 shows height-time intensity plot of monthly mean zonal and meridional winds at MLT region from June 2004 to September 2011. Most of the time eastward propagating winds were observed in the month of November to January and May to July. However, a weak eastward propagating wind is observed during November 2007 to January 2008. Similarly, northward propagating winds were observed during November to January. It is interesting to note that the eastward propagating wind shows semi-annual cycle (SAC), whereas the northward propagating wind shows only annual cycle (AC). Figure 4 shows the time series plot of mesospheric temperature at 88±2 km derived from SKiYMET meteor wind radar. The variability of mesospheric temperature is between 185 and 225 K. Both AC and SAC are observed in the time series of temperature (please referee Fig.8 of *Das et al*., (2011) for amplitude spectrum of temperature).

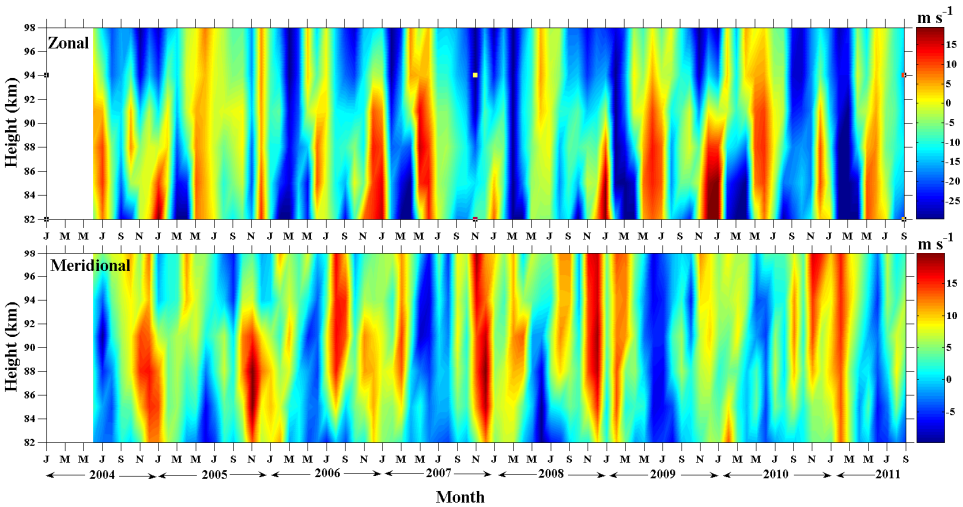

Fig. 3. Height-time intensity plot of monthly mean zonal (top panel) and meridional (bottom panel) winds at Mesosphere and Lower Thermosphere (MLT) region from Jun.-2004 to Sep.-2011.

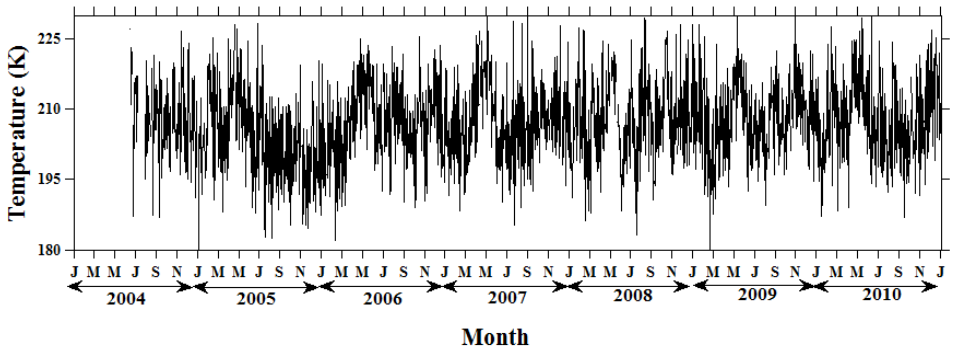

Fig. 4. Daily mean mesospheric temperature between 88±2 km from Jun.2004 to Dec. 2010.

