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Long-term MST radar observations of vertical wave number spectra of gravity waves in the tropical troposphere over Gadanki (13.5° N, 79.2° E): comparison with model spectra

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Abstract. The potential utility of Mesosphere-Stratosphere-Troposphere (MST) radar measurements of zonal, meridional and vertical winds for divulging the gravity wave vertical wave number spectra is discussed. The data collected during the years 1995–2004 are used to obtain the mean vertical wave number spectra of gravity wave kinetic energy in the tropical troposphere over Gadanki (13.5° N, 79.2° E). First, the climatology of 3-dimensional wind components is developed using ten years of radar observations, for the first time, over this latitude. This climatology brought out the salient features of background tropospheric winds over Gadanki. Further, using the second order polynomial fit as background, the day-to-day wind anomalies are estimated. These wind anomalies in the 4–14 km height regions are used to estimate the profiles of zonal, meridional and vertical kinetic energy per unit mass, which are then used to estimate the height profile of total kinetic energy. Finally, the height profiles of total kinetic energy are subjected to Fourier analysis to obtain the monthly mean vertical wave number spectra of gravity wave kinetic energy. The monthly mean vertical wave number spectra are then compared with a saturation spectrum predicted by gravity wave saturation theory. A slope of 5/3 is used for the model gravity wave spectrum estimation. In general, the agreement is good during all the months. However, it is noticed that the model spectrum overestimates the PSD at lower vertical wave numbers and underestimates it at higher vertical wave numbers, which is consistently observed during all the months. The observed discrepancies are attributed to the differences in the slopes of theoretical and observed gravity wave spectra. The slopes of the observed vertical wave number spectra are estimated and compared with the model spectrum slope, which are in good agreement. The estimated slopes of the observed monthly vertical wave number spectra are in the range of −2 to −2.8. The significance of the present study lies in using the ten years of data to estimate the monthly mean vertical wave number spectra of gravity waves, which will find their application in representing the realistic gravity wave characteristics in atmospheric models.

Keywords. Meteorology and atmospheric dynamics (Climatology; Turbulence; Waves and tides)

1 Introduction

Studies of the atmospheric gravity waves are cynosures for many atmospheric researchers, as they play a major role in a variety of phenomena taking place right from the planetary boundary layer to the upper atmosphere. Hines (1960) was the first to propose a theory, interpreting the observed atmospheric fluctuations as manifestations of the upward propagating internal gravity waves. This theory has since been universally accepted and has provided a firm foundation for subsequent gravity wave studies. One of the important effects of the gravity waves in the atmosphere, a nonlinear cascade of energy to smaller-scale waves and the possible modulation of the middle atmosphere response due to the variable characteristics of propagating gravity waves, was also recognized

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by Hines (1960). Thus, gravity waves and their interactions with the mean flow of the atmosphere became a very important area of study in the atmospheric science community. By now, there is no need to emphasize the importance of these waves in altering the mean flow of the middle atmosphere. However, apart from affecting the mean flow, these waves play a major role in momentum and energy transport, in turbulence production, in triggering convection, and account for a significant portion of the spectrum of atmospheric motions and also make an important contribution to the shape of the thermal structure of the lower and middle atmosphere. Two decades back, it has been realized that Global Circulation Models should include gravity wave generation and dissipation in their models. Since then a considerable amount of effort is being focused towards the exploration of gravity waves. Most of these studies identified frontal systems, orography, jet streams and convective systems as major sources for the gravity waves. Still, all these numerical modeling and observational studies do not provide adequate information to parameterize the full spectrum of gravity waves and their sources. To date, the orography-generated waves have been treated extensively and waves generated by the frontal system and jet streams have also been understood to some extent. However, the convectively generated gravity waves, which are as important as orographic forcing, are yet to be explored. It is not possible to observe the wave field generated by the convective sources in sufficient detail in both space and time (Lane et al., 2001; Kumar, 2006, 2007). The convective systems are complicated and it is difficult to accurately observe their evolution and internal structures. At the same time, the convective dynamics is highly variable both in space and time. There are very few observational studies on convectively generated gravity waves; here we emphasis observational studies, as there exist considerable studies using numerical simulations and models. Since the convective phenomena is dominant in the tropical region, it is of considerable significance to study gravity wave activity over tropics.

