Responses to comments of Anonymous Referee #1

We thank anonymous referee #1 for reviewing our manuscript and considering our manuscript suitable for publication in ACP after minor revision. Please find below our detailed response to the comments.

General Comments:

The referee #1 has recommend language revision for the manuscript.

Response: We highly appreciate Referee #1's suggestion and efforts in providing list of grammatical corrections. In the revised manuscript we have taken all the possible care besides including corrections suggested by the reviewer. In addition, the manuscript will go through language editing by professional language editor before being published in ACP.

Specific Comments:

(1) p. 15795: In the description of the NARL lidar the orthogonal aligned PMT are mentioned. This sounds like the NARL lidar is able to measure the depolarization of particles. If so, why not using the depolarization data as indicator for ice clouds?

Response: Though the NARL lidar has orthogonally aligned PMTs and hence the ability to measure depolarization of particles, during many years the depolarization measurements were not made. Hence, the use of depolarization as an indicator of ice-clouds would have significantly reduced the number of profiles available for cirrus cloud climatology. So, for uniformity and continuity, we have chosen temperature as a parameter to distinguish cirrus clouds from water clouds.

(2) p. 15798 Section 3.1: In this Section the cloud detection algorithm is described briefly. You state that the algorithm is optimized to detect very thin clouds. Can you please provide some numbers, what is the smallest/ thinest cloud with respect to vertical and spatial extent you could detect with the algorithm. This numbers should also stated for CALIPSO, as they are quite important for comparing numbers/frequencies of thin clouds. Are you applying any additional profile smoothing in time or vertical ? How sensitive is the detection algorithm with respect to noise in the backscatter profiles ?

Response: Our cloud detection algorithm is based on wavelet covariance transform (WCT) method using Haar wavelet. The algorithm is able to detect clouds which have geometrical thickness greater than or equal to 600 m (two altitude bins). While no smoothing along vertical direction is applied to raw profiles, use of dilation value equal to 3 in the WCT algorithm has effect somewhat similar to 2 point smoothing. Individual raw profile is a time integration of four minutes of data acquisition. The algorithm uses a threshold in transformed profile for detecting the cloud layers. The threshold value is a linear function of altitude. Altitude varying threshold has benefit of low noise in near range and avoids false detection at the far end. In addition, each LIDAR profile (clear/cloudy) before being considered for inclusion undergoes quality check based on signal to noise ratio (SNR) at 5 km and 20 km altitude bins. Only those LIDAR profiles which had SNR greater than 1000 at 5 km and SNR greater than 10 at 20 km are used in the analysis. Also, to avoid false detection for noisy data, if the detected cloud layer has peak photon counts less than background plus 3 x std then they are not considered. Though CALIOP profiles have vertical resolution of 60 m, the lowest geometrical thickness of clouds that we could find in the data-set used in current study is 360 m. This information is included in the revised manuscript.

(3) p. 15798 ll 8: You considered only those clouds with a base temperature of below -20 ˚C. Would it be better to use a temperature of -38˚C (235 K) for classification of cirrus layer, since below this temperature liquid cloud droplets no longer form. The temperature range between -38˚C - 0˚C is assigned to mixed phase clouds where the coexistence of water droplets and ice particles typically occur. The ice water content as well as the optical depth in such even though completely frozen clouds is much higher compared to real cirrus clouds found in temperatures below -38˚C. How would your results change, if you take only those clouds below -38˚C which are then most certainly cirrus clouds?

