Layered clouds in the Indian monsoon region

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Contrary to the prevalent belief that tropical region is characterized by convective clouds rather than by layer clouds, we have suggested that deep convective clouds occur on meso-scale, but layer clouds occur on larger synoptic-scale with a relatively small region of deep convective clouds. Sustenance of deep convective clouds is inhibited by the presence of inertio-gravity waves, which have alternating layers of upward and downward motion in the vertical. We have also shown that inertio-gravity waves generate regions of relatively strong horizontal velocity, vertically separated by layers of relatively weak horizontal velocity. Layers of strong horizontal velocity are created by inertio-gravity wave system through convergence of vertical flux of horizontal momentum. We have also suggested that horizontal convergence/divergence of moisture flux is generated by inertio-gravity waves, giving rise to vertically alternating layers of high/low humidity, and visible or sub-visible clouds. Layers of high humidity become layers of strong radar reflectivity at frequency of 53 MHz at which MST Radar at Gadanki, near Tirupati, India, operates. These observations, more than 2,50,000 in number, for vertical grid points, spread over all the months of the year, have helped us, among other observations, to arrive at these conclusions. Further, the analysis suggests that the main source of strong MST radar reflectivity is not mechanical turbulence as is commonly believed.

1. Introduction

During the last half century, a belief has grown that a tropical region is characterized mainly by deep convective clouds rather than by layered clouds. The reason for this belief has been two-fold: firstly, tropical atmosphere is convectively unstable; secondly, 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 growth of large-sized drops (Asnani 1993).

From some of the recent observations, over extensive areas in Australian monsoon region and elsewhere, there have been found extensive layered clouds in addition to convective clouds over limited regions (Webster and Stephens 1980; Williams *et al* 1992; Houze 1993; Cifelli and Rutledge 1994; Houze 1997; Nee *et al* 1998). Over the Indian monsoon region, so far such an extensive study using sophisticated and collocated measurements have not been carried out. Then the question is whether, we have extensive areas of layered clouds in the Indian monsoon region also.

The answer to the above-mentioned question appears to be 'yes' by considering the following phenomenon. The routine synoptic observations over the Indian region show that when a monsoon depression forms over the head Bay of Bengal, we get light continuous rain/drizzle over the whole belt extending from the Konkan coast to the north Bay of Bengal. Surface observatories report thick alto-stratus clouds in this belt. Heavy rain is confined to a relatively small area in the SW-sector of monsoon depression. The heavy rain comes from the convective type of clouds whereas the widespread light rain is from extensive areas of alto-stratus clouds.

Keywords. Layered clouds; convective clouds; visible clouds; sub-visible clouds; inertio-gravity waves; Brunt-Vaisala oscillations; Kelvin-Helmholtz waves; turbulence; MST radar reflectivity.

Proc. Indian Acad. Sci. (Earth Planet. Sci.), **108**, No. 4, December 1999, pp. 287–295

The existence of extensive areas of layered clouds in the tropical region raises the question: "Do these clouds arise only out of the spreading of anvil clouds from deep convective clouds, or is there also an independent mechanism to generate layered clouds in the tropics?" Is it also possible that these layered alto-stratus type clouds form due to the upgliding motion of air of the north over the underlying relatively cool air below the inclined surface of ITCZ like a warm front?

The present paper reports some preliminary results of the observational study of layered clouds occurring over the Indian peninsular region, near the east coast, using Indian MST radar observations. The study tries to address the above-mentioned questions about the existence of extensive areas of layered clouds over this Indian region and their generation mechanism. It appears to us that the above-mentioned belief, mentioned in the first paragraph of this section needs to be modified and replaced by the following statement:

Deep convective clouds occur in the tropics only in meso-scale (sub-synoptic scale) configurations at a few locations. On the synoptic scale (~4000 km), the tropical clouds have essentially layered structure, the cloud layers having vertical depth of the order of 2 to 3 km.

This is due to the fact, (a fact that has not been well recognized so far) that there are inertio-gravity waves of horizontal wave-lengths ranging from a few hundreds to a few thousands kilometer and vertical wave-lengths of the order of a few kilometers. Within this vertical wave-length, one half wave-length is characterized by upward vertical motion and the other half by downward vertical motion. This downward vertical motion inhibits the sustenance of deep convective clouds for a long time, giving place to layered clouds.

Inertio-gravity waves with a wide spectrum of horizontal and vertical wavelengths are generated in the lower troposphere by orography and diabatic heating. These waves move horizontally as well as vertically. Relatively larger inertio-gravity waves have horizontal wavelengths of the order of 1000 km and vertical wavelengths of the order of 5 km.

