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Correlation analysis of lidar derived optical parameters for investigations on thin cirrus features at a tropical station Gadanki(13.5°N and 79.2°E), India

Jayeshlal G. S.[a]*, Satyanarayana M.[a,b], Motty G S[a], Reji K Dhaman[a] & Mahadevan Pillai V P[a]

[a]Department of Optoelectronics, University of Kerala, Karyavattom, Thiruvananthapuram 695 581, India

[b]VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad 500 090, India

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The optical characterization of thin cirrus clouds is very important to understand its radiative effects. The optical parameters of cirrus clouds namely extinction (σ), Optical depth (τ) and Linear depolarization ratio (LDR), have been derived from lidar data, obtained from a ground based polarization lidar at a tropical station, Gadanki (13.5^{0}N and 79.2^{0}E), India. The range dependent Lidar ratio (LR) has been derived by using an in-house developed iterative method. The present study makes an effort to understand the correlation between different optical parameters, and to get an insight in to the structure, composition and stability of the topical cirrus clouds. The variation of LR values with LDR gives an idea about the nature of aerosol content present within the cloud. It has been observed that there is a negative correlation between LDR and LR with a second degree polynomial fit for thin cirrus cloud conditions. The correlation between ice water content (IWC) derived directly from extinction value and LDR has been found to be positive and it has been used to establish cloud phase accurately instead of from the LDR value itself. From the time series observation it has been also found that the extinction and hence the IWC increases due to the growth of cirrus particle.

Keywords: Lidar, Lidar ratio, Optical depth, Linear depolarisation ratio, Ice water content

1 Introduction

Cirrus are thin wispy clouds, present globally both in the upper troposphere and lower stratosphere, cover about 30% of the entire earth at any time, while 70% of cirrus is observed to be present in the low latitude region (±30^0)[1]. Based on their optical depth (τ), the cirrus are classified in to sub visible ($\tau \leq 0.03$), thin ($\tau \leq 0.3$), and opaque ($\tau \geq 3$)[2]. Cirrus clouds play an important role in the global and regional climate via two complex processes. One of them, the albedo effect, caused due to scattering and absorption of the cirrus, gives rise to cooling of the atmosphere. The albedo or cooling is associated mostly with the opaque clouds. The second is the greenhouse effect which results in the warming of the atmosphere due to trapping of long wave radiation emitted from the earth's surface[3]. The warming effect is known to be due to optically thin or sub visible cirrus clouds[4]. Thus the optical characterisation of cirrus is important to understand the radiative forcing caused by them in the earth's atmosphere.

The optical properties of tropical cirrus are found to be different from the cirrus observed in mid and high latitude regions[1]. The cirrus in the tropics are mostly formed closed to the TTL region and are optically thin[5]. The optical and microphysical characteristics of the cirrus primarily depend on the altitude, temperature and humidity. Apart from the radiative forcing, the cirrus present at the TTL region can control the humidity and dehydration in the upper troposephere and lower stratosphere[6]. The optical and the radiative properties of cirrus clouds depend on their shape, number density of ice particle and the spatial structure[7]. The liquid water content with in the cirrus cloud also affects the radiative behaviour[8]. The convective activity in the tropical region is very high, and therefore the microphysical conditions of cirrus clouds in the TTL region and their temporal variations are extremely dynamic in nature[9]. Due to this, the role of cirrus at the TTL region is not yet fully understood and quantified.

The present work attempts to study the relationship between the different optical parameters of thin cirrus derived using a ground based lidar (Light detection and ranging) system. The lidar measurement is used to derive the profile of the extinction coefficient (σ), backscattering coefficient (β), linear depolarization ratio (LDR) and lidar ratio (LR).

*Corresponding Author (E-mail: jayeshlalgs@gmail.com)

Linearly polarized backscattered signals from the cloud particle become depolarize if they are crystalline and are irregularly oriented. Hence the LDR gives information about the physical state of the cloud particle. It is known that in a real atmosphere, LR is a range dependent parameter and varies with physical and chemical properties of atmospheric scatterers like aerosols[9].The LDR and LR values together determine the thermodynamic state and micro physical structure of the cirrus clouds. For example in an earlier study Hu (2007)[10] made the phase discrimination using LDR and LR relationship in opaque clouds($\tau \leq 3$). The present study attempted to make use of the LDR-LR relationship for optically thin cirrus clouds ($\tau \leq 0.3$).

Ice Water Content (IWC) is an important parameter which gives the information about cloud particle phase and size distribution. The direct relationship between extinction and IWC as explained in an earlier study by Heymsfield *et al*. (2005)[11] is used to calculate the IWC[12]. Along with LDR, IWC also is used to quantify the ice content in the cirrus clouds[13].

The correlation between LDR - LR and LDR - IWC is calculated and it provides more insight into the microphysical properties, namely phase, and stability of the thin cirrus clouds present in the TTL region. These aspects are expected to yield more quantitative information on the radiative effects of cirrus in the TTL.

2 Experimental Method

The data obtained from a ground based lidar system operational at night on a regular basis at the National Atmospheric Research Laboratory (NARL) Gadanki (13.5 ^{0}N and 79.2 ^{0}E) India. As described previously (Ref. 14) the monostatic elastic backscatter lidar system employs a linearly polarized pulsed Nd:YAG laser transmitter operating at 532 nm, with an energy of 550 mJ per pulse[14]. The lidar system is aligned to make the complete overlapping between the transmitter and receiver at a height of about 4 km, so as to avoid the intense backscattered signals from the low altitude clouds and aerosols. The receiver system employs a 350 mm-diameter Schmidt-Cassegrain-type telescope with a field of view of 1 mrad and a photo multiplayer tube (PMT-Hamamastu R3234-01) along with a narrow band interference filter centered at 532 nm (band width of 1.13 nm). The received signal passes through a beam splitter which separates the beam in to cross and co polarized components referred to as P and S channels respectively Vertical temperature information is obtained simultaneously using the GPS radio-sonde, launched daily at 17:30 IST (Indian Standard Time) from the same station.

Lidar data obtained during the period from January 2009 to March 2011 are used in the present study for analysis. Also to investigate the temporal variation of the optical parameters, three typical days are considered as a case study corresponding to the three different seasons, namely 4-Feb-2011(winter), 04-Mar-2009(summer) and 13-Oct-2010 (post monsoon). Also the correlation between LDR-LR and LDR-IWC is determined in this study.