Response: We agree with the concern of the referee that use of temperature range -20 to -38 ˚C may result in misclassification of few mixed phase clouds as cirrus clouds. However, equally valid argument may have been raised that we may under-sample cirrus clouds if we would have used "< -38 ˚C" as cirrus cloud criteria. Cirrus clouds also form at warmer temperatures (greater than -38˚C) through one or two heterogeneous freezing mechanisms (Lynch et al., 2002; Cziczo and Froyd, 2014). Moreover, cirrus clouds formed at higher altitudes (lower temperatures) many times gradually descend down to lower altitudes (higher temperatures) due to the sedimentation of ice-crystals. We have considered all the cloud layers below -20˚C as cirrus layers. In case of ground-based observations (NARL lidar), the observations were carried out only when low level clouds were not present (to prevent the saturation of PMT due to very strong backscatter from the deep convective clouds/water clouds where particles are in mixed phase and to avoid accidental exposure of system to rain water). In absence of big convective system, chance of having mixed phase clouds is small. Using < -38˚C as criteria may not have much bearing on trend analysis as we see that statistically significant trends are found only for sub-visible cirrus clouds which form at ultra low temperature. The mean, median and standard deviation of the various cirrus cloud properties shown in Table 3 change slightly when we take only those clouds below -38˚C (see the table below). The histograms shown in Figure 4 will become slightly sharper if this criterion is chosen.

Table2: Cirrus properties for cirrus clouds below -38 ˚C.

Cirrus cloud properties	NARL Lidar	CALIOP (night)	CALIOP (day)
Base altitude (km)	13.5±1.8 (13.4)	13.6±1.6 (13.6)	13.5±1.5 (13.3)
Top altitude (km)	15.7±1.6 (15.8)	15.5±1.6 (15.9)	15.1±1.5 (15.4)
Mid-cloud altitude (km)	14.6±1.6 (14.6)	14.6 ± 1.5 (14.7)	14.3±1.4 (14.2)
Geometrical thickness (km)	2.2±1.2 (1.8)	2.0±1.3 (1.6)	1.6±1.1 (1.2)
Mid-cloud temperature (˚C)	-68.1±8.6 (-69.8)	-67.5±10.1 (-69.6)	-65.7±9.9 (-66.9)

Distance from tropopause (km)	-2.1±1.7 (-2.1)	-2.0±1.5 (-1.7)	-2.2±1.5 (-2.0)

(4) p. 15799 ll 22-25: As you wrote before, multiple scattering is important to consider. Why do you use different multiple scattering correction factors (0.75 and 0.6) for the NARL and CALIPSO extinction retrieval ? The correction factor depends strongly on the Field of View (FOV) of the lidar receiver. Does NARL have a similar FOV as Sassen Cho (1992) used in their study or why did you chose the same correction factor ?

Response: Sassen & Comstock (2001) used multiple scattering factor, η=0.6 to 0.7 for optically thick clouds, η=0.8 for thin cirrus and η=0.9 for sub-visible cirrus clouds. Instead of variable multiple scattering factor, we have selected an intermediate value 0.75 for all cloud types. The field of view (FoV) of NARL lidar (1 mrad) and the lidar system (3 mrad) used by Sassen & Cho (1992) is comparable. Value of η affects the magnitude of estimated cloud optical depth. In our manuscript we have reported that NARL lidar detects more sub-visible cirrus clouds than CALIOP. If we would have used η=0.6 instead of 0.75 then the difference between the two would have been even larger. In other words while we do not find strong justification to use 0.6 value for η, use of value 0.75 is not affecting one of our major conclusion. In the revised manuscript, we have included justification for our choice of multiple scattering correction factor.

(5) p. 15801 ll 14-15: You mentioned the quite large difference between CALIOP and NARL PO distribution and explained it with occurrence of cloudy nights during the monsoon season. However, Figure 2d shows no significant difference between CALIPSO and NARL PO distribution during the monsoon season in order that this may not be the right reason for the difference. Except for the post-monsoon season all PO distributions from the NARL lidar appear to be comparable with CALIOP. For combining Figures 2b-e into the Figure 2a it seems that the most of the data are collected during Post-monsoon season. That brings me to the question of how many profiles are used for each season for CALIOP and NARL? Another reason for the difference could be attributed to different bin-width in determining the PO distribution for the CALIOP and the NARL lidar. Are you using the same bin-width for the NARL and CALIOP PO distribution ?

