Chapter V

Investigation on the Cloud Asymmetry, Lidar Ratio and Depolarisation Ratio and their Dependence on Dynamics of the Atmosphere
5.1 Introduction

Clouds are major regulators of Earth’s radiation budget. Typically, they reflect more solar or shortwave radiation back to space than the unobscured surface, thus decreasing the energy gained by the Earth. Upper troposphere ice phase clouds (cirrus clouds) in the tropics are characterized by their extensive lateral and vertical coverage (Mace et al., 1998). Cirrus clouds can impose a large-scale radiative effect on the earth’s climate system as 1/5\(^{\text{th}}\)of the global tropics are regularly covered by extensive cirrus systems (Liou, 1986). Tropical cirrus in the 10-15 km layer is associated with deep convective sources.

Tropical cirrus clouds are believed to originate in outflow from deep convective systems, producing a wide range of high-level clouds from thick anvils to thin cirrus. Other dynamic processes, such as the mesoscale circulations of larger storm systems, large-scale lifting or gravity waves, can also result in the formation of cirrus clouds. The cloud generated in different convection activities will have different microphysical properties. The cirrus microphysical properties are analysed using Mie lidar data obtained from the ground based lidar system established at the tropical inland station Gadanki (13.5\(^{\circ}\)N, 79.2\(^{\circ}\)E), India. In this case study we present the results on lidar ratio and depolarisation ratio of cirrus clouds for the observation period 2009-2010. Most of the physical parameters are addressed in the previous chapter. The result of the study is assimilated over the extended period of observation (2002-2010). The extinction, optical depth and the effective lidar ratio of the cirrus
clouds are determined as described in the chapter II. Lidar ratio is derived
using the iterative process developed by satyanarayana et al., (2010).

The lidar ratio and the depolarisation are related to the microphysics
and ice composition of the cirrus clouds. These properties are so far less
understood in cloud research. The range resolved lidar ratio, depolarisation
ratio, optical depth with respect to temperature distribution, altitude, and their
mutual relationship are discussed with the data analysed in the previous
chapters.

5.2 Experimental methods

The experiments are carried out using the elastic back scatter lidar
system operational on a regular basis at NARL, Gadanki. The lidar transmitter
and receiver characteristics are explained in detail in chapter II. The lidar
transmitter employs a Nd:YAG laser which emits the laser radiation (frequency
doubled) at wavelength 532 nm and with an energy 550mJ per pulse (pulse-
width - 7 ns and repetition rate - 20 Hz). The laser beam is expanded using a
10x beam expander, which makes the beam divergence < 0.1 mrad. The
receiver telescope is a 350-mm-diameter Schmidt–Cassegrain-type telescope
with a field of view (FOV) 1 mrad. This is used to study the vertical structure of
cloud and atmospheric aerosols by receiving the Mie scattered signal.

A narrow-band interference filter with centre wavelength 532 nm is
used to minimize the noise from the sky background radiation. The receiver
has the depolarization measurement capability. A polarized beam splitter splits
the beam into parallel and perpendicular components and are recorded
separately using two independent and identical photo multiplier tube (PMT)
channels which are referred as parallel (P) and cross (S) channels, respectively. PMT saturation is avoided by introducing variable attenuators in the channels. The optical power received by these two PMTs is recorded separately by two photon counters. Recording of data is achieved with a four-channel-PC based data acquisition system, out of which, two channels each are reserved for data acquisition from either telescope. In this work the data up to 20km from the Mie lidar was used for measuring the vertical profiles of depolarization ratios and extinction coefficients from background aerosol and clouds corresponding to the period from January 2009 to December 2010. Simultaneous data on atmospheric pressure, humidity and temperature is taken from radiosonde experiments conducted at the station during the period. During this period, lidar observations are made on 41 nights.

5.3 Results and Discussions

5.3.1 Monthly extinction Profile

The monthly mean vertical extinction profiles of the clouds are derived using the in-house developed algorithm based on the top to bottom approach of Fernald's method for the period 2009-2010 and are given in the Fig 5.1. The observed profiles show the presence of cirrus clouds of varying thickness throughout the period of observation. The significant variation in the values of extinction coefficient is due to the presence of cirrus clouds.

Out of the lidar data collected for 41 nights during the period 2009-2010, cirrus clouds are detected only for 29 nights (71%). This statistics is in agreement with observations by Sassen et al., (2001), who reported more than 50% cirrus cloud observation in a year in tropics. No cirrus clouds were observed in 2010 for the months of June, July and September.
Cirrus observed at different nights revealed different cloud structure and pattern. Out of 29 days of cirrus occurrences single layer formation are observed on 22 nights (76%). It can also be seen that only single layered cirrus clouds are observed for the year 2009. For the year 2010 single layer clouds are observed for most of the months with appearance of a few layered clouds during the month of April, May and August. The single layer formation can be either thin or thick. Thick cirrus is almost highly saturated. Generally these clouds occur very near to the tropopause.

Fig. 5.1: The effective extinction for different months during 2009 and 2010

5.3.2 Cirrus cloud physical properties

Lidar data collected during the period of study are analyzed to estimate the various physical and microphysical properties of the cirrus clouds viz., cloud top, cloud base, optical depth, cloud depolarisation ratio, lidar ratio and cloud turbidity.

The monthly variation of tropical cirrus property is examined for those nights in which single layer cirrus persist throughout the period of lidar observations. Lidar data is also studied to understand the seasonal variability. The four prominent seasons of the station are: south-west monsoon (June,
July, August), north-east monsoon (September, October, November), summer (March, April, May) and winter (December, January, February). The monthly mean and seasonal mean of the cloud properties are discussed in this work.

Details of the monthly variation of the cloud base and cloud top during the days of observation along with the tropopause height are plotted in the Fig.5.2. It can be seen that the cirrus clouds have higher values of base height in the months of February, April, June and October during the year 2009, with the highest value of base height observed in October. The cloud base has the lowest value in the month of August in 2009. For the year 2010, the cirrus clouds have high values of base height in the months of April and August. The observed values of cloud base are low in the month of March and October in 2010.

It is observed that in the year 2009, the top height of cirrus clouds have high values in the month of February and October. The highest value of
cirrus top height is observed in February. In the year 2010, the cirrus top height shows the highest value in the month of April and the lowest value in the month of March. The cloud top observed for the months February and October in 2009 lie closely to the tropopause. But for the year 2010 no cloud tops are seen near tropopause.