There have been a number of observational studies on gravity waves in the past using a variety of techniques (Röttger, 1980; Vincent, 1984; Wilson et al., 1990a, b; Namboothiri et al., 1996; Nastrom et al., 1997; Nastrom and VanZandt, 2001). The important aspects of these studies include: propagation characteristics of gravity waves in the realistic atmosphere (Midgley and Liemohn, 1966; Hines and Reddy, 1967; Lindzen, 1970), wave-mean flow interactions (Booker and Bretherton, 1967; Lindzen, 1973; Dunkerton, 1980; McIntyre, 1980), generation of turbulence and enhanced diffusion (Weinstock, 1976; Lindzen, 1981) and wave saturation and its effects (Fritts, 1984; Fritts and Rastogi, 1985). In recent years, the Rayleigh lidar technique has emerged as an effective means to study the gravity wave activity in the middle atmosphere over the height range of 30–70 km (Chanin and Hauchecorne, 1981, 1991; Wilson et al., 1990a, b; Gardner et al., 1989; Whiteway and Carswell, 1995; McDonald et al., 1998; Sivakumar et al., 2006; Ramkumar et al., 2006; Antonita et al., 2007). Further techniques provided important results, including rocketsonde measurements (Dewan et al., 1984), balloon soundings (Fritts et al., 1988; Nastrom et al., 1997). Radiosonde measurements, supplying wind velocity and temperature data in the troposphere and lower stratosphere, provided important information on wave climatology, sources, and effects in the lower atmosphere (Allen and Vincent, 1995; Vincent et al., 1997). The potential utility of radio occultation data in general, and of data from the Global Positioning System/ Meteorology (GPS/MET) experiment in particular, for studying atmospheric gravity waves (Steiner and Kirchengast, 2000) is now utilized by many researchers across the globe.

Invention of clear-air radars operating at VHF has revolutionized the atmospheric research. In particular, the potential of these radars to measure the three-dimensional wind fields with high temporal and spatial resolution is of great advantage to the atmospheric researchers. VHF radar observations have been providing a wealth of information on gravity wave activity in the lower and middle atmosphere. Even though the radar provides the information on both frequency and vertical wave number spectra, much of the current theoretical focus is on understanding the nature of the vertical wave number spectrum of gravity waves. A key finding of many experimental studies on wave number and frequency power spectra of atmospheric gravity wave motions was that their spectral characteristics are widely uniform in frequency and wave number, despite different generation sources, meteorological conditions, and locations of observations (VanZandt, 1982; Dewan et al., 1984; Tsuda et al., 1989). A number of different theories have been developed to explain these observations and thus predict essentially the same vertical wave number spectrum, independent of the varying background conditions (Dewan and Good, 1986; Smith et al., 1987; Weinstock, 1990; Hines, 1991; Zhu, 1994; Gardner, 1994). Based on these studies and similar ones of oceanic gravity wave power spectra, VanZandt (1982) introduced the concept of a universal spectrum of atmospheric gravity waves, which greatly eases the task of developing globally useful but still efficient parameterization schemes of the influence of gravity waves on the mean atmospheric state (Fritts and VanZandt, 1993; Hines, 1997). Thus, all these studies emphasize the importance of vertical wave number spectra of gravity waves and their comparison with the theoretical spectra.

Gravity wave studies have been carried out in the past using the Indian MST radar observations over this latitude (Dutta et al., 1999; Dhaka et al., 2001, 2002; Reddy et al., 2005; Kumar, 2006, 2007; Ratnam et al., 2008). Most of these studies aimed to explore the frequency spectra of gravity waves during various atmospheric conditions. The central objective of the present study is to estimate gravity wave vertical wave number spectra and to compare them with model spectra using ten years of Indian MST radar observations of zonal, meridional and vertical winds. An attempt is made to estimate the vertical wave number spectra of kinetic energy in the troposphere and discuss the discrepancies between the observed and model spectra. Section 2 provides a brief description of Indian MST radar and data analysis, Sect. 3 provides the results and discussion and concluding remarks are provided in Sect. 4.

2 Experimental setup and data analysis procedure

2.1 Indian MST radar

The radars operating at 50 MHz are used to explore the Mesosphere, Stratosphere and Troposphere and hence called MST radars. The present observations also made use of one such MST radar located at Gadanki (13.5° N, 79.2° E). This radar operates at 53 MHz (wavelength is 5.66 m and hence this instrument detects the backscattered echoes from approximately ∼3 m irregularities) with an average power aperture product of $\sim 7.7\times10^8$ W m^2 and an altitude resolution of 150 m in the vertical direction. This system uses the phased array antennas (32×32) for transmitting and receiving the signals using a duplexer. The radar system details are given by Jain et al. (1994) and Rao et al. (1995).