Reply:

Please note that the range of X-axes in Fig 2b to 2e is twice that of used in Fig 2a. Hence, differences between NARL lidar and CALIOP appear smaller in seasonal PO distributions. Total number of profiles measured and number of profiles with presence of clouds are shown in the table below. Since no weighting is applied for the differences in total number of profile available in different seasons, the mean PO distribution shown in Fig 2a is dominated by the season when large number of measurements were carried out. In case of NARL lidar winter and pre-monsoon are the seasons when more number of lidar measurements were made but these two are also the seasons when cloud fraction is low. In case of CALIOP, nearly same number of profiles are available in each season.

In the second part of the question, reviewer has asked whether we used same bin-width for NARL lidar and CALIOP. NARL Lidar has range resolution of 300m whereas CALIOP has range resolution 60m. To find out whether the difference in range resolution will have effect on PO distribution, we have carried-out sensitivity tests. We reduced CALIOP data to coarser resolutions like 120m, 240m, 300m and 600m by averaging and recalculated PO values. Effect of increasing bin-width is found to result in small increase in PO (less than 5% at 300m). This is because as we reduce the resolution, cloud presence spills to neighbouring bins which otherwise would have been counted as cloud free bins. Following table will be provided as supporting material.

	NARL Lidar		CALIOP	
Seasons	Total no. of profiles	Total no. of cloudy profiles	Total no. of profiles	Total no. of cloudy profiles
Winter (DJF)	41205	13515	720 (673)*	298 (218)
Pre-monsoon (MAM)	28695	13140	741 (674)	385 (334)
Monsoon (JJA)	9090	6900	781 (780)	698 (680)
Post-monsoon (SON)	14700	7725	780 (779)	495 (588)
Total	93690	41280	3022 (2906)	1876 (1820)

(* Value in the parentheses corresponds to CALIOP day-time observations.)

(6) p. 15803 ll 10-16: The day night time difference in PO depends strongly on the amount of CALIOP profiles. How significant are these differences, especially the slightly larger day-time PO during September and November ?? Can state some explanation, why the day-time PO could be larger compared to the night-time PO?

Reply: Number of total profiles available during day and night are not significantly different. This can be seen in the table provided in response to previous comment. In response to this comment, we carried out Student's T-test on day-night differences and found that the differences are not statistically significant. This is because we have chosen relatively small domain around Gadanki where number of overpasses and hence the available profiles is small. Since, the difference is not statistically significant, we have decided to drop the Fig 3c and 3d from revised manuscript.

(7) p. 15804 ll 20-21: "Quite a good number", can you please state a percentage number for NARL and also for CALIPSO. Did you checked the differences in the FNL and GMAO tropopause heights as well as the temperature data ?

Reply: We have found that on average FNL tropopause height is 16.559 km and GMAO tropopause height is 16.596 km which are very close. About 9% of the clouds were found above the tropopause in case of NARL Lidar. We have included this information in the revised manuscript.

(8) p. 15804 ll 24-25: Is there an explanation for the noticeable peak at 75_C in the NARL mid-cloud temperature ?

Reply: Both the lidars (CALIOP and NARL) have peak of frequency distribution at -75 deg C. However the peak is prominent in case of NARL Lidar. This is possibly due to fact that NARL Lidar detects more number of sub-visible cirrus clouds which are found to occur more frequently at temperature -75 deg C (see Fig. 10 of our manuscript). Also, the tropopause which is at approximately 16 km acts as cap for cloud top. With average cloud thickness of the order 2 km, cloud mid-altitude will be located at 15 km which corresponds to -75 C°.

(9) p. 15804 ll 26-28: Can please state the percentage of sub-visible, thin and thick cirrus clouds also in the respective panel of Figure 6 (b-d) as text. Than it is easier to understand the composition of panel a.

Reply: We agree with reviewer's suggestion. In the revised manuscript, we state the percentage of sub-visible, thin and thick cirrus clouds in the respective panel of Figure 6 (b-d) as text.