Parameswaran et al., (2003) has shown that turbulence can play a significant role in governing the cloud shape. The observed large variation in the cloud base height of cirrus clouds can be due to the variation in the degree of atmospheric turbulence below the clouds. Fig.5.2 shows large variation in the values of cloud base height for low altitude clouds. The variation in cloud base height for the cirrus clouds formed near the tropopause is relatively less. From this, it can be inferred that the effect of turbulence on the cloud properties will be significant for low altitude clouds. It is interesting to note that low altitude cirrus clouds down to a height of 9 km were observed during the period July to September in the year 2009. For the rest of the year and in the whole period of the year 2010, such clouds are not observed.

Fig.5.3 shows the variation of percentage of occurrence of cirrus clouds of different geometrical thickness in the years 2009 and 2010. From Fig.5.3 (a) it can be seen that about 60% of the cirrus clouds formed are thin with geometrical thickness varying from 1-2 km. Only 7% of the clouds formed are very thick (thickness > 4 km) for the year 2009. In the year 2010, about 77% of the total clouds formed are thin clouds having thickness 1-2 km as seen in Fig.5.3 (b). Interestingly no very thick clouds (thickness> 3 km) are found for the year 2010. From these observation it can be inferred that most of the cirrus clouds formed are thin with thickness in the range 1-2 km and the occurrence of very thick clouds are rare.
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**Fig 5.3:** The variation of percentage of occurrence of cirrus clouds of different geometrical thickness (a) for the year 2009 and (b) for the year 2010.

**Fig 5.4** The percentage of occurrence of cirrus clouds as a function of altitude (a) for the year 2009 and (b) for the year 2010.

Figs. 5.4(a) & (b) show the percentage of occurrence of cirrus clouds as a function of altitude in the years 2009 and 2010. From Fig.5.4 (a) it can be seen that the occurrence of clouds is highest (~27%) at altitude range 15-16 km in the year 2009. But no clouds are observed in that altitude range in the year 2010. For the year 2010 the occurrence of cloud is the highest (~46%) at altitude range 13-14 km. For the year 2009, both the altitude ranges 12-13 km and 13-14 km have recorded the same percentage of occurrence of the clouds (20% each). About 23% of the cloud occurrences is observed for both
altitude ranges 11-12 km and 14-15 km in the year 2010. It can also be seen
that in the tropical tropopause layer (altitude range 12-14 km) the occurrence
of clouds is about 40% in 2009 and more than 50% in 2010. This is in agreement
with the observations made by Sunilkumar et al., (2008) at the same station.

Fig. 5.5 Seasonal variation of the geometrical properties of the
cirrus clouds for the year 2009 and 2010.

The seasonal variation of the geometrical properties of the cirrus
clouds for the year 2009 and 2010 is also shown in the Fig. 5.5. From the
seasonal observation it is observed that the cloud top is the highest during the
north east monsoon in 2009 and during south west monsoon in 2010. The
cloud top height is the least during winter for 2009, whereas the cloud top
height remains almost same during north east monsoon and winter for 2010.
A dip in the cloud top height during winter is observed in previous years, 2002-
2008 (as explained in chapter III). The different observation with high altitude
clouds occurring in the year 2010 can be due to the presence of strong
convection activities prevailing at that period.
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Table 5.1 The seasonal variation of geometrical thickness of the clouds for the years 2009 and 2010

<table>
<thead>
<tr>
<th>Season</th>
<th>Geometrical Thickness of Clouds (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2009</td>
</tr>
<tr>
<td>Summer</td>
<td>1</td>
</tr>
<tr>
<td>South West Monsoon</td>
<td>2.9</td>
</tr>
<tr>
<td>North East Monsoon</td>
<td>1.9</td>
</tr>
<tr>
<td>Winter</td>
<td>1.45</td>
</tr>
</tbody>
</table>

From Fig. 5.5 it can be seen that the clouds are thin during summer and thicker during the south west monsoon for the year 2009, whereas for the year 2010, the clouds are thin during the south west monsoon and thicker during the north east monsoon. The seasonal variation of geometrical thickness of the clouds for the years 2009 and 2010 are given in the Table 5.1

5.3.2.1 Calculation of asymmetry factor $\xi$ of Cirrus Clouds

It is seen that the cloud back scattering ratio varies significantly in altitude with high values in the middle and low values towards the upper peripheries. A typical plot of extinction coefficient profile (for 4th March 2009) is shown in Fig. 5.6. It can be seen that the geometric center of the cloud and the altitude corresponding to the peak value of extinction coefficient

Fig 5.6 A typical plot of extinction coefficient profile (for 4th March 2009).
do not coincide. This means that the extinction coefficient profile within the cloud is not perfectly Gaussian in shape. In other words, as far as scattering is concerned, the cloud is neither homogeneous nor optically symmetric with respect to its centre. The degree of deviation from the symmetric nature of the extinction coefficient profile of the cloud can be determined in terms of the asymmetry factor $\xi$ (Sassen and Cho, 1992). The asymmetric factor of the cloud is defined by the following equation.

$$\xi = \frac{(h_m - h_{cb})}{(h_{ct} - h_{cb})}$$

(5.1)

Where $h_m$ is the altitude corresponding to the center of the cloud, $h_{cb}$ is the cloud base altitude and $h_{ct}$ is the cloud top altitude.

If the extinction profile within the cloud is Gaussian the value of $\xi$ will be close around 0.5. If the value of $\xi$ is less than 0.5, the scattering will be more from the lower half of the cloud and if $\xi$ is higher than 0.5, the scattering will be more from the upper half of the cloud. The amount of asymmetry could be quantified in terms of its absolute deviation from 0.5. The asymmetric factor for the cirrus clouds observed during the years 2009 and 2010 are calculated and are plotted in Fig.5.7. From Fig 5.7 it can be seen that

![Fig 5.7 Scatter plot of the asymmetry factor for cirrus clouds on different days (a) observed in the year 2009 and (b) observed in 2010](image-url)
the cirrus clouds seems to be almost symmetric during the entire period of the year 2009 except in the beginning of the North East monsoon, whereas during the entire period of 2010, the cloud shows asymmetric nature. During the year 2010 the value of the asymmetric factor shows high values and this suggests the cloud has high scattering from the upper portion.

