Response to the Reviewer #2

The authors state (line 353) that "the diurnal structure of the cirrus occurrence is of its first in kind". However, I can name at least two studies that yielded the diurnal cycle of cirrus clouds on a global scale. The first one (Noel et al, 2015) used space-borne lidar CATS operating between February 2015 to October 2017. This period overlaps with the period analyzed in the manuscript, and I believe it makes sense to compare the results with those of (Noel et al., 2015). An extensive analysis is not required, but at least some general comparisons should be made and discussed.

Reply: We thank the Reviewer for going through the manuscript and providing positive comments and valuable suggestions to improve the manuscript further. We have incorporated all the necessary corrections suggested in the revised manuscript.

We have revised the statement (line 353) as "the diurnal structure of the single, and multi-layer cirrus occurrence is of its first in kind."

We thank the Reviewer for providing the important information to compare our results with CATS data, this we have planned to explore data in a separate study. However, as suggested, the comparison of the total cirrus occurrence using MPL with high-level clouds using CATS is carried out as shown in Figure R1.

It can be seen that the diurnal features of the cirrus clouds occurrence during DJF and JJA calculated over the NH tropics (0-30 N) from CATS observations compared well with the MPL observations over Kattankulathur. The occurrence of the cirrus clouds over the altitude ~ 8-17 km is consistent in both ground-based and space-borne observations. Also, the occurrence is higher during the NH summer than NH winter. However, the total POC does not show pronounced diurnal variation.

