CHAPTER 4

GENERAL FEATURES OF HIGH ALTITUDE TROPICAL CIRRUS CLOUDS

4.1. INTRODUCTION

General features of high altitude cirrus clouds observed near the tropical tropopause are studied using the lidar data for the period 1998-2002. These clouds are classified based on their optical depths. The occurrence frequency of each cirrus type and their seasonal variation are examined separately. Cloud properties such as cloud strength, cloud mean altitude, cloud width, cloud asymmetry and depolarization for different types of cirrus clouds are examined in detail. Seasonal dependence of cloud parameters and the association of cirrus with tropical tropopause are investigated.

4.2. HIGH ALTITUDE CIRRUS

Cirrus clouds occur quite frequently at this tropical location. Figure 4.1 shows the altitude-time contour plots of $R_e(h, t)$ and $\delta(h, t)$ on a typical night, 19 January 1999 observed using lidar. The mean temperature profile in the 8-20 km altitude region during 22:00 IST to 24:00 IST derived from MST radar observations is also shown in Figure 4.1. High values of $R_e$ and $\delta$ observed in the altitude region from 15.5 to 16.5 km is due to the presence of cirrus clouds. Cirrus clouds are identified from the altitude profile of lidar backscatter ratio in the co-polarized and cross-polarized channels as described in Chapter 3. From the altitude profile of temperature the tropical tropopause is identified as the altitude at which the temperature reaches a minimum value (referred to as cold point tropopause). The cold point tropopause is indicated by an arrow head in Figure 4.1 (right panel). It would be worth in this context to note that tropical tropopause is defined differently in different context. Physically, tropopause is the region where a smooth transition from convective heating to radiative heating takes place [Highwood and Hoskins, 1998]. In the troposphere heat is transported up from the surface through convective eddies. The strength of the eddy convection is maximum near the surface (and in the Atmospheric Boundary Layer) and decreases with increase in altitude. In the stratosphere, the heat source is radiative heating. This radiative heating is not only confined to the altitudes
above the tropopause temperature inversion but also extends down below, though much weaker than in stratosphere. Thus the effect of radiative heating starts in the upper troposphere itself. As the 'convective process' dominates this radiative heating at these altitudes, temperature continues to decrease with altitude. But, the temperature lapse rate decreases with altitude. At higher altitude, the effect of radiative heating is increasingly felt and the effect of convection decreases. This process continues up to a certain altitude where the radiative heating starts dominating. From this altitude onwards the temperature starts increasing with increase in altitude. Thus tropopause is a convective-radiative domain and the cold point altitude indicates the level at which the radiative process just neutralizes the convective process. The conventional tropopause defined by WMO is based on temperature lapse rate. This is defined as the lower boundary of an atmospheric boundary layer (in the upper troposphere) in which the temperature lapse rate is less than 2° C km⁻¹ and this layer has to be at least 2 km thick [Krishna Murthy et al., 1986]. This level lies ~1-2 km below the cold point. It may be noted that the cold point tropopause is physically relevant in describing the transport of trace species like aerosols and water vapour [Highwood and Hoskins, 1998] and its location is critical for the dehydration processes [Jensen et al, 2001a]. For modelling the tropical cirrus it is recommended to use the cold point as tropical tropopause. Hence for the present study on tropical cirrus, the cold point is used to define the tropical tropopause.

From the Figure 4.1 it is seen that the cold point tropopause is located at 16.65 km whose temperature is 199.7 K. Examining the contour plots of the Rₜ(h, t) and δ(h, t), it is seen that cirrus clouds on this night lies close to the tropical tropopause. The linear depolarization ratio, δ, as well as the effective backscatter ratio, Rₜ, within the cirrus are found to be weak at the start of the lidar observation and becomes strong after 01:00 IST. The temperature profile shows that the cloud lies within the temperature range 199.7 to 200.5 K. High value of δ within the cloud and the temperature range in the altitude region where the cloud is located indicate that cloud particles could be composed of non-spherical ice crystals. All the observed values of δ within the cloud are large enough to exclude the presence of spherical particles. This confirms that supercooled liquid droplets cannot normally exist [Platt et al., 1989] at temperatures below 230 K. The lidar observations on different nights revealed the presence of the cirrus clouds with different structures/pattern whose vertical extent
varies from 0.5 km to 5 km. They mostly occur within an altitude region ~ 4 km below the tropical tropopause. The details of different manifestations of cirrus and its temporal variability are discussed in Chapter 5.

![Figure 4.1 Altitude-time contour plots of effective backscatter ratio (R_e) and LDR (δ) on a typical night, 19 January 1999 observed using lidar. The right panel shows the mean temperature profile in the altitude region 8-20 km derived from MST radar data.](image)

4.3. CLASSIFICATION OF CIRRUS CLOUD

As the important factor in distinguishing cloud type is its colour, the terms translucidus and opacus are applied to layers through which the blue-sky colour can or cannot be seen by a ground observer. Thus, cloud visible optical thickness (τ_v) is inherent in the identification of cloud type [Sassen, 2002]. The optical thickness of tropical cirrus shows large variability ranging from less than 0.01 to 1. Based on this, the cirrus clouds are classified as thin or dense cirrus. Though the classification based on optical depth is somewhat arbitrary it is useful for defining different cloud types. Wang et al. [1996] used Stratospheric Aerosol and Gas Experiment (SAGE) II extinction profiles at 1 μm wavelength for studying the occurrence altitude and horizontal extent of cirrus clouds. In this study they classified cirrus clouds with τ_v<0.03 as subvisual clouds and clouds with τ_v>0.03 as dense clouds. Guasta et al. [1993] used Ruby lidar (at 0.69 μm wavelength) for cirrus studies. They took a critical τ_v value of 0.05 for subvisual cirrus and clouds with τ_v above 0.05 as dense cirrus. Several researchers adopted τ_v ≤ 0.05 as a threshold for visible optical depth [Lynch, 1993; Schmidt et al., 1993; Schmidt and Lynch, 1995] in identifying subvisual
cirrus. Sassen and Cho [1992] made a detailed classification based on $\tau_c$ (at 0.69 $\mu$m wavelength) in which clouds with $\tau_c \leq 0.03$ are classified as subvisual cirrus (SVC). Cirrus clouds with $0.03 < \tau_c \leq 0.3$ are classified as thin (bluish coloured) cirrus (TC). Clouds with $\tau_c > 0.3$ are classified as dense cirrus (DC). The lidar-derived $\tau_c$ tends to reach saturation approximately when $\tau_c$ reaches about 2-3, in which case the clouds [Kinne et al., 1992] are the dense Cirrostratus (Cs). It may be noted in this context that though the above classification of cirrus is based on $\tau_c$ at different wavelengths, the criteria of fixing threshold $\tau_c$ is independent of wavelengths. This is because of the fact that the cloud optical depth does not show any significant wavelength dependence in the visible region of the electromagnetic spectrum as the scattering efficiency of cloud particles lies close to 2 for all wavelengths in this region [Mace et al., 1998].

