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Patchy layered structure of tropical troposphere as seen by Indian MST radar

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The MST radar observations at Gadanki (13.47° N, 79.18° E) show, almost every day throughout the year, stratified layers of intense reflectivity near the tropopause level (~17 km) and also at a couple of levels between 4 km and 10 km. Highest individual reflectivity values occur near 17 km, but they occur for a short while. The region between 11 km and 15 km shows the lowest values of reflectivity alongwith vertical downward motion almost on all days of the year. High values of reflectivity are attributed to the existence of visible or sub-visible clouds; the layered structure of clouds is attributed to inertio-gravity waves with vertical wavelength of 2-3 km. It is suggested that each high reflectivity layer consists mainly of thin sheets and patches of visible and sub-visible cloud material. Hydrometeors inside the cloud material go up and down due to gravity, precipitation-loading, Brunt-Vaisala oscillations, and Kelvin-Helmholtz waves. In these small-scale motions, thin air sheets and patches get formed with sharp temperature and humidity discontinuities through contact cooling, melting, evaporation, condensation and freezing. Also, melting and freezing at low temperatures generate electrical charges in these thin sheets and patches. These thin sheets and patches have vertical dimensions ranging from a few centimetres to several metres and horizontal dimensions of the order of 1km. These thin sheets and patches have corresponding vertical and horizontal discontinuities and sharp gradients in refractive index for the MST radar beam. These show up as regions of high values of reflectivity.

1 Introduction

During the last half century, a belief has grown that tropical region is characterized mainly by deep convective clouds rather than by layered clouds. The reason for this belief has been two-fold: first, tropical atmosphere is convectively unstable; and second, heavy rain which is experienced in the tropical region can have its origin only in deep convective clouds with sufficient cloud depth and subfreezing temperatures to allow the growth of large-sized drops.

Recent observations have shown that in addition to deep convective clouds over limited areas, there are layered clouds over extensive areas in the tropical region where layered clouds also give almost as much total amount of rainfall (totalled up over large areas) as given by convective clouds over smaller areas[1-4]. As stated by Houze[4], 'stratiform precipitation' is a term often used in meteorology, yet the term is not defined in the *Glossary of Meteorology*[5], and its meaning and usage continually evolve. This paper attempts to clarify the meaning of the term 'stratiform precipitation' as it is currently used in the particular context of tropical meteorology and other regions where clouds are generated by atmospheric convection. Such an article would have seemed paradoxical, if not out-right heretical, 30 years ago. Also the concept of the existence of thin sub-visible cloud layers, which have considerable horizontal extension in earth's atmosphere, is receiving much attention in the recent studies of atmospheric science[6-9]. These thin sub-visible cloud layers are very important because of their possible impact on earth's radiation budget and atmospheric chemistry.

In Indian monsoon region, layered clouds are known to be present over extensive areas, but their structure has not been studied in any detail. Also, to our knowledge there have been no studies so far, except those of Asnani *et al.*[10], Rama Varma Raja *et al.*[1] and Rama Varma Raja [12], dealing with thin sub-visible cloud layers in this tropical region. The MST radar at Gadanki has offered a very good opportunity for such type of studies over that area. An excellent description of Indian MST radar system is given by Rao *et al.*[13].

In this paper the results of the analysis of MST radar data at Gadanki, extending over a period of 15 months with a total time coverage of about 150 h are presented. The results are somewhat unconventional in the sense that what has been previously put in the 'black box of turbulence or stable layers' is now shown to reveal the role of water substance and aerosols in producing visible and sub-visible cloud layers. Asnani *et al.*[10], Rama Varma Raja *et al.*[11,14] and Rama Varma Raja[12] have clearly shown that clear-air mechanical turbulence is not the primary source for observed MST radar reflectivity in the lower atmosphere. It is believed that this line of thinking will stimulate more thinking and research in interpreting reflectivity data obtained from MST radars not only in the tropics but also elsewhere in the world.

2 Data analysis

We have done detailed analysis of the Doppler spectrum data of the MST radar, taken for at least half-an hour, almost every day, from September 1995 to November 1996. On some special occasions, we had data for 24 h a day. For the year 1997 also, data of a few days have been analyzed, which also confirms the conclusions derived from the data of 1995-1996 mentioned above.

From these data, range-corrected signal-to-noise ratio $\left(r^2 \frac{S}{N}\right)$ and u, v, w components of the wind vector have been computed. The $\frac{S}{N}$ is the signal-to-noise ratio. Reflectivity is proportional to $r^2 \frac{S}{N}$, the factor of proportionality depending on the configuration of the radar. For the sake of brevity we call this $r^2 \frac{S}{N}$ as reflectivity, of course, in arbitrary units. The spatial variations of this quantity $\left(r^2 \frac{S}{N}\right)$ are highlighted as spatial variations of reflectivity in the troposphere.

On days of disturbed weather, the visual cloud observations and infra-red satellite observations are used to get the temperatures and heights of cloud tops. Monthly normal radiosonde data of Madras and other stations in peninsular India have also been used to draw the present conclusions about large-scale temperature and humidity gradients in the vertical.

Reflectivity data have been analysed at each of 116 levels at intervals of 150 m from 3.6 km to 21 km. Monthly mean values of reflectivity have been calculated at each of the 116 levels and the vertical profiles of reflectivity analysed.

