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Morphology of tropical mesospheric echoes observed by VHF radar

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This short communication reports on an attempt which has been made to study mesospheric echo occurrence duration for the first time, using a large data base (1998 to 2004) collected from MST radar located at Gadanki (13.5°N, 79.2°E), a tropical station in India. It is well known that VHF radar echoes in the mesosphere are due to both the presence of irregularities with scales of half the radar wavelengths, and also the production and loss rates of electrons in the lower D-region. The main aim of the present paper is to estimate the duration of mesospheric echoes at each altitude and to establish the preference of their occurrence, if any, in altitude and time. In general, mesospheric echoes show tilted layers, a sporadic nature above/below the main layer (70–80 km), and a seasonal shift in the height of occurrence. Based on the time and height of echo occurrence, we broadly divide the periods of mesospheric echo occurrence (duration) into 5–20 minutes (T1), 20–40 minutes (T2), and ≥40 minutes (T3), and the height of occurrence into 65–70 km (R1), 70–80 km (R2), and 80–85 km (R3). It is observed that long duration echoes (T2 and T3) occur mostly in the R2 region and are highly sporadic in the R1 and R3 regions. In addition, the solar zenith angle dependence on the duration of mesospheric echoes is also studied and no significant variation was found in any of the above-mentioned categories. This study will contribute to a better understanding of the dynamical aspects of the mesosphere using VHF radar observations.
Key words: Mesospheric echoes, duration, VHF radar.

1. Introduction

The mesosphere is a region of transition, where wave and wave-dissipative processes play an important role in atmospheric energetics and dynamics. Our understanding of this region is still quite limited, as compared with other regions of the atmosphere. Since the pioneering work by Woodman and Guillen (1974), VHF radar has become a powerful tool for understanding the structure and dynamics of the middle atmosphere. Radar returns are thought to be mainly due to the scattering/partial reflections from refractive index gradients with scales equal to half of the radar wavelength/whose horizontal correlation length is larger than the first Fresnel zone (Balsley and Gage, 1980). Above 50 km, the radar refractive index depends mainly on the number of free electrons, and hence on the production and loss rates of electrons in the lower D-region. Thus, radar returns depend not only on the presence of irregularities with scales of half the radar wavelengths, and thin horizontally stratified layers, but also on the production and loss rates of electrons in the lower D-region.

VHF radar returns from the D-region are mainly due to turbulence acting on an electron density gradient (Balsley and Gage, 1980). Much of the turbulence in the mesosphere is believed to be produced by breaking/saturated tides and gravity waves (Fritts, 1984), and the main production mechanisms are thought to be through dynamical/convective instabilities. VHF radar echoes from the D-region were first detected by Flock and Balsley (1967) in the equatorial ionosphere. The first actual measurements of mesospheric winds and turbulence were made by Woodman and Guillen (1974) using the Jicamarca observatory. A wide range of observations have been made over different latitudes to examine the nature of the turbulence giving rise to scattering using VHF radar (for example, Cho and Kelly, 1993). Observations from the Middle and Upper atmosphere (MU) radar in Japan also showed a clear relation between the presence of long-period gravity waves and echoing layer structures (Muraoka *et al.*, 1987; Yamamoto *et al.*, 1988).

These mesospheric echoes are observed to be highly intermittent in space and time (Rastogi and Woodman, 1974) and appear only during daytime and disappear during nighttime (Balsley and Gage, 1980). The radar returns also showed a layered structure and descending with mean velocities of 1 m s^{-1} at mid- and low-latitudes (Harper and Woodman, 1977). The thickness and lifetime of the layers, as well as the height range where they occur, show a clear seasonal dependence (Balsley *et al.*, 1983; Czechowsky *et al.*, 1989). Earlier studies using the Indian MST radar has revealed that there exists a strong semi-annual variation in the mesospheric echo occurrence with a maximum during equinoxes and that the height of strong echo occurrence is higher in the spring equinox than the fall equinox (Ratnam *et al.*, 2002; Kumar *et al.*, 2007).

Although several studies have reported that the mesospheric echoes are highly sporadic in nature, so far no

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Table 1. Indian MST radar experimental specifications used for the present study.