Among different cirrus classification cited above, the one proposed by Sassen and Cho [1992] is adopted for the present study because of the fact that it provides three classes for which $\tau_c$ are significantly different and thus providing a finer classification for thin, medium and thick type clouds. McFarquhar et al. [2000] also used a similar classification for cirrus clouds for assessing their radiative impacts.

4.4. GENERAL CHARACTERISTICS OF TROPICAL CIRRUS

4.4.1. Occurrence of Cirrus

Lidar observations made during the period March 1998 to June 2002 on clear sky nights are used for the present study. If the backscatter ratio in either of the two (P or S) channels exceeds 2 it is taken as presence of the cloud and only when the backscatter ratio in both the channels decreases below 2 it is taken as the absence of cloud. This criterion of cloud detection is explained in detail in Chapter 3. Lidar profiles taken at every 250 s are used to examine the frequency of occurrence of cirrus clouds. In doing so, the occurrence frequencies of each of the three cloud types (SVC, TC and DC) are obtained separately. Lidar observations during the above period consist of 15862 profiles. Out of these 15862 profiles, 8667 profiles (54.64%) showed the presence of cirrus. In this, 5469 cases (34.48% of the total) were SVCs, 2628 cases (16.57% of the total) were TCs and 570 cases (3.59% of the total) were DCs. Table 4.1 shows the occurrence statistics of different cirrus types. Examining the 8667 profiles having cirrus cloud, 63.10% of these were SVCs, 30.32% were TCs and 6.58% were DCs. Out of these 8667 profiles, on 70.24% of cases the observed cirrus
clouds were having $\tau_c$ less than 0.05. This is in fairly good agreement with increased frequency of occurrence of SVC reported by Wang et al. [1996] based on six year climatology of cloud occurrence from SAGE II in this latitude region (i.e., $\sim$13°N). They also observed that the favoured locations for SVC to be centered over south eastern Asia, India and Mexico.

The profile statistics of occurrence of different types of cirrus discussed above are based on the 281 nights of lidar observation during the study period. Similar to the profile statistics the frequency of occurrence of different types of cirrus clouds have been examined based on average optical depth for each night. Considering the 281 nights of lidar observations, on 229 nights cirrus clouds are detected during the observation period. This indicates that the cirrus clouds were detected on 81.5% of the observational nights. This percentage is larger than the cirrus statistics derived from individual profiles (~55%); mainly due to the fact that in most of the nights the cirrus occurrence will be either intermittent or occurs only for a short duration during the period of lidar observation. Out of the 229 nights on which cirrus clouds are detected, SVCs are observed on 138 nights (60.3%), TCs are observed on 77 nights (33.6%) and DCs on 14 nights (6.1%). The frequency of occurrence of different cirrus types based on this mean statistics is also presented in Table 4.1. From the table it is seen that the frequency of occurrence of different types of cirrus clouds estimated based on profile statistics matches fairly well with that derived from night statistics. Both these statistics indicate the high occurrence of SVC at this tropical station, Gadanki.

Figure 4.2 shows the occurrence of the cirrus clouds for different nights. Hollow bars indicate total number of lidar profiles taken on each night and filled region of this bar indicates the number of profiles on which cirrus clouds are detected. Crossed hatches in the bar indicate that the observed cloud is SVC type. A light shade in hatch indicates that the observed cloud is TC and dark shade indicates that the cloud is DC. The dates of the corresponding observation nights are written on the top of the bars and their months and years are shown in the X-axis. It is seen that while the occurrence of SVC is large during winter months, when convective activity is low, TC/DC occurs quite frequently during the southwest (SW) monsoon period when convective activity is high.
Figure 4.2. Bar diagram showing the occurrence of cirrus on different nights. Hollow bars indicate total number of lidar profiles taken on that night and hatched region of this bar indicates the number of profiles on which cirrus clouds are detected. The cloud type (SVC, TC, DC) are distinguishable from the nature of hatch. The cirrus classification is based on the mean optical depth for the night. The dates of the corresponding observation nights are written on the top of the bar.
### Occurrence frequency of high altitude cirrus observed at a tropical station Gadanki during the period 1998-2002

<table>
<thead>
<tr>
<th>Cloud type</th>
<th>Profile statistics</th>
<th>Night statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of profiles</td>
<td>Percentage</td>
</tr>
<tr>
<td>SVC</td>
<td>5469</td>
<td>63.10</td>
</tr>
<tr>
<td>TC</td>
<td>2628</td>
<td>30.32</td>
</tr>
<tr>
<td>DC</td>
<td>570</td>
<td>6.58</td>
</tr>
<tr>
<td>SVC+TC+DC</td>
<td>8667</td>
<td></td>
</tr>
<tr>
<td>No cloud</td>
<td>7195</td>
<td></td>
</tr>
</tbody>
</table>

### Cirrus Properties

In order to study the general characteristics of cirrus clouds, the mean cloud parameters on different nights are estimated by averaging the respective parameter obtained from each lidar profile (with basic time resolution of 250 s) for the entire night. Based on the mean optical depth, \( \tau_c \), for the night, the cloud is classified as SVC, TC or DC and the properties of these individual classes are studied separately in addition to their overall property. Figure 4.3a shows the frequency of occurrence of cirrus cloud with different optical depths (in steps of 0.03) along with the cumulative probability distribution. The probability of occurrence for lower \( \tau_c \) is high and it decreases with increasing \( \tau_c \). As seen from the cumulative frequency curve, number of occurrences of clouds with \( \tau_c < 0.03 \) (SVC) is quite high. For \( \sim 93.9\% \) cases the average \( \tau_c \) is below 0.3 indicating that, in general, the tropical cirrus are optically thin (SVC/TC). It may be noted in this context that the cloud strength (\( M_o \)) and \( \tau_c \) are directly related even though the relationship may not be strictly linear. Figure 4.3b shows a plot of \( \tau_c \) with \( M_o \) depicting the amount of variability in \( M_o \) for the given \( \tau_c \). The Figure 4.3b shows considerable scatter of \( M_o \) values for the same value of \( \tau_c \). Hence there will be more than one value for \( M_o \) for the same value of \( \tau_c \). As the clouds are classified into SVC, TC and DC based on their optical depths there will be an overlap in the value of \( M_o \) (larger values of \( M_o \) observed for SVC will be encountered among the lower range of values observed for TC and similarly large values of \( M_o \) observed for TC will be encountered among lower range of values observed for DC) among these three types.
Figure 4.3 Frequency of occurrence of cirrus clouds with different optical depths and the cumulative frequency distribution (a) and a scatter plot showing the interdependence of $\tau_c$ on $M_0$ (b).

The statistics of cloud strength, $M_0$, cloud mean altitude or optic centre of cloud, $M_1$ (km), cloud half-width, $M_2$ (km), cloud asymmetry factor, $\xi$, LDR, $\delta$, and PDR, $\delta_a$, are examined in the following Sub-sections (4.4.2.1 to 4.4.2.6). This involves data on 229 nights during the study period in which cirrus clouds are observed. In each case the distributions for the total cirrus cloud system (all SVC, TC and DC inclusive) as well as for the individual types (SVC, TC and DC separately) are presented and discussed. As the percentages are drawn based on the total number of nights when cirrus clouds are observed; while the summation of the distributions presented in percentages for
the total cirrus cloud system yields a value of 100%, a similar summation yields 60.3% for SVC, 33.6% for TC and 6.1% for DC.