Very high values of reflectivity observed at each level were further examined to study the horizontal and vertical structure of reflectivity pattern. This analysis of reflectivity has been done in conjunction with horizontal and vertical wind components at each level. Spectral analysis was done for the height axis at an instant of time as well as for the time axis at a level. Recently, lower atmospheric wind profiler (LAWP) system has been installed at Gadanki which allows extension of MST radar results from 3.6 km down to 0.5 km level above ground.

3 Results of analysis

(i) The MST radar observations show, almost every day throughout the year, stratified layers of intense reflectivity near tropopause level (~17 km) and also at two-three levels between 4 km and 10 km. Contour plot of reflectivity, for 9 Sep. 1995 and for the period 16:27:58 - 17:04:38 hrs IST, given in Fig.1 is an illustration for these layers.

(ii) Highest individual reflectivity values (of the order of 20,000 units and more) occur near tropopause level (near 17 km), but for a short period of time. Figure 2 shows the vertical profile of reflectivity for an individual MST radar scan for 9 Sep. 1995 at 17:02:42 hrs IST. Within the vertical resolution of MST radar (150 m), half-width of reflectivity pattern comes out to be of the order of 120 m depth. In the horizontal, half-width is of the order of 1.5 km. Air parcels of these horizontal and vertical dimensions with very high reflectivity characteristics are advected horizontally as well as they move up and down in association with Brunt-Vaisala oscillations and Kelvin-Helmholtz waves.

(iii) At other levels (between 10 and 4 km), similar vertical and horizontal characteristics of reflectivity are seen, but the highest values of reflectivity(of the order of 10,000 units) seen at these levels are much smaller than the highest values seen at 17 km. This is illustrated in Figs 1 and 2.

(iv) The region between 11 km and 15 km gives the lowest values of reflectivity almost on all days of the year. Analysis of corresponding vertical wind velocity shows that this region (between 11 km and 15 km) is characterized largely by vertical downward motion. Figure 3, illustrates the vertical profile of monthly average of reflectivity and vertical velocity. Horizontal winds in the layer 11-15 km were quite strong and not light variable.

(v) Vertical wind observations show organized vertical upward and downward motions. Figure 4(a) shows the contour plot of vertical velocity for 9 Sep. 1995 for the time period 16:27:58-17:04:38 hrs IST, which illustrates clearly the organized vertical upward and downward motions.

(vi) The horizontal wind, $\sqrt{u^2 + v^2}$, tends to be maximum near the layers of high reflectivity. Figure 4(b)