Parameter	Specification
Power aperture product (peak)	3×10^{10} W m^2
Beam width	3^0
Pulse width	8/16 μs
Inter pulse period	1000 μs
No. of FFT points	128
No. of coherent integrations	32/64
No. of incoherent integrations	1/2/4
Range resolution	1.2/2.4 km
No. of beams	Five (E, W, Zenith Y, N and S)

attempt has been made to clarify how sporadic they are, whether there is any preference in echo occurrence height and time, and what is the mesospheric echo occurrence duration, etc. It is well known that winds and other turbulence parameters are derived from basic echo characteristics, and the fact that these echoes are highly sporadic in nature is well reported using VHF radars elsewhere, as mentioned above. However, to what extent these are sporadic is not discussed in the literature, to the best of our knowledge. In order to address some of these issues, the mesospheric echo duration as a function of time and space are studied for the first time using a large data base from MST radar located in the tropical station, Gadanki (13.5°N, 79.2°E).

2. Data Base

We make use of the Indian MST radar (Rao *et al.*, 1995) data obtained during the period March 1998 to October 2004. This radar is a high-power coherent pulsed Doppler radar operating at 53 MHz, and is located at Gadanki. The main experimental specifications used for the observations relating to the present study are given in Table 1. The data, from the MST radar operated continuously from 0930 to 1600 h Indian standard time (IST) (IST = UT + 0530 h) twice in a month, are used for the present study. Data from a total of 107 days is used with 23, 25, 35, and 24 days during winter (NDJF), spring equinox (MA), summer (MJJA), and fall equinox (SO), respectively.

3. Analysis Procedure

At mesospheric heights (~60–85 km), the received echoes are highly intermittent in space and time and also very weak. In addition, these echoes are often contaminated with different kinds of interferences which appear to be due to both unwanted atmospheric signals (meteor echoes) and system malfunctions. Usually, the interference caused by meteors has a very large intensity. On the other hand, system-related interference appears at all the mesospheric heights. Interference of a system origin can be removed easily, since it appears at a particular Doppler bin and in all ranges. To identify and remove interference of meteoric origin, an algorithm has been developed which is discussed in detail in Kumar *et al.* (2007). In short, this algorithm detects the sharp meteor echoes and removes them from the data set. These sharp echoes appear as spikes in the overall time series of echo power and hence deletion of these points is necessary in order to obtain a correct result. Severe interference was observed on a few days (about 5%) and that data has been discarded from the present analysis.

In addition, the mesospheric echoes are considered useful when Signal-to-Noise Ratio (SNR) > -12 dB (8 dB above the noise floor). To fix this threshold in SNR, detectability (defined as the ratio of peak spectral density and standard deviation of noise) is calculated. It is found that signals with a 3-dB detectability are often associated with an SNR of about -16 dB (Kumar *et al.*, 2007). For our analysis, a detectability level of more than 5 dB corresponding to an SNR of -12 dB has been chosen as a detection criterion to be on the safe side. In addition, a contribution from cosmic noise which varies as a function of local time and season depending on the position of the galactic center is also present in the noise floor together with system noise (although very small when compared to cosmic noise). However, this noise variation is not an issue for the signals (> -12 dB) that we have chosen.

A new algorithm has been developed to identify the echo duration for the data collected during ~0930 h–1600 h IST on each day. This algorithm identifies the echo duration for each height individually. First, it looks for the echo (SNR $>$ -12 dB). If an echo is present then the corresponding time is taken as the starting time, and then it looks for an echo absence. Once it detects the absence of an echo, it looks whether the absence of the echo is continuous for the next 5 minutes or not. If it is continuous then the corresponding time of the initial echo absence is taken as the echo ending time, otherwise it continues until no echo occurs. After identifying the end time it looks for another echo presence, etc., and continues this process until the end of the data. The difference between the ending time and the starting time is considered to be the echo duration. Note that only mesospheric echoes lasting for more than 5 minutes are considered in the present study. Sometimes there exists data gaps which can occur due to many reasons, such as power failure, malfunctioning in the radar, considering significant echoes only (SNR $\geq$ -12 dB), etc. During these data gaps, if the echo duration before and after is more than the data gap then the data gap is also considered as an echo presence, otherwise the data gap is considered as an echo absence. Using this algorithm, the duration of the mesospheric echoes at each altitude and in each season were estimated and this is discussed in the following sections.