### 4.4.2.1 Cloud Strength

The frequency distributions of cloud strength, $M_o$, for the entire cirrus system and for different cirrus types are shown in Figure 4.4. As seen from Equation (3.39) $M_o$ is nothing but the weighted mean effective backscatter ratio within the cloud. Figure 4.4a shows that frequency of occurrence of cirrus decreases almost exponentially with increasing cloud strength. This is similar to the plot of $\tau_c$ shown in Figure 4.3a, which shows that optically thin cirrus occur more frequently than dense cirrus. About 65% of the $M_o$ values are below 4 (panel a), which are mostly contributed by SVCs. For SVCs, in general, $M_o$ is less than 4 and mostly lies in the range 1 to 2.5, with high occurrence between 1.25 and 1.5. The distribution for SVCs is shown in steps of 0.25. For TCs, the value of $M_o$ generally lies in the range 2 to 14, though frequency of occurrence of TCs having $M_o \sim 6\pm 2$ is maximum. Both SVCs and TCs can occur with cloud strength in the range $2 < M_o < 6$, but in majority of such cases they will be TCs. Similarly for DCs, $M_o$ ranges from 6 to 18. The frequency distribution of $M_o$ is rather flat (with no significant peak). DCs with $M_o < 6$ seldom occur.

### 4.4.2.2 Cloud boundaries

The altitudes of cloud top ($h_{ct}$) and cloud base ($h_{cb}$) are determined from the altitude profile of backscatter ratio by fixing a threshold value ($R_T$) of 2 for the backscatter ratio as described in Chapter 3. The frequency distributions of $h_{ct}$ and $h_{cb}$ are presented in Figure 4.5. The top panel shows the frequency distribution of $h_{ct}$ and lower panel shows the same for $h_{cb}$ (in steps of 0.5 km). These distributions show that though cloud top generally lies between 9 and 20 km in most the cases it lies between 15 and 18 km. The cloud base generally lies between 8 and 18 km with higher probability of occurrence between 13 and 16 km. The distribution of cloud top is rather sharp compared to that of cloud base. In most of the cases cloud top lies very close to the tropopause, while cloud base can vary depending on cloud type. The most probable value of cloud top is 16 km and that of cloud base is 14 km indicating that in most cases the cloud width is $\sim 2$ km.
Figure 4.4 Frequency distribution of mean cloud strength ($M_o$), for the entire high altitude cirrus system (a), for subvisual cirrus (b), for thin cirrus (c) and for dense cirrus (d).
4.4.2.3 Cloud Mean Altitude (Cloud Optic Centre)

The first moment of $R_e$ gives the weighted (by scattering ratio) mean altitude ($M_1$) of the cloud. This is sometimes referred to as the altitude of cloud optic centre. Guasta et al. [1993] and Pace et al. [2003] followed a similar approach in determining the cloud optic centre based on the backscatter coefficient. Sassen and Comstock [2001] have determined the optic centre of the cloud at the altitude where the optical depth of the cloud falls by half. The frequency distribution (in steps of 0.5 km) of $M_1$ is shown in Figure 4.6. The distribution for the total cirrus system (panel a) shows that $M_1$ can vary from 9 to 19 km with most probable occurrence between 14 and 16 km. The distribution of $M_1$ for subvisual cirrus (SVC) shows that they can occur anywhere in the altitude region between 9 and 19 km, though in most of the cases they occurs in the region between 14.5 and 16.5 km (i.e.,~15.5 ± 1 km). TCs usually occur below 16 km with a maximum probability of occurrence around 14.5 ± 1 km. DCs always occur below 16 km with maximum probability of occurrence around 13.5 km. This shows that in most of the cases TCs and DCs occur at a lower altitude (by 1-2 km) compared to SVCs. All these distributions are skewed about their peaks. The decrease in the amplitude of the distribution above the peak is rather sharp compared to that below the peak.

4.4.2.4 Cloud Width

The dispersion of the cloud from its mean altitude is determined from the second moment of effective backscatter ratio $R_e$. The estimation of cloud half-width from the second moment of $R_e$ is described in Chapter 3. Figure 4.7 shows the distribution of $M_2$ for entire cirrus system and for different cirrus types (in steps of 0.2 km). The frequency distribution of cloud half-width shows that the vertical extent of tropical cirrus (cloud full width at half maximum is 2.355 times $M_2$) varies from 0.5 to 5 km. From Figure 4.7a it can be seen that in most of the cases the value $M_2$ for tropical cirrus lies between 0.2 and 0.6 km. This is true for SVCs also. The most probable value of $M_2$ for SVCs is around 0.3 km. The half-width of TC mostly lies in the range 0.9 ± 0.4 km. Dense cirrus are generally thicker, with half-width in most of the cases exceeding 1.2 km. A notable feature in Figure 4.7 is that all the three types of clouds can have half-widths up to ~2 km, but DC with half-width <0.8 km seldom occur. Figure 4.7 indicates that the frequency distribution of $M_2$ is more or less similar to that of the cloud optical depth.
Figure 4.5 Frequency distribution of cloud top and cloud base
Figure 4.6 Frequency distribution of cloud mean altitude (or optical centre of the cloud) ($M_1$) for the entire cirrus system (a), for subvisual cirrus (b), for thin cirrus (c) and for dense cirrus (d).
Figure 4.7 Frequency distribution of cloud half-width ($M_2$) for the entire high altitude cirrus system (a), for subvisual cirrus (b), for thin cirrus (c) and for dense cirrus (d).
4.4.2.5. Cloud Asymmetry Factor

The optical symmetry of cirrus can be quantified using either of the two asymmetry factors $\psi$ and $\xi$, the estimation of which are described in Chapter 3. An examination of cloud pattern on different nights reveals that in most of the cases the cloud pattern shows large temporal variability. The integrated backscatter from lower half and upper half of the cloud are not always equal in magnitude. This shows that cloud is not optically symmetric. But, when the overall pattern of the cirrus system for one night, in most of the cases they are symmetric. But in a very few cases they differ. This aspect is studied by examining the frequency distribution of $\psi$ and $\xi$. This is shown in Figure 4.8. The four panels on the left hand side show the distribution of $\psi$ and the four panels on the right hand side show the distribution of $\xi$. The top panel on left hand side (Figure 4.8a) shows the frequency distribution of $\psi$ for the entire cirrus system and the lower three panels respectively show the same for different types of cirrus (SVC, TC, and DC respectively) clouds. Similarly the top panel on right hand side (Figure 4.8a) shows the frequency distribution of $\xi$ for the entire cirrus system and the lower three panels on right hand side show the distribution of $\xi$ for SVC, TC, and DC respectively. As detailed in Chapter 3, a value of $\psi$ close to zero or a value of $\xi$ close to 0.5 indicates that the cloud is more or less symmetric. From Figure 4.8 (a and b) it can be seen that, for most of the cases $\xi \approx 0.5$ and $\psi \approx 0$ indicating that on an average the optical centre of the cloud lies very close to its geometric centre. In most of the clouds the deviation of optical centre from the geometric centre is less than $\pm 15\%$ (i.e., lies in the range $\xi = 0.5 \pm 0.075$). Number of clouds having their mean optical centre below the geometric centre is slightly more that those having the mean optic centre above the geometric centre. These histograms however indicate the average cloud property. The short-term temporal variations on $\psi$ and $\xi$ (over a night) are quite significant. This aspect however are detailed in Chapter 5. Examining the distribution of $\psi$ and $\xi$ for different types of cirrus clouds it can be seen that the above features are applicable for SVCs. But for TCs and DCs, which are geometrically thick, the spread in the values of $\psi$ and $\xi$ is more. For these clouds the optical centre shifts down in more number of cases than those shifting up. This shows that the profile of $R$ within the cloud deviates significantly from a mean Gaussian type distribution.
Figure 4.8 Frequency distributions of mean cloud asymmetry $\psi$ and $\xi$; for the entire cirrus system (a and b), for SVCs (c and d), for TCs (e and f) and for DCs (g and h).
4.4.2.6 Cloud Depolarization