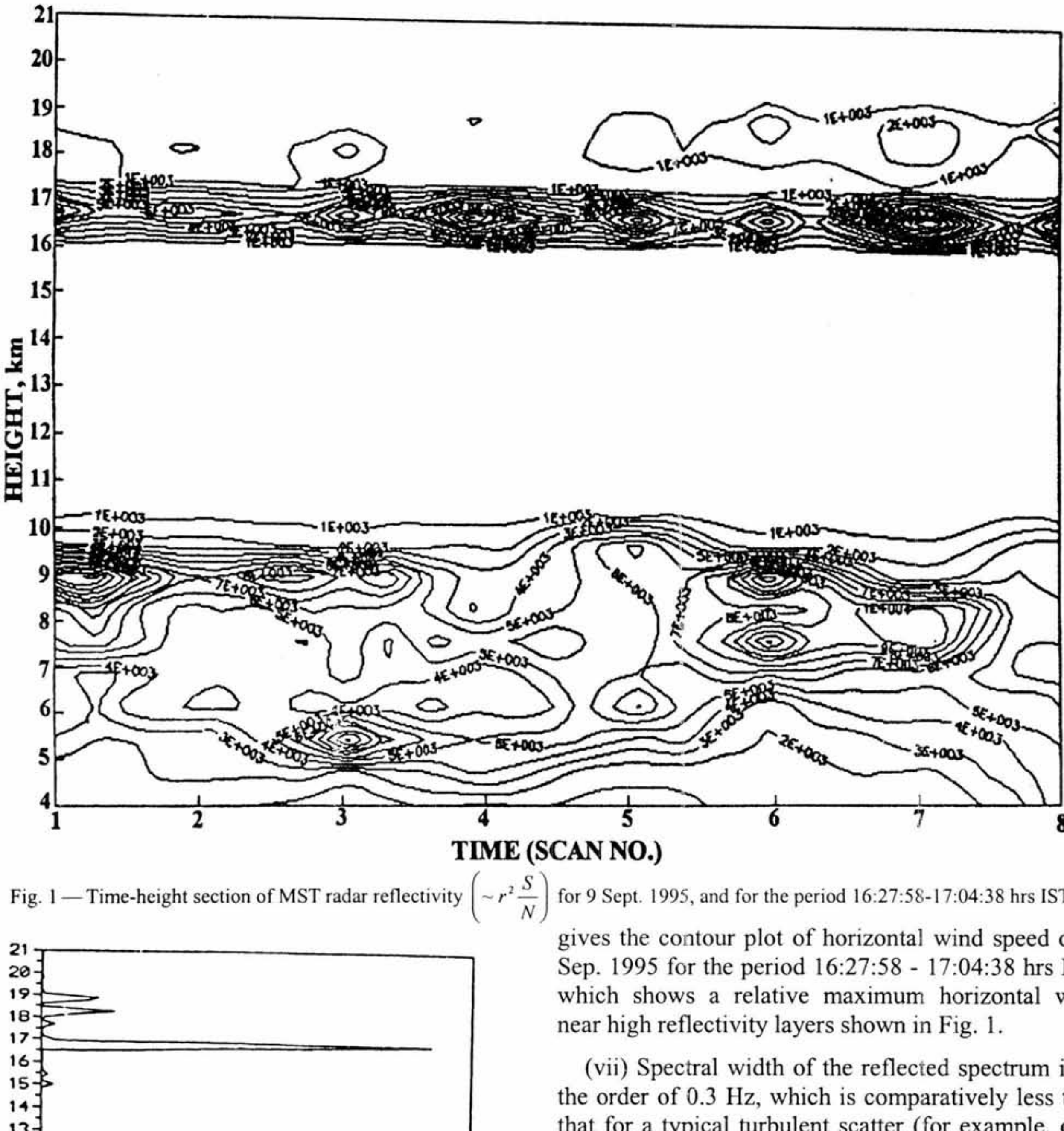

Fig. 1 — Time-height section of MST radar reflectivity $\left(\sim r^2 \frac{S}{N}\right)$ for 9 Sept. 1995, and for the period 16:27:58-17:04:38 hrs IST

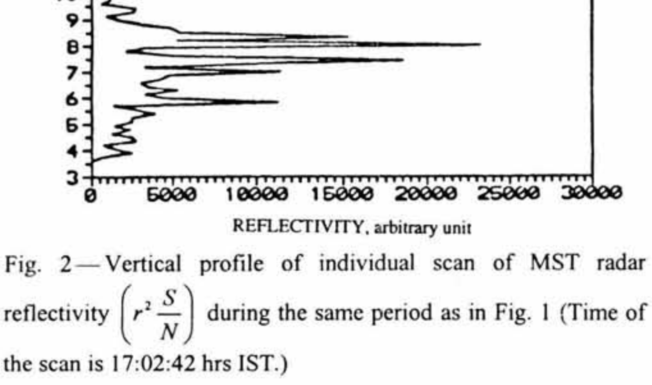

Fig. 2 — Vertical profile of individual scan of MST radar reflectivity $\left(r^2 \frac{S}{N}\right)$ during the same period as in Fig. 1 (Time of the scan is 17:02:42 hrs IST.)

gives the contour plot of horizontal wind speed on 9 Sep. 1995 for the period 16:27:58 - 17:04:38 hrs IST, which shows a relative maximum horizontal wind near high reflectivity layers shown in Fig. 1.

(vii) Spectral width of the reflected spectrum is of the order of 0.3 Hz, which is comparatively less than that for a typical turbulent scatter (for example, on a thunderstorm day it can be of the order of 1Hz), suggesting that reflection mechanism is not purely due to Kolmogorov type of turbulence.

(viii) Large-scale Richardson number (*Ri*) was calculated from:

(a) Monthly climatological values of temperature and its lapse rate over Tirupati, and
(b) Vertical shear of wind from MST radar wind data, interpolated from climatological charts of south India.

It was found that in the layers of high radar reflectivity, the value of large-scale Richardson number was quite high (of the order of 3 or 4), which is much

