Modulation of thermal structure in the upper troposphere and lower stratosphere (UTLS) region by inertia gravity waves: A case study inferred from simultaneous MST radar and GPS sonde observations

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Received 16 April 2013; revised 28 June 2013; accepted 16 July 2013

The observations of multiple layer structures in the MST radar backscattering echoes in the upper troposphere and lower stratosphere (UTLS) region are discussed in this paper. The fact remains same that the enhanced echoes seen in the radar backscattering are due to the strong positive and negative thermal gradients. Simultaneous observations of MST radar (1 hourly) and GPS sonde (6 hourly) over a tropical station Gadanki (13.5°N, 79.2°E) reveal the presence of 1.5-2 km vertical wavelength in the winds, temperature and radar backscattering echoes in the UTLS region during Indian summer monsoon (ISM). The analysis also reveals that the presence of inertia gravity wave (IGW) triggered due to tropical easterly jet (TEJ) associated with ISM is the prime candidate for the observed thermal gradients in the UTLS region.

Keywords: Radar backscattering echo, Inertia gravity wave (IGW), Temperature gradient, Upper troposphere and lower stratosphere (UTLS), Zonal wind, Meridional wind

PACS Nos: 92.60.hd; 92.60.hf; 92.60.hh

1 Introduction

VHF radars have been serving as prime tools in remotely sensing the lower, middle and upper atmosphere to understand the finer details of many physical processes since their invention. The popularity of these radars in observing the atmosphere is mainly due to their capabilities of providing the data with high temporal and spatial resolutions1-4. However, a clear interpretation of the radar observations depends largely on understanding of the radar backscattering mechanism. The main mechanism that give rise to atmospheric radar echoes at VHF range are isotropic/anisotropic backscattering and Fresnel reflection/scattering. The dominant scattering mechanism responsible for the observed VHF radar echoes is Bragg scattering, which arises from the inhomogeneities in the radio refractive index (function of temperature and humidity) caused by the atmospheric turbulence. The Fresnel reflection is associated with the partial reflection from strong temperature gradients (also known as stable layers), which are often referred as specular echoes. In general, VHF radar echoes are known to be aspect sensitive in nature5,6. The aspect sensitive characteristics of VHF radar echoes are mainly manifested either due to thin stable layers providing sharp refractive index gradient or/and shear driven steep layer structures7-10. The radar echoes from the vicinity of tropopause layer are found to be highly aspect sensitive compared to any other layer existing in the lower atmosphere5,6,9,11,12. It is observed that the radar backscattering signal in the vicinity of tropopause decreases rapidly with an average rate of 1.2 dB per degree from zenith to 10 degree off-zenith; and beyond it with a rate of 0.6 dB per degree (Refs 9,13) during clear air conditions. Das et al.9 have shown the unusual non-aspect sensitive layer structure in the vicinity of tropopause, i.e. radar backscattering signal strength from zenith to 20 degree off-zenith remained almost equal during the passage of a
tropical cyclone over Gadanki. These unusual radar echoes in the vicinity of tropopause are attributed to the presence of isotropic layer structure formed near the tropopause as a result of Kelvin-Helmholtz instability (KHI) billow formation by shear instability. The VHF radar echoes at the upper troposphere and lower stratosphere (UTLS) region are also used to characterize the stratospheric intrusion\textsuperscript{10,14,15}.

Till now, many studies have reported the presence of multiple layer structures in the VHF radar echoes from the zenith direction in the UTLS region\textsuperscript{3,4,16,17}. Such layer structures observed in the radar echoes are due to the presence of strong thermal gradients\textsuperscript{18}. These gradients are commonly known as ‘temperature sheets’, which are similar to stably stratified structures and waves over oceans and lakes\textsuperscript{17,19}. Thermal gradients are mainly responsible for the VHF radar aspect sensitivity in the UTLS region\textsuperscript{16,17,20,21}.