3 Method of Analysis

The optical parameters used for the analysis are derived from the lidar signals as below.

3.1 Range dependent lidar ratio (LR)

In a single scattering condition the relationship between extinction coefficient (σ) and Backscattering coefficient (β) is expressed as:

$$\sigma^k(h) = S\,\beta\,(h) \qquad \dots (1)$$

where S is the extinction to backscattering ratio and is known as the lidar ratio. The various experiments observed that the exponent k is a range independent constant and its value may fall in the range of 0.8 to 1.2[15,16]. The lidar ratio is a key parameter which indicates the nature and type of scatterers present in a particular region. Most of the lidar inversion techniques the lidar ratio is taken as a constant for a particular condition. But this may make large uncertainty in the computation of cloud extinction[17]. In a real atmosphere, at a particular site is filled with particulate matter from different sources having different sizes, compositions, etc as such the lidar ratio varies significantly along with the lidar measurement path. Satyanarayana *et al*.(2010) studied the characteristics of range dependent lidar ratio (LR), which gives additional information on the atmospheric particulate (aerosol) heterogeneity[18]. In this method, the total altitude of the study region is segmented and for each altitude bin, the corresponding LR value is calculated based on an iterative process as explained by Satyanarayana *et al*.,(2010). Though this method does not give precise value of LR, it provides values close to realistic values. The present study makes use of the range dependent lidar ratio (LR) derived using this method to calculate the backscatter coefficient $\beta(h)$ and $\sigma(h)$.Based on the various experimental findings it is observed that the lidar ratio varies widely between 10 and 100 sr depending on the nature of aerosols present in the atmosphere like, dust, yellow sand marine etc[20-22]. In the case of ice cloud particle the lidar ratios strongly varies between 2 and 20 sr [23,24].

3.2 Backscattering ratio (R(h))

The cloud backscattering coefficient β(h) is obtained by the lidar inversion method as described by Fernald (1984)[25]. The backscatter ratio $R(h)$ is derived from:

$$R(h) = \frac{\beta_a(h) + \beta_m(h)}{\beta_m(h)} \quad \ldots (2)$$

In Eq. (2), $\beta_a(h)$and $\beta_m(h)$are the aerosol/cloud particle and molecular backscattering coefficients respectively. The $\beta_m(h)$is obtained from the molecular density profile by using the Rayleigh theory [26]. The lidar signals from P and S channels are processed separately to obtain the corresponding backscatter ratios R_P and R_S . The effective lidar ratio, $Re(h)$ can be obtained from the following equation:

$$R_e(h) = \frac{R_P(h) + \delta_m R_S(h)}{1 + \delta_m} \quad \ldots (3)$$

Where δ_m is the molecular depolarization factor, which is assumed to be 0.028 in accordance with Bucholtz, (1995) [27, 28].The sub visible or thin cloud boundary is identified from the profiles of either R_P or R_S exceeding the value 2 and mean cloud height is determined by calculating the moments of $R_e(h)$ as explained by Sunil Kumar *et al*.,(2003)[28].

3.3 Optical depth (τ)

The extinction coefficient is calculated from the following Eq. (4) [29].

$$\sigma(h) = S[R_e(h) - 1]\, \beta_m(h) \quad \ldots (4)$$

where S is the extinction to backscattering called lidar ratio of the cirrus cloud. The optical depth (τ) can be obtained by integrating the extinction coefficient from cloud base to its top shown in Eq. (5). It is based on the radiation and scattering processes of the cloud which depend on the composition and thickness of the cloud.

$$\tau = \int_{h_{base}}^{h_{top}} \sigma(h)dh \quad \ldots (5)$$

3.4 Ice water content (IWC)

There is an empirical power law relationship between IWC and extinction coefficient (σ) explained by Hemsfield *et al*. (2003)[30,11].

$$IWC = a\sigma^b \quad \ldots (6)$$

Where a=119 and b=1.22. Power-law parameterized equation was used in this study to obtain the IWC of optically thin clouds typically present in the TTL region. The satellite based lidar experiments (CALIPSO-Satellite) show that even very low values of IWC ($\sim 0.4\, mg/m^3$) can be detected using this method[12].

3.5 Linear depolarization ratio (LDR)

The Linear depolarization ratio is the measure of non-spherical characteristic of the cloud particles, since a spherical particle does not show any depolarization. From the backscattered signals, we calculate the linear depolarization ratio (LDR) The depolarization measurements provide information on the distribution of ice and water within the clouds. The LDR is estimated as:

$$\text{LDR} = \frac{\beta_{as}(h)}{\beta_{ap}(h)} = \frac{\delta_m(R_s - 1)}{(R_p - 1)} \quad \ldots (7)$$

LDR value from a ground based lidar normally varies between 0.05 and 1. For non-spherical particle the LDR threshold is 0.04 and above which the medium is composed of predominantly ice cloud particle in addition to the background aerosols[31]. The vertical profile of IWC together with LDR gives information on the ice particle distribution within the cloud.

4 Results and Discussion

Cirrus spread globally and in the tropics their occurrence is relatively high. It is still unknown clearly which are the key mechanisms for the formation of cirrus in the tropics. The close association of cirrus with convective clouds implies that tropical cirrus are linked to deep convective activity, but it may not be applicable to thin cirrus found in the TTL region[4]. In order to understand the characteristics of the cirrus present in the TTL region, first we calculated the thickness of the TTL region from the vertical temperature profile obtained from GPS radiosonde data. The mean temperature profile obtained during these observation period and thin cirrus mean cloud height are plotted along with their τ values and shown in Fig.1.