Layered stratiform clouds have a profound influence on the radiation budget of our earth's atmosphere. They can obstruct a part of the Outgoing Longwave Radiation (OLR) as well as the incoming shortwave solar radiation. Recent radiation budget studies show that there is greater absorption of incoming solar radiation in the atmosphere than has been accepted so far in meteorological literature, the error being of the order of 25 Wm^{-2} (Barker and Li 1995; Imre *et al* 1996; Cess *et al* 1995). Therefore a detailed study of these layered clouds such as their bases, tops, depths, microphysical properties, generation mechanism, dynamics etc., over a tropical atmosphere, including the Indian monsoon region, is of fundamental importance for Numerical General Circulation Modelling.

2. Observations and discussion

The Indian MST radar which is a Very High Frequency radar (VHF radar) operating at 53 MHz frequency, located at Gadanki (13.47°N, 79.18°E), near Tirupati, India, was operated from September

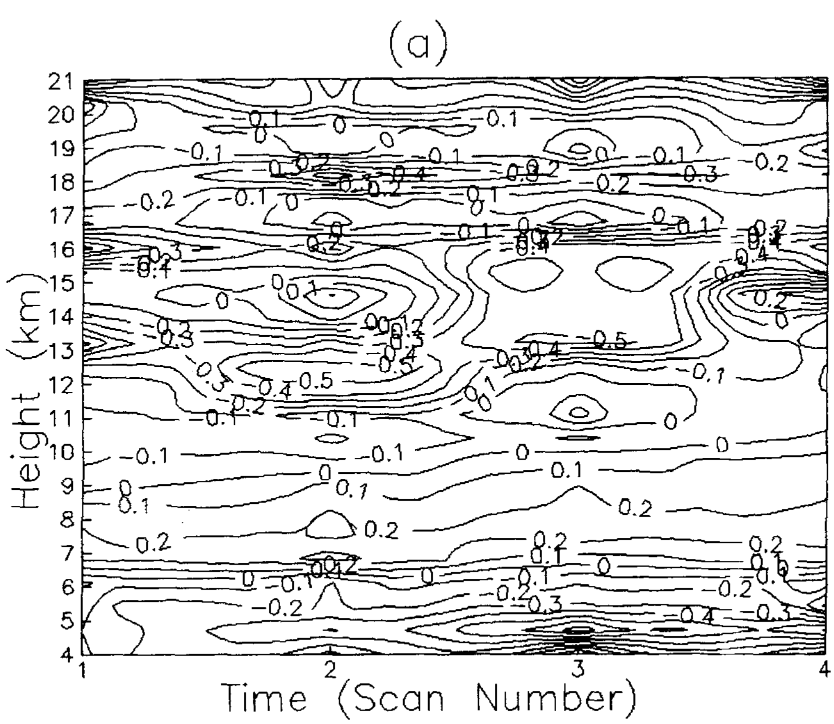


Figure 1. (*Continued*)