2.2 Data analysis procedure

2.2.1 Daily mean wind profiles

Indian MST radar observations of zonal, meridional and vertical winds in the troposphere in the height region of 4–14 km during the years 1995–2004 are used for the present study. This height region 4–14 km is chosen to avoid the tropical easterly jet region, which is one of the prime candidates for exciting the gravity waves. The radar was operated daily with a 150-m height resolution for 45 min during 17:00–17:45 h (local time). The data availability is shown in Fig. 1. There exists a considerable amount of data gaps, as shown in Fig. 1, which are mainly due to annual maintenance of the radar system. However, as the central objective of the present study is to estimate monthly mean vertical wave number spectra, these data gaps are insignificant. Thus, the daily radar observations on available dates are averaged for 45 min to obtain the representative wind profiles on that particular day. These daily averaged zonal, meridional and vertical wind profiles form the basis for the present study.

2.2.2 Removal of background wind profiles using 2nd order polynomial fits

By now, it is well established that the observed fluctuations in the height profiles of some of the geophysical parameters, such as wind and temperature profiles, are due to the propagating gravity waves. For extracting gravity wave disturbances from the observed wind profiles, one should suitably remove the background wind. The best method is to estimate the amplitude and phase of all other possible waves such as Kelvin, Rossby-gravity waves and other well-known planetary waves over the observational site and removing it from the data. But this exercise needs continuous day-to-day MST radar observations, which are not available, as shown in Fig. 1. The alternative procedure is to construct the climatological wind profiles using long-term observations and subtracting these profiles from the instantaneous profiles. Using this procedure it has been noticed that the wind fields over this latitude show considerable interannual variability (change of winds from one year to other). When we used climatological winds profiles as background profiles to subtract from the instantaneous profiles to obtain the wind fluctuations, on some of the months, we observed that the background profiles differ a lot from instantaneous profiles. For example, on some occasions, if climatological winds were showing easterlies the instantaneous profiles were showing westerlies in some of the altitudes. If we use this type of background profiles to extract the velocity fluctuations, the resultant gravity wave spectrum will be biased towards these large differences. Thus, keeping the interannual variability of winds in view, the climatological wind profiles are not used for estimating the wind fluctuations. Now we are left with only one alternative, i.e. to use the polynomial fit as background profiles. However, before using the polynomial fit one should decide the order of the polynomial to be used. Very recently, Zhang et al. (2006) successfully used a 2nd order polynomial fit to remove the background and to estimate the vertical wave number spectra of gravity waves using radiosonde observations. In general, the gravity wave energy increases with increasing wavelength, but the subtraction of a polynomial decreases the energy at the longest wavelengths. The cut-off wavelength above which the gravity wave energy decreases also depends on the order of the

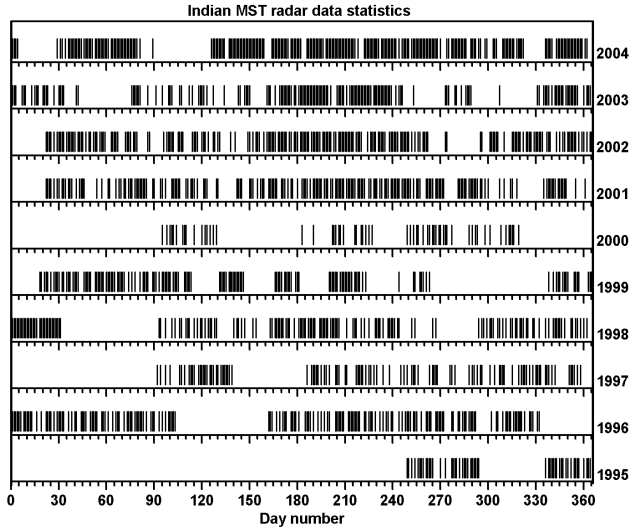

Fig. 1. Data availability of MST radar during the years 1995–2004.