In the vertical temperature profile (Fig. 1(a)) the average altitude range of cold point in the troposphere (CPZ) is identified at about 17.2 km, and the corresponding maximum convective outflow level (COZ) is noticed in the altitude range of about 12.3 km, where the potential temperature gradients are minimum. These points correspond to the upper and lower limits of the TTL region[32]. TTL thickness is calculated by taking the difference between these points. In the specified location the average TTL thickness is found to be around 5 km (between 18km and 12 km region). Fig. 1b shows the cloud mean height with their optical depth (‘τ’). opaque (τ >3) clouds[2]. From a three year lidar observation it is found that within the TTL region the ‘τ’ varies from 0.01 to 0.8 and most of the cirrus present in the TTL region are optically thin (τ <0.3). More than convection, the positive radiative forcing and the upwelling of cirrus by absorbing the long wave radiations emitted from the earth’s surface are the observed reasons for the TTL thin cirrus[33]. Any small variations in their optical characteristics will directly influences the radiative and microphysical characteristics.

The microphysical variances of thin cirrus are studied by analyzing their optical characteristics namely LDR, LR and IWC. Out of the 154 days of lidar observations, we selected 66 observations from different seasons wherein single layered optically thin cirrus clouds are present in the TTL region. Here the cloud LR value varies from 25 to 2 sr and it is comparable with earlier reports[23]. Based on the fundamental scattering theory, low LR value (< 5) implies that extinction and backscattering due to the cloud particle are of the same order. The LDR varies from 0.1 - 0.6 within the cloud region. The variation of TTL cirrus LR with LDR is shown in the Fig. 2.

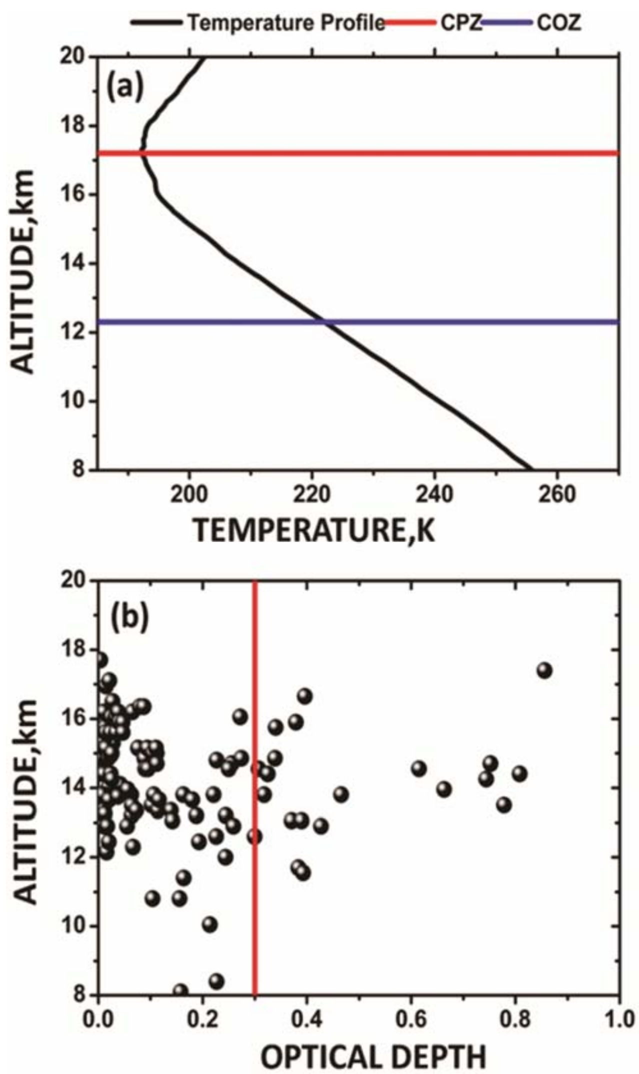

Fig. 1 — (a) Represents the regular vertical temperature profile. Horizontal solid red line shows the cold point region (CPZ) and the blue line shows the maximum convective out flow level (COZ). And (b) represents the cloud occurrence height with the optical depth vertical red line shows the optical depth 0.3.

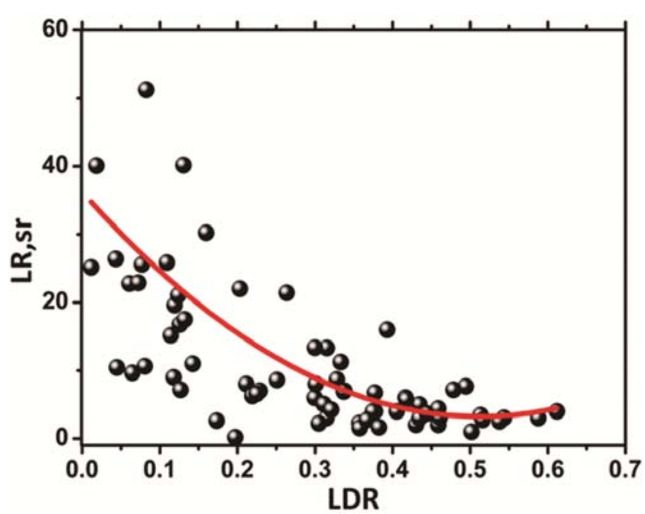

Fig. 2 — The relation between Lidar ratio (LR) and Linear depolarization ratio (LDR) for the thin cirrus clouds during the period from January 2009 to March 2011. The scattered dot shows the LR-LDR variation and solid curve shows its second degree polynomial fit.

Figure 2 shows the variation of LDR with LR and it can be seen that the average LR value is relatively small (< 15) and gradually falls as LDR increases. Randomly oriented ice crystals with fine irregular shape are formed under this condition[34]. Thus the LDR and LR of fine ice cloud particles are negatively correlated with a second degree polynomial fit. In the case of opaque cirrus clouds, (τ >3), Hu (2007) observed a second degree relationship between layer integrated depolarization ratio and effective lidar ratio[10,35]. He reported a negative correlation for water clouds and positive correlation for ice cloud particles. But the present study which focused on the optically thin ice clouds observed a different LDR-LR variation with negative correlation as shown above. The range dependent LR is based on the single scattering which varies with size, phase and type of ice nucleating aerosol particles present in the cloud[22]. The present study shows small LR values along with some anomalies in some cases and this could be due to the presence of various irregular ice crystals with its complex shape, size and the background aerosols layers[36].

It is noted that any change in the microphysical characteristics directly affect the cirrus optical characteristics. Hence the temporal variation of LR and IWC with LDR and its correlation analysis gives an insight in to the consistency of the microphysical properties and stability of the clouds at a particular ambient condition. Here we chose three specific days from three different seasons as a cause study to authenticate this perception.