The time-series of both the daily mean winds and temperature, discussed above, were further analyzed to examine for the existence of planetary wave with a period of quasi 16 day. In this context, the perturbation of winds and temperature were obtained by removing annual mean from the time series of each year. The perturbation time series of winds and temperature is then subjected to Fast Fourier Transform (FFT) to explore the prominent periodicities. Figure 5 and 6 show the amplitude spectra of zonal and meridional winds at 88 km for the year 2005-2010. It is interesting to note that all the 6 years have dominant period of quasi 16 day (12-20 day) in both the wind components. However, the amplitude of this oscillation varies from year

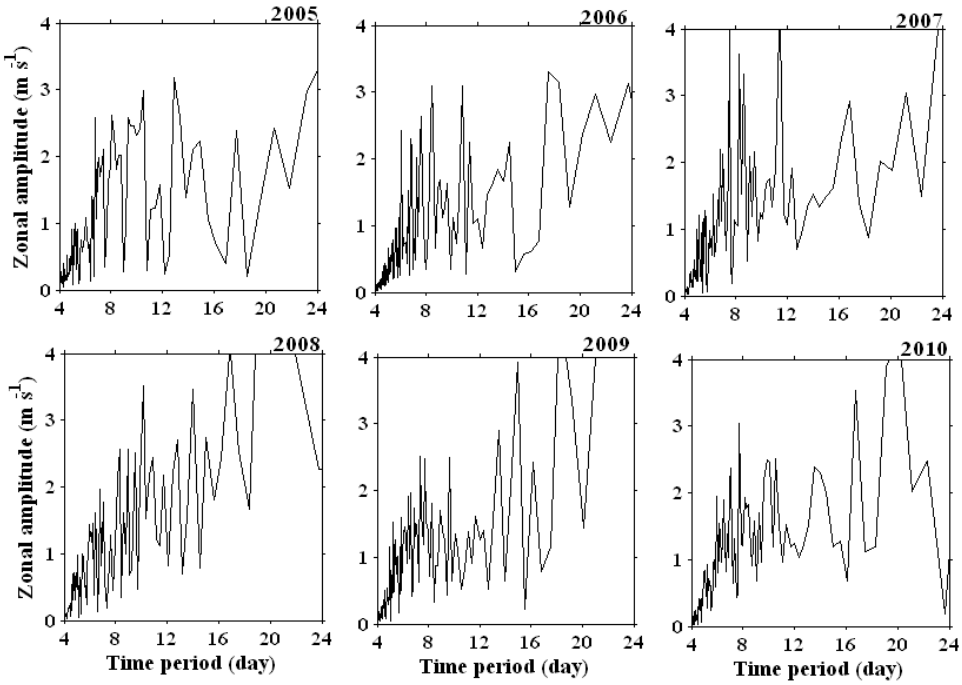

Fig. 5. Amplitude spectra of daily mean zonal wind at 88 km for the year 2005-2010.

to year with small variation in the dominant periodicities. The amplitude of both the zonal and meridional winds is found to be 3-4 m s $^{-1}$. Maximum amplitude of zonal wind is found to be 4 m s $^{-1}$ for 2007 and 2008, whereas for meridional wind it is found be in 4 m s $^{-1}$ for 2007 only. Figure 7 shows the amplitude spectra of mesospheric temperature at 88±2 km for the year 2005-2010.The amplitude of temperature is found to be ~1-1.5 K. Maximum amplitude of temperature is found to be ~2 K for the year 2007. Thus, the above observations clearly reveal the presence of quasi 16 day wave in the MLT region over the equatorial station Thumba. In the year 2007, both the winds and temperature shows maximum amplitude of quasi 16 day, indicating the presence of strong planetary wave activity.

In order to study the seasonal characteristics of quasi 16 day wave, we have extracted the amplitude of zonal and meridional wind averaged between 12 and 20 day at different heights using wavelet analysis. Figure 8 shows the height-time amplitude plot of quasi 16 day wave in zonal and meridional winds from 2004-2010. These plots do not show any seasonal dependence of the planetary wave of the order quasi 16 day in both the wind components. However, maximum amplitudes were observed in the month of January to February. It is also noted that the zonal component is larger in amplitude than the meridional component. Earlier observations have shown that these planetary scale wave exhibits year-to-year variability but do not show any seasonal behavior (e.g. *Namboothri et al*. 2002; *Lima et al*., 2006). However, these authors have shown that stronger wave activities occur during January-February and this is attributed to vertical propagation from lower atmosphere. The present analysis also shows the enhanced wave activity during January-February.