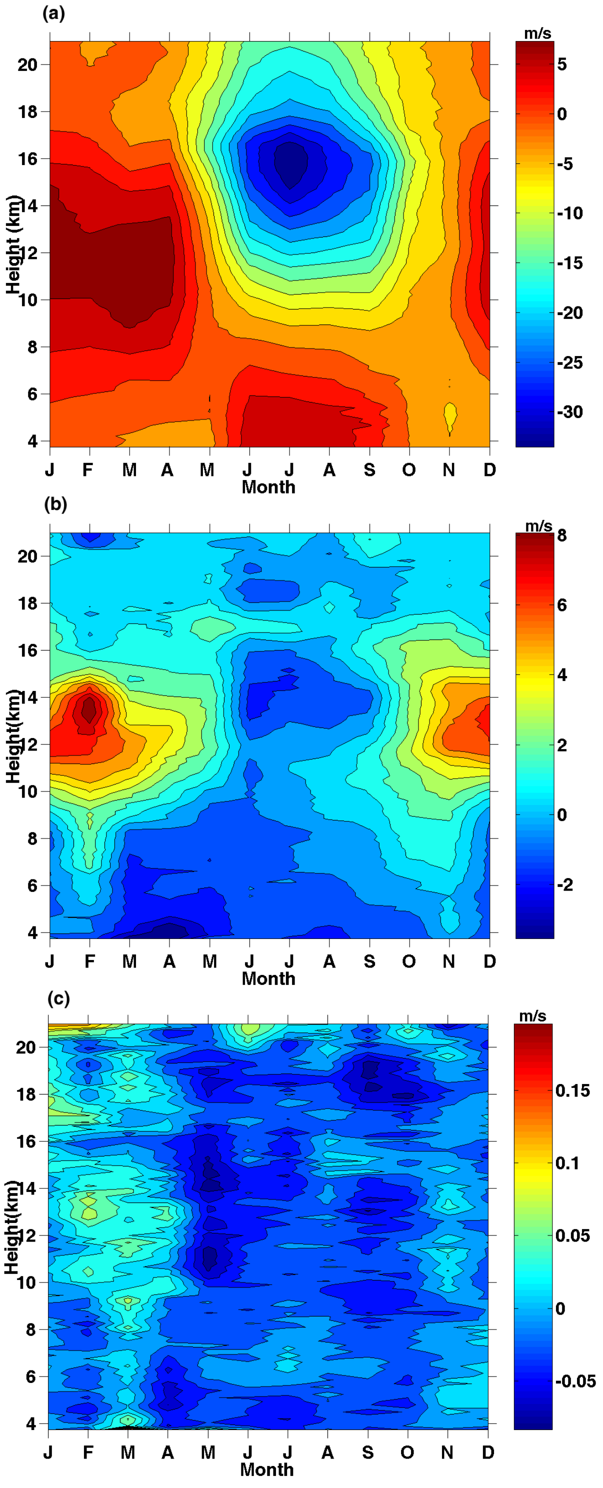

Fig. 2. Ten-year climatology of **(a)** Zonal, **(b)** Meridional and **(c)** vertical winds over Gadanki.

polynomial. The rule of thumb is, the higher the order of the polynomial fit, the lower the cut-off wavelength is, which will be affected. However, there is unavoidably some arbitrariness in the choice of the polynomial fit. In the present study, wind profiles in the 4–14 km height region with 150-m height resolution are used, which allows us to study the gravity wave spectra in the 0.3–10 km wavelength region. By using the 2nd order polynomial fit, we observed that the gravity wave energy only at a 10-km wavelength is affected. By using a higher order polynomial, for example, a 3rd order, gravity wave energy both at 10 and 5 km wavelengths are affected, and so on. Thus, the instantaneous profiles are fitted with a 2nd order polynomial and by subtracting the fit from the instantaneous profiles, the wind fluctuations are obtained. However, in spite of our best efforts to obtain solely the wind fluctuations contributed by the gravity waves, we admit the possibility that the resultant spectra may also contain non-gravity wave contributions.

2.2.3 Fourier analysis

After obtaining the wind fluctuations, the zonal, meridional and vertical kinetic energy profiles are estimated and further more, these profiles are added together to obtain the total kinetic energy profiles, which are then subjected to Fourier analysis to obtain the vertical wave number spectra of gravity wave kinetic energy. Before subjecting the profiles to a Fourier analysis, the profiles are weighted with a hamming window to minimize the spectral leakage effects.

3 Results and discussion

3.1 Climatology of mean winds over Gadanki

Using the ten years of Indian MST radar observations, a climatology of zonal, meridional and vertical winds is developed and the same is shown in Fig. 2a, b and c, respectively. It is very interesting to observe the features of the Tropical Easterly Jet (TEJ) in the upper tropospheric region (13–17 km) (refer to Fig. 2a), which is a well-established gravity wave source apart from atmospheric convection and orography over the present observational site. Extensive observations of TEJ using an Indian MST radar over this latitude were reported by Vasanta et al. (2002). Meridional winds in the upper troposphere (10–15 km) show a pronounced annual oscillation (refer to Fig. 2b) with a southerly direction during October–March and a northerly during April–September. From Fig. 2c it can be seen that for direction almost all the months except for a few, the mean vertical motions are downward, which is consistent with earlier MST radar observations from other geographical locations. A detailed discussion on the mean vertical velocities over this latitude is reported by Jaggannadha Rao et al. (2003). Thus, using the long-term database of MST radar observations, climatology of mean winds over this latitude is brought out, which is very useful to interpret the observed variances and trends in the wind fields.