![Fig. 5.8 Scatter plot for the asymmetric factor of the cirrus clouds as a function of altitude (a) in the year 2009 and (b) in the year 2010.](image)

![Fig. 5.9 Scatter plot showing the dependence of cloud asymmetry factor ($\xi$) on cloud geometric thickness during the year 2009.](image)
Fig. 5.8 shows scattered plot for the asymmetric factor of the cirrus clouds as a function of altitude for the period 2009 to 2010. In the year 2009 the cirrus clouds observed along different altitude seems to be more symmetric with asymmetric factor around 0.5 with a few exceptions at altitudes 14km and 18 km. In the year 2010, clouds observed at almost all altitudes seem to be asymmetric with the asymmetric factor varying widely from the normal value of 0.5. This may be due to the rapid ice nucleation and high ice content of the clouds observed during 2010. Fig. 5.9 shows the variation of asymmetric factor as a function of geometrical thickness of the clouds.

5.3.2.2 Cloud optical depth

Optical depth of a cloud means the integrated extinction coefficient for the entire cloud region. Extinction coefficient of cirrus clouds for the period of observation was calculated from the lidar data using the Fernald's inversion technique. The optical depths of the clouds were calculated by integrating the extinction coefficients in the cloud region. Fig.5.10 shows the variation of monthly average of cloud optical depth for the years 2009 and 2010. For both the years the optical depth calculated shows the highest values during the summer season (March to April). Usually in the summer season the clouds are thin and they

![Fig. 5.10 Monthly average of cloud optical depth and cloud geometrical thickness (a) for the year 2009 and (b) for the year 2010](image-url)
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consist of ice crystals of regular shape like hexagonal, thick plates and thin plates. In the monsoon and winter seasons the clouds observed were generally thick, but the probability of having ordered crystals in them are less. The crystal shape may be spherical or dendrites in them. In summer periods, usually the clouds are observed very near to the tropopause and hence the chances for the formation of regular ice crystals are high. But in the other seasons the chance of occurrence of low altitude clouds are high. In such clouds the influence of atmospheric turbulence will be more and hence the cloud precipitation will be less. The extinction coefficients obtained from the regular ice crystals will be high compared to spherical or dendrite crystals. Hence the cloud containing regular ice crystals may have higher values of optical depth. In the summer seasons of 2009 and 2010 the clouds were observed close to the tropopause (Fig. 5.2). The observation of higher values of cloud optical depth in the present case for the summer seasons of 2009 and 2010 is an indication of the presence of regular hexagonal, thick and thin plate ice crystals in the cirrus clouds formed during that period. From Fig.5.2 it can be seen that high altitude cirrus clouds (near to tropopause) were observed in the month of October 2009. However from the Fig.5.10, it can be seen that the cloud optical depth obtained for this month is low. The month of October belongs to the North East Monsoon of Gadanki Station. During the monsoon season the atmospheric turbulence will be higher and as a result the chance for precipitation of the clouds into regular ice crystals in these clouds is less, even though they are close to tropopause. Also there is large transport of aerosols and water vapor to high altitudes during the monsoon season due to the prevailing convection activities. This effect enhances the ice nuclei concentration in the clouds and hence the chance for growing big regular crystals is reduced. This can also have an effect on the observed dip in the value of the cloud optical depth in the October 2009.
The cirrus cloud can also be classified into sub-visual, optically thin and optically dense clouds on the basis of optical depth. Sub visual clouds have optical depth lesser than 0.03, thin clouds have optical depth lying between 0.03 and 0.3 and thick clouds have optical depth higher than 0.3. The sub-visual clouds with optical depth less than $10^{-3}$ are classified as ultra-thin clouds. In the current observation during the year 2009, the observed clouds belongs to the classification "optically dense" except for the months October and December, whereas during the year 2010 the observed clouds belong to the classification optically thin except for the months January, February and May. There are reports about the formation of ultra-thin clouds near the tropopause in tropics by Immler et al., (2007), Peter et al., (2003) and Luo et al., (2003). Even though the Gadanki station belongs to tropical inland region, ultra-thin clouds are not observed in our investigation.

From the GPS Sonde data obtained for the year 2009 and 2010, the cloud bottom temperature is derived for 29 observational days. Fig.5.11 shows the variation of cloud optical depth with cloud bottom temperature for this period. For the year 2009 it can be seen that the optical depth shows an
increasing trend as the cloud bottom temperature increases and it shows the highest value for a cloud bottom temperature around -50 °C. In the year 2010, it can be seen that the optical depth shows higher values in the cloud base temperature ranging from -60 to -40 °C, with an exception around -70 °C.

This relation is in agreement with Norris et al., (2005) who reported that the crystal growth is aggravated at high temperature between -60°C and -50°C.

5.3.2.3 Multiple scattering effects

For clouds of large optical depth (close to unity) the multi scattering effect needs to be considered, which will bring a change to the backscattering coefficient and the lidar ratio. Multi scattering effect is complex and it depends on different factors like laser penetration depth, the cloud height, field of view of the receiver, particle size distribution, crystal shape etc (K.Sassen et al., 1989, K.Sassen et al., 1992, E.W. Eloranta 1998). The maximum scattering signal can be expressed as an exponential function of the cloud optical depth $\tau_c$ as follows,

$$\frac{P_c(z)}{P_{c}(z)} \approx e^{\tau_c} \quad (5.2)$$

where $P_c(z)$ and $P_{c}(z)$ are the multiple scattering power and single scattering power respectively and both of them are dependent of the range $z$.

For optically thin clouds, $\tau_c << 1$ and $P_i(z) \approx P_c(z)$.