4.1 Case study-1

For understanding the short term temporal variations of the cirrus, three typical days, one in each of the three seasons, are chosen for the study. The temporal variation on 14-Feb-2011, a typical day during winter season, is studied. We have six hours of uninterrupted observation from 20.30 Hrs. IST on that day. The cloud is located at a height of about 16 km, close to the top of TTL region, with an average geometrical thickness of 0.9 km and temperature of 197 K, The time series of IWC, LDR and LR profiles are plotted in Fig. 3.

During the first one hour, no cloud is present (Fig. 3(a)). It is noted that the average values of LR (Fig. 3(c)), IWC and τ .are 24 sr, ≤ 0.04 mg/m^3 and ≤ 0.03 respectively. In contrast to IWC the LDR shows moderately good values. For cloud free hour (first hour) the vertical distribution of LDR ranges from 0.17 to 0.22. The LR and LDR values indicate the presence of non-spherical aerosol in the TTL region[31]. During the cloudy hours (second hour onwards), there is a significant variation in the LDR values (~0.4). During the last hour the average mid cloud height slightly decreases and 'τ' increases to 0.07.

Within the cloud the LR profile varies from 20±5sr to 5±3sr and in the cloud background region, the LR values vary from 20±5sr to 35±2sr. During the international study program called Indian Ocean Experiment (INDOEX) over tropical Indian Ocean executed long back, a classification was given on aerosol types based on their range of LR values[22]**.** Keeping this knowledge and by considering the location of the ground station it may be presumed that the background aerosol present in this particular occasion might be coming from marine region[37,36]. From the beginning of second hour onwards, the IWC increases from 0.03 mg/m^3 to 0.45mg/m^3 and optical depth increases from 0.03 to 0.07. Even though IWC values are very small within the cloud, the positive correlation between LDR and IWC confirms the existence of small ice crystals in the cloud. In winter

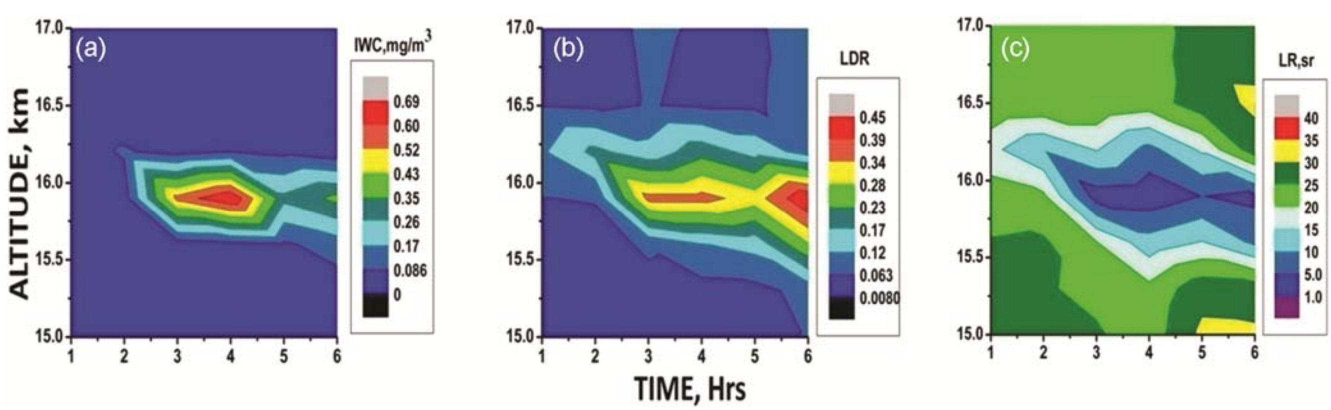

Fig. 3 — The temporal variation of cirrus cloud IWC, LDR and LR profiles (a - c) starting from 20:30 IST on 14 Feb 2011.

season, even though the convective activities are low, the aerosol present in the TTL region could be due to the Brewer Dobson circulation and due to Tropical Easterly Jet (TEJ)[38]. We may conclude that during this period the possibility of in-situ cirrus formation is predominant at upper troposphere region. (UTLS)[39,40].

It is interesting to quantify the observed correlation between these important parameters as depicted in Fig. 2. It is reported that the LDR values are fairly within the known range and found to increase from 0.1 to 1.0 when ice crystals are being formed within the cloud[31]. At the same time, the corresponding LR values decrease from 25 sr to below10 sr[23]. Thus a negative relationship between LR and LDR is established.

The LDR-LR and LDR- IWC variations for each hour are plotted in Fig. 4. A negative correlation and a second degree polynomial fit were noticed in LDR-LR variation and a positive correlation with second degree polynomial fit noticed in LDR-IWC variation during the cloud observation time.

The time series of the correlation coefficients relating LDR-LR and LDR-IWC variations are obtained and plotted in Fig. 5. It brings out the fact that this kind of relationship is very dominant within the cloud only. Also it can be seen that during the cloud free hours the correlation is minimum and during the time when cirrus is present it reaches almost a maximum. The above observation (Fig. 4)