3.2 Height profiles of wind fluctuations

Any method aiming at estimating the wind fluctuation should suitably subtract the background mean wind profile from the instantaneous profile. As discussed in Sect. 2.2.2, in the present study, a first attempt is made to use the monthly mean profile as a background profile in the respective months. But, keeping the interannual variability of winds in view, the climatological wind profiles are not used for estimating the wind fluctuations. The second order polynomial fit is subtracted from the instantaneous zonal, meridional and vertical wind profiles and the resultant profiles are further used for obtaining the height profiles of total kinetic energy of gravity waves. Figure 3 shows zonal, meridional and vertical wind fluctuations on a typical day. It is very interesting to note the wave-like structure in the zonal and meridional winds, which confirms the suitability of the 2nd order polynomial fit as a background profile. A statistical study on the various parameters of gravity waves, including vertical wavelengths using a hodographic analysis, using the present data set, has been made and will be reported in a separate work.

3.3 Model gravity wave spectra estimation

A universal wave number spectrum is one of the most striking features of the gravity waves, which means that for the vertical wave number (m) spectra of horizontal winds and temperature disturbances, the spectral slope and intensity remain nearly constant. Since these spectral features appear to be independent of time and space, thus, the spectrum is said to be universal. According to the theoretical analyses, in the saturation region, the theoretical vertical wave number spectrum of gravity wave kinetic and potential energies, i.e. E_K (m) and E_P (m), can, respectively, be expressed as (Smith et al., 1987; Allen and Vincent, 1995; Fritts and Alexander, 2003; Zhang et al., 2006):

$$E_K(m) = p\mathrm{N}^2/10\,\mathrm{m}^3 \tag{1}$$

$$E_P(m) = \mathrm{N}^2/6pm^3 \tag{2}$$

N is the buoyancy frequency given by

$$\mathrm{N}^2 = g/T(dT/dZ + g/C_p),$$

where g is the gravitational acceleration, T is the temperature, m is the vertical wave number of the gravity wave and p is the slope of the one-dimension frequency spectrum. The best estimate of p from previous literature is 5/3, and this value is used for the present study. From the above-mentioned expression it can be noted that the buoyancy frequency controls the amplitudes of the power spectra. For the present study, the average buoyancy frequency in the troposphere is calculated using the Chennai radiosonde station observations, which is 120 km away from the radar site. Radiosonde used for the present measurements employ thermistors for temperature measurements. These thermistors have semiconducting properties and are composed of inorganic oxides and ceramic materials, and are coated with a white pigment which has a reflectivity of ∼0.89 and consequently the absorbity of radiation is ∼0.11. Therefore, the error due to radiation, if any, would be minimal. The error in the basic temperature measurements due to the temperature sensor as given by the India Meteorological Department (IMD) is ∼1 K. The accuracy of the relative humidity measurements is within 4%. Carbon hygristors are used for the humidity measurements. At any height level, there is an uncertainty in determination of pressure which is ∼1 mb. Aneroid in the baroswitch (mechanical pressure sensor) is used as a pressure sensor. At the level of ∼100 mb, it corresponds to an uncertainty in height of ∼60 m. This could further add an uncertainty of ∼0.4 K in temperature determination. An intercomparison of US and IMD MKIII radiosonde data has shown that up to the 100 mb level, for 1-min interval data for the IMD radiosonde, the mean difference and standard deviation is <1 K. The precision determined for IMD radiosondes is 0.66 K (Schmidlin, 1988; Chakrabarty et al., 2000). Using the radiosonde observed temperature profiles, the gradients are estimated using three points and the same are used to calculate N^2. With the above-mentioned errors in temperature measurements, the error in N^2 estimation is of the order of $3\times10^{-6}\,\mathrm{s}^{-2}$. Substituting these values in Eq. (1), the model gravity wave spectrum is estimated for the troposphere. This spectrum is extensively compared with the radar observed gravity wave spectra.

3.4 MST radar observations of vertical wave number spectra of total kinetic energy of gravity waves

Using the ten years of MST radar derived height profiles of zonal, meridional and vertical winds, day-to-day height profiles of wind fluctuations are obtained. Using these profiles zonal, meridional and vertical kinetic energies per unit mass are calculated using the following expressions,

$$E_{kz} = \frac{1}{2}U'^2 \tag{3}$$

$$E_{km} = \frac{1}{2}V'^2 \tag{4}$$

$$E_{kv} = \frac{1}{2}W'^2. \tag{5}$$

These height profiles in the 4–14 km height region are then subjected to Fourier analysis to obtain the vertical wave number spectrum on all the available days shown in Fig. 1. Further, these day-to-day vertical wave number spectra in a particular month are averaged to obtain the monthly mean spectra. A typical monthly mean vertical wave number spectrum for the month of March 2004 is shown in Fig. 4. This figure shows that the vertical wavenumber spectra of zonal and meridional kinetic energy exhibit similar trends, as well as a similar order of magnitude. One more interesting item to