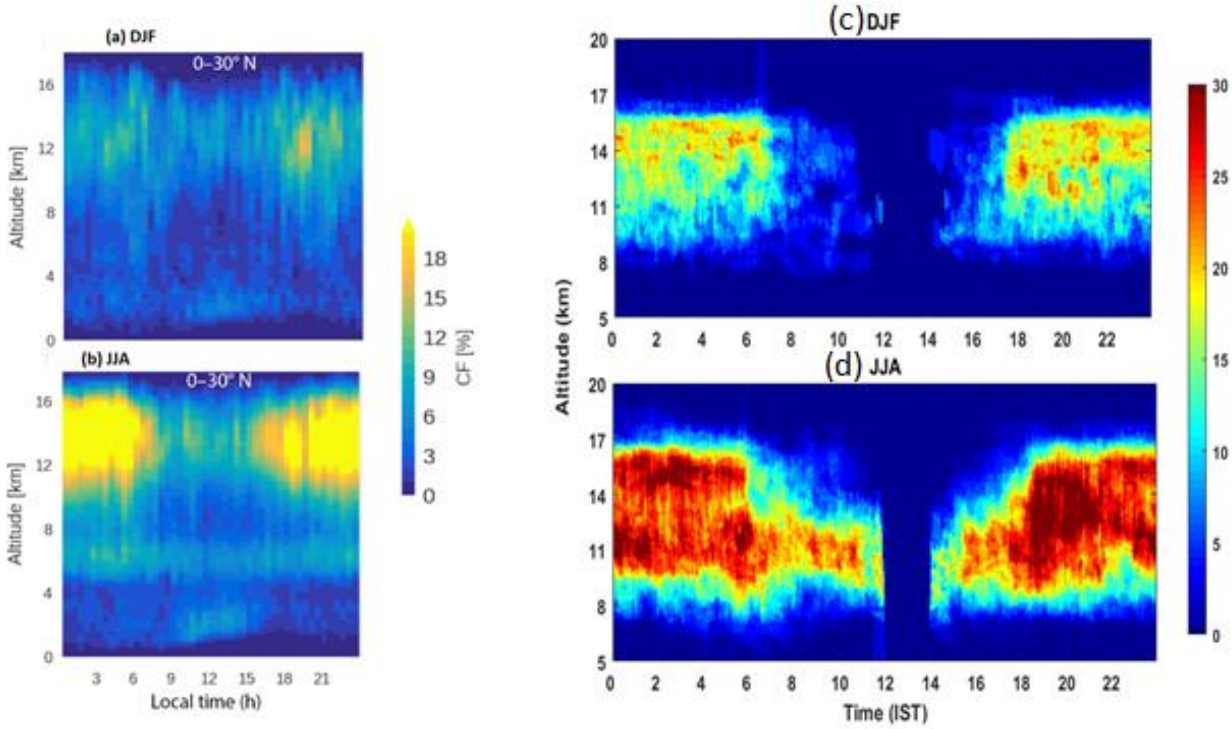

Figure R1. The vertical profile of cloud fraction as a function of local time of observation over the land in the Northern Hemisphere tropics during (a) DJF and (b) JJA from 2015 to 2017 (Reproduced from Noel et al., 2018). The occurrence of cirrus clouds as a function of time and altitude observed over Kattankulathur (India) during (c) DJF and (d) JJA from 2016 to 2018.

In the second work (Feofilov and Stubenrauch, 2019), high clouds have been retrieved from two space-borne infrared sounders, AIRS and IASI, which observe the atmosphere both day and night and their daytime SNRs are the same as the nighttime ones. Even though Fig. 5 and 6 of this work show that the diurnal cycle is not that pronounced at the considered location, I tried to compare its properties to those reported by the authors of the reviewed manuscript. For this, I retrieved the amplitude and peak time values for the point closest to (12.82N, 80.04E) from the publicly available dataset (doi:10.13140/RG.2.2.13038.15681) and analyzed the data. The direct comparison is hindered by differences in the cirrus cloud definitions between the reviewed manuscript and in (Feofilov and Stubenrauch, 2019), differences in sensitivities, wavelengths, and observation geometry. Still, one can see a correlation between the monthly occurrence of cirrus clouds (Fig. 6 of the reviewed manuscript) and the diurnal cycle amplitude (Fig. 1a) and between the peak times occurrence frequency for DJF, MAM, JJA, and SON (Fig. 1b). The latter plot is a combination of single- and multi-layer clouds because the infrared sounders use to retrieve the upper cloud in the case of a multi-layer cloud. Therefore, it should be compared to a weighted average of Fig. 5a and 5b of the manuscript. One can note that JJA peak of Fig. 1b corresponds to JJA peak in Fig. 5a of the manuscript, MAM peak of Fig. 1b corresponds to MAM peak of Fig. 5b, whereas DJF and SON peaks correspond to a superposition of Fig. 5a and 5b. Further analysis is beyond the scope of this review. The main purpose of this exercise was to put the results obtained by the authors in a more general context. The authors are encouraged to develop this further themselves

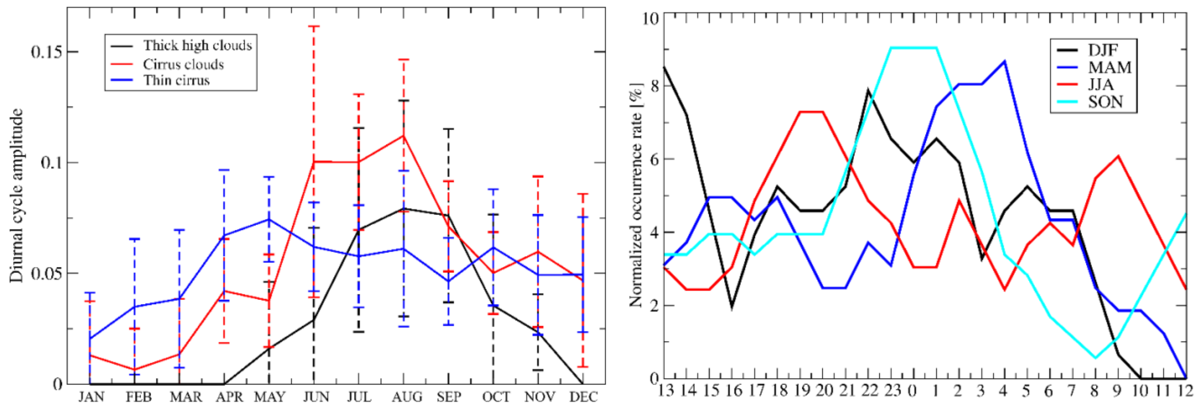

Figure 1. Diurnal cycle of high clouds (P <440 hPa) retrieved from a combination of AIRS and IASI space-borne infrared sounders (Feofilov and Stubenrauch, 2019) in 1ºx1º bin containing the point (12.82N, 80.04E), to be compared with Fig. 5 and 6 of the manuscript under review. (a) diurnal cycle amplitude; (b) occurrence rate of peak time values for DJF, MAM, JJA, and SON for thin cirrus clouds