The multiple scattering factor $\eta(z)$ which can be obtained from the following equation.

$$\tau_c = \int_{z_{base}}^{z_{top}} \eta(z) \beta(z) S(z) dz \quad (5.3)$$
where $\beta$ is the back scattering coefficient for an altitude $z$ and $S(z)$ is the corresponding lidar ratio. The eqn.5.3 can be written as

$$\tau_c = \eta(z)S(z) \int_{z_{\text{base}}}^{z_{\text{top}}} \beta(z) \, dz$$

(5.4)

When the multiple scattering effect is negligible $\eta(z) = 1$. Smaller values of $\eta(z)$ corresponds to larger multiple scattering effect. Ignoring the multiple scattering effect due to the air molecules, the value of $\eta$ can be estimated by the following equation.

$$\eta = \frac{D}{\int_0^{\tau_c(h)} e^{\tau_c(h)} \, dh} = \frac{\tau_c}{e^{\tau_c} - 1}$$

(5.5)

Where $D$ is the physical thickness of the cloud and $h$ is the laser penetration depth. For smaller values of optical depth $\eta \approx 1$. Fig.5.12 shows the scatter plot of the multiple scattering factor ($\eta$) for the observation periods in the year 2009 and 2010. From the Fig. it can be seen that the value of multiple scattering factor ($\eta$) is almost equal to unity in most of the months for

Fig 5.12 Scatter plot showing the Multiple scattering factor ($\eta$) for the observation periods in the year 2009 and 2010
the year 2009, indicating negligible multiple scattering effect. The value of multiple scattering factors ($\eta$) is less than unity for the months of monsoon. However for the year 2010 the values of the multiple scattering factor ($\eta$) is less than unity in most of the months indicating the presence of significant multiple scattering in the cirrus clouds. The multiple scattering effects observed during the monsoon period of 2009 can be due to the following reason. This period has abundant water and particulates being transported to higher altitude due to prevailing Inter Tropical Convergence Zone (ITCZ) and convective cells like Hadley cells (Meenu et al., 2010). The significant multiple scattering effects noticed throughout the year 2010 can be due to anomalous effect of the atmosphere in that period due to various reasons like El Nino etc.

Indian Ocean dipole (IOD): also known as the Indian Nino occurred in 2010. The IOD involves a periodic oscillation of sea-surface temperatures, between “positive”, “neutral” and “negative” phases. A positive phase sees greater-than-average sea-surface temperatures and greater precipitation in the western Indian Ocean region, with a corresponding cooling of waters in the eastern Indian Ocean—which tends to cause droughts in adjacent land areas of Indonesia and Australia. The negative phase of the IOD brings about the opposite conditions, with warmer water and greater precipitation in the eastern Indian Ocean, and cooler and drier conditions in the west. It was reported that an average of four each positive/negative IOD events occur during every 30 year period with each event lasting around six months. Since 1980 12 positive IOD have been reported. However in 2010 a strong negative IOD have been reported. This can be the reason for the anomalous behavior of cloud pattern for the year 2010.
Recent studies show that, in the tropics, a "near cancellation" between shortwave cooling and long wave warming exists, which indicates that the amount of incoming radiant energy is roughly equal to the amount of outgoing radiation. However, small changes in tropical cloudiness can disrupt this precarious balance. The NASA (National Aeronautics and Space Agency) reports reveal that 1998 El Nino triggered a radical change in cloud structure. It was reported that the strong 1998 El Nino both high-level clouds and middle-level clouds exerted a strong impact upon the warm pool's radiation budget. Since middle-level clouds produced less long wave warming than do high-level clouds, there was no longer a near cancellation between shortwave cooling and long wave warming. Hence during the El Nino the clouds produced cooling over the warm pool. The reported strong negative IOD can be the reason for the anomalous behavior of cloud pattern for the year 2010.

5.3.3 Cloud depolarisation measurement

The depolarisation ratio is defined as the ratio of the return signal in perpendicular to parallel polarization relative to the outgoing laser light, as given by the equation equation 3.4. in chapter III. Cirrus cloud especially over tropics are mostly composed of non-spherical ice crystals. These particles will cause significant depolarisation. The depolarisation ratio within the cloud is an indicator of cloud microphysical properties. It is seen that during the summer months, depolarisation is high. The Fig.5.13 shows the monthly evolution of depolarization ratio of cirrus cloud observed during the years 2009 and 2010.

The depolarisation ratio is related to the ice crystal shapes which are largely unknown for specific type of crystal. For spherical particle and pure air, depolarisation ratio should be nearly 0. However, simulations for hexagonal
ice revealed the plate and columns had different polarization ratios. Depending upon the depolarisation value Sassen et al., (2001) has identified the crystal structure of the clouds into randomly oriented hexagonal thin plates, hexagonal thick plates and hexagonal column crystals (Table 5.2). Low values of extinction coefficient with low values of depolarization ratio (<0.3) suggest the formation of horizontal oriented ice crystals. High values of extinction coefficient and high values of depolarization ratio (>0.3) suggest formation of hexagonal plate crystals. Moderate value of extinction and depolarization ratio (around 0.3) suggests the formation of thin plates.

**Fig. 5.13** Contour plot of the monthly evolution of depolarization ratio of cirrus clouds observed in the year 2009 and 2010

**Fig. 5.14(a)** Variation of depolarisation ratio with altitude for the period 2009

**Fig. 5.14(b)** Variation of depolarisation ratio with altitude for the period 2010
Fig. 5.14(a) and 5.14(b) shows the Variation of depolarization ratio with altitude for years 2009 and 2010. The year 2009 shows majority of clouds with depolarization ratio greater than 0.3 indicating the presence of hexagonal ice crystals. Some of the clouds which are at relatively high altitudes exhibit depolarization ratios less than 0.3 indicating the presence of horizontally oriented ice crystals or thin plates of ice crystals. In the year 2010 most of the clouds except those in the higher altitudes show depolarization ratio lower than 0.3 indicating most of the clouds consist of horizontally oriented ice crystals or thin plates of ice crystals. Most of the clouds lying in the altitude range 13-15km have comparatively higher depolarization ratio indicating that these clouds consist of hexagonal ice crystals. Tables 5.3 and 5.4 summaries the physical, optical and morphological parameters of the cirrus clouds observed for the years 2009 and 2010 respectively.