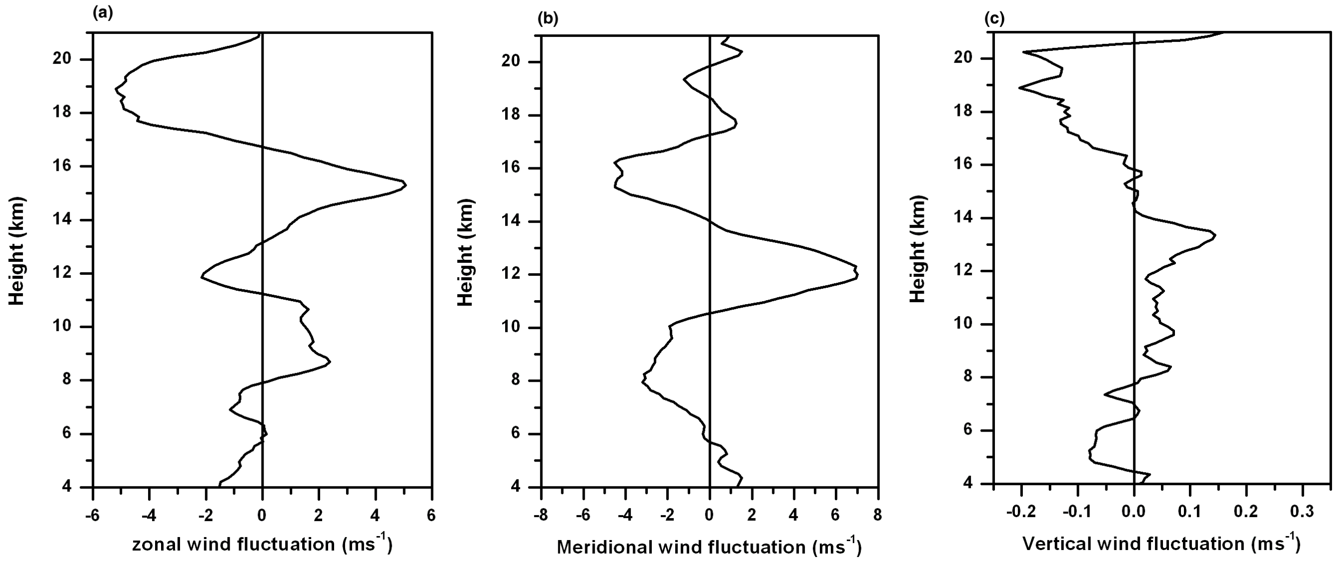

Fig. 3. Typical height profiles of **(a)** Zonal, **(b)** Meridional and **(c)** vertical wind fluctuations estimated by subtracting the second order polynomial as background.

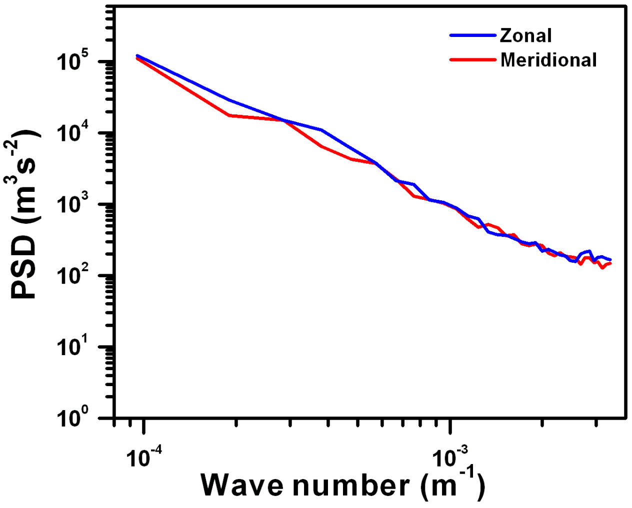

Fig. 4. A typical observed vertical wave number spectra of zonal and meridional kinetic energy for the month of March 2004.

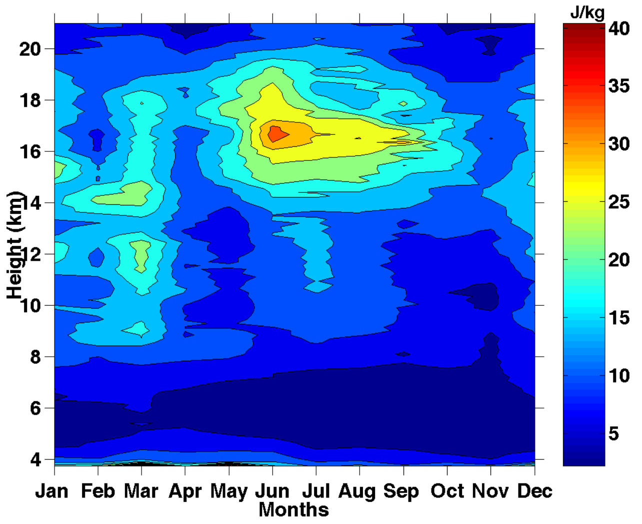

Fig. 5. Height-month section of total kinetic energy estimated using ten-years of observations.