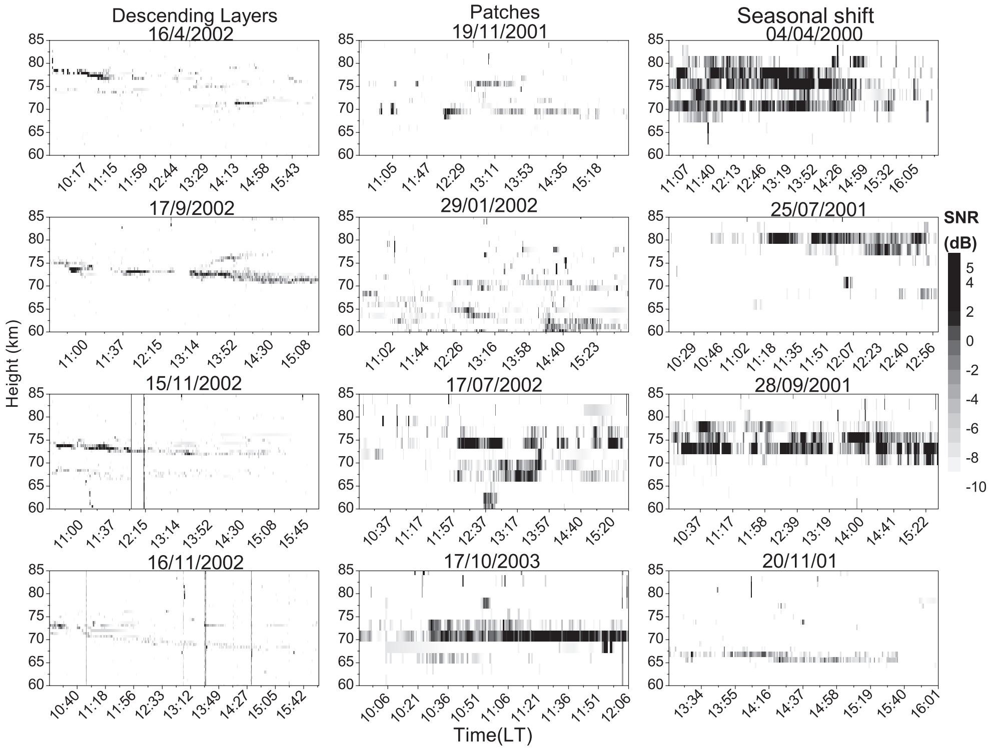

Fig. 1. Typical range-time Signal-to-Noise Ratio (SNR) contours showing (a) descending layers, (b) patchy layers above/below the main layer, and (c) echoes showing a seasonal shift in the height of occurrence observed in different seasons.

4. Results

To illustrate the general nature of mesospheric echo characteristics, Fig. 1 presents typical cases of the time-height section of the SNR observed in a vertical beam during different seasons. Note that only an SNR greater than -10 dB is plotted in this figure. Three striking features can be noticed from Fig. 1. The mesospheric echoes sometimes show (1) descending layers as shown in the left panels of Fig. 1, (2) patchy layers above/below the main layer (middle panels), and (3) a seasonal shift in the echo occurrence height (right panels). In the first case, a 5 km decrease in the height of echo occurrence can be noticed, in general, in 5 hours of observations providing strong evidence of tides modulating the mesospheric echo occurrence. Sometimes there exist two layers separated by 5 km, as in the cases of 16 April 2002 and 15 November 2002 and sometimes a single layer as observed on 17 September 2002. Interestingly, both the layers show a descending behavior. It is worth mentioning that descending layers are more clearly observed in a fine resolution mode (1.2 km) than in a course resolution mode (2.4 km).