Many researchers suggest that the formation of these temperature layer structures in the UTLS region is mainly due to KHI\textsuperscript{9,18,22-24}. KHI is a dynamical instability produced with the hydrostatically stable layers in the presence of a strong stratified shear flow\textsuperscript{25,26}. In earlier studies, KHI and breaking of gravity waves have been observed using UHF radar\textsuperscript{27,28}. Van Zandt & Vincent\textsuperscript{29} suggested that these structures were associated with low frequency gravity waves. Whereas, Hockings et al.\textsuperscript{30} and Hookes & Jones\textsuperscript{31} mentioned that the generation of layers is due to viscous or thermal conductive waves, which may have a potential to produce specular reflectors. In spite of several studies on temperature layer structure in the UTLS region, the uncertainty of the causative mechanisms is still persisting. For the meteorological community, it is important to understand the turbulent mixing process around these layers (UTLS), whereas for radar community, it is important to understand the scattering mechanisms associated with these layers. But due to the lack of continuous high resolution \textit{in situ} measurements of atmospheric temperature, wind and VHF radar observations simultaneously, the causative mechanisms for the formation of such layer structures have been documented insufficiently.

The state-of-the-art of Indian Mesosphere-Troposphere-Stratosphere (MST) radar located at Gadanki (13.5°N, 79.2°E) provides a better opportunity to study the layer structures in the UTLS region with better temporal and height resolutions\textsuperscript{3,32}. In the present study, using simultaneous MST radar and GPS sonde measurements, an attempt has been made to report the observations of temperature layer structures and discuss the possible generation mechanism in the light of present understanding.

### 2 Data analysis

A programme named ‘Study of Atmospheric Forcing and Responses (SAFAR)’ was initiated at National Atmospheric Research Laboratory (NARL), Gadanki, India by operating various ground based and \textit{in situ} instruments to study the vertical coupling between the forcing and responses from surface layer to the ionosphere\textsuperscript{33}. Under this programme, Indian MST radar was continuously operated for ~70 h to study three dimensional winds, turbulence structure and various dynamical processes in the UTLS region from 09:00 hrs IST of 15 July to 06:00 hrs IST (=GMT+05:30 hrs) of 18 July 2008. Indian MST radar is a high power pulse coherent radar, operating at 53 MHz, corresponding to the wavelength of 5.66 m with an average power aperture product of 7x10\textsuperscript{8} Wm\textsuperscript{2}. Detailed system description of Indian MST radar can be found in Jain et al.\textsuperscript{3} and Rao et al.\textsuperscript{32}. During the SAFAR campaign, the operating parameters of MST radar are listed in Table 1. The height resolution of the radar observations was 150 m and the time resolution of the three dimensional wind measurements was ~4 min. However, data has been averaged for every one hour to remove the high frequency fluctuations. Along with the radar observations, simultaneous GPS sondes were flown with an interval of 6 hours from the radar site to obtain the meteorological parameters, viz. temperature, pressure, humidity, wind speed and

### Table 1—Gadanki MST radar parameters used in the present experiment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar observational period</td>
<td>15 - 18 July 2008</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>53</td>
</tr>
<tr>
<td>Peak power (MW)</td>
<td>2.5</td>
</tr>
<tr>
<td>Pulse width (µs)</td>
<td>16</td>
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<tr>
<td>Inter pulse period (µs)</td>
<td>1000</td>
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<tr>
<td>Pulse code</td>
<td>Complimentary with 1 µs baud</td>
</tr>
<tr>
<td>Range resolution (m)</td>
<td>150</td>
</tr>
<tr>
<td>No. of beams</td>
<td>E\textsubscript{10}, W\textsubscript{10}, Z\textsubscript{y}, Z\textsubscript{x}, N\textsubscript{10}, S\textsubscript{10}</td>
</tr>
<tr>
<td>No. of Coherent Integrations</td>
<td>64</td>
</tr>
<tr>
<td>No. of incoherent integration</td>
<td>1</td>
</tr>
<tr>
<td>No. of FFT points</td>
<td>512</td>
</tr>
</tbody>
</table>

E, W, N, S and Z represent east, west, north, south and zenith beam, respectively. The numbers indicate the oblique angle in degree, y and x indicate the east-west and north-south plane, respectively.
direction. The height resolution of GPS sonde ascent is ~3-10 m and to make the height profiles of meteorological parameters equidistant, the data has been down scaled to 100 m height resolution using linear interpolation method. Table 2 shows the details of the GPS sonde flights.