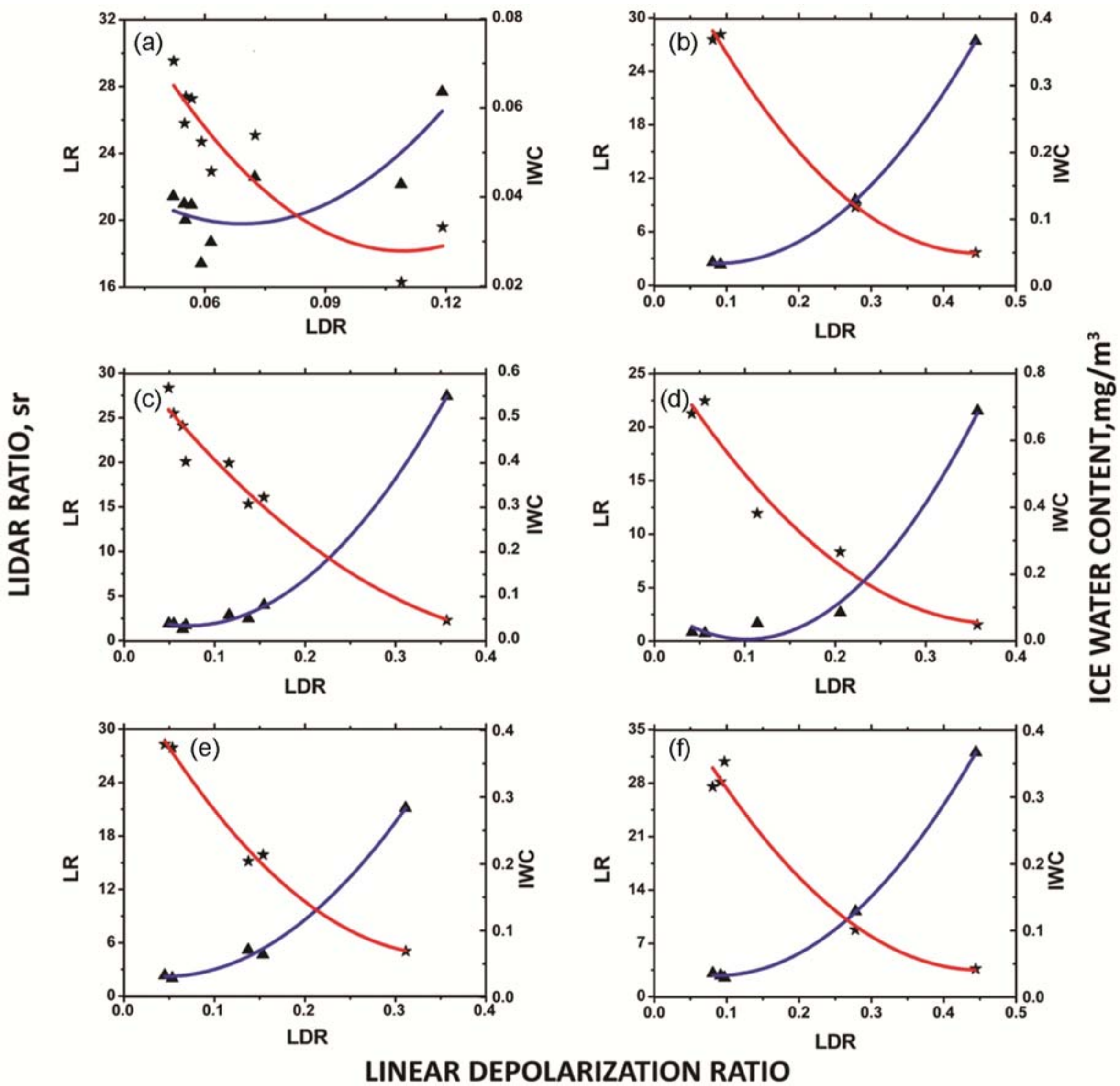

Fig. 4 — The variation of LDR with LR and LDR with IWC for each hour during 14 Feb 2011 represent (a-f), respectively. The star dot shows the LDR - LR relationship and triangle dot shows the LDR-IWC relationship. The solid red line shows the polynomial fit for LDR - LR variation and the solid blue line shows the the polynomial fit for LDR-IWC variations.

shows that the ice clouds have a negative LDR-LR variation which agrees well as a second degree polynomial relationship. During this period the microphysical parameters shows very low inconsistency. It implies that the negative correlation between LDR and LR variation of cirrus is an indicator of a stable ice cloud condition.

4.2 Case study-2

Another typical day, the October 13, 2010, during the post monsoon period is selected and analysed. In this case the cirrus was observed in the lower part of the TTL region as between 10km and 14 km with an average geometrical thickness of 3.6 km as shown in Fig. 6. The average cloud temperature is 220 K. The LDR and LR profiles show significant values in the 10 km to 15 km region. The cloud shows high back scattering and extinction throughout the observation period. The IWC varies from ~3 mg/m^3 to ~19 mg/m^3 and LDR varies from 0.1 to 0.4. The temporal variation of LDR, IWC and LR profiles are plotted in Fig. 6**.**

Contrary to the expectation, the IWC and LDR show a strange temporal variation. In the first hour of the observation, with in the cloud the maximum IWC value is observed at 12.5 km and maximum LDR is at 13.5 km. During the second hour of observation, IWC shows a maximum of 18.375 mg/m^3 at an altitude of 13.25 km and LDR shows a low value of 0.1, According to basic scattering theory, for large size distribution, the forward scattering is higher than the backscattering, resulting an increase in extinction and IWC. During the second hour the cloud height slowly increases and reaches up to a maximum of 14 km and has low LDR value of 0.12 and high IWC value of 18.375 mg/m^3. This suggests that during the second hour the ice crystals present in the cloud are large spherical or quasi spherical in nature. The formation of large spherical or quasi spherical shaped scatterers implies that the cloud is formed due to homogeneous nucleation[7]. Just after the second hour the average cloud height increases continuously throughout. Here the IWC values decrease and LDR values increase but the vertical LR distribution remains the same. This may be due to the dissipation of ice crystals within the cloud adiabatically and increase of number density. Thus, we may conclude that during the homogeneous nucleation large ice particles are made and they are unstable.

In this particular observation the background LR shows a very strange behavior with high values particularly in the bottom and at top of the cloud. But within the cloud the average LR value appears to be 10±5 sr throughout the observation period. The LR variation within the cloud mainly depends on the crystal structure [21]. The LR at the top and bottom (from 11 to 15 km) of the cloud show high values of >100 sr, while the corresponding LDR varies between 0.1 and 0.15. The light scattering computations show that these observed LR and LDR values are mostly due to the presence of small ice crystals of a few micrometers size [41,42,43,21].