In the second case, in general, mesospheric echoes are highly sporadic but some times strong echoing layers which last for more than 4 hours can be noticed from the middle panels of Fig. 1. The main layer between 70 and 80 km is more or less long lasting and above/below this main layer there exists a patchy layer. Finally, there exists a considerable height shift from one season to other and also from morning to evening hours. In the winter case (20 November 2001) presented in Fig. 1, note that a strong echoing layer existed between 65 and 70 km, whereas during summer (25 July 2001) these layers are observed between 75 and 80 km. During the equinoxes (04 April 2000 and 28 September 2001), these strong echoing layers are observed between 70 and 80 km. This feature reveals that there will be a seasonal shift in the echo occurrence height. In general, more intense echoes will be observed during noon hours and will last for more than 2 hours. During equinoxes and summer, strong echoes extend over a larger height coverage. From previous studies (Ratnam *et al.*, 2002; Kumar *et al.*, 2007), it was observed that strong echoes occurred at higher heights during the spring equinox than the fall equinox and showed a strong semi-annual oscillation with a maximum during equinoxes followed by summer and winter. However, in the present study we concentrate more on the duration of mesospheric echoes observed within a day in the different seasons.

Using the algorithm explained in Section 3, the duration of mesospheric echoes was estimated and after verifying large data base, the duration of the mesospheric echoes are further categorized into 3 types, viz., echoes occurring for 5 to 20 minutes (hereafter referred as T1), 20 to 40 minutes (T2) and more than 40 minutes (T3). These categories/events are first calculated for each beam separately at each height. Since no significant difference in the percentage occurrence (PO $=$ (samples having SNR ≥ -12 dB/total number of samples) $\times$ 100) of each category in different beams is noticed (figure not shown), we have averaged all the occurrences observed in different beams at each height. Figure 2 shows the PO profiles of the lifetime of the mesospheric echoes for the three different categories (T1, T2, and T3) mentioned above observed in different seasons during the period March 1998 to October 2004. Note that there would not be much difference in the variability

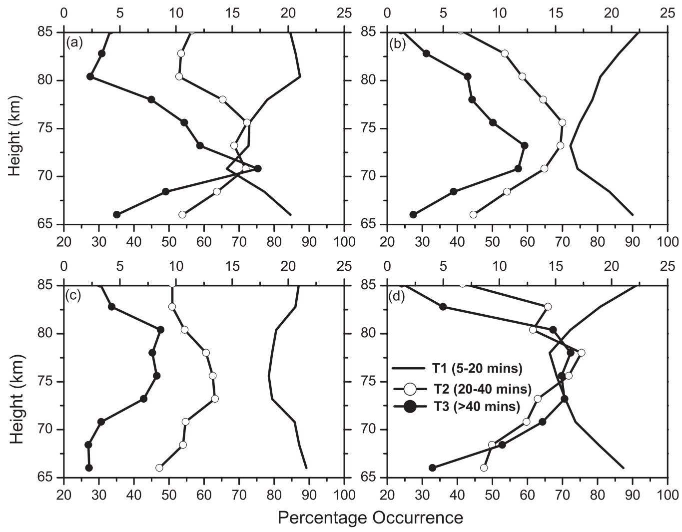

Fig. 2. Percentage occurrence of echoes categorized with echoes occurring for 5–20 minutes (T1), 20 to 40 minutes (T2), and more than 40 minutes (T3), observed during the different seasons, (a) winter, (b) spring equinox, (c) summer and (d) fall equinox. The percentage occurrence shown on the bottom (top) axis is for T1 (T2 and T3), respectively.