note from this figure is its similarity with the wave number spectra reported by Tsuda et al. (1989) using MU radar (35° N, 136° E) and Arecibo radar (18° N, 67° E) observations. However, the spectra reported by those authors are derived using a few days of data, which they compared with the model gravity wave spectra. The comparison between the model and observed horizontal wind spectra was remarkably good. The present vertical wave number spectra shown in Fig. 4 also exhibit an increase in gravity wave kinetic energy with wavelength, consistent with the gravity wave theory. Thus, the similarity of the spectra reported by Tsuda et al. (1989) and the spectra reported here confirms the reliability of the analysis procedure adopted in the present study.

Instead of comparing zonal, meridional and vertical kinetic energy wave number spectra individually with model spectrum (model spectrum corresponds to total kinetic energy), we estimated the profiles of total kinetic energy by combing the expressions (3), (4) and (5). Figure 5 shows the height-month section of monthly mean total kinetic energy estimated using ten-years of observations. This figure shows pronounced seasonal variation of total kinetic energy. An enhanced kinetic energy around the tropopause during

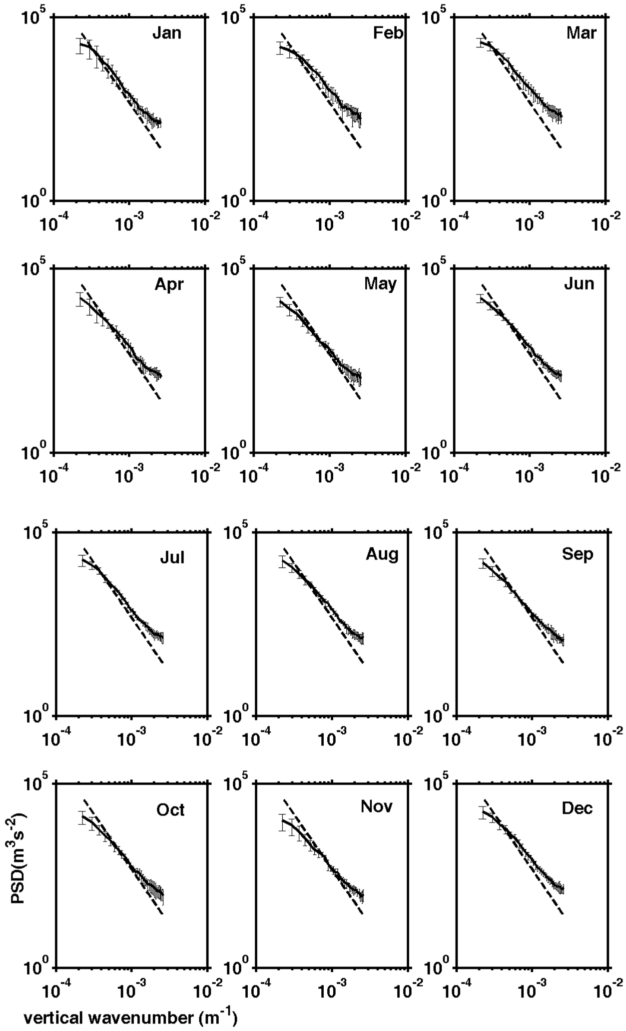

Fig. 6. Ten-year monthly mean vertical wavenumber spectra of total kinetic energy (solid line) along with the model predicted spectra (dashed line) for 12 months (January to December).