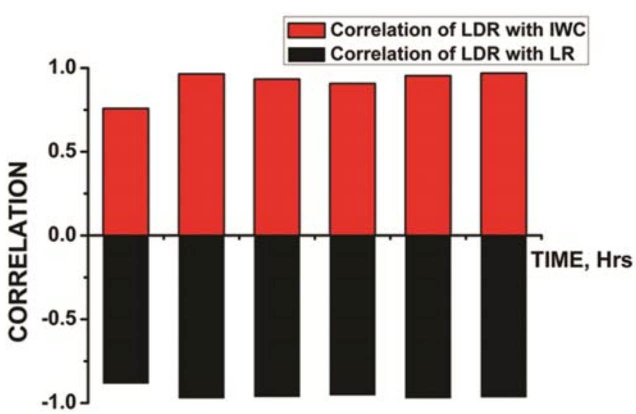

Fig. 5 — Correlation of LDR with LR and LDR with IWC during each hour on 14-Feb-2011

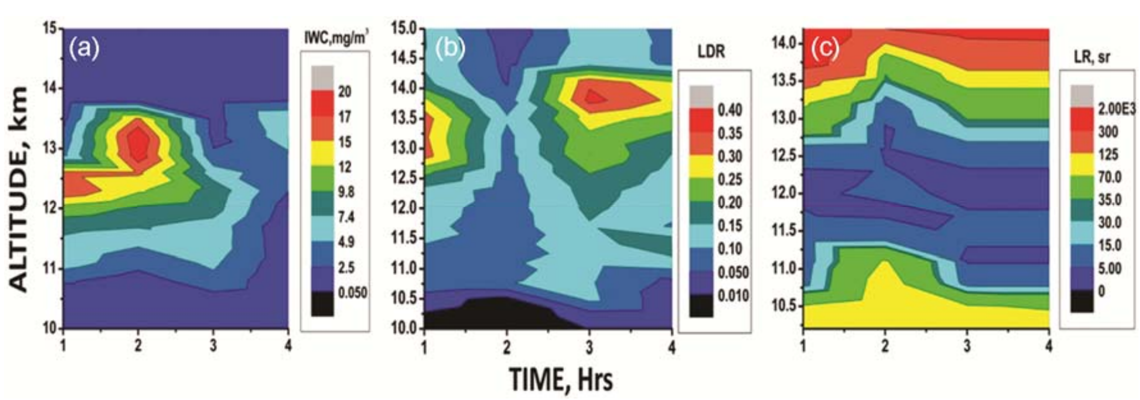

Fig. 6 — The temporal variation of cirrus cloud IWC, LDR and LR (a-c) starting from 2030 IST during 13 Oct 2010.

The relationship between LDR-LR and LDR-IWC are plotted in Fig. 7. A second degree polynomial relationship between LDR and LR with a low correlation values are noticed during the all observation hours (Fig. 8). The correlation between LDR- LR and LDR- IWC are plotted in Fig. 8 in intervals of one hour in the 4 hours of observation period.

At the beginning hour of the observation, LDR has a small positive correlation with LR and a small negative correlation with IWC. During the second hour, LR shows good negative correlation with LDR and positive correlation with IWC, indicating the presence of ice crystals. Again during the third hour the relationship reverses. In the last hour of observation both LR and IWC positively correlated with LDR. The temporal variation in the correlation values is particularly due the changes in the microphysical conditions. During the second hour the IWC value becomes maximum and the corresponding LDR-LR variation shows very well negative correlation and LDR-IWC variation shows a positive correlation. After the second hour (Fig.6 a & 8), the dissipation of the cloud happening. During this period the LDR-LR shows a positive correlation where as LDR-IWC is negatively correlated. The above observations implies that during the intense or stable ice cloud condition, the LDR-LR correlation become negative and in all other conditions the relationship varies.

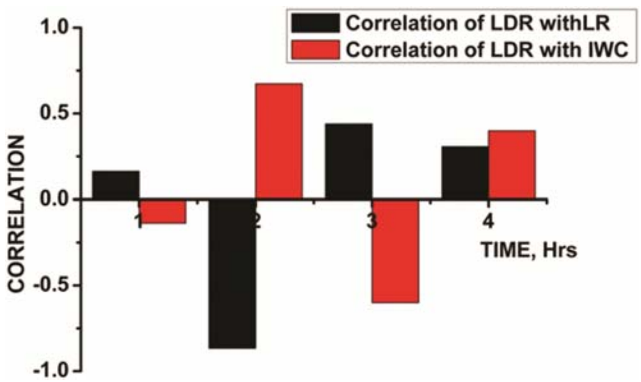

Fig. 8 — Correlation of LDR with LR and LDR with IWC during each hour on13-Oct-2010.

4.3 Case study-3

The summer season is represented by the typical day, March 04, 2009. Fig. 9 shows the temporal variations of the cloud parameters. It can be seen that the cloud appeared above the middle portion of the TTL region (~ 14 km) with an average thickness of 1.2 km. The six hour temporal variation of IWC, LDR and LR profiles shows an upwelling trend of the cloud.