### 3 Results and Discussion

In principle, the MST radar beam can be steered with 1 degree step between ±20 degree off-zenith in the two orthogonal planes [i.e. east-west (EW) and north-south (NS)] of the antenna array. However, in the present study, the radar beam was configured to 10 degree off-zenith of East, West, North, South and Zenith as described in Table 1. Figure 1 shows the height-time intensity maps of radar signal-to-noise ratio.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time of launch, hrs IST</th>
<th>Max height, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 July 2008</td>
<td>10:27</td>
<td>22</td>
</tr>
<tr>
<td>15 July 2008</td>
<td>17:38</td>
<td>32</td>
</tr>
<tr>
<td>15 July 2008</td>
<td>22:33</td>
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<tr>
<td>16 July 2008</td>
<td>4:49</td>
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<td>16 July 2008</td>
<td>11:00</td>
<td>21.85</td>
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<td>16:41</td>
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<td>17 July 2008</td>
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</tr>
<tr>
<td>18 July 2008</td>
<td>4:30</td>
<td>33.1</td>
</tr>
</tbody>
</table>

![Figure 1](image.png)

Fig. 1 — Height-time intensity plots of radar signal-to-noise ratio (SNR): (a) in zenith; and 10 degree off-zenith: (b) East, (c) West, (d) North, and (e) South during 09:30-10:30 hrs IST on 15 July 2008
ratio (SNR) in vertical and various off-zenith beams (East, West, North and South) during 09:30-10:30 hrs IST with a time resolution of ~4 min on 15 July 2008. Multiple enhancements in the SNR of zenith (Zsnr) beam in the UTLS region can be clearly observed from Fig. 1(a). The enhancement in Zsnr are observed at 16, 17.5 and 18.5 km altitudes. The signal strengths at 17.5 and 18.5 are almost of the same intensity and higher than that of at 16 km altitude. Further, the SNR of off-zenith (10 degree) beams of east, west, north and south direction (Esnr, Wsnr, Nsnr, and Ssnr,) have been analyzed and shown in Figs 1(b-e), respectively. The enhancement in the Esnr, Wsnr, Nsnr, and Ssnr at 17.5 and 18.5 km are clearly seen but there is no enhancement in the signal strength at 16 km in any of the off-zenith beams. As discussed above, the radar echoes from the tropopause height is highly aspect sensitive compared to any other layer existing in the UTLS region and the signal strength rapidly decreases by 1.2 dB per degree from zenith to 10 degree off-zenith. At the tropopause level, which acts as an interface to the stable and unstable atmosphere, the presence of sharp gradients in the temperature lapse rate gives the enhanced radar echo power. The air around the tropopause has a sharp change in the refractive index, which gives rise to a persistent radar reflectivity layer in the zenith direction at the tropopause level. These strong echoes from zenith beam at tropopause height, which act as a perfect reflector, are mainly due to Fresnel scattering/reflection. Thus, the signal strength at 16 km in off-zenith is too weak or negligible as compared to zenith and thus, indicates the tropopause height. Figure 2 shows the height-time intensity maps of differences in radar SNR between zenith and 10 degree off-zenith beams of: (a) east, (b) west, (c) north and (d) south during 09:30-10:30 hrs IST on 15 July 2008. The prime mechanism for the radar backscattering/reflecting echoes is the irregularities in the radio refractive index fluctuations, which depends on the vertical gradients of temperature and humidity. As discussed earlier, the thermal gradients are mainly responsible for refractive index fluctuations in the UTLS region, which give rise to the enhanced radar reflectivity. The difference in the radar SNR for the zenith and off-zenith beams observed here indicates the presence of many layer structures associated with strong thermal gradients in the UTLS region.