The LDR and PDR within the cloud shows significant temporal and altitude variations (Figure 4.1). As the depolarization ratio is an indicator of cloud microphysical properties its variation with time and altitude depicts the corresponding variation in particle habit and size. However, to study the general characteristics of cirrus on different nights it is necessary to examine the mean property on each night. Considering the cloud as a single ensemble an average value of LDR, \( \delta(t) \), and PDR, \( \delta_a(t) \), for the cloud at a particular time \( t \) can be defined by taking the weighted mean values of \( \delta(h, t) \) and \( \delta_a(h, t) \) over the cloud thickness. These quantities can be expressed mathematically as

\[
\delta_i(t) = \frac{1}{h_e - h_a} \int_{h_a}^{h_e} \delta(h, t) \, dh
\]

(4.1)

\[
\delta_{i,a}(t) = \frac{1}{h_e - h_a} \int_{h_a}^{h_e} \delta_a(h, t) \, dh
\]

(4.2)

where \( \delta_i(t) \) and \( \delta_{i,a}(t) \) represents the height averaged values of \( \delta \) and \( \delta_a \) along the cloud thickness. The mean value of \( \delta_i(t) \) and \( \delta_{i,a}(t) \) for each night is obtained by averaging the respective values from lidar profiles over that night. This mean values of LDR and PDR over each night are also represented by \( \delta \) and \( \delta_a \) respectively. Figures 4.9 and 4.10 show the frequency distributions of \( \delta \) and \( \delta_a \) in steps of 0.03 and 0.05 respectively for the entire cirrus system and for different cirrus types. In most of the cases the LDR lies below 0.1 even though it exceeds 0.25 in a few cases. The LDR goes up to 0.6 for SVC and TC whereas it is always less than 0.4 for DC. These value of \( \delta \) are smaller than those observed [Sassen and Benson, 2001] for midlatitude cirrus (where \( \delta \) is found to exceed 0.6). On examining the Figure 4.10, mean PDR varies from a very small value close to zero to \(~0.9\) with maximum number of occurrence below \(~0.4\) for all types of cirrus (SVC, TC and DC). The value of \( \delta_a \) can go upto 0.9 for SVC and TC whereas it is generally less than 0.5 for DC. Larger values of \( \delta \) (or \( \delta_a \)) indicate the presence of randomly oriented highly non-spherical ice crystals. Low values of \( \delta \) can be attributed to the phenomenon of specular reflection of vertically probed lidar beam from horizontally aligned ice crystals as pointed out by Thomas et al. [1990] or due to the presence of relatively small quasi-spherical ice crystals with rounded edges [McFarquhar and Heymsfield, 1996] which are more regular in their shape.
Figure 4.9. Frequency distribution of mean linear depolarization ratio ($\delta$) for the entire cirrus system (a), for subvisual cirrus (b), for thin cirrus (c) and for dense cirrus (d).
Figure 4.10. Frequency distribution of mean particulate depolarization ratio ($\delta_a$) for the entire cirrus system (a), for subvisual cirrus (b), for thin cirrus (c) and for dense cirrus (d).
4.4.3 Seasonal Variation of Cirrus Occurrence

The lidar data during the period March 1998 to June 2002 are used to examine the seasonal dependence of cirrus occurrence. As described above lidar profiles taken at every 250 sec on each night are scrutinized for the occurrence of cirrus. Figure 4.11 shows the histogram of total number of lidar profiles and the number of profiles on which cirrus clouds were detected as a function of month. The lidar profiles for same months in different years are grouped together to plot this monthly mean histogram. The bars indicate the total number of lidar profiles in each month with their shaded portion presenting the number profiles in which cirrus were present. The unshaded portion of each bar indicates the number of profiles in which no cirrus could be detected. As the number of lidar observation nights was more during the November to April period than that during summer (May to October), the number of profiles available for this analysis also was more during the November to April period. During summer months (May to October) observations are relatively low mainly due to the difficulty in conducting lidar observations in the presence of thick low-level clouds.

![Graph showing seasonal variation of cirrus occurrence](image)

Figure 4.11 A histogram showing total number of lidar profiles in each month along with the number of profiles on which cirrus clouds are detected, obtained from the data during the period March 1998 to June 2002.
Figure 4.11 shows that cirrus clouds are present irrespective of season in all the months. But their occurrence is high during summer months even though the lidar observations are less. In spite of the fact that in the present study the lidar observations were less during July, August and September months the inference agrees favourably with the winter (December, January, February) to summer (June, July, August) contrast in the mean frequency of cirrus occurrence reported from High Resolution Infrared Spectrometer (HIRS) observations during 1989-1997 by Wylie and Menzel [1999] over this region.

Figure 4.12 shows the month-to-month variation of the percentage of occurrence of SVC, TC and DC generated by considering the optical depth from each lidar profile. The total number of profiles and number of profiles in which different types of cirrus clouds (SVC, TC and DC) were observed in each month are grouped for estimating these percentages. The frequency of occurrence of each cirrus type is determined separately and the stacked bar diagram is drawn as shown in Figure 4.12. Percentage occurrence of different cirrus types is distinguished by choosing different shades for the hatch. The total length of each bar represents the cumulative percentage
of occurrence of cirrus in total. It is also seen that the frequency of occurrence of cirrus are high during the May-September period and low in February. During winter (November-February) occurrence of SVC is more than that of TC and DC. Occurrence of TC and DC is high during the Monsoon period (June -September). This pattern is consistent with the cirrus climatology derived from satellite measurements by Wang et al. [1996] over this region.