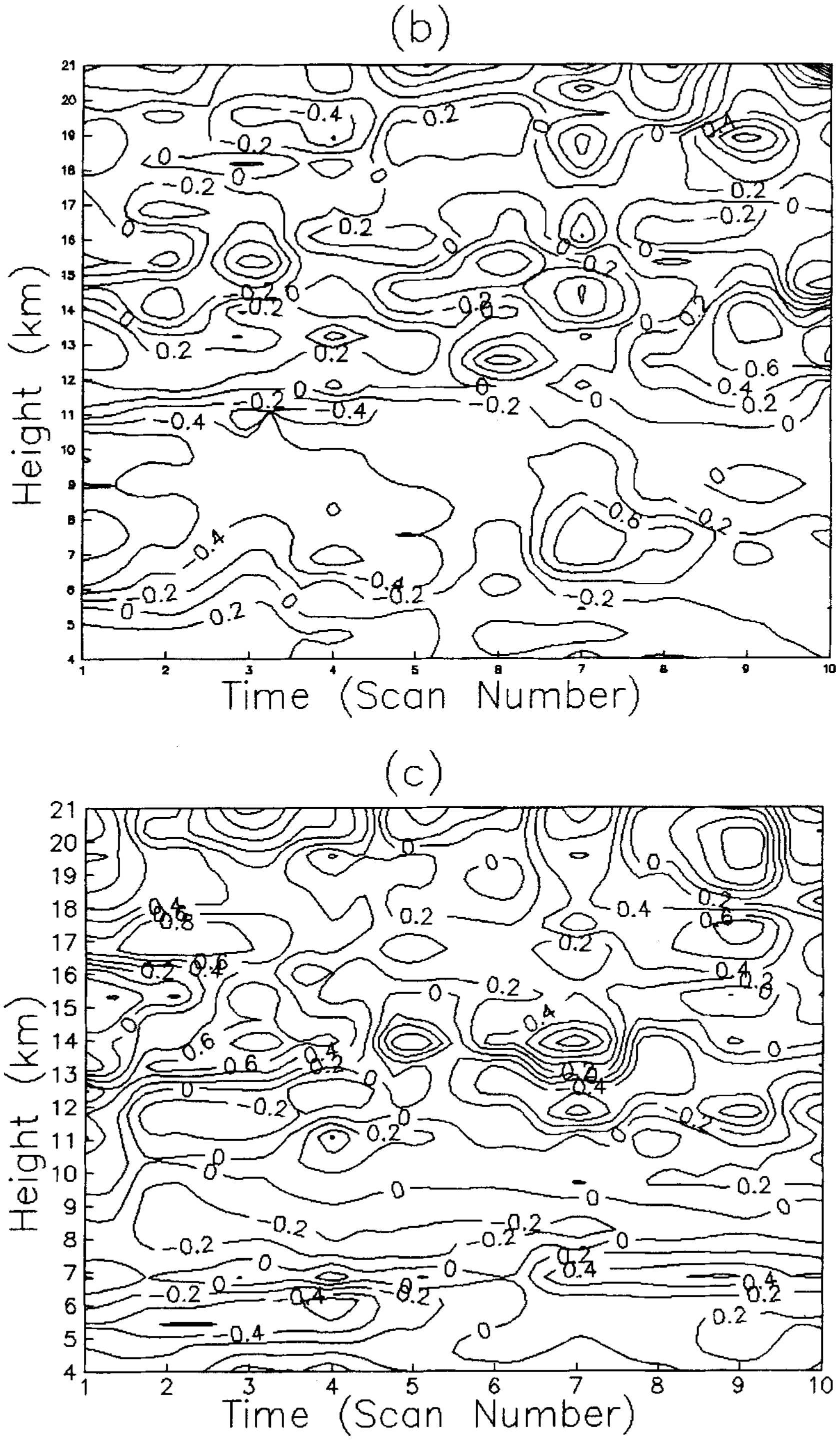


Figure 1(a, b and c). Vertical velocity (w) contours for MST radar scan for the days 13th June 1996 (16 : 46 : 03 IST to 16 : 51 : 50 IST), 14th June 1996 (12 : 11 : 45 IST to 12 : 29 : 4 IST), and 15th June 1996 (00 : 32 : 15 IST to 00 : 49 : 35 IST), respectively. Unit: ms^{-1}. The consistent alternating layers of vertical upward and downward motions are clearly seen in these figures. Thickness of an upward motion layer or a downward motion layer is approximately 2 to 3 km. Positive values of vertical velocity indicate upward motion and negative values of vertical velocity indicate downward motion.

1995 to November 1996, on a daily basis (these data sets are also known as Common Mode Data and are available at the National MST Radar Facility, Tirupati, India). A special set of observations was taken, on a diurnal cycle basis, from 13th June to 15th June 1996. The purpose of the experiment was mainly to study the layered clouds occurring over the region. On some days, the Gadanki area was covered by visible widespread layered clouds. Reflectivity, which is approximately (r^2S), where r is the range and S is the signal, is obtained from MST radar moments data. Also, the three wind components viz. zonal (u), meridional (v), and vertical (w), are obtained from MST radar moments data.

We have inferred the structure of these inertio-gravity waves with the help of the single-station MST radar data as mentioned above. Certainly, single-station observations cannot give a comprehensive three-dimensional structure of the inertio-gravity waves we are speaking about. We have also used satellite data over an extensive area and also used the data and analyses reported over other parts of the world. Using all this information, we are led to our hypothesis that inertio-gravity waves inhibit the prevalence of synoptic-scale convective clouds, and favour the growth and maintenance of layered clouds in the Indian monsoon region, based on the following physical and dynamical considerations:

- MST Radar observations consistently show alternating layers of upward and downward vertical motion along the vertical, each layer having a depth of about 3 km. As an illustration, we present figure 1(a to c). This alternation between layers of