5.3.4 Effective lidar ratio measurement

Lidar ratio depends on the properties of ice crystals. As shown by Hemsfield and Platt, (1984) many type of ice crystals exist inside the cirrus clouds at temperatures \(-50 ^\circ\text{C}\) i.e. around 12km. Satyanaryana et al., (2010) have a developed a method to derive the range dependent lidar ratio. The method is discussed in detail in the previous chapters. By this method it is found that the lidar ratio at cloud bottom and cloud top is higher than that of the cloud midpoint. It is found that the lidar ratio varied randomly below 12.5 km. Above 12.5 km the lidar ratio values are mainly distributed between 20 to 40 sr. In this calculation, the effect due to multiple scattering is not accounted. From the calculated values of the lidar ratio some information regarding the multiple scattering can also be obtained. The contour plots for the monthly mean lidar ratio for the years 2009 and 2010 are plotted and shown in Fig. 5.15.
Fig 5.15 (a): The contour plot of the monthly variation of lidar ratio of cirrus cloud observed in the year 2009

Fig 5.15 (b): The contour plot of the monthly variation of lidar ratio of cirrus cloud observed in the year 2010

The calculated values of the lidar ratios for the years 2009 and 2010 are given in Tables 5.3 and 5.4. The calculated values are consistent with the values reported by Platt et.al (1987) and Sassen et.al (1992). The value of extinction coefficient, lidar ratio and depolarisation ratio together can be used to get more information regarding the morphology of ice crystals formed. Sassen et.al (1992) has given a classification of hexagonal ice crystals based on the values of lidar ratio and the depolarization ratio (Table 5.2).

<table>
<thead>
<tr>
<th>Crystal Types</th>
<th>Lidar ratio</th>
<th>Depolarisation ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexagonal Thin plates</td>
<td>38.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Hexagonal Thick plates</td>
<td>11.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Hexagonal long column</td>
<td>26.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Based on the classification given by Sassen et al., (1992, 2001) the shape of the ice crystals in the clouds are identified and are presented in Tables 5.3 and 5.4.
Table 5.3: Summary of the optical properties of cirrus clouds over Gadanki station during the observation period 2009.

<table>
<thead>
<tr>
<th>Date of Observation</th>
<th>CBH km</th>
<th>CTH km</th>
<th>T km</th>
<th>CMH km</th>
<th>Temp (K)</th>
<th>DR</th>
<th>Extinction (m(^{-1}))</th>
<th>OD (m)</th>
<th>LR</th>
<th>Morphology of crystals predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>21/1/2009</td>
<td>15.6</td>
<td>16.8</td>
<td>1.2</td>
<td>16.2</td>
<td>195</td>
<td>0.31465</td>
<td>3.43E-06 - 2.96E-06</td>
<td>0.01013</td>
<td>12-3-11</td>
<td>hexagonal thick plates</td>
</tr>
<tr>
<td>26/1/2009</td>
<td>14.7</td>
<td>15.9</td>
<td>1.2</td>
<td>15.3</td>
<td>200</td>
<td>0.3378</td>
<td>4.04E-06 - 2.71E-06</td>
<td>0.028</td>
<td>9-9-3</td>
<td>hexagonal thick plates</td>
</tr>
<tr>
<td>11/2/2009</td>
<td>15.9</td>
<td>17.1</td>
<td>1.2</td>
<td>16.5</td>
<td>188</td>
<td>0.39314</td>
<td>1.02E-05 - 7.04E-06</td>
<td>0.027</td>
<td>32-16-57</td>
<td>hexagonal thin plates</td>
</tr>
<tr>
<td>4/3/2009</td>
<td>13.5</td>
<td>14.7</td>
<td>1.2</td>
<td>14.0</td>
<td>211</td>
<td>0.6118</td>
<td>4.96E-06 - 4.22E-06</td>
<td>0.01907</td>
<td>19-4-20</td>
<td>hexagonal long columns</td>
</tr>
<tr>
<td>1/4/2009</td>
<td>15.6</td>
<td>16.5</td>
<td>1</td>
<td>16</td>
<td>199</td>
<td>0.40543</td>
<td>4.44E-06 - 3.61E-06</td>
<td>0.025</td>
<td>7-4-7</td>
<td>hexagonal thick plates</td>
</tr>
<tr>
<td>13/5/2009</td>
<td>13.8</td>
<td>14.7</td>
<td>0.9</td>
<td>14</td>
<td>211</td>
<td>0.58777</td>
<td>6.49E-06 - 3.45E-06</td>
<td>0.01909</td>
<td>20-3-10</td>
<td>hexagonal long columns</td>
</tr>
<tr>
<td>03/06/2009</td>
<td>11</td>
<td>15</td>
<td>3</td>
<td>13.2</td>
<td>199</td>
<td>0.45877</td>
<td>1.14E-05 - 3.45E-06</td>
<td>0.24447</td>
<td>26-2-14</td>
<td>hexagonal long columns</td>
</tr>
<tr>
<td>22/7/2009</td>
<td>10.8</td>
<td>13.6</td>
<td>2.8</td>
<td>12.3</td>
<td>236</td>
<td>0.43023</td>
<td>8.18E-06 - 3.38E-06</td>
<td>0.06638</td>
<td>22-2-9</td>
<td>hexagonal long columns</td>
</tr>
<tr>
<td>05/08/2009</td>
<td>9.6</td>
<td>14.0</td>
<td>4.4</td>
<td>11.7</td>
<td>245</td>
<td>0.29958</td>
<td>1.19E-05 - 1.09E-05</td>
<td>0.38373</td>
<td>12-6-32</td>
<td>thin plates / oriented other type of crystals</td>
</tr>
<tr>
<td>16/9/2009</td>
<td>12</td>
<td>14.4</td>
<td>2.4</td>
<td>13.8</td>
<td>224</td>
<td>0.37739</td>
<td>4.35E-06 - 3.77E-06</td>
<td>0.4665</td>
<td>14-4-26</td>
<td>Hexagonal Thick plate</td>
</tr>
<tr>
<td>07/10/2009</td>
<td>16.8</td>
<td>18</td>
<td>1.2</td>
<td>17.7</td>
<td>193</td>
<td>0.14251</td>
<td>2.35E-06 - 2.22E-06</td>
<td>0.00379</td>
<td>12-11-13</td>
<td>oriented other type of crystals</td>
</tr>
<tr>
<td>21/10/2009</td>
<td>15</td>
<td>16.2</td>
<td>1.2</td>
<td>15.6</td>
<td>199</td>
<td>0.11792</td>
<td>2.99E-06 - 2.58E-06</td>
<td>0.00502</td>
<td>14-9-14</td>
<td>thin plates</td>
</tr>
<tr>
<td>19/11/2009</td>
<td>12.3</td>
<td>14.4</td>
<td>2.1</td>
<td>13.2</td>
<td>221</td>
<td>0.50166</td>
<td>5.34E-06 - 4.29E-06</td>
<td>0.06371</td>
<td>24-1-20</td>
<td>hexagonal long column</td>
</tr>
<tr>
<td>25/11/2009</td>
<td>13.2</td>
<td>14.7</td>
<td>1.5</td>
<td>13.8</td>
<td>214</td>
<td>0.37467</td>
<td>3.64E-06 - 3.04E-06</td>
<td>0.01194</td>
<td>13-4-12</td>
<td>hexagonal Thick plate</td>
</tr>
<tr>
<td>30/12/2009</td>
<td>12.9</td>
<td>14.7</td>
<td>1.8</td>
<td>13.8</td>
<td>215</td>
<td>0.21125</td>
<td>5.53E-06 - 3.25E-06</td>
<td>0.0632</td>
<td>12-8-12</td>
<td>thin plates / oriented other type of crystals</td>
</tr>
</tbody>
</table>
Table 5. 4: Summary of the optical properties of cirrus clouds over Gadanki station during the observation period 2010.