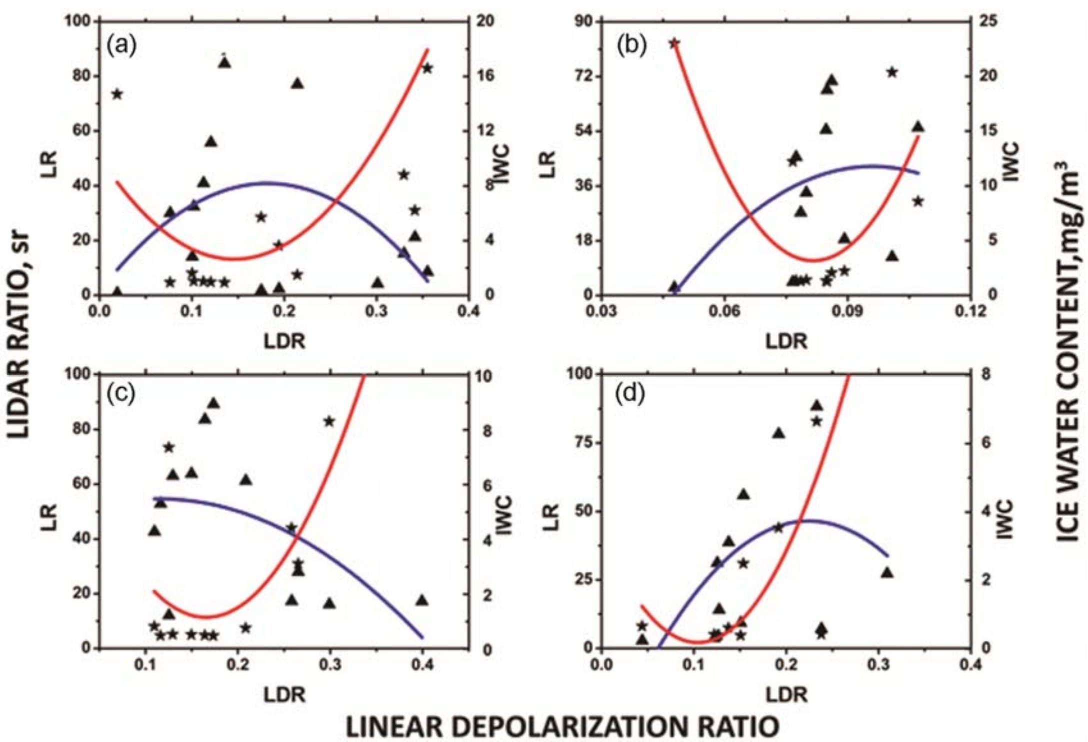

Fig. 7 — The variation of LDR with LR and LDR with IWC for each hour during 13 Oct 2010 represent (a-d), respectively. The star dot shows the LDR - LR relationship and triangle dot shows the LDR-IWC relationship. The solid red line shows the polynomial fit for LDR - LR variation and the solid blue line shows the the polynomial fit for LDR-IWC variations.

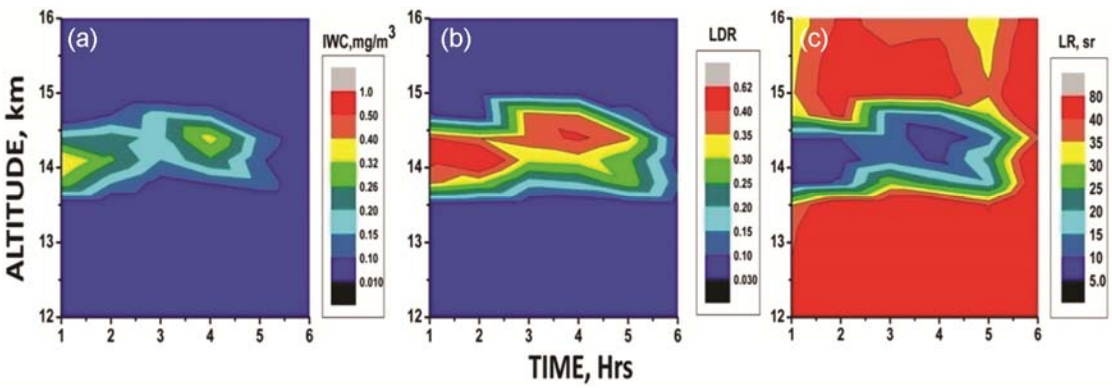

Fig. 9 — The temporal variation of cirrus cloud IWC, LDR and LR (a-c) starting from 2030 IST during 04 Mar 2009

The average cloud mid height reaches up to ~14.5 km during the third hour of the observation and after that the cloud dissipates completely. The average cloud temperature is found to be 204 K and the average optical depth is 0.077. The IWC values vary from 0.1 to 0.4 mg/m^3 and the LR values within the cloud vary from 7±4 sr to 25±3 sr. The LDR varies from 0.1 to 0.5. The cloud background LR profiles are high compared to those of the winter season (Fig. 3(c)), and noted to vary from 30±2 to70±6 (Fig.9(c)), The LDR values $\geq$ 0.04 indicates the presence of high concentration of non spherical particles and heterogeneous ice nucleation[38]. From the observed values of LR, it may be concluded that during this day the surrounding aerosols could possibly be some type of continental dust particles, as concluded earlier making use of satellite based lidar measurements[44].

The LDR - LR and LDR-IWC relationship are plotted Fig.10. The analysis shows that there is very good second degree polynomial fit for LDR-LR relationship. Cloud dissipation occurs in the last hour and the LDR-LR variation shows a poor second degree polynomial fit as shown in Fig. 10. The temporal variation of correlation values of LDR - LR and LDR-IWC relationships are plotted in Fig. 11.

From Fig. 11 it is clear that during the cirrus cloud condition, the LDR-LR shows negative correlation and reaches up to a maximum during the third hour, During this period, the cloud microphysical parameters does not show any specific variation. Throughout the observation time the LDR -IWC variation shows a positive correlation between the two. The positive correlation of LDR -IWC variation confirms the presence of ice cloud. From the start of sixth hour the cloud slowly dissipates and during this period it is found that the negative correlation of LDR-LR and the positive correlation of LDR-IWC start decreasing to lower values.

4.4 Summary of the case studies

The following observations were made by comparing the results obtained from the three different days.

(i) In all the three cases, within the cirrus cloud the LR values vary from 2 to 20 sr with an average value of 10 sr. But the surrounding LR values generally vary from 20 to 100 sr depending upon the constituent particles present in the atmosphere.

(ii) The unexpected high LR values ($> 100\, sr$) observed during the particular day (case-2) is well compared with theoretical LR values of fine ice crystal of few micron in size.

(iii) The LDR measurements show that the LDR values vary from 0.1 to 0.7, depending upon the ice crystal size, shape and orientation within the cloud..

(iv) The cloud with low variation values in the microphysical properties is considered to be relatively stable. During the stable cloud condition the LDR-LR variations are negatively correlated and due to the presence of ice particle the LDR-IWC variations are positively correlated.

(v) The correlation and curve fitting analysis show that the cirrus cloud LDR- shows a second degree polynomial relationship with LR and IWC.

(vi) The LDR shows a negative correlation with LR in a stable and intense cirrus cloud condition.

(vii) During intense cirrus condition the LDR-LR variation have a high correlation (negative) and during cloud dissipation time the correlation value decreases or it become positive.

(viii) The positive correlation value of LDR-IWC variation will change only when the ice particle concentration changes within the cloud as shown in (Figs. 9(a) & 11).