To gain further insight into the radar backscattering mechanism, the height-time intensity maps of half power full spectral width and vertical velocity during the observational period have been constructed and are shown in Fig. 3. The spectral width (two times the square of variances) is an indicator of atmospheric turbulence. Enhanced spectral width observed in the UTLS region [Fig. 3(a)] indicates the presence of turbulence activity. Periodic updraft and downdraft are also observed in the UTLS region [Fig. 3(b)],

Fig. 2 — Height-time intensity plots of difference in radar SNR between zenith and 10 degree off-zenith of: (a) East, (b) West, (c) North, and (d) South during 09:30-10:30 hrs IST on 15 July 2008
which may be attributed to the presence of short period gravity waves. In order to confirm the presence of strong thermal gradient, use of the height profile of temperature measured at 10:27 hrs IST (near to the radar observational time) on 15 July 2008 has been made and is shown in Fig. 4 (a). From this figure, one can notice the strong thermal gradients at the lower stratospheric heights. The blue arrow indicates the cold-point tropopause (CPT) height (16.7 km) and the red line indicates the third order polynomial fit to the temperature profile. Figure 4 (b) shows the height profile of differences in the temperature and its polynomial fit. The fluctuation in the temperature of the order ±4 K is clearly observed in the lower stratospheric heights which corresponds to the regions where enhanced layer structures are observed in the radar backscattering signals.

To investigate the source mechanism for the formation of strong thermal gradients of order ±4 K in the UTLS region, use of zonal, meridional, and square of vertical shear of the horizontal wind derived from GPS sonde at 10:27 hrs IST on 15 July 2008 is made, which are shown in Fig. 5. It is interesting to note that the heights of the enhanced wind shears are coincident with the heights where layered structures in radar backscattering echoes are observed. Similar analyses were carried out for all other observations during 15-18 July 2008. Figure 6 shows the height-time intensity maps of: (a) mean removed signal-to-noise ratio (SNR), (b) half power full spectral width (FSW), and (c) vertical velocity (w) from 09:16 hrs IST on 15 July to 06:00 hrs IST on 18 July 2008. From Fig. 6(a), one can notice the strong layered structures in the radar SNR in the UTLS region. The presence of enhanced turbulence as indicated by spectral width is also observed at the same altitude as that of layered structure. During 15:00-18:00 hrs IST on 15 July 2008, there is a strong enhancement in SNR and FSW in the 8-16 km altitude region accompanied by strong updrafts. The strong updrafts are due to the presence of a mesoscale convective system over the radar site. Interestingly, the layer structure observed in the UTLS region in the radar echoes is diluted during the passage of convective system. During convection, the over shooting convective clouds above the tropopause height dilute the thermal gradient structure and thus, any layer structure in the radar backscattering echoes was not observed from UTLS region. Once the convective system weakened, the layered structure reappeared in the radar SNR. Figure 7 shows the height profiles of temperature gradients with an interval of 6 h during 15-17 July 2008. Strong positive and negative thermal gradients (±4 K) can be observed above the tropopause. One of the possibilities for the observed thermal gradient in the UTLS region may be the presence of long period gravity waves [i.e. inertia gravity wave (IGW)], which needs to be accounted for.

As mentioned earlier, the observational period was during the Indian summer monsoon (ISM) and one of the prime features of ISM is the presence of tropical easterly jet (TEJ). The height profiles of zonal wind
show the presence of TEJ (u≥-30 | ms$^{-1}$) and its core is observed in the vicinity of tropopause. The magnitude of meridional winds, however, is very less. It is well known that wind shear is one of the important generative mechanisms for the excitation of short and long period gravity waves$^{36-39}$. Gravity waves are one of the dominant mechanisms for the transport of energy and momentum, which in turn can change the

Fig. 4 — (a) Height profile of temperature at 10:27 hrs IST on 15 July 2008 [blue arrow indicates the cold-point tropopause height and red line indicates the third order polynomial fit to the temperature profile]; (b) Height profile of differences in the temperature and its polynomial fit line