Reply: We appreciate the Reviewer's effort in comparing the results and agree with the Reviewer that cirrus occurrence using space-borne observations (IASI and AIRS) shows a nearly similar diurnal pattern with a single layer cirrus occurrence using observation (MPL) during JJA. Similarly, multi-layer occurrence using MPL during MAM also agrees with space-borne observations. This indicates that both ground and space-borne observations are consistent. However, the space-borne observation usually detects the cloud top layer, so the distinction between single and multi-layer cirrus is difficult from the AIRS and IASI observation. As suggested by the Reviewer, we have compared the results by combining the single and multiple layer cirrus clouds occurrence from the MPL observations, as shown in Figure R2. As mentioned by the Reviewer, the total occurrence of the cirrus clouds does not reveal any pronounced diurnal cycle. The result was kept aside from the original manuscript and single and multi-layer clouds that show the pronounced diurnal cycle are analyzed.

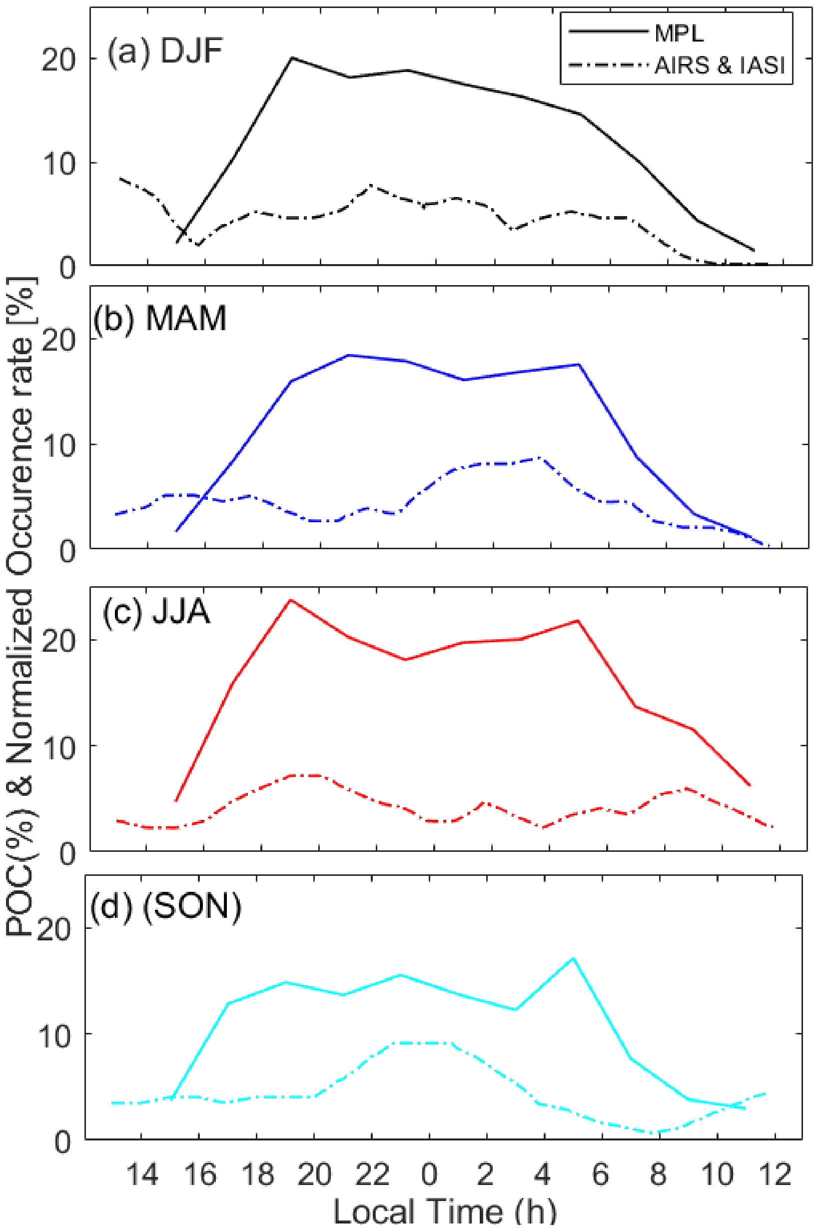

Figure R2. Comparison of the diurnal variation of the total percentage occurrence of the cirrus clouds using the ground-based (MPL) and space-borne (AIRS and IASI) observations over Kattankulathur.

Comment:
Line 30: Please, specify the heights and/or state that the effect applies to the whole column.

Reply: The cirrus clouds affect the whole column (Fleming and Cox, 1974); however, its effect is most pronounced in the TTL region. Yang et al (2010) quantified the radiative impacts of the cirrus clouds on the TTL and observed the net cloud radiative heating below ~16 km and mostly cooling above ~17 km.

Yang, Q., Fu, Q., & Hu, Y. (2010). Radiative impacts of clouds in the tropical tropopause layer. *Journal of Geophysical Research: Atmospheres, 115*(D4).

Line 56: To my knowledge, the probability of inhomogeneous nucleation is much higher than that of homogeneous one. The way the phrase is formulated makes one think that their probability is comparable and homogeneous one might be even more preferable.

Reply: We agree with the Reviewer that the formation of cirrus clouds due to inhomogeneous nucleation is higher than that of homogeneous nucleation. This sentence is rephrased in the revised manuscript.