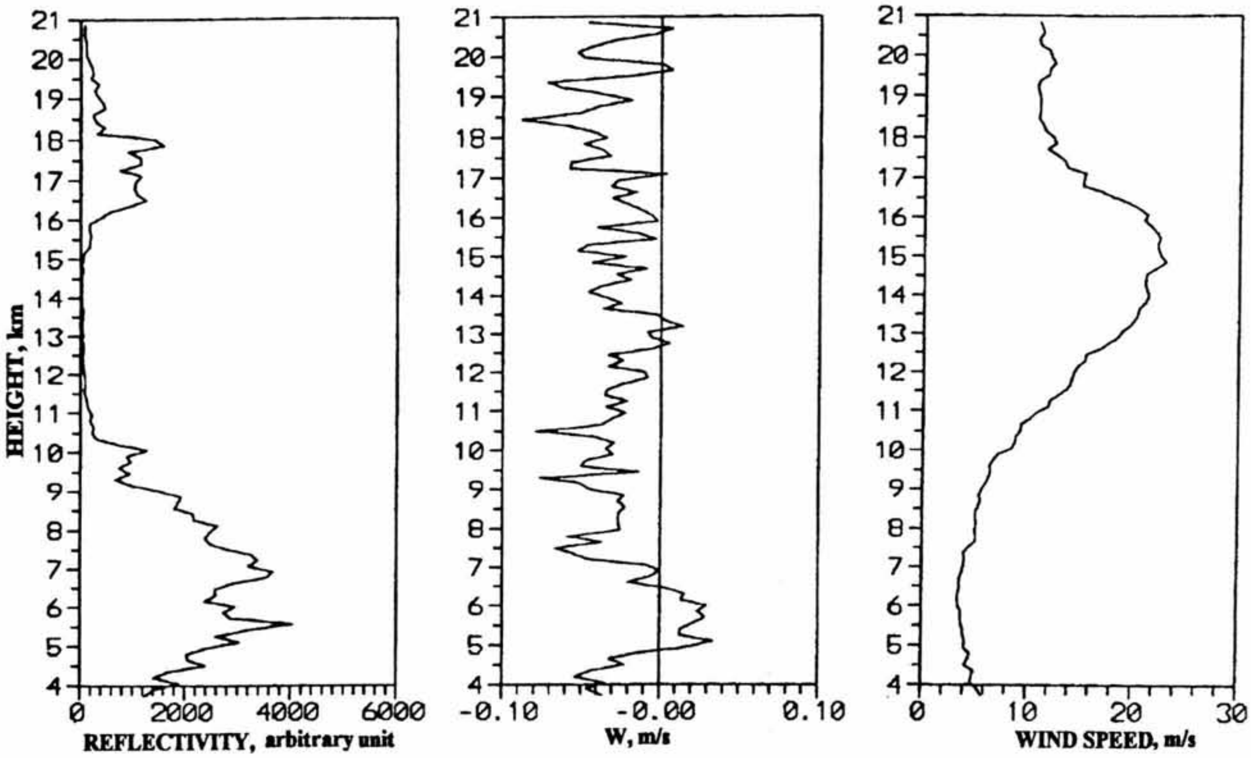

Fig. 3 — Vertical profile of monthly averages of MST radar reflectivity, vertical velocity and total horizontal wind speed for the month of September 1995

larger than the critical value of 1/4 for the occurrence of Kolmogorov type of turbulence. It is possible that inside the thin sheets and patches postulated in the hypothesis presented in Sec. 4, *Ri* is less than 1/4 on some occasions. In these thin sheets and patches, it is possible, as shown by some observations elsewhere[15], that temperature lapse rate may reach very high values (30-100 K/km), which is quite different from large-scale monthly climatological values of temperature lapse rate used by us. In such cases *Ri* may be less than 1/4. At present, we have no means to measure such high lapse rates near Tirupati. But from theoretical reasoning, it is very clear that very high lapse rates in air can occur in thin sheets due to micro-physical and micro-dynamical processes associated with hydrometeors existing inside a visible or sub-visible cloud mass.

4 Discussion

The results of this analysis and supportive evidence from published literature are fitted into the following hypothesis:

4.1 High reflectivity near tropopause level

The existence of an aerosol/haze/cloud layer near tropical tropopause level was first suggested by Asnani *et al.*[16] They attributed the high-MST radar reflectivity from near tropopause region to this tropopause aerosol/haze layer. Further research in the same direction and the supporting evidences from published literature have clearly shown that there is an aerosol/haze layer near the global tropopause region[12]. In the tropics, inter-tropical convergence zone (ITCZ) and other semi-permanent convergence zones in the troposphere are continuously pumping moisture and aerosols from the lower troposphere into the upper troposphere. In case of deep cumulus convection, water substance and aerosols spread in the form of thick cirrus and cirro-stratus clouds, generally, below the tropopause level, but occasionally breaking through the tropopause into the lower stratosphere. When the cirrus clouds melt, water vapour and aerosols separate out, giving large relative humidity and high aerosol content in the air layer surrounding them near the tropopause[16]. Due to high values of static stability, vertical turbulent mixing of aerosols and water vapour is inhibited in this layer. In this layer, at very low temperatures (about −70°C) prevailing near the tropical tropopause level, aerosols and water vapour also coagulate or get frozen into ice-cloud particles. These particles go up and down due to gravitational pull, precipitation-loading, Brunt-Vaisala oscillations and Kelvin-Helmholtz waves. In these small-scale upward and downward motions of ice-aerosol particles, thin air sheets and patches with temperature and humidity