<table>
<thead>
<tr>
<th>Date</th>
<th>CTH km</th>
<th>CBH km</th>
<th>CMH km</th>
<th>T km</th>
<th>Temp (K)</th>
<th>DR</th>
<th>Extinction (m⁻¹)</th>
<th>OD (m)</th>
<th>LR (CT-CM-CB)</th>
<th>Morphology of crystals predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/01/2010</td>
<td>14.7</td>
<td>13.8</td>
<td>14.1</td>
<td>0.9</td>
<td>209</td>
<td>0.38631</td>
<td>2.87 E-05 – 2.99 E-05</td>
<td>0.04168</td>
<td>38-10-24</td>
<td>Hexagonal Long column</td>
</tr>
<tr>
<td>13/1/2010</td>
<td>14.4</td>
<td>13.2</td>
<td>13.8</td>
<td>1.2</td>
<td>212</td>
<td>0.35762</td>
<td>3.06 E-05 – 3.49 E-05</td>
<td>0.1631</td>
<td>44-44-47</td>
<td>Hexagonal Thin plate</td>
</tr>
<tr>
<td>03/02/2010</td>
<td>13.5</td>
<td>11.4</td>
<td>12.9</td>
<td>2.1</td>
<td>228</td>
<td>0.28951</td>
<td>1.566 E-05 – 2.97 E-05</td>
<td>0.4272</td>
<td>39-5-42</td>
<td>Hexagonal Thin plate</td>
</tr>
<tr>
<td>10/02/2010</td>
<td>15.3</td>
<td>14.4</td>
<td>14.7</td>
<td>0.6</td>
<td>211</td>
<td>0.43461</td>
<td>2.72 E-05 – 5.53 E-05</td>
<td>0.2559</td>
<td>22-5-38</td>
<td>hexagonal Thin plates</td>
</tr>
<tr>
<td>17/2/2010</td>
<td>15</td>
<td>13.5</td>
<td>14.8</td>
<td>1.5</td>
<td>169</td>
<td>0.45574</td>
<td>1.95 E-05 – 2.83 E-05</td>
<td>0.227</td>
<td>31-10-31</td>
<td>hexagonal Thin plates</td>
</tr>
<tr>
<td>17/3/2010</td>
<td>13.2</td>
<td>11.7</td>
<td>12.6</td>
<td>1.5</td>
<td>224</td>
<td>0.25284</td>
<td>2 E-05 – 2.93 E-05</td>
<td>0.29978</td>
<td>36-10-37</td>
<td>thin plates / oriented other type of crystals</td>
</tr>
<tr>
<td>28/4/2010</td>
<td>13.5</td>
<td>12.4</td>
<td>12.9</td>
<td>1.1</td>
<td>206</td>
<td>0.21496</td>
<td>1.53 E-05 – 2.54 E-05</td>
<td>0.4763</td>
<td>16-5-39</td>
<td>thin plates / oriented other type of crystals</td>
</tr>
<tr>
<td>12/05/2010</td>
<td>13.8</td>
<td>12.0</td>
<td>13.3</td>
<td>1.8</td>
<td>214</td>
<td>0.64775</td>
<td>1.368 E-05 – 4.899 E-05</td>
<td>0.6333</td>
<td>18-11-46</td>
<td>Hexagonal Long column</td>
</tr>
<tr>
<td>11/08/2010</td>
<td>15.6</td>
<td>14.4</td>
<td>15.1</td>
<td>1.2</td>
<td>207</td>
<td>(S comp noisy)</td>
<td>1.16 E-05 – 8.08 E-05</td>
<td>0.7692</td>
<td>21-8-32</td>
<td>thin plates / oriented other type of crystals</td>
</tr>
<tr>
<td>13/10/2010</td>
<td>14.1</td>
<td>11.4</td>
<td>13.5</td>
<td>2.7</td>
<td>227</td>
<td>0.2113</td>
<td>3.22 E-05 – 3.1 E-05</td>
<td>0.7782</td>
<td>30-5-9</td>
<td>thin plates / oriented other type of crystals</td>
</tr>
<tr>
<td>19/11/2010</td>
<td>15.1</td>
<td>12.6</td>
<td>14.7</td>
<td>2.5</td>
<td>210</td>
<td>0.2694</td>
<td>2.12 E-05 – 5.17 E-05</td>
<td>0.752</td>
<td>31-5-8</td>
<td>thin plates / oriented other type of crystals</td>
</tr>
<tr>
<td>22/12/2010</td>
<td>16.2</td>
<td>14.1</td>
<td>15</td>
<td>2.1</td>
<td>205</td>
<td>0.2839</td>
<td>2.2 E-05 – 3.27 E-05</td>
<td>0.1122</td>
<td>22-6-10</td>
<td>thin plates / oriented other type of crystals</td>
</tr>
<tr>
<td>31/12/2010</td>
<td>13.5</td>
<td>12.3</td>
<td>12.9</td>
<td>1.2</td>
<td>220</td>
<td>0.2088</td>
<td>1.97 E-05 – 3.22 E-05</td>
<td>0.2591</td>
<td>10-7-25</td>
<td>thin plates / oriented other type of crystals</td>
</tr>
</tbody>
</table>

1. CBH: Cloud Base Height; 2. CTH: Cloud Top Height; 3. T: Thickness 4. Temp: Temperature in Kelvin; 5. OD: Optical Depth

6. DR: Deplorisation Ratio; 7. LR: Lidar Ratio
5.3.4.1 Temporal variation of lidar ratio, extinction coefficient and depolarization ratio

To study the temporal behavior of the lidar ratio, extinction coefficient and depolarization ratio the lidar signal were collected for five days viz.21/1/2009, 1/4/2009, 03/02/2010, 05/05/2010 and 19/11/2010. Out of these five days on 21/1/2009 only the depolarization measurements was possible. All observations were started on 7 pm. The profiles were integrated for 30 minutes.