Line 110, Eq. 1: I would expand alpha and beta coefficients and add the coefficient of multiple scattering here. By the way, what is the value of this coefficient for the MPL lidar? Does it affect the analysis?

Reply: We thank the Reviewer for the important point to consider for the retrieval of the cloud signal from the MPL observations. This study detects the cirrus clouds using the normalized backscatter (NRB) signal after correcting the system-dependent parameters such as deadtime, after pulse, and the overlap corrections. However, the multiple scattering effects were not considered as it is negligible for our MPL due to its narrow field of view (FOV) (Comstock 2002; Campbell et al., 2002; Bissonnette 2005; Lewis et al., 2022).

Moreover, NRB signals above 8 km are mainly from the clouds and the background molecules, as the signals from the aerosol are almost negligible. Thus, for the study the cirrus clouds, especially their occurrence, NRB data is utilized.

Bissonnette, L. R., 2005: Lidar and multiple scattering. Lidar: Range-Resolved Optical Remote Sensing of the Atmosphere, C. Weitkamp, Ed., Springer, 43–103.

Comstock, J. M., Ackerman T. P. , and Mace G. G. , 2002: Ground-based lidar and radar remote sensing of tropical cirrus clouds at Nauru Island: Cloud statistics and radiative impacts. J. Geophys. Res., 107, 4714, doi:10.1029/2002JD002203.

Campbell, J. R., Hlavka, D. L., Welton, E. J., Flynn, C. J., Turner, D. D., Spinhirne, J. D., Scott , V. S., III, & Hwang, I. H. (2002). Full-Time, Eye-Safe Cloud and Aerosol Lidar Observation at Atmospheric Radiation Measurement Program Sites: Instruments and Data Processing, Journal of Atmospheric and Oceanic Technology, 19(4), 431-442.

Lewis, J. R., Campbell, J. R., Welton, E. J., Stewart, S. A., & Haftings, P. C. (2016). Overview of MPLNET Version 3 Cloud Detection, Journal of Atmospheric and Oceanic Technology, 33(10), 2113-2134. Retrieved Mar 17, 2022, from

Line 154: Indeed, the vertical smoothing increases SNR. But, wouldn't it be better to average in time and keep the original vertical resolution? What is the rational for vertical averaging?