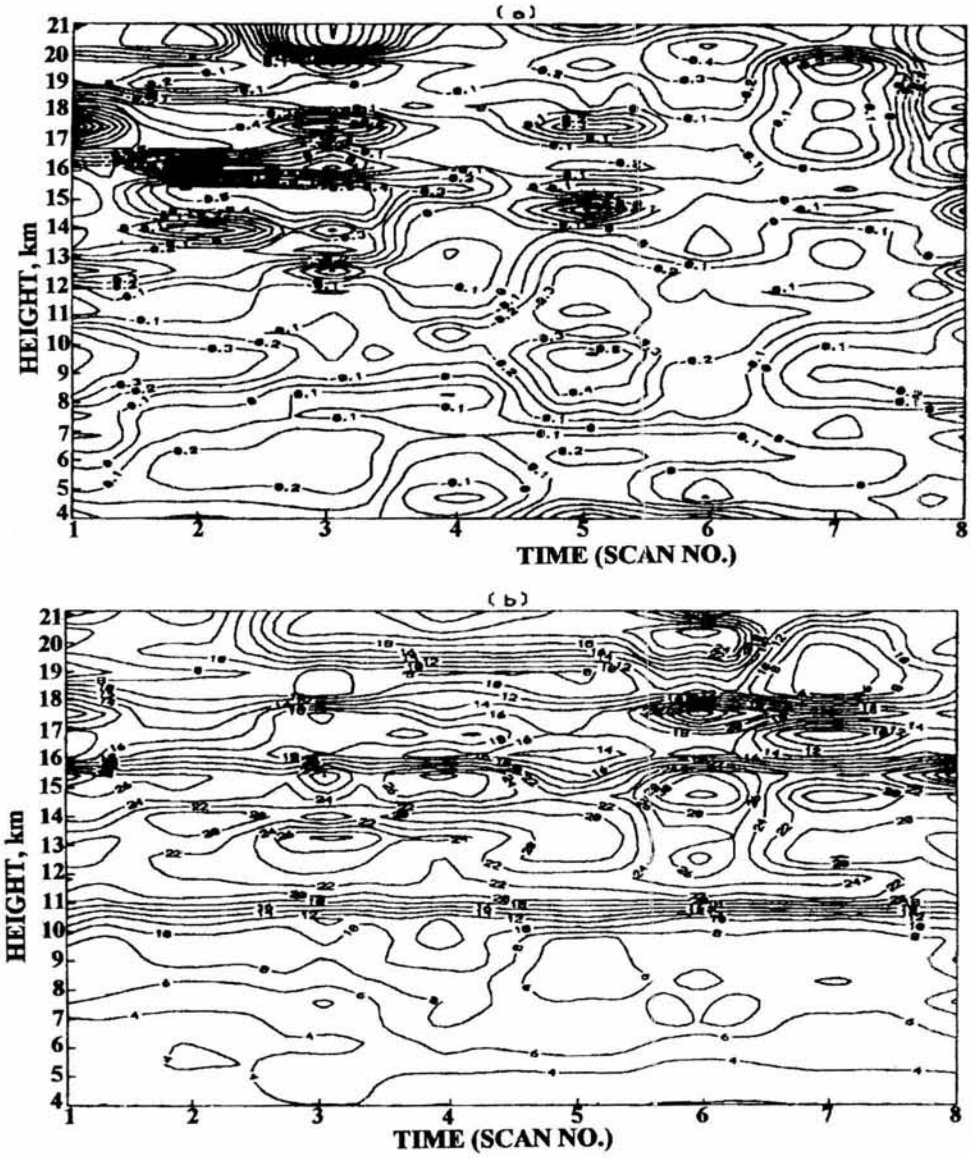

Fig. 4 — (a) Time-height section of vertical velocity (m/s) and (b) Time-height section of total horinzontal wind speed, $\sqrt{u^2 + v^2}$, for the same period as in Fig. 1.

discontinuities in the vertical and horizontal directions get formed through contact cooling, melting, evaporation, condensation and freezing. Also, melting and freezing at low temperatures generate electrical charges in these thin sheets/patches. These thin sheets/patches have vertical dimensions ranging from a few centimetres to several metres[15]. These thin sheets have corresponding discontinuities and steep vertical and horizontal gradients in refractive index for the MST radar beam which has the frequency 53 MHz and wavelength about 6 m. These discontinuities and steep gradients in refractive index show themselves up in the form of high values of reflectivity from the layer near the tropopause[16]. The clusters of hydrometeors and aerosols inside thin sheets/patches cause Rayleigh as well as Mie scattering of MST radar beam, while thin sheets/patches themselves with steep gradients of refractive index inside cloud layers cause Bragg/Fresnel scattering. Thus inside a layer-cloud, there is a combination of different types of scattering/reflection, such as Rayleigh, Mie, Fresnel/ Specular and Bragg types giving the observed reflectivity patterns. It is the present belief that at the relatively larger wavelength of Indian MST radar (~6m), Rayleigh scattering or Mie scattering may not give rise to detectable radar beam return. But it is felt here that, certainly the scattered signal due to Rayleigh scattering and Mie scattering from thousands of particles (aerosol particles or hydrometeors) inside the layer cloud can contribute to the part of the back-scattered signal received at the ground. However, it must be admitted that more research work needs to be done to explore this connection between Rayleigh/Mie scattering and Bragg scattering in as much clusters of hundreds and thousands of small particles as are created for detectable variations in physical properties of the air over distances ranging from a few centimetres to several tens of metres of the air medium.

4.2 High reflectivity between 10 km and 4 km

In other layers also, between 10 and 4 km levels, similar thin sheets/patches with sharp discontinuities and steep vertical and horizontal gradients in the refractive index get generated and show themselves up in the form of high values of reflectivity for the MST radar beam.

4.3 Low reflectivity between 11 and 15 km

Subsidence creates relative dryness, lack of clouds and hydrometeors in this layer and hence low reflectivity. This is connected with large-scale planetary circulation over the region.

5. Discussion of some aspects of hypothesis

5.1 Inertio-gravity waves

Figure 5 shows a picture from geostationary satellite over the Indian Ocean on 19 Oct. 1994. The following features are noteworthy:

There is a line of clouds running N-E to S-W from coastal Orissa (20°N, 85°E) to south of equator (5°S, 55°E) in the Indian Ocean and then in N-W to S-E direction up to (15°S, 90°E). Along this line of clouds, we see clouds clustered around some points, 500 km-1000 km apart. The large-scale line of clouds, first from N-E to S-W and then from N-W to S-E is a part of planetary-scale Rossby-type wave motion. The smaller-scale waves in the form of cloud clusters with wavelength separation of 500-1000 km are inertio-gravity waves which are larger than pure gravity waves (wavelength ~50 km) but smaller than Rossby