4.4.4 Seasonal Variation of Cloud Parameters

Monthly mean values of $M_0$, $M_1$, and $M_2$ are estimated by averaging the mean values of these parameters in different nights for the same month in different years during the study period. Figure 4.13 shows the monthly variations of these mean parameters along with the standard errors represented by vertical bars. The cloud is generally

![Figure 4.13 Month-to-month variation of average cirrus cloud parameters ($M_0$, $M_1$, $M_2$). The vertical bars indicate the standard error.](image)
weak \((M_0 \sim 3)\) and of SVC type with low vertical extent \((M_2 \sim 0.5 \text{ km})\) during the winter months. These parameters are generally high during June to September, the southwest (SW) monsoon period over the Indian subcontinent. In this period \(M_2\) is greater than 1 km (cloud full width half maximum is greater than 2.4 km). The cloud mean altitude generally lies in the range 14 to 16 km with a small decrease in June-July months. As seen from Figure 4.12 the cirrus clouds encountered during this period are generally TC/DC type. This migration behaviour of occurrence SVC to TC/DC during the monsoon period can be attributed to the intense convective activity prevailing in the troposphere during the Indian summer monsoon season. During this period water vapour as well as ice particles are injected into upper troposphere from active convective cells. The residuals left behind from deep convection leads to the formation of thick cirrus. This inference is consistent with the observed association of cirrus occurrence and precipitation \([Sassen and Campbell, 2001]\).

### 4.4.5 Interdependence of Cirrus Properties

The cloud parameters such as \(M_0, M_1, M_2\) and \(\xi\) show significant variations on different nights. The interdependence of these parameters are examined in this section. As pointed out in Section 4.4.2 the cloud strength and optical depth are related. Cloud with high \(\tau_c\) will have larger values of \(M_0\). Figure 4.14 shows a plot of \(\tau_c\) against the cloud strength and cloud half-width, the two parameters governing the cloud optical depth. Figure 4.14a is a re-plot of Figure 4.3b in log-log scale. Both these parameters \((M_0 \text{ and } M_2)\) show an increase with increase in \(\tau_c\). A simple linear relationship is sought between these two parameters and \(\tau_c\). The approximate linear relationship between \(M_0\) and \(\tau_c\) is of the form \(M_0 = a_0 + b_0 \tau_c\) with \(a_0 = -0.07 \pm 0.007, b_0 = 0.035 \pm 0.001\), with correlation coefficient of 0.88 (significant at 99.99% level of significance). Even though such a relationship also can be seen for \(M_2\) and \(\tau_c\) in Figure 4.14b, the scatter is very high. For example cloud with half-width 1 km can have \(\tau_c\) anywhere in the range \(3 \times 10^{-3}\) to 0.4 not withstanding the approximate linear trend (with large \(\tau_c\) for thick clouds) of the form \(M_2 = a_2 + b_2 \tau_c, a_2 = -0.05 \pm 0.01, b_2 = 0.17 \pm 0.02\) with a moderate correlation coefficient of 0.59. A similar relation between cloud optical depth and geometrical depth (physical depth) has been reported for tropical and mid-latitude cirrus by various researchers \([Sassen and cho, 1992; Thomas et al., 2002]\).
Figure 4.14 Scatter plots showing the dependence of cloud optical depth on cloud strength and cloud half-width.

The dependence of cloud strength on cloud mean altitude and cloud half-width are presented in Figure 4.15. While the black dots represent the relevant parameters for SVCs, blue and red dots represent those for TCs and DCs respectively. The mean altitude $M_1$ varies in the range 8 to 20 km, and weak clouds (optically thin) can occur anywhere in this altitude region. But strong clouds with $M_o > 10$ generally occur between (Figure 4.15a) 13 and 15 km. Figure 4.15b shows that thin clouds with half-width < 0.5 km are generally weak with $M_o < 5$ (region marked with small dashed-square). But thick clouds ($M_2 > 1$ km) are generally strong with $3 < M_o < 20$ (region embedded by the large dashed-square).

Figure 4.16 shows the interdependence between cloud mean altitude and cloud half-width. Different colour dots are used to distinguish different cirrus types as in Figure 4.15. This figure shows that low and high altitude cirrus are generally thin. Thick clouds with half-width greater than 1 km generally occur between 13 and 17 km, even though all cirrus clouds occurring in this altitude range need not be thick. Largest value for $M_2$ is observed for those clouds with mean altitude ~14 km, for which $M_o$ also is high. It may be noted (from Figure 4.6a) that this is the most favoured altitude for cirrus formation.
Figure 4.15 Interdependence of $M_0$ on $M_1$ and $M_2$. Black dots represent the parameters for SVCs, blue dots those for TCs and red dots those for DCs.

Figure 4.16 Interdependence of $M_1$ and $M_2$. Black dots represent the parameters for SVCs, blue dots those for TCs and red dots those for DCs.
Figure 4.17 shows the dependence of cloud asymmetry factor on \( M_0, M_1 \) and \( M_2 \). The horizontal line in these panels drawn at \( \xi = 0.5 \) indicates symmetric clouds. The figure shows that the cloud mean altitude (optic centre) is more or less close to the geometrical centre (with \( \xi \approx 0.5 \)) for weak clouds (\( M_0 < 3 \)). As the value of \( M_0 \) increases the clouds becomes more asymmetric even though quite a few clouds with high \( M_0 \) values continues to be symmetric. Among these strong asymmetric clouds in majority of cases the optic centre significantly descends from the geometric centre as indicated by larger occurrence of \( \xi \) values < 0.5. For a few cases, the optic centre ascends (\( \xi > 0.5 \)) above the geometric centre, though the deviation is relatively small. Figure 4.17b shows that high and low cirrus are more or less symmetric. Significant asymmetry is observed only for clouds forming in the favoured altitude region 12-16 km. In most of the cases \( \xi \) is less than 0.5. Figure 4.17c shows that thin clouds (with low \( M_2 \) values) are more or less symmetric. The asymmetry increases with increases in \( M_2 \). In majority of cases the optic centre descends from geometric centre (\( \xi < 0.5 \)). The LDR and PDR do not show any significant dependence on any of the cloud parameters such as \( M_0, M_1 \) and \( M_2 \).

The above interdependence of cloud parameters has also been examined for three types of cirrus clouds (SVC, TC, and DC) separately. The features are same as that of total cirrus cloud system not withstanding the fact that while for SVCs, \( M_1 \) can vary from 9 to 18 km, for TCs and DCs the range of variation is 12-16 km and 12-14 km respectively. While \( M_0 \) for SVCs will vary from 1 to 5, that for TCs varies from 2 to 14 and DCs from 6 to 18. While \( M_2 \) for SVCs vary from 0.2 to 1.6 km, that for TCs will vary from 0.3 to 2 km and DCs from 0.8 to 2 km. The respective scatter plots of different pairs of the above parameters for different cirrus types will be similar to the corresponding ones shown in Figure 4.15 and 4.16 except for the fact that the points will be seen only in the limited range of values of the parameters as cited above. This can be visualized from Figure 4.15 and 4.16 by considering only those coloured points, which are applicable for respective cirrus type. For DCs, a weak decrease in \( M_0 \) with increase in half-width is observed. High altitude DCs are found be thinner but stronger (with high values for \( M_0 \)). Thick cirrus clouds are more asymmetric. Most of the SVCs are almost symmetric in nature.
Figure 4.17 Dependence of cloud asymmetry factor $\xi$ on $M_0$, $M_1$ and $M_2$. Black dots represent the parameters for SVCs, blue dots those for TCs and red dots those for DCs.
4.4.6 Discussion

Above studies indicates that the region just below the tropical tropopause is conducive for cirrus formation. On most of the occasions the cloud formation occurs in the altitude region 14 -16 km indicating that the conditions prevailing in this altitude region is highly favorable for cirrus formation. Though the cloud depth varies from 0.4 km to 4 km, in most of the cases cloud is thin (with depth ≤0.5km). Occurrence of SVC (with $\tau_c< 0.03$) is more frequent than that of TC or DC. It may also be noted that on a few cases dense cirrus clouds are formed in multilayers capped by TC or SVC above. In the present analysis these fine structures are not delineated. The entire cirrus cloud system is taken as a single ensemble. As stated earlier, the fine structures within DC are not treated separately for this study.