Fig 5.16 (a): The contour plot of the time variation of extinction of cirrus cloud observed on 21/1/2009

Fig 5.16 (b): The contour plot of the time variation of lidar ratio of cirrus cloud observed on 21/1/2009

Fig 5.16 (c): The contour plot of the time variation of depolarisation ratio of cirrus cloud observed on 21/1/2009
The contour plots for the temporal variation of extinction coefficient, lidar ratio and depolarization ratio are shown in Figs 5.16(a), (b), and (c) respectively. This day falls in the winter period of the year 2009 and is well within the TTL range. The extinction plot clearly shows the dispersion of the cirrus clouds after three and half hours. The value of the lidar ratio in the presence of the cloud is around 4sr and changes to a value around 10sr after the cloud disappears. The corresponding variation in lidar ratio is very slow. The temporal variation of depolarization ratio of this cirrus cloud varies rapidly showing an oscillatory behavior between 0.2 and 0.1. This oscillatory variation is an indication of the presence of small oriented crystals which grows and disappears rapidly (precipitates).

The contour plots showing the temporal variation of extinction coefficient, lidar ratio, and depolarisation ratio for the rest of the observational days viz. 1/4/2009, 03/02/2010, 05/05/2010 and 19/11/2010 are plotted and shown in Fig. 5.17.

The Fig. 5.17 shows the temporal variation of lidar ratio for different days in the period of observation. The period of observation with more than two hours of continuous observation is taken and analyzed. During the south west and north east monsoon period there are frequent showers and rain which hinder continuous data collection. So long time temporal data was not available on those days. It is seen that during summer periods of April 1, the cloud occur near 16km and a steady lidar ratio value exist over this region without much variation. The depolarisation shows dispersion and re-formation of regular crystals. 03 February 2010 which falls in the winter period of 2009 shows some variability in cirrus lidar ratio, the region inside the cirrus cloud shows small
Fig 5.17 The contour plot of temporal variation of extinction coefficient, lidar ratio, and depolarisation ratio cirrus cloud observed during the observational days 1/4/2009, 03/02/2010, 05/05/2010 and 19/11/2010.
values of lidar ratio with variability from 4-20 sr and an average of 30 sr around the cloud. The depolarisation is high inside the cloud structure, showing the presence of ordered crystals. The observation on 5th May 2010 shows some active convection on a temporal frame. The lidar ratio, depolarisation ratio shows large spread to higher altitudes. The spread may be associated with ice particulates transported up due to convection. The ITCZ is getting positive over the station in this season as discussed in previous chapters. This rapid fluctuation of lidar ratio and depolarisation ratio is also visible in the profile taken on 19th November 2010. It may be noted that rapid change in lidar ratio occurs only during the periods of active convection. The Fig.5.17 also shows the temporal variation of lidar ratio and depolarisation ratio for the above said days of observation. There is a negative correlation existing between the extinction coefficient and lidar ratio. Lidar ratio decreases inside the cloud due to the scattering effect of ice particulates present inside the clouds. The temporal observations made on April 01 2009 shows the depolarisation decreases after one hour and the value increases and reaches peak about 0.8 in the next two hours. This clearly shows the formation, dispersion and reformation of ice crystal structures inside the high altitude clouds with respect to time. The ice in cirrus can disperse easily and reform again.

5.3.5 Effect of turbulence on cloud microphysics

There are two types of fluid flow namely laminar flow, and turbulent flow. Laminar flow is smooth and steady whereas turbulent flow is unstable and random. Turbulence is a characteristic of the turbulent flow and is defined as irregular or random motions in a fluid.

This turbulent mixing in atmosphere generates local changes in
temperature, humidity, and atmospheric composition, which can lead to changes in the index of refraction.

Turbulence also behaves over a range of different scale lengths. Larger eddies transfer their kinetic energy to smaller eddies until all of the energy is dissipated by viscosity. This effect is clear from Kolmogorov's mathematical model, who formulated that the non-homogeneous turbulence effect ranges from 10's to 100's of meters. The model also suggested that for homogeneous, isotropic turbulence effect the range is of the order of 0.1 to 10 mm. In earth's atmosphere, solar heating generates atmospheric kinetic energy over scale sizes that range from a few meters to a global scale. Other large scale energy transfers occur from infrared radiation exchange processes, gravity wave effects, and wind interactions with the ground. This kinetic energy is then dissipated through frictional heating near the earth's surface, with a scale size less than one centimetre. The range over which this occurs is called the inertial sub range (Hufnagel, 1985).

Atmospheric turbulence induces random irregularities in the index of refraction. Electromagnetic wavefronts propagating through this turbulence become distorted, which causes the beam to wander and spread. Statistics are used to quantify these characteristics because the changes in the atmosphere's index of refraction are random. Thus, the end result is a quantitative description of the laser system's performance. (Hufnagel, 1985). Since lidar uses laser probe the effect of turbulence has a direct effect on its signal. Atmospheric turbulence is usually characterized by the refractive index structure constant $C_n^2$ or eddy dissipation rate $\varepsilon$ or $\sigma_w^2$. 
Turbulence occurs in all three velocity components (Zonal, Meridional and Vertical) and is unpredictable in detail; however, statistically distinct properties of the turbulence can be identified and analyzed. Turbulence exhibits a broad range of spatial and temporal scales resulting in efficient mixing of fluid properties. Turbulence is important because it mixes and churns the atmosphere and causes water vapour, smoke, and other substances, as well as energy, to become distributed both vertically and horizontally.

In this section the effect of turbulence strength particularly in ice crystal formation in the cirrus by studying the refractive index structure parameter $C_n^2$ is presented. This is done by using one of the most used models, Hufnagel-Valley defined by the following equation:

$$C_n^2 = 0.00594 \left( \frac{v}{27} \right)^2 \left( 10^{-5} h \right)^9 \exp\left( \frac{-h}{1000} \right) + 2.7 \times 10^{-16} \exp\left( \frac{-h}{1500} \right) + A_0 \exp\left( \frac{-h}{100} \right)$$

(5.6)

$h$ : is the altitude in (m) 
$v$ : is the wind speed at high altitude (m/s) 
$A_0$ : is the turbulence strength at ground level, $A_0=1.7 \times 10^{-14} m^{-2/3}$

Fig 5.18 (a): The variation of refractive index with respect to altitude for different days of observation of the year 2009. 