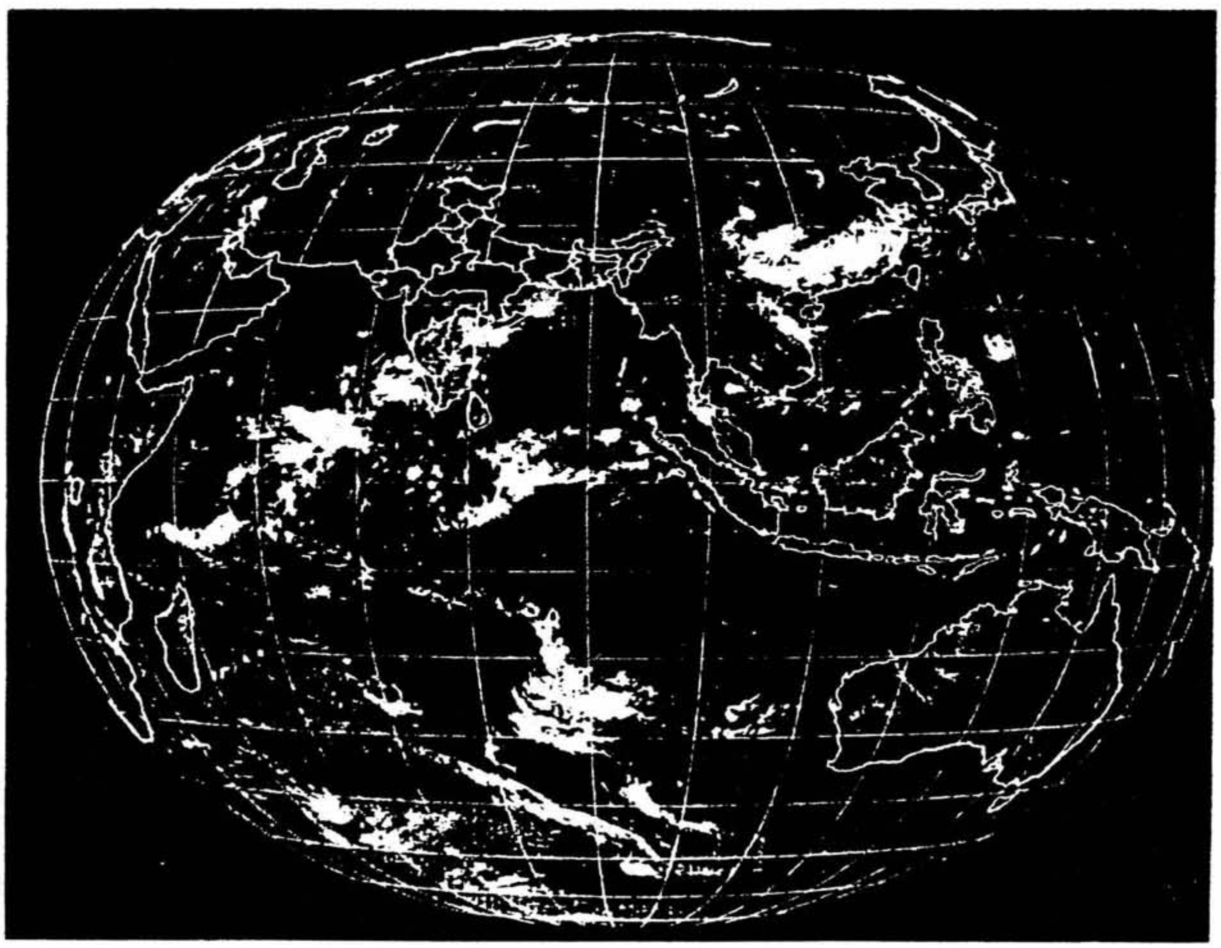

Fig. 5 — Satellite picture (visible) from Indian National Satellite (INSAT 2B), over the Indian region on 19 Oct. 1994 at 06.00 hrs GMT [From Orissa coast (20°N, 85°E) to south of equator (5°S, 55°E) in the Indian ocean, line of cloud clusters which are separated by a distance of 500 km are seen.]

waves or inertial waves (wavelength ~4000 km), as suggested by Asnani[17] and others[11,12,17-24]. Such inertio-gravity waves are seen in many satellite pictures over the Indian Ocean and also elsewhere in the world.

The dynamical theory of such inertio-gravity waves is still in the initial stages of development. Inertio-gravity waves are known to be generated in the lower troposphere through irregularities in the terrain and also by irregularities in diabatic heating. The wave energy moves upward, the energy of the smaller wave components gets absorbed in the lower troposphere itself; relatively larger wavelengths survive and transmit energy into the middle and upper tropopshere and also into the stratosphere[18-22]. Every horizontal wavelength in orographic and diabatic heating has its corresponding horizontal and vertical wavelengths in the spectrum of inertio-gravity waves generated by the irregularities. According to Jones[23] and Wurtele *et al.*[24], every wavelength of inertio-gravity waves has three singular levels at which the fluxes of momentum and energy tend to get trapped. In the present reflectivity pattern also, we get, almost every day, a bunch of high reflectivity layers below 10 km level. Near these levels, horizontal wind maxima are also observed suggesting trapping of momentum and energy. Near these levels convergence of vertical flux of momentum is often seen. These horizontal wind maxima and minima as well as organized convergence of vertical flux of momentum are obviously of dynamical origin. We are still working on making a consistent observational-cum-dynamical model of this interesting phenomenon. At present, we can only qualitatively suggest that these are due to inertio-gravity waves generated near the ground, with upward flux of energy, trapped below 10 km level. The LAWP data extending down up to 0.5 km ground confirm this suggestion.