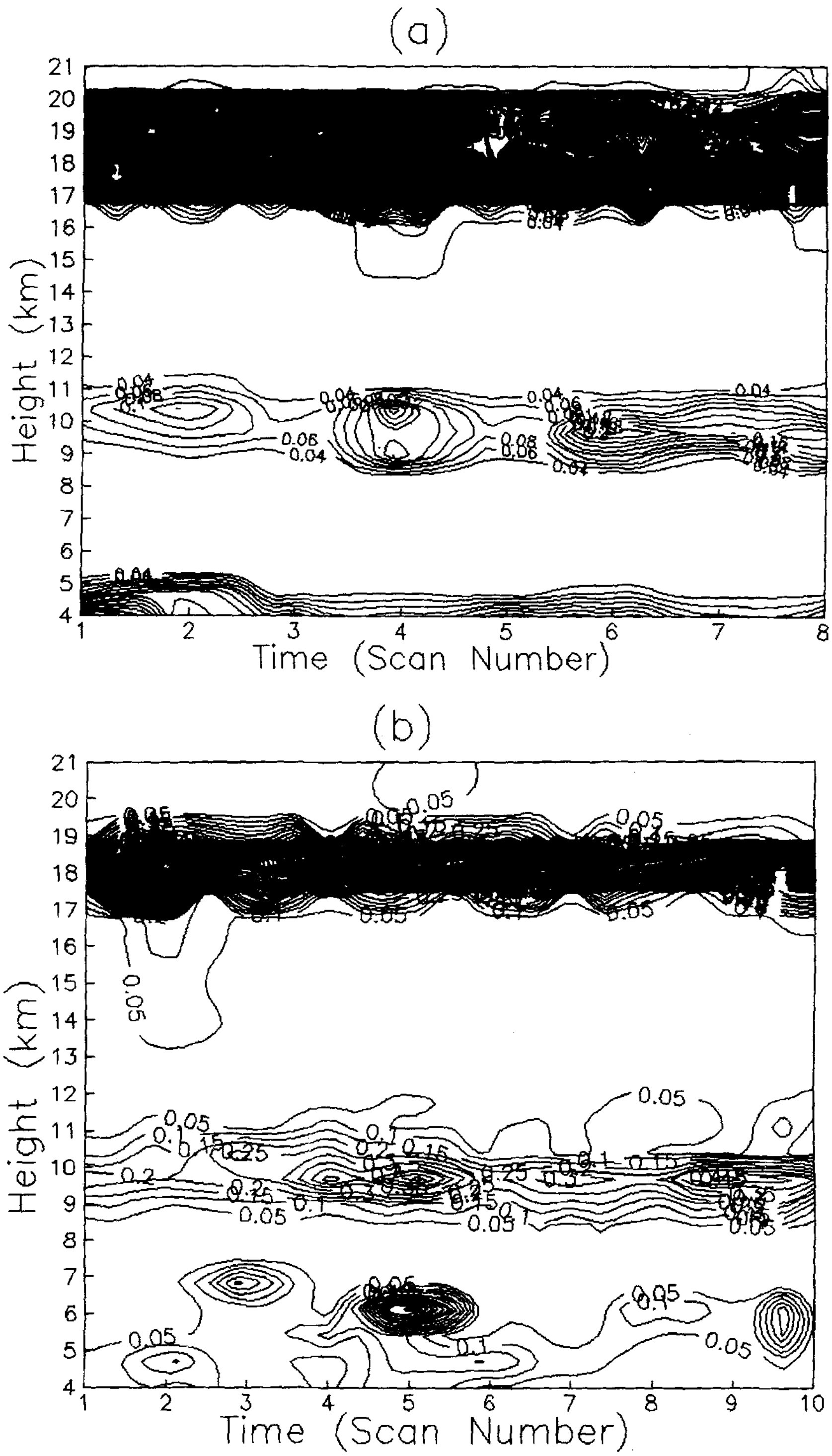


Figure 2(a and b). (*Continued*)