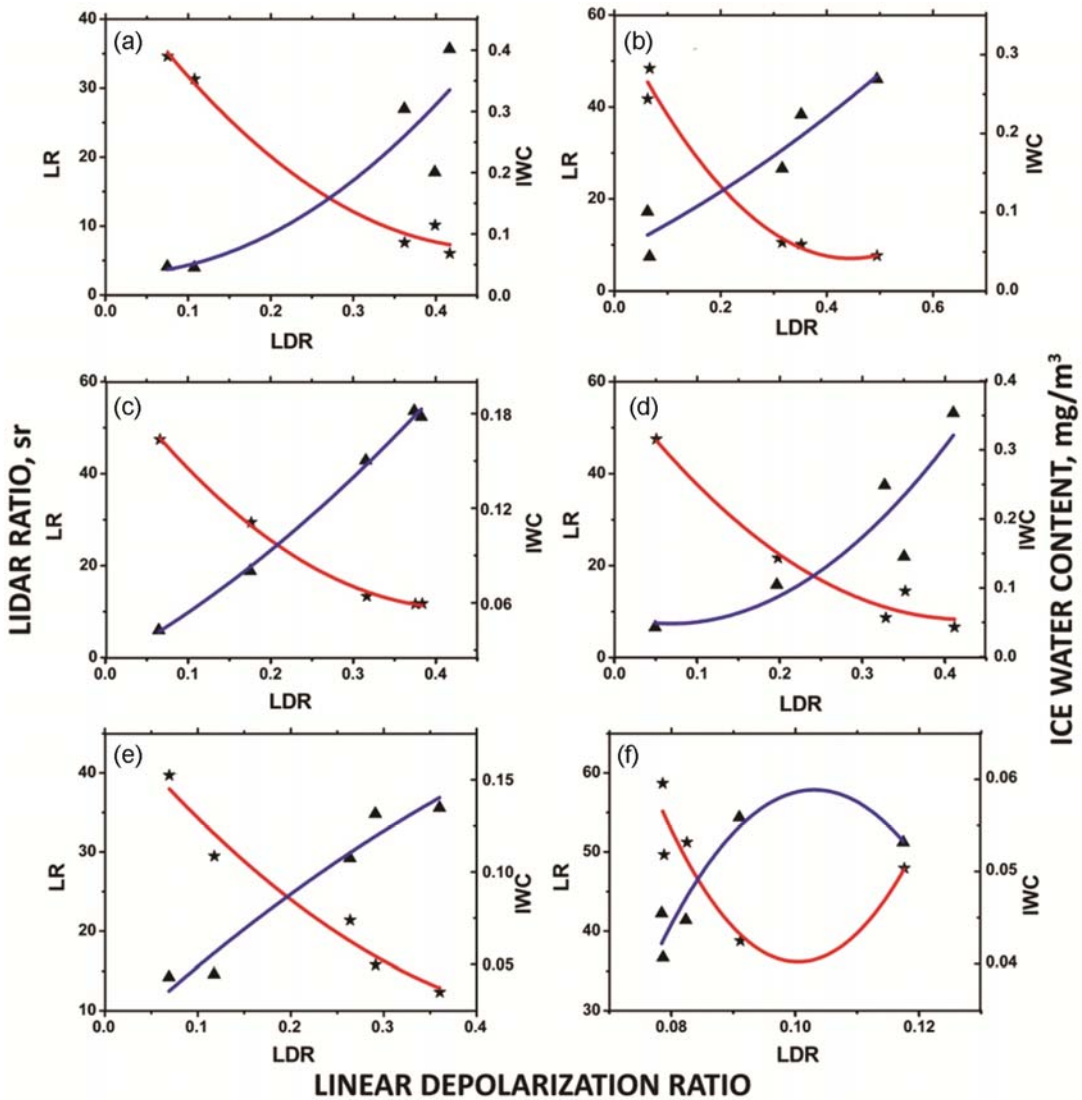

Fig. 10 — The variation of LDR with LR and LDR with IWC for each hour during 04 Mar 2009 represent 'A' to 'F', respectively. The star dot shows the LDR - LR relationship and triangle dot shows the LDR-IWC relationship. The solid red line shows the polynomial fit for LDR - LR variation and the solid blue line shows the the polynomial fit for LDR-IWC variations.

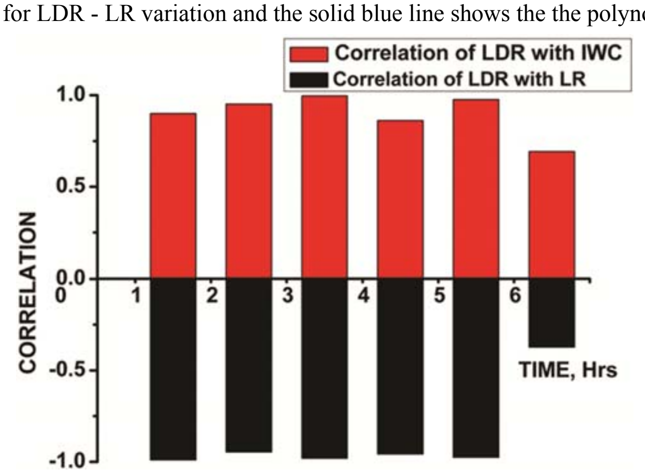

Fig. 11 — Correlation of LDR with LR and LDR with IWC during each hour on 04-Mar-2009.

5 Conclusions

The microphysical and optical properties of optically thin cirrus clouds present in the TTL region are studied during the period from January 2009 to March 2010. From the temperature profiles, the average thickness of TTL layer was calculated and also observed that most of the cirrus appeared in this region are optically thin. To study the temporal variation of the thin cirrus, three particular days were selected as case study. The temporal variation of IWC, LDR and LR and their inter-relationship shows that; there was a second degree polynomial relationship between LDR and LR variation. It was observed that correlation between LDR and LR becomes high and negative when the thin cirrus cloud microphysical conditions were consistent and at the same time correlation between LDR and IWC is high and positive. The range dependent LR values and its relationship with LDR showed that LR was something beyond the ice cloud shape and phase, more over it was related to vertical distribution of aerosol and also related with cloud aerosol interaction. IWC was calculated using an empirical formula and along with LDR. It was used to confirm the presence of ice cloud particles. The correlation between LDR and IWC was calculated and found that for stable ice cloud condition it was positive and is just opposite to LDR-LR correlation behavior. Normally LDR-IWC relationship was positively correlated due to the presence of ice cloud particle but some time it shows a negative correlation. This might be due to aerosol layer or due to super cooled water. Both situations were clearly unstable in TTL region. The external and internal cloud thermo dynamical factors were the main reason for this kind of observation, which needed further investigation.

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