It would be worth in this context to examine the present findings in the light of those reported by other investigators. Wang et al. [1996] from a six-year climatology of cirrus reported that SVCs occur about 45% of cases at an altitude of ~15 km over the equator. Their study showed that the favoured locations for SVC are centered over southeastern Asia and India and Mexico. The histogram of tropical cirrus optical depth, $\tau_c$, derived from Cloud Lidar System (CLS) measurements during Central Equatorial Pacific Experiment (CEPEX) shows the values of $\tau_c$ ranges from 0.0001 to 0.2 with maximum number of occurrences between 0.002 and 0.01 [McFarquhar et al., 2000]. Based on lidar measurements at Nauru Island (0.52°S, 166.91°E) Comstock et al. [2002] reported that the tropical cirrus occur for 44% of the time during the lidar observation. The observed cirrus clouds were virtually thinner than 1 km and with optical depth values for 92% of cases below 0.01. Studies on the occurrence of different types of cirrus at different latitudes [Goldfarb et al., 2001; Sassen and Comstock, 2001; Comstock et al., 2002] indicate that frequency of occurrence of SVC is larger at tropics than that at mid-latitudes. This is in good agreement with the present study. The distribution of cloud altitudes shown in Figure 4.5 and 4.6 compares fairly well with that reported from other tropical locations [Sassen et al., 2000; Comstock et al., 2002].

Sub-tropical cirrus cloud climatology from OPAR (Observatoire de Physique de l'Atmosphere de la Reunion, 21°S, 55°E) [Cadet et al., 2003] shows a mean altitude of 12.9±1.5 km for cirrus occurrence. Though they observed cirrus only in 7% of the lidar observation period, 65% of these clouds were SVCs with mean cloud width of
0.4±0.4 km. A climatology of cirrus from OHP (Observatoire de haute Provence, 44° N, 6° E) in France shows that the mid-latitude cirrus generally form [Goldfarb et al., 2001] centered around 10±1.3 km with a mean thickness of 1.4±1.3 km. Of these in ~20% of cases the clouds were very thin (width 0.8±0.7 km) and subvisible in nature. A similar study over Salt Lake City, Utah, [Sassen and Comstock, 2001] shows that the optical depth of cirrus varies from 0.003 to 3.0 and in 30% of the cases the cloud optical depth was less than 0.3. In most of the cases the cloud thickness is in the range 0.5 to 2.5 km forming around 9 to 10 km. The cloud top varies from 11-12 km while the cloud bases are around 6-10 km. This shows that the mid-latitude cirrus occurs at a lower altitude compared to the tropical cirrus [Goldfarb et al., 2001; Sassen and Comsstock, 2001]. These studies thus conclude that occurrence of cirrus is low over subtropics compared to tropics and mid-latitude. It could be due to the intrusion of dry-air from the stratosphere to the upper troposphere in sub-tropics where the tropical hardely cell meets the mid-latitude Ferrel cell. Most of the cirrus clouds observed in this region are SVC type because of the low moisture content in the upper troposphere.

Sassen and Campbell [2001] suggested that as the cirrus cloud is a product of weather processes that inject water vapour into dry upper troposphere, it is expected that local cirrus cloud properties will depend significantly on geographic location and the prevailing upper-level weather patterns. However, it is cautioned that the findings are likely to be site specific. Jensen et al. [1996b] suggested two possible mechanisms for the formation of cirrus clouds. The first mechanism is spreading and decay of energetic outflow from cumulonimbus anvils, which transport large amount of water into the upper troposphere, leaving behind a thin layer of ice crystals (residual effects of cumulonimbus clouds). The other is due to in situ nucleation of ice crystals associated with large scale rising motion. The present study shows that usually thick cirrus clouds are observed mostly during the SW monsoon period. This probably suggests that while the formation of SVC is mostly associated with in situ nucleation and freezing to ice crystals from the in situ available water vapour or remnants of thick cirrus, the optically thick cirrus are directly associated with out-flow of cumulonimbus anvils.

The geometric thickness of SVC and TC shows large variability but DCs are always thicker in size and their width is always greater than 1.5 km. Most probable
cloud mean-altitude for TCs and DCs is found to be lower than those of SVCs (by ~1.2 km). Wang et al. [1996] observed the most probable altitude for SVCs as 15 km and that for thick clouds as 13 km, while the present findings also suggest that the most probable mean altitude for SVCs at 15.5 km for TC at 14.5 km and that of DC at 13.5 km. The values of LDR within the cloud suggest that these clouds contain significant amount of non-spherical ice crystals. Low values of δ can be due to lesser nonsphericity of these ice crystals and/or due to horizontal alignment of flat ice crystals causing specular reflection for zenith lidar beam [Thomas et al., 1990; Sassen and Benson, 2001] to generate strong parallel polarized backscattering [Sassen, 1991; Sassen, 2002]. In situ measurements in cirrus clouds reveal the presence of quasi-spherical ice crystals [McFarquhar and Heymsfield, 1996; Gerber et al., 1998], which also can lead to a very low value of the depolarization ratio. Aircraft observations by Ono [1969] indicated that cloud ice crystals settled down such that the greatest areas of the plate ice crystals and longest edges of column ice crystals lie horizontal such that the resistance of air is a maximum. Further, favourable horizontal wind may contribute to orienting the crystals horizontally.

4.5. ASSOCIATION OF CIRRUS CLOUD PROPERTIES WITH TROPOPAUSE CHARACTERISTICS

A perusal of the mean altitude of cirrus clouds indicates that the location of cirrus with respect to the tropical tropopause (cold point tropopause) is not the same for all the nights. While on some nights they are located very close to the tropical tropopause on some other nights they are relatively far below the tropopause. This prompted a study on the association between the cloud altitude and tropopause parameters (tropopause temperature and altitude). The tropopause parameters are derived from the high-resolution temperature profiles estimated from vertical wind data obtained from MST radar [Parameswaran et al., 2000]. The method of estimation of temperature is given detail in Chapter 2.