5.2 Relative humidity in the tropical upper troposphere

Recent analysis of satellite data shows that relative humidity in the upper troposphere in the tropics has very high values ($\geq 70\%$) in general. Figure 6 taken from Newell *et al.*[25] shows that relative humidity in the tropics above 16 km is generally more than 90% on climatological basis. They[25] have shown the latitude -height distribution of relative humidity along 145°E in mid-Pacific region, in the month of February when ITCZ is south of the equator and south pacific convergence zone (SPCZ) is active. These tropospheric convergence zones with accompanied deep convection inject considerable amounts of moisture and aerosols from the lower troposphere into the middle and upper troposphere. As stated earlier, near the convective cloud tops, the moisture and aerosols spread out as cirrus clouds. When these clouds melt they leave large and small patches of water vapour and aerosols. Hadley cell circulations, Walker circulations, Rossby waves, Kelvin waves, mixed Rossby-gravity waves, tropical easterly waves and other large-scale eddy systems help in diffusing the water substance and aerosols throughout the tropical troposphere north and south of the equator. This injection and diffusion process goes on throughout the year. Using data from the satellite SAGE II (Stratospheric Aerosol and Gas Experiment II), Kent *et al.*[7] have confirmed large amounts of cloud, often in sub-visible form above 16 km level over tropics, which cannot be identified even by ordinary satellite measurements, particularly, when they are in thin sub-visible form. Through lidar measurements over Chung-Li, Taiwan (25° N), Nee *et al.*[8,9] observed, very often for almost throughout the year, very thin cirrus clouds often in sub-visible form near tropopause level. There are many reports of cirrus clouds staying for long time and finally getting dissolved near the tropical tropopause level[8,9]. Recent observations over the American region using airborne lidar and other sophisticated instruments have provided evidence of the occurrence of precipitating cirrus clouds quite often near the tropopause level[26].

Anywhere in the tropical region, if one looks at the sky during twilight hours in the morning and in the evening he will almost always see golden coloured cirrus clouds in the form of streaks, streets or layered sheets at various levels.

5.3 Small-scale fine structure inside each layer

Inside and at the upper and lower boundaries of each such high-reflectivity layer, one can clearly discern small-scale fine-structure oscillations or wave motions. The time period of these small-scale waves is of the order of a few minutes. Maximum value of reflectivity occurs near the centre of the layer. Value of reflectivity decreases systematically away from the centre, vertically upwards, vertically downwards and in the horizontal. There is a lot of orderliness in the reflectivity pattern, like fine embroidery work, in the vertical as well as in the horizontal (time) scale. It cannot be dispensed with as chaotic turbulent motion as has generally been done in earlier works. Our hypothesis is that the high reflectivity layer consists of 'thin sheets' or 'patches' of air having structural discontinuities, particulalry in the vertical, of temperature

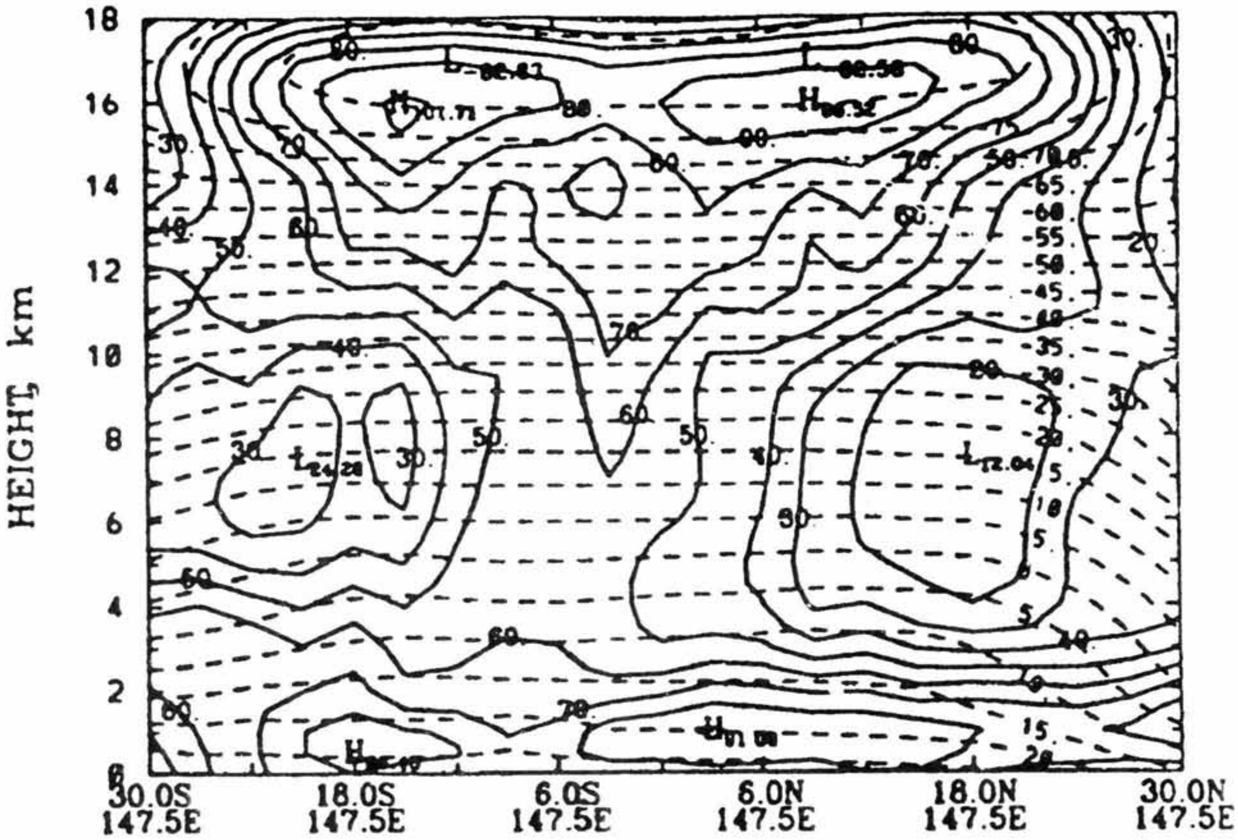

Fig. 6 — Cross-section of monthly mean relative humidity and temperature for February 1994 along 147.5°E [Solid line indicates relative humidity (%) while dashed line indicates temperature (°C); after Newell *et al.*[25]]