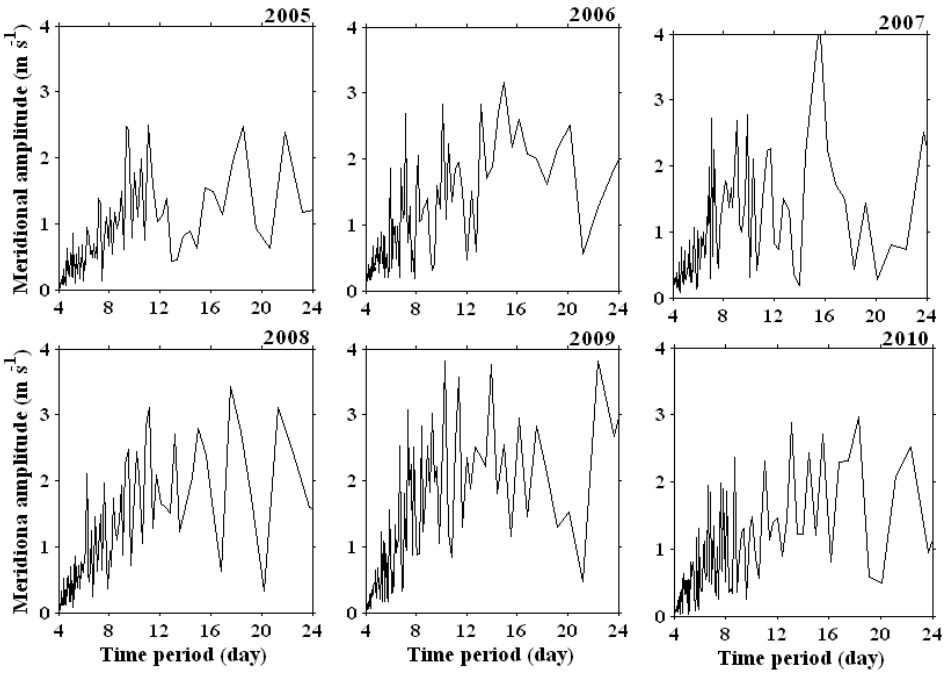

Fig. 6. Same as Fig.3, but for meridional wind at 88 km.

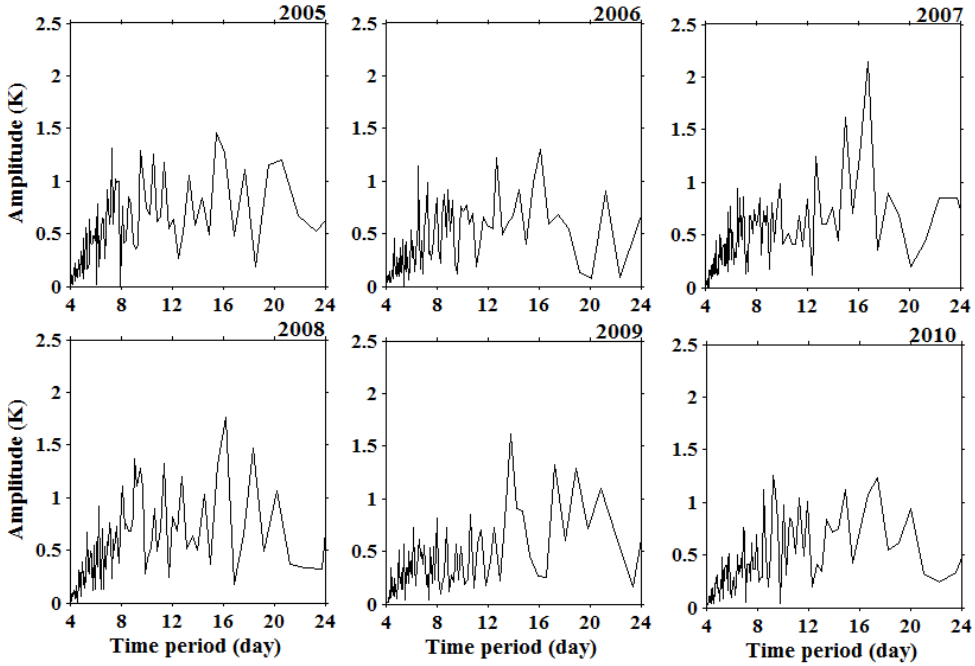

Fig. 7. Same as Fig.3 but for mesospheric temperature at 88±2 km for the year 2005-2010.