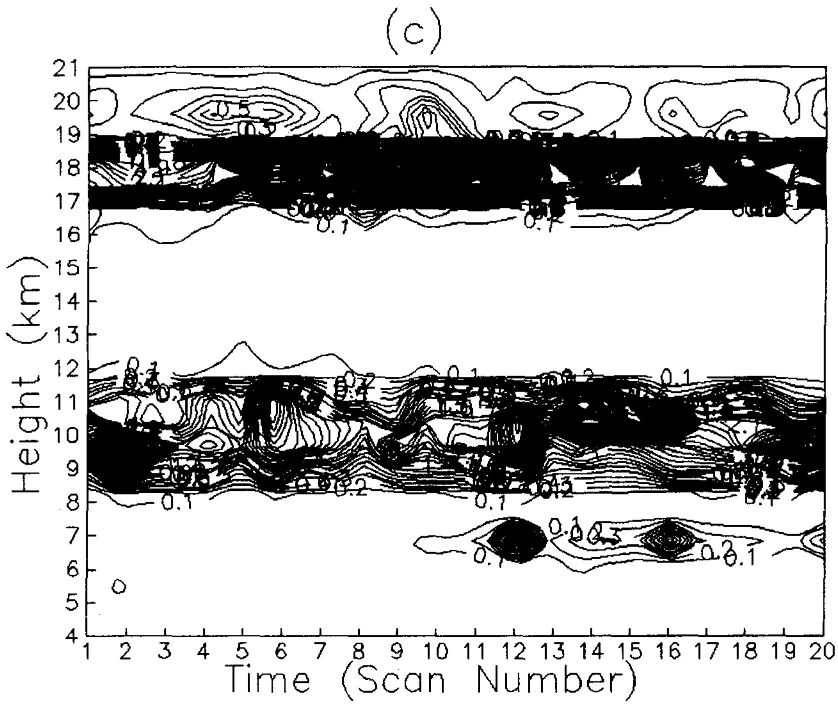


Figure 2(a, b and c). Contours of MST radar reflectivity pattern for the same period as given in figure 1(a, b and c) respectively. MST radar reflectivity is approximately taken as r^2S. Unit: Arbitrary. There are layers of relatively high reflectivity with thickness about 2 to 3 km. Relatively high reflectivity is occurring near the levels of vertical upward motion or vertical velocity convergence.

upward and downward motion appear to be of the type of inertio-gravity waves theoretically suggested in published literature (Jones 1967; Wurtele *et al* 1996; Chunchuzov 1996; Joseph 1997). This theory is still in a developing stage and cannot give answers relating to the behaviour of a wide range of wave-lengths and their nonlinear interactions.

- INSAT pictures on many occasions, during the 14-month period mentioned above, show large-scale clouds with cloud tops reaching near about 17 km level. Also these satellite pictures show that there is a marked tendency for development of the 500–1000 km wave-lengths in very moist regions (Asnani 1999).
- Our experience of sky observations in the Indian monsoon region suggests repeated occurrence of layered clouds, far away from their possible cumulonimbus source.
- Our MST radar observations also suggest the following points:

(**a**). The inertio-gravity waves tend to create layers of jetlets, layers of relatively strong winds vertically separated by layers of relatively weak winds, with a vertical wavelength of approximately 5 km. The wave phenomenon appears to create vertical transport of horizontal momentum; relatively strong winds occur in the layer of convergence of vertical flux of horizontal momentum. Also it is now known from recent studies that these inertio-gravity waves are capable of transporting aerosol particles vertically (Joseph 1997; Joseph, personal communication).

(**b**). The inertio-gravity waves also tend to create layers of strong and weak moisture content in the atmosphere, with a vertical wave-length of ~5 km. Concentration of moisture mainly occurs at those levels where the convergence of vertical flux of moisture takes place. These layers are very favourable for cloud formation and cloud sustenance. The layers having divergence of vertical flux of moisture generally tend to be free from clouds.

(**c**). High concentration of mositure gives high values of radar reflectivity, at the frequency 53 MHz at which MST radar at Gadanki (near Tirupati, India) operates. The MST radar reflectivity pattern is displayed in figure 2(a to c). High-reflectivity layers tend to occur near the layers where vertical convergence of moisture takes place.

(**d**). Deep convection sprays large quantities of moisture and aerosols into the upper troposphere. The moisture and aerosols get confined to and stratified near about the tropopause level, particularly below the tropopause level. There is observational evidence of high relative humidity, cirrus clouds and aerosol concentration near the tropopause level (Newell *et al* 1997; Schroder and Strom 1997; Nee *et al* 1998). The inertio-gravity waves along with smaller-scale Kelvin-Helmholtz waves (K-H waves) and Brunt-Vaisala oscillations (B-V oscillations) in the upper troposphere, together with high values of static stability, relative humidity, aerosol concentration and low values of Richardson number, favour building up of thin sheets with discontinuities of temperature, humidity, density and radar refractive index near the tropopause level. These thin sheets with refractive index discontinuities near the tropopause level give rise to high values of essentially Bragg-type radar reflectivity near the tropopause level. This is the main cause of high values of MST radar reflectivity, near the tropopause, practically in every radar scan throughout the year.