(10) p. 15807 ll 19-22: Is there an explanation why CALIPSO underestimates the thickness in day-time profiles ?

Reply: Thorsen et al. (2013) have considered high noise level in day-time lidar profiles as a reason for underestimation of cloud thickness during day by CALIOP. The background noise in CALIOP data during day time increases by factor of 10. The high background level makes it difficult to detect tenuous cloud top and base which results in overall smaller geometrical thickness. They arrived on this conclusion based on comparison with Raman lidar which has low background noise during day and does not have statistically significant difference in day and night thickness of clouds at Darwin, Australia. We have included this information in the revised manuscript.

(11) p. 15808 ll 9-13: This point is very unclear and needs further explanation: The difference in geometrical thickness between Sunilkumar and Parameswaran (2005) and your study can be hardly explained by different temperature data. The geometrical thickness measurement itself does not depend on temperature due to the good resolution of a lidar. Only the individual cloud thickness could be shifted to other temperature bins, but this would require a temperature difference between both datasets of more than 20K to explain the big difference of temperature / geometrical thickness distribution.

Reply: We agree with the referee that the differences in temperature profiles alone are not sufficient to explain the observed difference between our results and that of Sunil Kumar and Parameswaran (2005). Other factors such as size of data set, differences in cloud detection algorithm, etc. can also contribute to the observed differences. In the revised manuscript, we have included this caveat to our explanation.

(12) p. 15808 ll 15-17: The dependence could be weaker, but as you wrote before (p. 15807 ll 19-22) the cloud thickness in CALIPSO day-time profiles could also be underestimated. I think this needs a bit more discussion what is the reason for the day/night time difference.

Reply: Yes, we agree with the referee's point that the weaker dependence could be due to the underestimation of geometrical thickness of clouds. We have added statement that the weaker dependence could be due to underestimation of cloud thickness during day-time by CALIOP in the revised manuscript.

(13) p. 15810 l 2: Can you please state the trend of decreasing optical thickness of thick cirrus clouds in the text. Maybe it is also helpful, to show this significant trend also in a Figure.

Reply: As suggested by the review we have added the trend of the optical thickness of thick cirrus clouds in the text, also we have included figure with trend analysis for thick cirrus clouds in the supporting material.

(14) p. 15810 l 12-15: This statement needs clarification, because the intention is not clear and the arguments are contradictory. First you wrote that there is a warming trend at 100 hPa. In the next sentence you wrote the warming decreases rapidly and becomes

Reply: In this statement we mean to say that CMIP5 projections showed a warming trend at 100 hPa over the wide region of 60°N to 45°S. However, this warming trend decreases rapidly and becomes cooling with increase in altitudes. At 100 hPa the temperature increases by ~3.27 K at the end of twenty-first century and at 10 hPa, the temperature decreases by ~8.8 K at the end of twenty-first century. We have changed the statement in revised manuscript to avoid confusion.

(15) p. 15811 l 3-5: Can you please state a percentage number also in the conclusion section. Because it is an important point for water vapor entry into the TTL.

Reply: Number of cirrus clouds above tropopause is found to be 9% in NARL lidar. This is mentioned in the revised manuscript.

(16) p. 15811 l 8-11: As i mentioned before, i did not understand the difference in the Temperature/Thickness distribution and the corresponding explanation.

Reply: See our response to comment 11.

3 Technical comments:

We agree with all the technical corrections and implemented them in the revised manuscript except two suggestions which were about improving readability of Fig. 1 and 6. Our software does not support suggested correction, hence we are looking for alternative software. If necessary we will be doing that at later stage (proof reading stage).

References:

Cziczo, D.J. and Fryod, K.D.: Sampling the composition of cirrus ice residuals, Atmospheric Research, 142, 15–31,

Lynch, D. K., Sassen, K., Starr, D., and Stephens, G. (Eds.): Cirrus, Oxford University Press, New York, USA, 499 pp., 2002.