Reply: We agree with the Reviewer, and we would like to mention that we have applied the time averaging of the data. The MPL observations are obtained at 1 min. Time interval and 30 m vertical interval which has been averaged to 5 min interval profiles without doing any vertical averaging. The 5-min averaged NRB gradient profiles have several small-scale fluctuations besides the stronger fluctuations due to the cirrus cloud layer. Thus, we have applied the running mean averaging to the NRB gradient profile only to detect the cirrus cloud base and top as well as to reduce the computation timings. It is to be noted that, the signal also fluctuates within the cloud layer which is not

important while computing its base and top that gets smoothed out by the running mean filter. The running mean filter does not affect the cloud signal and its base and top.

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Line 164 and elsewhere (e.g. line 284): the authors mention the difference between daytime and nighttime SNR. Indeed, the sensitivity of cloud detection is not the same for daytime and nighttime, and clouds of certain type cannot be detected during the day. Normally, this should reduce the diurnal cycle retrieval only to optically thicker clouds, but I do not see a clear threshold defined for the analysis. Another methodological issue I see here is the attenuation of the backscattered radiation. This does not affect the lower cloud boundary detection, but it might affect the upper boundary and if the photons are absorbed then there's no information coming from the upper layers. This makes these layers indistinguishable from clear sky. I did not get whether the methodology described in lines 155- 164 manages to tell the attenuated signal from clear sky one. I would say that the reference molecular backscatter profile could be estimated from the atmospheric pressure/temperature profile and added to the analysis, but I do not see this in this section. Could you, please, clarify?

Reply: We agree with the Reviewer that estimation of the diurnal cycle of the cirrus clouds occurrence normally will be limited to the optically thicker clouds. In our study, we have mange to operate the Lidar during day time except 11:00-14:00 IST in clear sky conditions. Before detecting the cirrus clouds using the NRB signal, we have checked for the presence of the signals above the threshold value taken as the mean plus two standard deviations of the background NRB signal from ambient air (over the altitude ~ 25-30 km).

We again agree with the Reviewer that cloud top detection depends upon its optical thickness. In the cases of optically thick clouds, the photon (lidar signal) may get absorbed by the clouds, and hence detection of the cloud top may not be accurate. Hence, the cloud top detected is considered an apparent cloud top. As mentioned earlier, the cloud base or top is detected only when the signal is more than two standard deviations from the molecular and attenuated backscatter from the background /ambient air.

It is to be noted that the backscatter signal in the cloud-free condition is the combination of the molecular and attenuated backscatter. Thus, the signal from the molecular backscatter (obtained from the temperature and pressure profiles) is removed before obtaining the aerosol backscatter.

However, as the signal from the molecular backscatter is very low, the backscatter signals above the threshold value (mean plus two standard deviations of the background NRB signal from ambient air over the altitude 25-30 km) will be much higher than the molecular backscatter. It will not affect the detection of the cloud base and top heights.

To illustrate the threshold value for identifying the cirrus cloud, we have considered the typical case of the multiple cirrus clouds observations as shown in Figure R3. The details of these cirrus cloud observations have been described in the main manuscript (Figure 2d). We have taken the vertical profiles of the NRB signals from surface to 30 km at 16:30 IST, 20:30 IST, 03:40 IST, and 06:00 IST, as shown in Figures R3b-e, respectively. As mentioned earlier, the background mean plus one and two standard deviations are obtained from the NRB signal between 25 km and 30 km. During daytime (16:30 IST), the NRB signal up to the attitude of ~ 6 km is much higher than the background signals

shown as dashed lines (cyan and red for one and two standard deviations, respectively). Above it, the NRB signals again go below the threshold value. However, the NRB signal again started to increase and become higher than the threshold value at ~ 9 km due to the cirrus clouds. During night times (20:30 IST and 3:40 IST), the NRB signals are higher than the threshold value up to altitude ~16-17 km. However, during the morning hours, the NRB signals are higher than the threshold value up to the altitude of ~ 10 km. The cirrus clouds were ~ 12 km and ~ 16 km.