Of the 281 nights of lidar observations during the study period, the cirrus is observed on 229 nights out of which simultaneous MST radar observations (of temperature) were available on 82 nights. This database is used for the present study. A histogram showing the frequency distribution of tropopause altitude (hₚ) and tropopause temperature (Tₚ) as observed from the temperature profiles is presented in Figure 4.18. The distribution shows a high frequency of occurrence of tropopause altitude in the range 15.5 to 19.5 km. In most of the cases the tropopause altitude lies
between 16.5 and 18.5 km with peak occurrence around 17 km. The tropopause temperature generally lies in the range $-90^\circ$ C to $-60^\circ$ C. In most of the cases $T_p$ lies in the range $-90^\circ$ C and $-70^\circ$ C.

![Histogram showing the frequency distribution of tropopause altitude and tropopause temperature observed at Gadanki](image)

**Figure 4.18.** Histogram showing the frequency distribution of tropopause altitude and tropopause temperature observed at Gadanki

### 4.5.1. Cloud Altitude and Tropopause Parameters

The association of cloud mean altitude ($M_l$) and cloud top ($h_{ct}$) with tropopause altitude ($h_p$) and tropopause temperature ($T_p$) is examined. A first look on tropopause altitude with $M_l$ and $h_{ct}$ does not indicate any significant dependence. But the tropopause temperature ($T_p$) indicated a significant dependence on $M_l$ and $h_{ct}$. Figure 4.19 shows a scatter plot of $M_l$ and $h_{ct}$ with $T_p$. This figure shows that both $M_l$ and $h_{ct}$ decreases with increase in $T_p$. Even though the scatter of points in this figure is not negligible, the dependence is quite significant. This shows that when the tropopause temperature is high, the cloud is at a lower altitude far from tropopause.

In order to quantify the significance of these dependencies the correlation coefficient has been estimated for different cloud parameters with tropopause parameters, which are presented in Table 4.2. Column 2 of this table shows the total correlation of different cloud parameters with tropopause parameters (presented in column 1) along with the level of significance (P) within parenthesis. As seen from Table 4.2, the negative correlation of $h_{ct}$ and $M_l$ with $T_p$ is significant at P< 0.0001 and 0.0062 respectively [Fisher, 1970]. But there exists a weak negative correlation between $T_p$ and $h_p$. 

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Figure 4.19 Scatter plots of $h_{cl}$ and $M_1$ with tropopause temperature $T_p$.

### TABLE 4.2 Correlation of cloud mean altitude and cloud top altitude with tropopause parameters and the significant level (P) within parenthesis along with the partial correlations.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Total correlation</th>
<th>Partial correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{ct}$, $T_p$</td>
<td>-0.503 ($&lt;0.0001$)</td>
<td>-0.506</td>
</tr>
<tr>
<td>$h_{ct}$, $h_{tp}$</td>
<td>0.097 (0.431)</td>
<td>-0.115</td>
</tr>
<tr>
<td>$M_1$, $T_p$</td>
<td>-0.329 (0.0062)</td>
<td>-0.31</td>
</tr>
<tr>
<td>$M_1$, $h_{tp}$</td>
<td>0.117 (0.342)</td>
<td>-0.0074</td>
</tr>
<tr>
<td>$h_{tp}$, $T_p$</td>
<td>-0.376 (0.0016)</td>
<td>---</td>
</tr>
</tbody>
</table>
When one parameter depends on more than one interdependent parameter, to quantify its dependence on either of them the partial correlation is to be examined. If a parameter x depends on y and z which are mutually dependent and the total correlation between x and y is $\rho_{xy}$, between y and z is $\rho_{yz}$, between z and x is $\rho_{zx}$, then the partial correlation between x and y eliminating the effect of z, $(\rho_{xy})_z$, can be written as

$$ (\rho_{xy})_z = \frac{\rho_{xy} - \rho_{xz}\rho_{yz}}{\sqrt{1 - \rho_{xz}^2\rho_{yz}^2}} $$

(4.3)

In the present case $h_{ct}$, $h_{tp}$ and $T_P$ are mutually dependable parameters and hence to examine the dependence of $h_{tp}$ and $T_P$ on $h_{ct}$, the partial correlation analysis is done. The partial correlation of $h_{ct}$ and $T_P$ eliminating the effect of $h_{tp}$, say $(h_{ct}, T_P)_{h_{tp}}$, is estimated using Equation (4.3). Similarly the partial correlation between $h_{ct}$ and $h_{tp}$ is

![Figure 4.20 Scatter plots of $h_{tp}$-$h_{ct}$ and $h_{tp}$-$M_1$ with tropopause temperature, $T_P$](image)

Figure 4.20 Scatter plots of $h_{tp}$-$h_{ct}$ and $h_{tp}$-$M_1$ with tropopause temperature, $T_P$
obtained by eliminating the effect of $T_p$ say $(h_{p}, h_{c}, T_{p})$. Similarly partial correlation of $M_1$ with $h_{p}$ and $T_p$ are also estimated. These are presented in the fourth column of Table 4.2. It can be seen from Table 4.2 that by taking the partial correlation the correlation between $h_{c}$ and $T_{p}$ improves. The partial correlation of $h_{c}$ and $M_1$ with $T_p$, eliminating the effect of $h_{p}$ is significant above 99.9% level of significance. This shows that lower the tropopause temperature higher the altitude of cirrus formation. This prompted examining the dependence of the altitude separation of cirrus from tropopause with $T_p$. Scatter plots of $h_{p}$-$h_{c}$ and $h_{p}$-$M_1$ with $T_p$ are presented in Figure 4.20. Both these parameters show moderate positive correlation with $T_p$ (correlation coefficients 0.28 and 0.1 respectively) indicating that when the cloud is very near to the tropopause, the tropopause is cold.

4.5.2 Dependence of Cloud Depolarization and Cloud Extinction on Tropopause Temperature

The LDR provides information on the nature of cloud particles. Figure 4.21 shows the scatter plot of $\delta$ and $\delta_a$ with $T_p$. The LDR varies in the range 0.03 to 0.6 and $\delta_a$ varies in the range 0.04 to 1 when $T_p$ varies in the range -95° C to -55° C. Both $\delta$ and $\delta_a$ show a decrease with increase in $T_p$. A close examination of this figure indicates that when $T_p$ is low (≈ -85°C) while the observed values of $\delta$ ranges between 0.03 and 0.6 the values of $\delta_a$ ranges between 0.04 and 0.8. But for a higher value of $T_p$ ≈ -65°C, the value of $\delta$ ranges from 0.04 to 0.2 and values of $\delta_a$ ranges from 0.08 to 0.5 only. This shows that for low values of $T_p$, $\delta$ (and $\delta_a$) can have both low and high values, but when $T_p$ is high, larger values of $\delta$ (and $\delta_a$) are greatly suppressed.