(e). The high values of MST radar reflectivity in the lower, middle and upper troposphere have previously been attributed by scientists to the large intensity of turbulence. In our view, high gradients of humidity, which are created by inertio-gravity waves together with K-H waves and B-V oscillations in the atmosphere play an important contributory role in creating layers of high radar reflectivity in middle and upper troposphere. To come to this conclusion, we have also examined the spectral width of the reflected spectrum, which is narrow and not broad as for a turbulent scatter. Values of large-scale Richardson number are also sufficiently large in these layers to discount suggestion of turbulence. Monthly scatter diagrams of radar reflectivity versus vertical wind shear display nearly

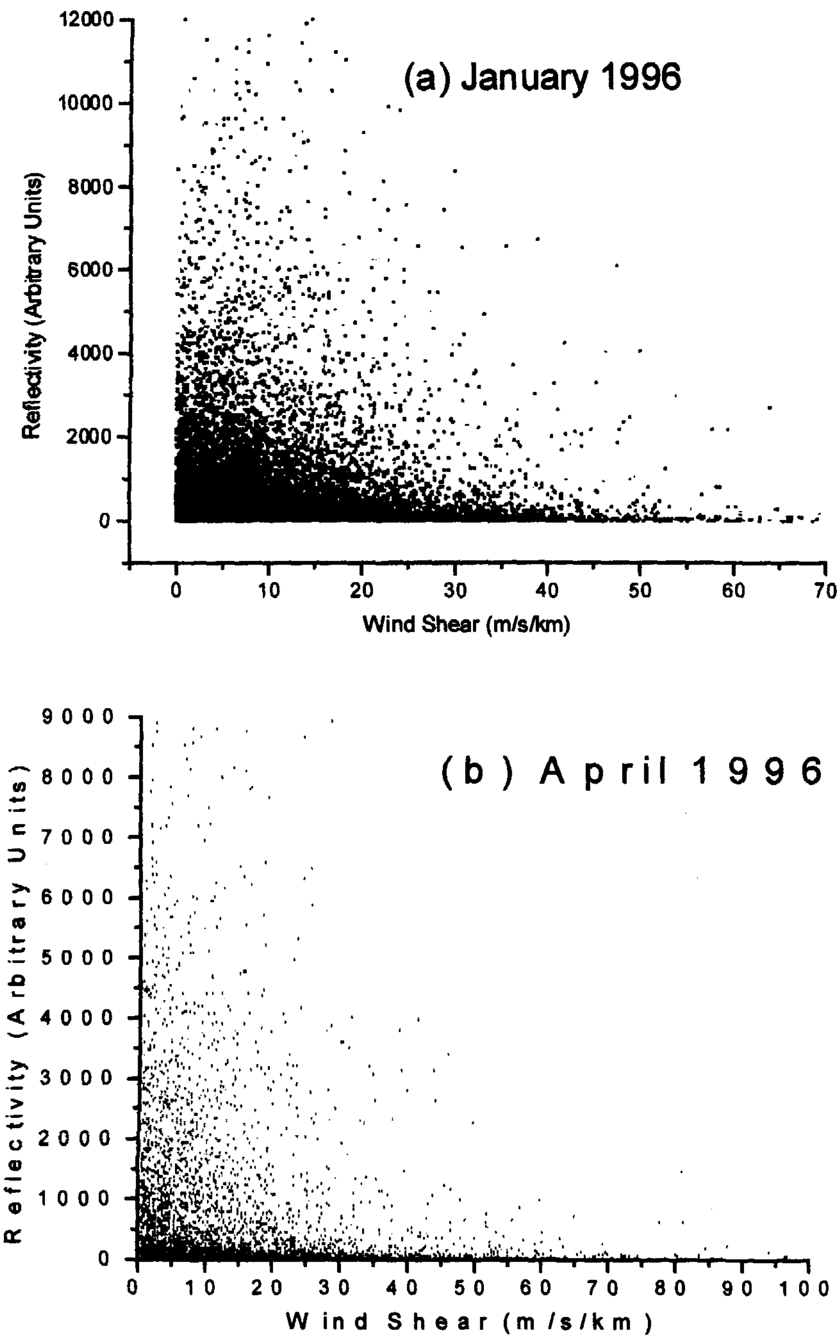
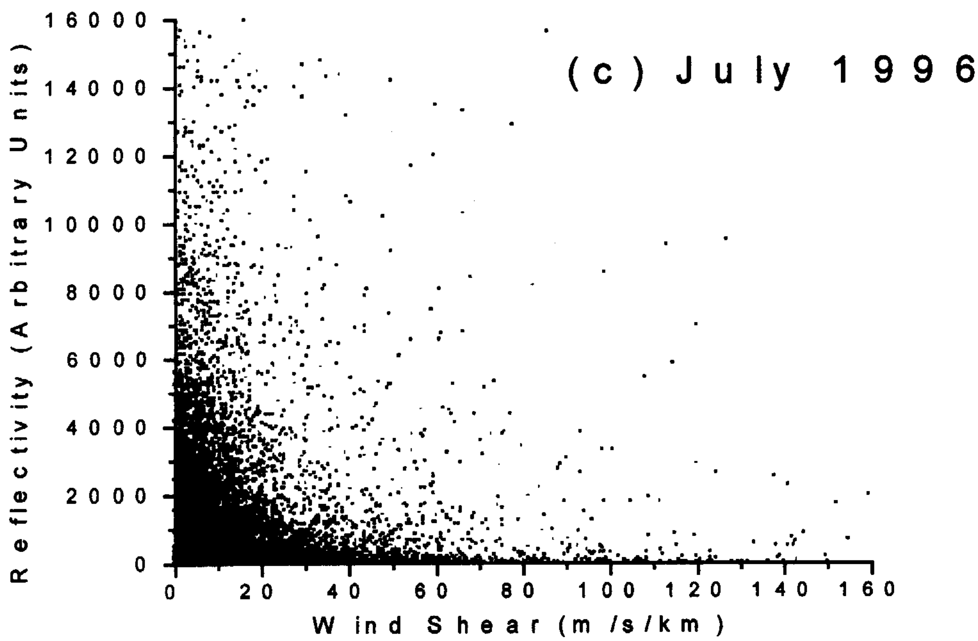