Fig 5.18 (b): The variation of refractive index with respect to altitude for different days of observation of the year 2010.
The Fig. 5.18 shows the measure of turbulence as a measure of refractive index \((Cn^2)\) for the two years of study. High turbulence is found during the observation days in February for both 2009 and 2010. For the rest of the months in 2009 in which turbulence data is available with us, relatively lower turbulence values are observed. Whereas for the year 2010 moderately high values of turbulence are observed for all the observation days except in winter period. In the altitude range 8-12 km shows the higher value of turbulence during the days of observation for the year 2009. Above 12 km the value of turbulence is relatively less for the year. For the year 2010 relatively higher turbulence is maintained for the altitude 8-16 km for the days of observation except for winter season. The high level of turbulence observed for the month February 2009 and for almost all months except in winter season (Nov-Jan) in 2010 can be due to the convection activities like ITCZ and the Hadley cell. Their influence reduces in winter season.

The effect of turbulence in extinction, lidar ratio and depolarisation ratio is discussed in the Fig 5.19 and 5.20. Four days of near simultaneous observation of lidar ratio, extinction coefficient, depolarisation ratio and turbulence are taken for the study during the period 2009-2010. Out of the four days two days of turbulent days and two days of relatively turbulence free days are selected for the study. Turbulence can increases the interaction between the ice nuclei particulates inside the cloud and this can aggravates the growth of ordered ice crystals. It is observed that cloud occurring during the highly turbulent days of February 2010 have high depolarisation ratio. The effect of turbulence can be attributed to this particular observation.

The Fig. 5.19 to Fig. 5.21 shows the negative correlation between
Fig 5.19: The variation in refractive index factor, lidar ratio, extinction coefficient and depolarisation ratio as a function of altitude for observation day 22-07-2009 (a day with less atmospheric turbulence)

the lidar ratio and extinction inside a cloud structure. The extinction coefficient increases inside the cloud near the cloud centre and the lidar ratio decreases inside the same region of the cloud. The depolarisation value also increase inside the cloud. The region of cloud which has more ordered crystals has high depolarisation value. It is seen that the turbulence can have a direct effect on the symmetric nature of the clouds. The clouds seem to be more asymmetric
Fig 5.20: The variation in refractive index factor, lidar ratio, extinction coefficient and depolarisation ratio as a function of altitude for observation day 17-10-2009 (a day with less atmospheric turbulence)

in nature with presence of turbulence in the region of cloud occurrence. The depolarisation ratio is found to be high in the cloud region where the turbulence effect is high.

5.4 Effect of turbidity on cloud microphysics

Turbulence increases turbidity. Turbidity is an important parameter,
Fig 5.21: The variation in refractive index factor, lidar ratio, extinction coefficient and depolarisation ratio as a function of altitude for observation day 13-10-2010 (a day with atmospheric turbulence)

which is often used in the studies of atmospheric visibility, pollution, and transmittance. It expresses the total scattering by the entire atmosphere (by molecules and particles) in terms of molecular scattering and is given by the expression,

\[ T_u = \frac{\tau_m + \tau_a}{\tau_m} \]  

(5.8)
where $\tau_m$ and $\tau_a$ represent the optical depths due to molecules and aerosols respectively. Angstrom (1964) related the turbidity to the aerosol optical depth and wavelength of radiation with expression $\tau_a = \beta \lambda^{-\gamma}$ where $\gamma$ is called the wavelength exponent and $\beta$ is the Angstrom turbidity coefficient.
The Fig. 5.23 shows the monthly average of atmospheric turbulence. The turbulence is found to be high during the monsoon periods where the turbulence is active. The churning of atmosphere by turbulence in the convective periods decreases visibility and thereby transmittance. In 2009 it is clearly seen that south west monsoon periods of June, July and August has maximum turbidity. Due to the less number of data available during the south west monsoon period of 2010, significant turbidity is not observed during that period. But in the north east monsoon period the increase in turbidity is well seen.

5.5 Conclusion

This study reveals different forms of cirrus manifestations prevailing over the tropics. The most preferred altitude for cirrus formation is found to be 13-14 km height.

- Cloud height values show a maximum occurrence in the narrow 13-14 km range, while their thickness is not always as narrow as was generally accepted in the current understanding. In
fact, the cloud average thickness derived from our lidar system is 1.5 km when the temperature is in the range -17°C to -87°C.

- Regarding the extinction coefficient there is a maximum in the narrow 6.8-1.6x10^4 m^{-1} range. Comparisons of the results of the present analysis with other tropical and mid latitude cirrus studies were presented.

- The Cloud assymetric factor \( \xi \) shows that cloud observed during the year 2009 has the maximum scattering at the cloud center. Whereas the clouds observed in 2010 shows the anomaly of scattering occurring in the upper layer of the clouds.

- The multiple scattering effect study shows that there is an anomaly of observed clouds being more multiple scattering in nature than in 2009.

- Observed differences in the properties of optical depth, extinction coefficient may be explained by different factors such as geographical conditions, mechanism forms and probably by the local prevailing dynamical processes.

- Cloud optical depth is high during the monsoon period. These differences could also be responsible of the probably different particle size and composition of the cirrus clouds at this latitude range, which must be further investigated. Table 5.3 and 5.4 summarize the representative values for the cirrus clouds under study. The cloud depolarisation study shows the possible crystal structure formed inside the cloud and it is of intrinsic value for validating and advancing our understanding of the microphysical processes underlying the production and evolution of the ice particles.
The effect of cloud turbulence and turbidity is also studied by taking these two years as model years. High turbulence is found during months of February and the high level is maintained through the monsoon period, but it decreases during the winter period. This is related to the convection activities like ITCZ and the Hadley cell. So their influence reduces in winter and simultaneously the turbulence also weakens. The increase in turbulence in the 10-15 km range, increases the optical depth of cirrus observed there.

The increase in turbulence consequently increases the turbidity in the monsoon periods.