The mean extinction of the cloud ($\alpha_c$) is estimated by dividing the cloud optical depth $\tau_c$ by cloud geometrical thickness. This can be written as

$$\alpha_c(t) = \frac{\tau_c(t)}{h_{c_t} - h_{c_e}} \quad (4.4)$$

The mean cloud extinction coefficient for each night ($\alpha_c$) is estimated by averaging the extinction coefficient for the duration of cirrus observed on the night. Variation of $\alpha_c$ with $T_p$ is examined by making a scatter plot. Figure 4.22 shows a scatter plot of $\alpha_c$ with $T_p$. Though the scatter of points in Figure 4.22 is rather moderate, it clearly indicates that when $T_p$ is large, values of $\alpha_c$ encountered are generally low compared to those with when $T_p$ is large. The above study indicates that low values of $\delta$, $\delta_a$ and $\alpha_c$ are observed at all values of $T_p$. But when $T_p$ is low, these parameters show large
variability and quite frequently very large values of these parameters are observed. But when $T_p$ is high, large values of these parameters are inhibited. Large value of $\delta$ (or $\delta_a$) is indicative of the presence of highly non-spherical particles in the cloud. When $T_p$ is large, the cloud is located farther down from the tropopause (Figure 4.20);
the cloud particles tend to be relatively quasi-spherical. Consequently the observed values of $\delta$ and $\delta_a$ are small. Similarly clouds with low $\delta_a$ occur at all altitudes (in the altitude range 12-18 km) but clouds with higher values of $\delta_a$ are more frequent at higher altitudes.

4.5.3 Association of Cirrus with Tropopause

As seen in Figure 4.20, tropical cirrus occurs very near to the tropical tropopause, mostly below the cold point level. The altitude separation increases with increase in $T_p$. It would be worth in this context to examine the probability distribution of the altitude separation of cirrus from the tropopause. Histograms are plotted showing the percentage occurrence of cirrus clouds with different values of $h_{tp}-h_{ct}$ and $h_{tp}-M_1$ which is shown in Figure 4.23. Positive values of $h_{tp}-h_{ct}$ indicate that the cloud top is below the cold point (tropopause) and negative values indicate that the cloud top is above the tropopause. Similarly negative values for $h_{tp}-M_1$ indicate that the cloud mean altitude is above the tropopause. As seen from Figure 4.23a the cloud top goes as low as 8 km below the tropopause and also in few cases it penetrates the inversion level (cold point) and goes to stratosphere up to ~2 km above the tropopause. The cloud optic center mostly lies below the tropopause and it can go as low as 9 km below the tropopause. As can be seen from Figure 4.23b in three cases (3.6% of total) $M_1$ is above the tropopause. On these nights the cirrus clouds were observed in the

![Figure 4.23](image-url)
lower stratosphere. The peak in the distribution shown in Figure 4.23 is quite sharp indicating that in most of the cases the cloud occurs at a small altitude region just below the tropopause. In most of the cases the cloud top and the mean altitude lies 1.5±0.5 km and 2.5±1.5 km below the tropopause. Figure 4.23a shows that for a quite few cases (15.9% of the nights) the cloud top goes above the tropopause even though cloud mean altitude remains below \( h_p \). Such clouds play a significant role in the exchange of particles and water vapour between the troposphere and stratosphere.

Several researchers have reported occurrence of tropical as well as the mid-latitude cirrus above and below the tropopause [Sassen et al., 2000; Omar and Gardner, 2001; Goldfarb et al., 2001; Santacesarai et al., 2002; Thomas et al., 2002]. However this again depends on the definition of tropopause itself. The airborne lidar measurements over the tropical western Pacific Ocean showed that more than half of the cloud top heights occur within ±2 km of the average tropopause [Sassen et al., 2000]. A similar study made by Goldfarb et al. [2001] at a northern mid-latitude location in France (44°N, 6°E) also shows that the cirrus cloud tops tend to track the tropopause consistently. They reported that a significant portion (53%) of the cirrus top heights are within ±0.75 km of the tropopause and in 5% of the cases the cloud tops were observed at least 1 km above the tropopause. However, in their study the tropopause altitude was estimated based on conventional WMO definition of tropopause, which will be ~2 km below the altitude of temperature inversion. Measurements on cirrus associated with deep convection during the Tropical Ocean and Global Atmosphere/Coupled Ocean-Atmosphere Regional Experiment (TOGA/COARE) over the western Pacific using airborne lidar [Sassen et al., 2000] have shown high occurrence of cloud top very close to the tropopause (WMO, defined) with a separation of ~0.5 km below the tropopause.

Cirrus forms at varying distance from the tropopause. But in most of the cases they occur ~2 km below the cold point tropopause. This study also shows that when the cirrus is very close to the tropopause, the tropopause temperature is relatively low. The cloud mean altitude and cloud top decreases with increase in tropopause temperature. The altitude separation of the cirrus from the tropopause increases with increase in \( T_p \). The cloud extinction and cloud depolarization increases with decrease in \( T_p \).
The above observed features can be attributed to the either of the two following plausible processes. Lower tropopause temperature is indicative of stronger vertical convection in the troposphere (provided all other meteorological conditions remain unchanged), which elevates the tropopause altitude. As a consequence, the super saturation leading to cloud formation also occurs at a higher altitude, close to the tropopause leading to cloud formation under favourable circumstances. The clouds forming under such conditions will be associated with colder temperatures containing highly non-spherical particles. Conversely, if the convective activity is relatively weak, the tropopause forms at a lower altitude with higher temperature. The super saturation in such a case occurs at a lower altitude farther from the tropopause leading to cloud formation under favourable conditions. The clouds formed under this condition would be associated with higher temperatures. The cloud particles under such conditions will be quasi-spherical with rounded edges and thus the value of $\delta$ (or $\delta_a$) will be relatively small. The other process is the cirrus affecting the tropopause temperature. It has been pointed out by Hartmann et al. [2001] that though most of the tropospheric convection detrains below $\sim$150 hpa pressure level, a large amount of optically thin cirrus occurs above this level, especially where deep convection occurs at lower levels. Model studies [Hartmann et al., 2001] show that thin cirrus in the upper tropical troposphere in otherwise clear conditions will be heated by absorption of up-welling long wave radiation from below, which makes it difficult to sustain the cirrus unless compensating cooling is assumed [Ackerman et al., 1988; Boehm et al., 1999]. Then ice clouds near the tropopause can provide cooling above [Hartmann et al., 2001]. If the cloud is nearer to the tropopause, the effect of cooling the tropopause would be pronounced. If the cloud were farther from the tropopause, the effect of cloud on tropopause temperature would be small.

4.6. SUMMARY

Cirrus clouds occur quite frequently, of about 55% of cases, at this tropical region. Among these cirri, about 63.1% were SVCs, 30.3% were TCs and 6.6% were DCs. SVC occurrence is very high compared to TC and DC in winter. Occurrence of TC and DC is large during the summer (SW) monsoon period. The region just below the tropical tropopause is conducive for cirrus formation. In most of the cases they occur $\sim$2 km below the cold point tropopause. Most favourable mean altitude for SVC formation is $\sim$15.5 $\pm$ 1 km. The mean altitude of TC and DC are found to be 1-2 km.
less than that of SVC. Vertical extent of the cirrus varies from 0.5 to 5 km. The LDR in cirrus varies from 0.03 to 0.6, indicating the presence of highly non-spherical ice crystals. A close association between the cloud altitude and tropopause temperature is observed. When the cirrus is very close to the tropopause, the tropopause temperature is relatively low. Cloud extinction and depolarization ratio shows a general decrease with increase in tropopause temperature.