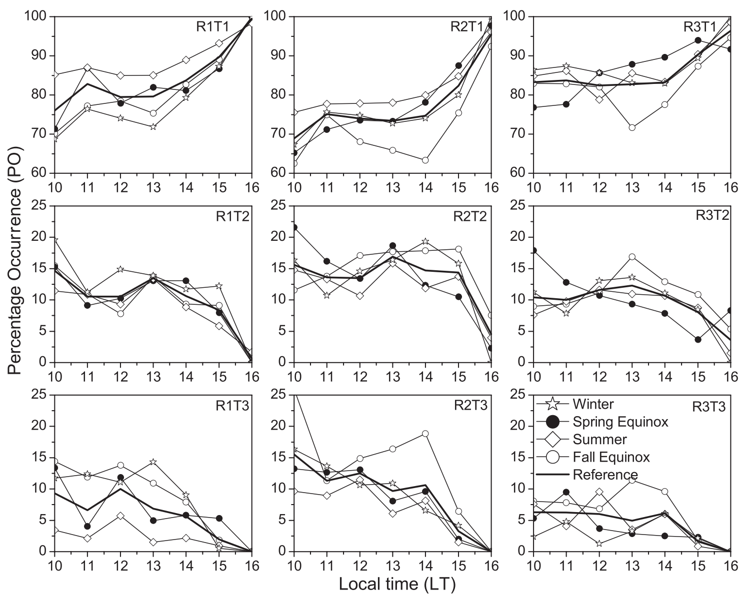

Fig. 3. Same as Fig. 2 but showing the local time dependence of echoes occurring for 5–20 minutes (T1), 20 to 40 minutes (T2), and more than 40 minutes (T3) at 65–70 km (R1), 70–80 km (R2), and 80–85 km (R3), observed during the different seasons. The seasonal average for each combination is also shown (black line) as a reference.

if we changed the criteria of echo duration and this would affect only the percentage occurrence. The echo occurrence in category T1 predominantly occurs in all seasons and is significantly higher in 65–70 km and 80–85 km. This reveals that the mesospheric echoes are highly sporadic in nature at these heights and between 70 and 80 km long-lasting echoes occur when compared to the other two regions. By considering this result, we have further divided the entire height coverage (65–85 km) into three regions, i.e., 65–70 km (hereafter referred as R1), 70–80 km (R2) and 80–85 km (R3).

From Fig. 2, it is clear that the lifetime of the mesospheric echoes with T2 and T3 is dominant in the R2 region, as compared with the R1 and R3 regions. Interestingly, note that there is a height shift in the maximum PO in T2 and T3 within the R2 region depending upon the season. The maximum height is observed during the fall equinox followed by the summer and spring equinoxes and the minimum height during winter for T2. But in the case of T3, the maximum height is observed during summer followed by the fall and spring equinoxes and the minimum during winter. This reveals another interesting result that the duration of the mesospheric echoes highly depends on the height region.

Since it is already reported that the mesospheric echoes follows closely the solar zenith angle (Kumar *et al.*, 2007), we have further checked whether there exists a preferred time for different durations occurring in the mesospheric echoes. Figure 3 shows the local time variations of PO in the starting time of the different time periods T1, T2, T3, in

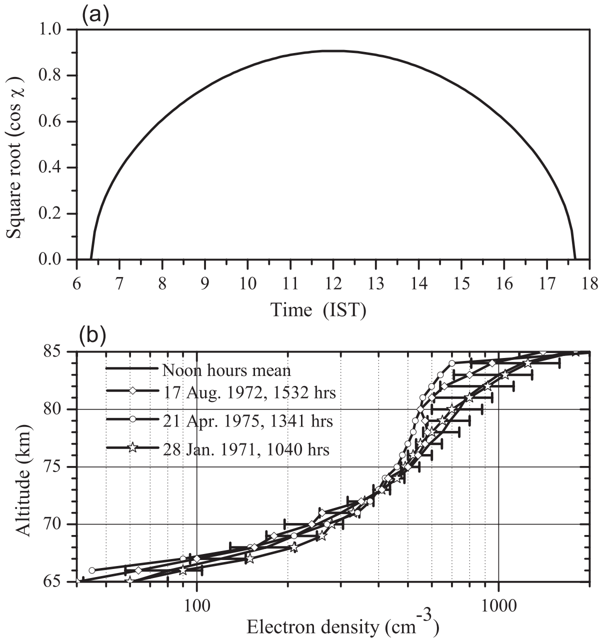

Fig. 4. (a) Variation of $\sqrt{\cos\chi}$ with time on a normal day. (b) Mean profile of electron density along with standard deviation observed using rocket sondes during the 1970s released from Thumba during noon times along with profiles of different time on different days.

the different height regions R1, R2, and R3. Note that we have used all the nine possibilities with three different time periods and three different regions in this figure observed during different seasons. The average of all the seasons plotted in different panels is used as a reference point. It is worth mentioning here that, at around 1600 h IST for the time T1, the PO shows a steep increase whereas for the periods T2 and T3 it shows a moderate to steep decrease which is mainly due to the limitation in the data set used but not true signal. Since mesospheric echoes are daytime phenomena, we have started our experiment at around 0930 h and ends at 1600 h IST. Hence, the calculation of the PO will result in a serious limitation in detecting the starting and ending times. Thus, with the current data set we need to focus between 1100 h and 1400 h IST only. After considering these issues, it is clear that there is no local time preference for different time periods considered here in any of the combinations. This reveals that there is no solar zenith angle dependence in the occurrence time of mesospheric echoes.