June–September is directly attributed to the presence of TEJ, which can be seen in the climatology of zonal winds over this latitude, as shown in Fig. 2a. From this figure, it also can be noted that there is a secondary peak in kinetic energy during the month of March, which is the vernal equinox. The height profiles of total kinetic energy are then used to compute the vertical wave number spectra, as discussed in the above section. The monthly mean wave number spectra are averaged for a total number of ten years on a monthly basis and are compared with the model gravity wave spectrum. Figure 6 depicts the observed vertical wave number spectra of total kinetic energy of gravity waves for the months January–December. For comparison purpose, the model spectrum is shown in each panel (dashed line). It appears that in all the months the observed spectra are very similar in trend and there is considerable difference in the magnitude. Coming to the comparison with the model spectrum, in general, the agreement is very good. However, a close examination of this figure reveals that the model overestimates at lower wave numbers and underestimates at higher wave numbers. This is consistently observed in all the months. It is quite interesting to note the excellent agreement in the middle portion of the observed and model spectra. To know the difference between the model and observations quantitatively, we estimated the slopes of observed vertical wave number spectra and are shown in Fig. 7. Here it is emphasized that these are logarithmic slopes. The slope of the model spectra is also shown in the figure as a dotted line for the comparison. Except for the month of May the slopes of the observed spectra are more or less in the same range. Overall, the slope ranges from -2 to -2.8. However, according to the universal spectral theory of gravity waves, their spectral characteristics should be widely uniform in frequency and wave number, despite different generation sources, meteorological conditions, and locations of observations (VanZandt, 1982). Nastrom and Gage (1985) reported that there were no systematic differences between the spectra over land and ocean, or during winter and summer. In the present study, qualitatively, the above-mentioned characteristics are found, however, quantitatively, the present observations show variations in the spectral slopes. It is evident from Eq. (1) that the buoyancy frequency controls the amplitudes of the power spectra and it is obvious that the buoyancy frequency will have seasonal variation, which will reflect in the vertical wave number spectra. One more possibility for the observed discrepancy may be varying shearing background winds with season. Manuel and Caranti (2000) suggested that spectral slopes varied from -4 to -2, due to the background wind shears. If the observed spectra are compensated for these effects, then the differences between observations and model can be further

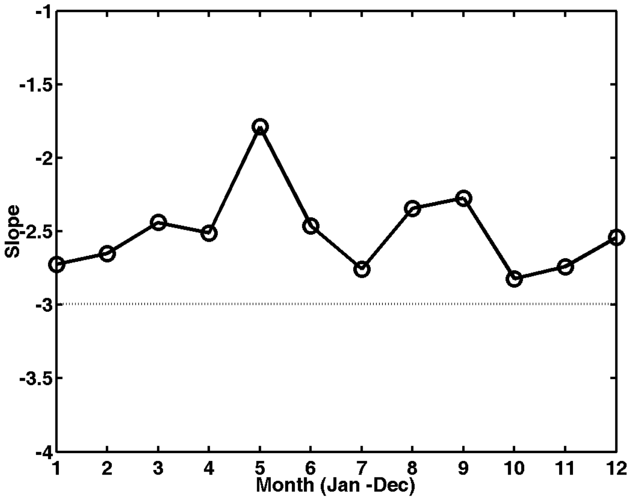

Fig. 7. Monthly variation of logarithmic spectral slopes. The dotted line shows the theoretical slope.

minimized. It should also be remembered that the model spectrum is intrinsic and there is every possibility that the observed vertical wave number spectra may be Doppler shifted due to background winds. However, as we are limiting our analysis in 4–14 km height region where winds are not very strong, the Doppler shift may be minimal. Thus, the Doppler shift of vertical wave number spectrum can also be held responsible for observed discrepancies between model and estimated slopes. In spite of all these effects, the results from the present study are very encouraging and the efforts are under way to carry out an extensive study on gravity wave vertical wave number spectra using GPS occultation temperature profiles across the globe, which will shed more light on the latitudinal variation of gravity wave vertical wave number spectra and their slopes. The gravity wave characteristics and their dependency on their generating mechanisms will also be explored in subsequent studies over this latitude.

4 Concluding remarks

The present study using the long-term tropospheric observations of MST radar provided an opportunity to investigate the vertical wave number spectra of gravity waves in the troposphere. The climatology of zonal, meridional and vertical winds using the ten-years of observations is established. Both zonal and meridional wind climatology has shown the pronounced annual oscillation in the upper tropospheric region. By fitting a second order polynomial as background, height profiles of zonal, meridional and vertical wind fluctuations are estimated. Subsequently, these profiles are used to estimate the zonal, meridional and vertical kinetic energy per unit mass, which are added together to obtain the height profiles of total kinetic energy. The vertical wave number spectra are then estimated by subjecting these profiles to Fourier analysis using the hamming window for smoothing at the boundaries. The observed spectra agreed remarkably well in trend with those reported in the literature. However, there were considerable differences in the magnitudes, which can be attributed to the latitudinal variation of gravity wave characteristics. Using the well-established expression, model gravity wave spectra of kinetic energy is estimated and it is used extensively for the comparison with observations. The observed total kinetic energy spectra showed very good agreement with model spectrum. An attempt is also made to study the quantitative difference between model and observed spectra by estimating the slopes of the observed spectra. Except for the month of May, the slopes of the observed spectra are in very good agreement with that of the model spectrum. It is believed that the monthly mean gravity wave spectra reported in the present study are very important for representing the gravity wave characteristics in the atmospheric models.

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