Figure 3(a). (*Continued*)



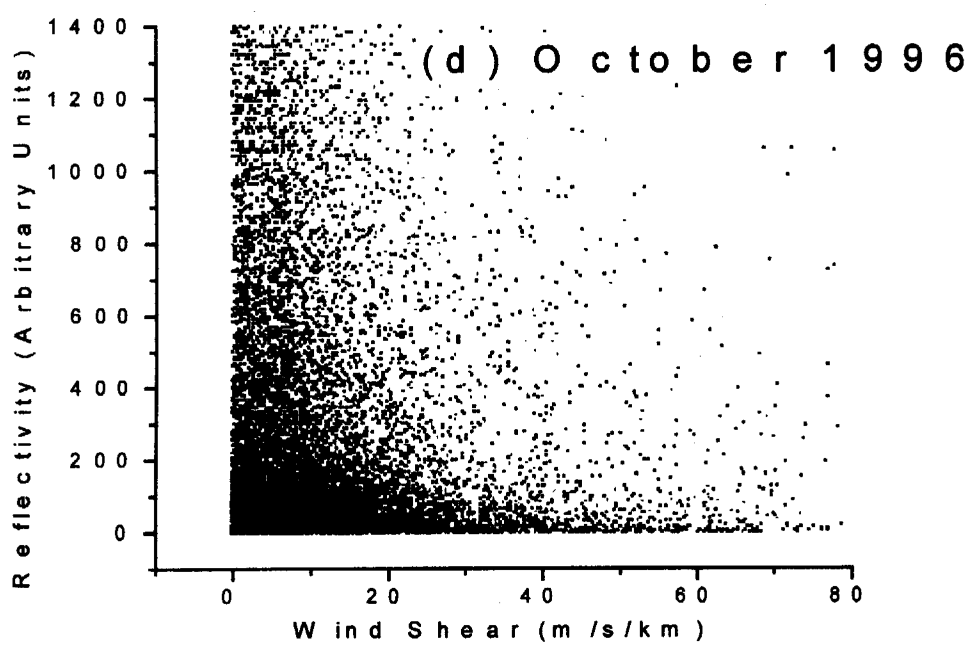


Figure 3(a, b, c and d). Monthly scatter diagrams of reflectivity versus vertical shear of horizontal wind, for four representative months (January, April, July and October, 1996) at MST radar site, Tirupati. Unit of wind shear: $ms^{-1}\ km^{-1}$. There is a general decrease of reflectivity with the enhancement in wind shear.

exponential decrease of reflectivity with increasing wind shear (figure 3(a to d)).

(f). Micro-scale gravity waves with a period of a few minutes (Brunt-Vaisala Oscillations) get superimposed on the large-scale radar reflectivity picture. As such, micro-scale gravity waves give a beautiful pattern of embroidery superimposed on the radar reflectivity picture (see figure 2(a to c)). These micro-scale gravity waves can also give and do give rise to visible streaks of clouds in regions where large-scale inertio-gravity waves have already created large concentrations of moisture.