lapse rate, humidity lapse rate, liquid water content, ice and aerosol content. There are hydrometeors inside these thin sheets/patches. These hydrometeors go up and down inside the 'mother layer' under gravitational influence of buoyancy, hydrometeor-loading and frictional stress. The surrounding air exchanges heat with the vertically moving hydrometeors through contact cooling, melting, freezing, condensation and evaporation. Detailed quantitative calculations of such effects were presented by Asnani[27-29] when analysing the surface pressure fluctuations accompanying hail storms of different intensities, severe hail storms being accompanied by a pressure dip rather than by conventional pressure hump. These micro-physical and micro-dynamical processes inside a cloud-mass create air density gradients in the horizontal and correspondingly upward and downward buoyancy accelerations of an air parcel. In general, upward motion of an air parcel tends to create unstable temperature lapse rate in the vertical and higher value of relative humidity, while downward vertical motion tends to create stable vertical lapse rate of temperature and lower value of relative humidity.

These gravity oscillations due to density gradients in the horizontal and vertical are known as Brunt-Vaisala oscillations with periods of the order of a few minutes. In addition, when there is vertical wind shear along with density gradients, we get Kelvin-Helmholtz waves with horizontal wavelengths of a couple of kilometres[30].

Refractive index is a function of temperature and humidity in the troposphere and lower stratosphere. Thin sheets having large vertical gradients of temperature and humidity have also strong gradients and discontinuities in refractive index with respect to the MST radar beam. Mother cloud layers containing these thin sheets scatter and reflect the radar beam. As such, these layers show strong reflectivity as measured by the power received back at the source level[11,12,14,22].

Freezing of water substance is also known to be accompanied by the separation of electrical charges[31]. In the high-reflectivity (cloud) layers above the freezing level at sub-zero temperatures, ions and free electrons attached to the frozen ice particles are also likely to be present. Their role in causing high radar reflectivity in the troposphere cannot be ruled out although more observational and calculation needs to be done on this aspect. Extremely high values of reflectivity near 17 km reported in Sec. 3 of this paper might be, partly at least, due to such electrical processes. These observations open up a fascinating field of exploration.

5.4 Clouds and reflectivity

Until recently, layers of high reflectivity of MST radar from troposphere and stratosphere were put into something like black box called 'turbulence' or 'stable layers'. The role of water substance (water vapour, liquid water and ice) and aerosols in creating thin sheets and patches of air with irregularities and discontinuities in density, temperature, humidity and hydrometeor loading, and hence irregularities in refractive index, ultimately creating large scattering and reflection of MST radar beam in these high-reflectivity layers has not been sufficiently brought out in earlier studies. We are emphasizing the crucial role played by water substance in these MST radar-reflectivity layers. These layers are cloud layers which are either visible to the naked eye or sub-visible[11,12,14,22]. On a few occasions, we have verified the existence of cloud layers at levels of high reflectivity through infra-red satellite pictures and also through visual observations.

6 Summary and conclusions

(i) The 1-2 km thick layer of air near the tropopause is a layer of high relative humidity and high aerosol content. Temperatures are very low(~70°C). Condensation, freezing and coagulation of aerosols with water substance make this a layer of visible or sub-visible clouds. Upward and downward motion associated with small-scale Brunt-Vaisala oscillations and Kelvin-Helmholtz waves inside this layer make parts of this layer prominently visible in the form of cirrus cloud streets, streaks or sheets. Morning and evening twilight gives beautiful golden colours to these cirrus clouds.

(ii) Inertio-gravity waves originating near the ground generate 2 - 3 high-reflectivity cloud layers, each about 1 km thick and with vertical separation of 1-2 km, below 10 km level over Indian MST radar location.

This vertical arrangement of cloud layers gives the appearance of wave-breaking near 10 km level with a horizontal wind velocity, maximum near this level.

(iii) Layer between 11 and 15 km, generally, shows very low values of radar reflectivity. Vertical motion in this layer is almost invariably downward. This subsidence is attributed to large-scale flow characteristics over Tirupati, the location of the MST radar.

(iv) We call the high-reflectivity layers, each 1-2 km thick, as 'Mother layers'. These mother layers contain clusters of small-scale thin sheets and patches of cloud matter along with hydrometeors. The thin sheets and patches have vertical dimensions ranging from a few centimetres to several metres and horizontal dimensions of the order of 1 km. These thin sheets and patches exchange heat, mass and momentum with their environment through micro-physical and micro-dynamical processes involving melting, freezing, evaporation, conduction, precipitation, Brunt-Vaisala oscillations and Kelvin-Helmholtz waves.

These thin sheets and patches create corresponding vertical and horizontal discontinuities and steep gradients in refractive index for the MST radar beam. These show up as regions of high values of radar reflectivity, through combination of Rayleigh, Mie, Fresnel and Bragg type of reflections and scattering mechanisms. Water substance and aerosols in various forms are the main cause of high reflectivity.

(v) Electrical charges generated during freezing and melting at very low temperatures may also contribute towards high reflectivity.

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