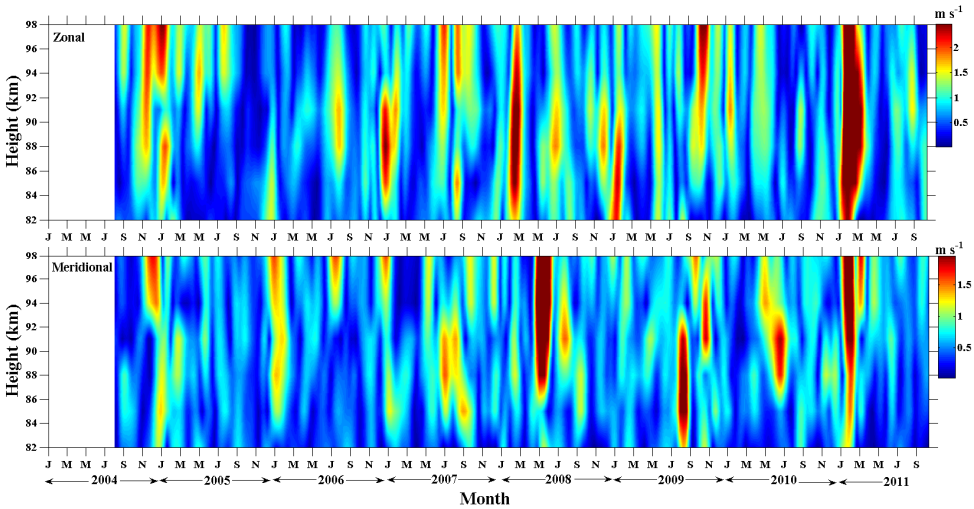

Fig. 8. Amplitude of quasi 16 day oscillation in zonal (top panel) and meridional (bottom panel) winds from 2004-2010.

In addition to winds, amplitude is also been extracted for temperature measurements. In the present analysis, we have used a band-pass Butterworth filter of 12-20 day to extract

the temperature amplitude. Figure 9 shows the filtered (12-20 day) time series plot of temperature at 88±2 km over Thumba. This plot clearly shows the seasonal dependence of quasi 16 day wave amplitude. It is remarkable to note that the quasi 16 day wave in temperature is modulated by SAO. The maximum peak of SAO in 16 day wave activity is observed between January-March and August-September with amplitudes around ±5 K. The presence of summer wave activity is due to the inter-hemispheric ducting of quasi 16 day wave or by the in-situ generation through gravity wave, which is dissipated in summer hemisphere. Since quasi 16 day wave is westward propagating (e.g. *Das et al.*, 2010 and reference therein), eastward phase of zonal wind is favorable for its propagation in the MLT region. It is also clear that the intensity of quasi 16 day amplitude in temperature is stronger when the background wind exhibit eastward phase. As discussed above that the eastward phase of background wind is favourable for westward propagating waves (in the present case 16 day oscillation). However, for some years, phase delay of few months is also observed. The phase delay is generally found to be 1-2 months between temperature and background winds. In earlier studies, it is found that these planetary scale waves are sensitive to background winds and also to quasi-biennial oscillation (QBO) (e.g. *Luo et al.*, 2000 and *Espy et al.,* 1997). This can further effectively moves the zero wind line closer to the summer hemisphere during the eastward phase of QBO. Thus, the widening or narrowing equatorial duct due to QBO can modulate the normal mode structure and possible forcing source linking to the phase delay of 1-2 months between temperature and background wind in our present observations.

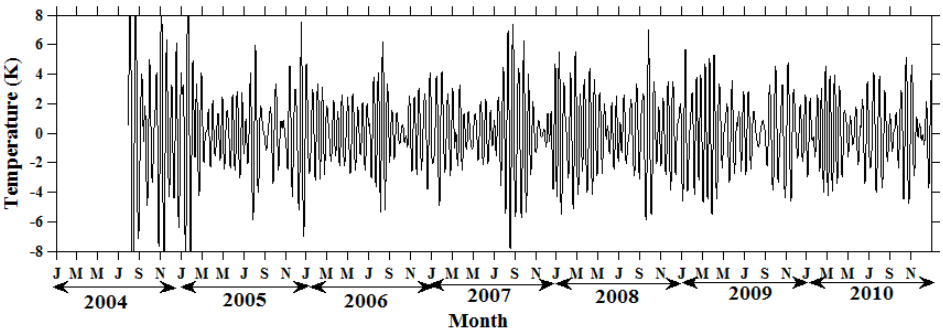

Fig. 9. Filtered (12-20 day) mesospheric temperature from 2004-2010.

Vineeth et al. (2007a) have shown the presence of quasi 16 day wave in mesospheric temperature measured from day glow multi-wavelength photometer and the electrojet-induced surface magnetic field over the same equatorial region Thumba. The day glow multi-wavelength photometer measurements are weighted average in 80-98 km height region. The important findings of these authors were (i) amplification of the quasi 16 day wave in the equatorial mesopause temperature and the equatorial electrojet (EEJ) induced magnetic field, and (ii) occurrence of counter electrojet (CEJ) with periodicity of quasi 16 day, which further decreases its strength with decrease of amplitude of these wave oscillation. It is explained that the occurrence of consecutive CEJ events of quasi 16 day is due to the interaction of intensified planetary wave with the prevailing tidal winds. *Vineeth et al*. (2011) have studied the role of quasi 16 day wave in controlling day-to-day variability

of EEJ in association with the planetary wave-tidal interaction in the MLT region and found it is more during the winter month. The present observation also shows that the enhancement of quasi 16 day wave in both winds and temperature during winter months.