Fig. 5 — Height profiles of: (a) zonal; (b) meridional; and (c) square of vertical shear of horizontal wind derived from GPS sonde at 10:27 hrs IST on 15 July 2008
background thermal and dynamical structure of the atmosphere. It is well established that the topography, frontal activity, wind shear, jet-streams, convection and cyclones are the major sources for the generation of short and long period gravity waves.\textsuperscript{40,41} Shear intensification by TEJ is also one of the source mechanisms for the generation of IGW, which is a long period gravity wave influenced by the rotation of the Earth (Ref. 41 and references therein). Figures 8 and 9 show the height-time intensity plot of zonal, meridional wind and vertical shear of horizontal winds derived from MST radar from 09:16 hrs IST on 15 July to 06:00 hrs IST on 18 July 2008. Strong wind shears are observed in the UTLS region due to the presence of TEJ. It is interesting to note that the height of enhanced wind shear is coincident with the height of layer structure observed in radar backscattering echoes.

Further, one needs to establish the presence of IGW in the present observations such that one can attribute the observed thermal gradients to these waves. The inertial period for IGW over the observational site is \(~52\) h (Refs 38, 42). The observations were carried out for \(~70\) h, thus, the data is not sufficient to do the spectral analysis to detect the periodicity of IGW. Sasi \textit{et al.}\textsuperscript{42} and Das \textit{et al.}\textsuperscript{38} have reported the presence of IGW of \(~56\) h associated with TEJ during ISM and cyclone, respectively over the present observational site, Gadanki. The vertical wavelengths observed were \(~1\) km during ISM and \(~2.8\) km during cyclonic conditions. Further analyses were carried out to determine the vertical wavelength by subjecting the vertical profiles of temperature, zonal and meridional wind to the Fast Fourier Transform (FFT) in the lower stratosphere. Figure 10 shows the vertical wavelength

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Fig. 6 — Height-time intensity plot of: (a) mean removed signal-to-noise ratio; (b) half power full spectral width; and (c) vertical velocity from 09:16 hrs IST on 15 July to 06:00 IST on 18 July 2008

Fig. 7 — Height profiles of temperature gradient with an interval of 6 h during 15-17 July 2008

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Fig. 8 — Height-time intensity plot of: (a) zonal wind; and (b) meridional wind derived from MST radar from 09:16 hrs IST on 15 July to 06:00 hrs IST on 18 July 2008.

Fig. 9 — Square of vertical shear of horizontal wind derived from MST radar from 09:16 hrs IST on 15 July to 06:00 hrs IST on 18 July 2008.
amplitude spectra of temperature, zonal and meridional winds in the lower stratosphere at 10:27 and 17:38 hrs IST on 15 July; 16:41 hrs IST on 16 July; 04:36 and 15:30 hrs IST on 17 July; and 04:30 hrs IST on 18 July 2008. The wind data derived from radar observations were averaged for 15 min during the launch of the balloon. The spectral analysis shows the dominant wavelength of 1.5-2 km vertical wavelength in the temperature, zonal and meridional winds, which is in the range of vertical wavelength of IGW

To investigate the time evolution of the observed vertical wavelength, wavelet analysis (Morlet as mother wavelet) was applied to the zonal, meridional and SNR as high temporal resolution measurements of these three parameters were available. Figure 11 shows the wavelet spectra of the zonal, meridional winds and radar SNR from 09:16 hrs IST on 15 July to 06:00 hrs IST on 18 July 2008. All the spectra show the presence of 1.5 to 2 km vertical wavelength. The time evolution of each spectrum shows the similar characteristics. One of the typical behaviour of the IGW is the propagation of its phase. As mentioned earlier, sufficient data is not available to do spectral analysis but with the available data, one can determine the propagation characteristics of IGW by detecting amplitude and phase of the ~52 h oscillation using least-square fitting analysis. Figure 12 shows the reconstructed height-time intensity plots of zonal and meridional winds corresponding to the inertial period of IGW. The phase fronts of the wave are clearly identified from these figures. Downward phase propagation in both zonal and meridional winds indicates the presence of vertical propagating IGW. Shorter vertical wavelength of 1.5-2 km is observed in winds and temperature; and the propagation characteristic of observed waves confirms the

Fig. 10 — Vertical wavelength amplitude spectra of temperature, zonal and meridional winds in the lower stratosphere
presence of IGW. Moreover, the vertical wavelength observed in the radar backscattering echoes are identical to the wavelength estimated in winds and temperature indicating the influence of IGW modulations of thermal structure and hence, the radar backscattering in the UTLS region.