This aspect is further verified with the well-known D-region estimations. In general, during the day the rate of production of electrons is proportional to $\cos\chi$, where χ is the solar zenith angle. The ionospheric D-region electron density can be taken to be proportional to the square root of the rate of production and hence $\sqrt{\cos\chi}$. The nature of D-region electron density (proportional to $\sqrt{\cos\chi}$) variation with time on a given day is estimated and is shown in Fig. 4(a). Note that the electron density is expected to be high ($\sqrt{\cos\chi} \approx 0.8$) between 1100 h IST and 1400 h IST when mesospheric echoes are observed more frequently. This is further confirmed (though the dates are quite different) from the mean profile of electron density observed using rocket sondes during the 1970s (Subbaraya *et al.*, 1983) released from Thumba (8.5°N, 77°E) Equatorial Rocket Launching Station (TERLS) during noon time along with profiles of different times on different days shown in Fig. 4(b). It is interesting to notice that the variation (from standard deviations) in electron density is minimum during noon time hours (±2 hours from noon) between 70 and 75 km (and more or less throughout the R2 region) where long duration mesospheric echoes are frequently observed. From the profiles released during different timings of the day (∼1030 and ∼1530 h), it is clear that the mean electron density values range between 300 and 500 cm^{-3}. Since there are no diurnal variations in the electron density between 1100 h and 1400 h IST, it is quite natural to expect long-duration echoes (assuming no change in the background turbulence).

5. Summary and Discussion

It is well recognized that echoes from the mesospheric heights from VHF radar are highly sporadic in nature. However, so far no attempt has been made to clarify up to what level they are sporadic, whether there is any preference in echo occurrence height and time, and what is the duration of the mesospheric echoes, etc. In order to address some of these issues, in the present work, the duration of mesospheric echoes are studied for the first time using a large data base from the Indian MST radar located at the tropical station, Gadanki. The following are the main conclusions drawn from the present study:

(1) The mesospheric echoes often show descending layers, patchy layers above/below the main layer between 70 and 80 km, and a strong seasonal dependence in the height of occurrence.

(2) In general, long-duration mesospheric echoes occur preferentially in the height region 70 and 80 km and above and below this region echoes are highly sporadic in nature.

(3) There exists no local time dependence and hence solar zenith angle dependence in the lifetime of mesospheric echoes which is confirmed from earlier rocket sonde data.

One striking result observed from the present study is the existence of long-lasting echoes in the height region of 70–80 km. In this context, it is worth mentioning another interesting fact reported using the Rayleigh lidar observations from this location which is the existence of a mesospheric temperature inversion (MTI) of about 20–30 K between 70 and 75 km (Ratnam *et al.*, 2002, 2003). A strong correlation ($R = 0.72$) of the MTI with the MST radar echoes has also been reported (Ratnam *et al.*, 2002; Kumar *et al.*, 2007). The presence of a temperature inversion and enhanced radar echoes can be discussed in the light of gravity-wave breaking processes in that height region. Gravity waves propagating with increasing amplitudes will preferentially break whenever there is a strong inversion leading to turbulence generation hence long-lasting echoes from VHF radar returns occur. Also there exists another echoing layer at $\sim$80 km whose occurrence probability is less than that of the $\sim$72 km which coincides with the height of the secondary minimum of the mesopause observed from SABER/TIMED measurements (Venkat Ratnam *et al.*, 2010).

In addition, the descending height of the MTI is also noticed within a given night providing strong evidence that these layers are the manifestation of background mean thermal structure due to tides and gravity waves. However, it is worth mentioning here that the data availability during 0930 h to 1600 h IST restricts the study of the local time dependence for long periods and short periods at the ending and starting time, respectively. In order to address this issue, we have extended the data collection period in ongoing experiments from 0600 h to 1800 h IST and will be reported in a future study after accumulating reasonably sufficient data.

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