- *Interannual property*

Espy et al. (1997) have shown the inter-annual variation of quasi 16 day wave oscillation in the polar summer mesospheric temperature and found the amplitude as high as ~5 K. The quasi 16 day wave observed over the equatorial station Thumba is in good agreement with the observations at other latitudes. The modulation of 16 day wave by SAO was first reported by *Das et al.* (2010) over this latitude (Thumba). The authors have also extracted the phase and amplitude for both the wind components during the intense burst of quasi 16 day. The maximum amplitude is found at 88-92 km and the vertical wavelength is found to be 30-50 km. However, most of the phase profiles shows constant phase with height which also indicates the presence of longer vertical wavelength. *Das et al.* (2010) have also established for the first time the phase relationship between winds and temperature of quasi 16 day wave during the intense events over the equatorial station Thumba. The intense events mean the period when the amplitude of quasi 16 day is maximum. The intese event corresponding to quasi 16 day is between January-February. It is found that the zonal and meridional winds are in phase, whereas temperature leads zonal wind by 5 ±1 days. The present observation over this latitude brought out the seasonal characteristics and the effect of background wind on quasi 16 day wave in the MLT region. However, the exact mechanism for the enhanced quasi 16 day wave activity over Thumba is yet to be explored, which require the observational data from the other locations simultaneously and will be our focus in the near future.

4. Summary

Simultaneous observational evidence of planetary scale wave with a periodicity of quasi 16 day wave in winds and temperature at Mesosphere and Lower Thermosphere (MLT) region are reported in the equatorial station Thumba (8.5^{o}N, 76.5^{o}E) using SKiYMET meteor wind radar. The mesospheric temperature shows a seasonal characteristic and follows semi-annual oscillation (SAO) with peak during January-March and August-September. Unlike mesospheric temperature, both the wind components, i.e. zonal and meridional winds do not exhibit any clear seasonal characteristics. During the eastward phase of background wind in MLT region, the intensity of quasi 16 day wave in mesospheric temperature is stronger. It is also noticed that a phase delay of 1-2 months is observed between the maximum events of such planetary wave activities and peak eastward phase of background wind. The maximum amplitude is found to be 88-92 km and most of the time with constant phase with height. The vertical wavelength is estimated to be 30-50 km. It is also found zonal and meridional winds are in phase, whereas the temperature leads zonal wind by 5±1 days.

As discussed in the introductory section, 16 day wave generated by heating due to moist convection in the troposphere and thus many of the planetary waves appearing in the MLT region are not in-situ excited but comes from the lower atmospheric source. These planetary scale waves propagate upwards from lower stratosphere to mesosphere under certain condition and while propagating, these waves interact and couple between various layers of the atmosphere through their generation, propagation and dissipation. Further, these waves affect

the global redistribution of momentum and energy and finally change the thermodynamics and even electrodynamics characteristics in these regions. Studies have also showed that the 16 day wave significantly contributes to the polar summer mesopause temperature.

5. Acknowledgement

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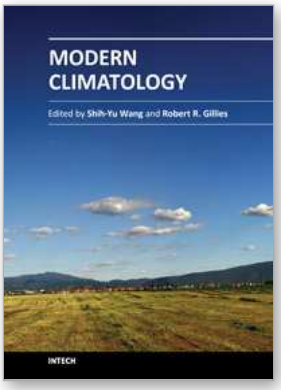

Modern Climatology

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Climatology, the study of climate, is no longer regarded as a single discipline that treats climate as something that fluctuates only within the unchanging boundaries described by historical statistics. The field has recognized that climate is something that changes continually under the influence of physical and biological forces and so, cannot be understood in isolation but rather, is one that includes diverse scientific disciplines that play their role in understanding a highly complex coupled "whole system" that is the earth's climate. The modern era of climatology is echoed in this book. On the one hand it offers a broad synoptic perspective but also considers the regional standpoint, as it is this that affects what people need from climatology. Aspects on the topic of climate change - what is often considered a contradiction in terms - is also addressed. It is all too evident these days that what recent work in climatology has revealed carries profound implications for economic and social policy; it is with these in mind that the final chapters consider acumens as to the application of what has been learned to date.

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University Campus STeP Ri
Slavka Krautzeka 83/A
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Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
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InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821