Luce et al.\textsuperscript{17} have described that non-linear steeping of gravity waves as well as viscous or thermal conductive waves can produce strong temperature gradients. However, viscous or thermal conductive waves do not propagate and get partially reflected\textsuperscript{30}. Initial stages of KHI billow may also develop the strong temperature gradients as discussed earlier\textsuperscript{9,18,22-24}. Luce et al.\textsuperscript{17} have also discussed that KHI billows may dissolve the gradient in the temperature as strong mixing takes place in the region of occurrence of KHI. Turbulence mixing is also one of the other causative mechanisms for the enhanced temperature gradient in its edges. The turbulence created by KHI or the KHI alone can create the strong thermal gradients as observed in the UTLS region of temperature profiles. It is known that the IGW can easily trigger the formation of KHI in the lower stratosphere\textsuperscript{43}. This gives a clue that the IGW is the prime candidate for the observed thermal gradients in the UTLS region, which is the responsible mechanism for the observed enhanced VHF radar backscattering echoes. To summarize, the IGW excited by the strong shears associated with TEJ modulate the thermal structure in the UTLS region by creating thermal gradients. These thermal gradients, in turn, are responsible for observed layer structures in the radar.

Fig. 11 — Intensity plot of vertical amplitude spectra of: (a) zonal wind; (b) meridional wind; and (c) signal-to-noise ratio from 09:16 hrs IST on 15 July to 06:00 hrs IST on 18 July 2008.
backscattering echoes. In the near future, similar experiments will be conducted every month to understand the seasonal characteristics of thermal structure modulated by wave motions in the UTLS region.

4 Summary
The observations of layer structures in the VHF radar backscattering echoes in the upper troposphere and lower stratosphere are discussed including their causative mechanisms. Analysis shows that the layer structures in radar echoes are due to the presence of strong negative and positive thermal gradients existing in the UTLS region. Moreover, these layer structures (except the tropopause height) seem to be non-aspect sensitive in nature, viz. the radar echoes from zenith and off-zenith beams are almost of the same order. The analysis also showed the presence of turbulence activity and strong up and downdraft in the UTLS region. Wind shears associated with tropical easterly jet, which is one of the prime features of Indian summer monsoon is observed in the vicinity of tropopause. The vertical wavelengths observed in the zonal wind, meridional wind, temperature and radar backscattering echoes are in the range of 1.5-2 km. The order of the observed vertical wavelengths in these parameters is similar to IGWs triggered due to tropical easterly jet over this latitude. It is believed that the layer structures in the radar backscattering echoes observed in the UTLS region are associated with the thermal gradients induced by KHI, which in turn triggered by the propagation of inertia gravity waves during the observational period. However, further studies on consequences of gravity wave breaking/dissipation in the UTLS region are required to arrive at any general conclusions on generating mechanisms of the observed temperature gradients and associated radar’s layer structures. More experiments using simultaneous measurements of GPS sonde and MST radar are necessary to study the seasonal characteristics and to draw final conclusions.

Acknowledgement
The authors gratefully acknowledge the support provided by the scientific and technical staff of the National Atmospheric Research Laboratory (NARL), who has contributed to the collection of the data reported in this paper. The support and encouragement provided by Dr K Krishna Moorthy and Dr Geetha Ramkumar are greatly appreciated. The authors greatly acknowledge Prof A Jayaraman, Director, NARL for initiating and implementing the 5-year SAFAR programme, under which these experiments are conducted.

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