(g). We further suggest that haziness in the sky sometimes seen during day time at very high levels is perhaps due to very thin cirrus type clouds forming in the upper troposphere, near the tropopause level, by the mechanism mentioned above. Some of the recent articles show that there are "sub-visual" clouds in the tropical region near and above 16 km level, which are not seen by the naked eye and even by ordinary satellite sensors (Kent *et al* 1995). Also there is evidence of the presence of cirrus clouds near the tropopause level, almost all the time (Spinhirne *et al* 1996; Nee *et al* 1998).

3. Conclusions

- Indian MST radar observations extending over more than 14 months, consistently show mainly three layers of higher reflectivity pattern near 5 to 6 km level, 10 km level and 17 km level. Embedded in the higher reflectivity layers, there are again patches of higher reflectivity which give an embroidery-like structure for the reflectivity pattern.
- Corresponding wind observations using MST radar show that there are alternate layers of upward and downward vertical motion, the depth of each layer approximately being 2.5 km. This appears to be due to the presence of inertio-gravity waves of vertical wave-length of the order of 5 km. The total horizontal wind speed tends to be relatively maximum in the neighbourhood of highly reflecting layers mentioned above.
- The multi-layered structure of the reflectivity pattern is attributed to the fact that there are layered visible and sub-visible clouds or highly humid layers of vertical depth of the order of 2 to 3 km, which are created by large-scale inertio-gravity waves present in the Indian tropical region. These inertio-gravity waves have a horizontal wave-length of a few hundred kilometers and vertical wave-length of approximately 5 km. Hydrometeors inside the layered clouds contribute considerably towards creation of micro-scale horizontal and vertical inhomogeneities in temperature, humidity, density, and refractive index through different microphysical and micro-dynamical processes such as condensation, evaporation, freezing, sublimation, heat diffusion and hydrometeor loading. These layered clouds created by inertio-gravity waves give rise to high MST radar reflectivity. These may be called "Mother Layers".
- Inside each of the above-mentioned highly reflecting mother layers, there is an embroidery-like structure. This is attributed to the presence of small-scale Brunt-Vaisala oscillations and Kelvin-Helmholtz waves embedded in the large-scale inertio-gravity waves. There are waves within waves. These Brunt-Vaisala oscillations and Kelvin-Helmholtz waves can also give rise to visible streaks of clouds, particularly under favourable illumination conditions during twilight hours.
- It is suggested that haziness in the tropical sky seen quite often during day time at very high levels is due to sub-visible cirrus-type clouds forming in the upper troposphere, by the mechanism of inertio-gravity waves, Kelvin-Helmholtz waves and Brunt-Vaisala oscillations mentioned above.
- It is also suggested that there is a great possibility of MST radar being used as high-resolution humidity profiler both in space and time. More co-ordinated experiments and analyses are to be done for utilizing this capability of MST radar.
- These suggestions would stimulate greater interest in accurate measurements of heights of layered type clouds; we may also have to revise the general concept of layer-cloud heights currently prevailing in the field of meteorological forecasting for aviation and non-aviation purposes.
- Also, in General Circulation Modelling of radiation, it has now been realised that there is greater absorption of incoming solar radiation in the atmosphere than has been so far accepted in meteorological literature, the error being of the order of 25 $\mathrm{Wm^{-2}}$. Recognition of cirrus type clouds or haze near the tropopause and other levels may help us to remove the present discrepancy in the estimate of absorption of incoming solar radiation in the atmosphere.
- India should launch a National Level Programme to measure the base and top of these visible and sub-visible layered clouds, their horizontal areal extent, vertical motion structure inside these layered clouds, the microphysical properties of this type of layered clouds, the amount of precipitation which these clouds contribute to the total precipitation, their detailed dynamics etc. It can become a part of the Global Monsoon Experiment, along with the current Numerical Modelling work on cirrus clouds (Khvorostyanov and Sassen 1998a, b).

Acknowledgements

We are grateful to Prof. P B Rao, Ex-Director of National MST Radar Facility at Gadanki, India and Dr. Praveen Kumar Devarajan, NCMRWF (National Center for Medium Range Weather Forecasting), New Delhi, India, for their immense co-operation, in taking observations and also for their valuable participation in the interpretation of some of the radar observations. M K Rama Varma Raja also thanks the Director of Indian Institute of Tropical Meteorology for a research fellowship during the course of this work.

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MS received 6 September 1997; revised 21 October 1999