Thus, we see that, though the NRB signal is poor during the daytime, it provides the detection of the cirrus clouds. However, detection is limited to the optically thicker clouds.

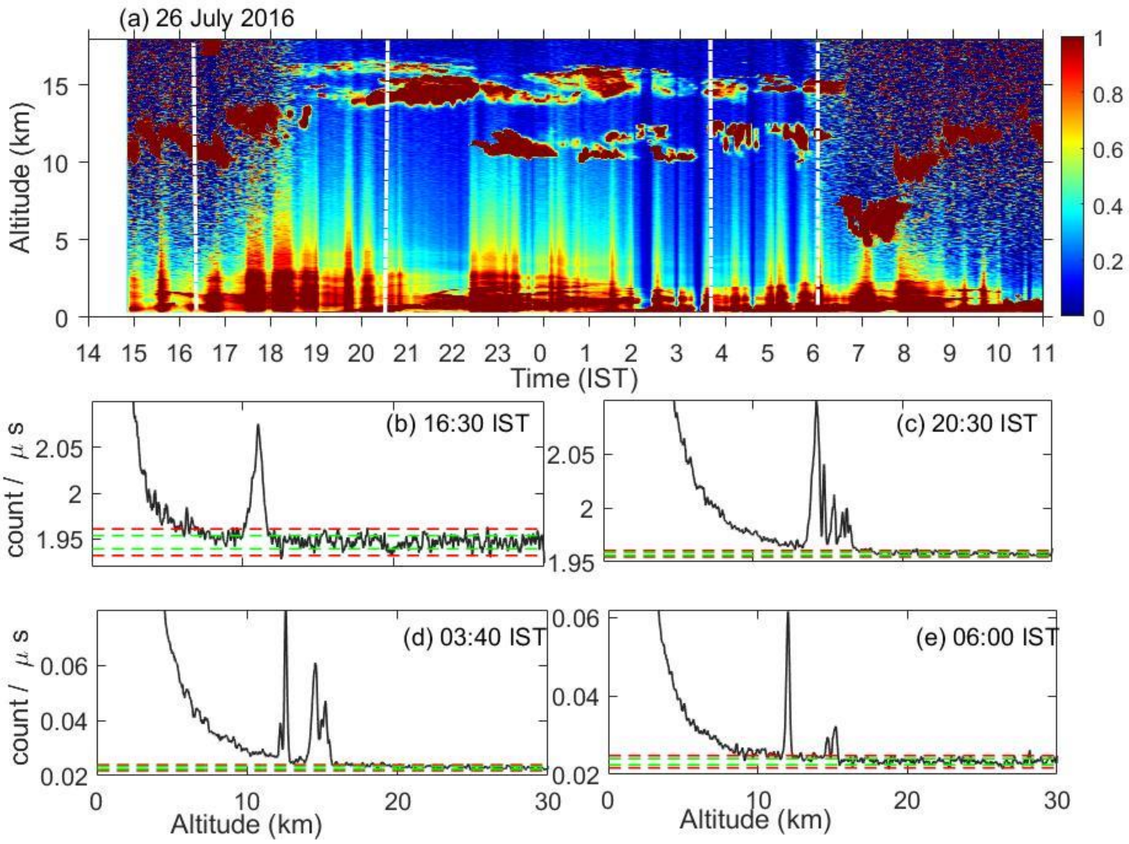

Figure R3: (a) Time height section of the normalized backscattered (NRB) signals over the altitude 0.3 -20 km observed on 15:00 IST on the first day (26-07-2016) to 11:00 IST on the second day (27-07-2016) displaying the multi-layered cirrus clouds. The vertical dashed lines indicate the timings that are taken for SNR analysis. (b)-(e) display the NRB signals from surface to 30 km at 16:30 IST, 20:30 IST, 03:40 IST, and 06:00 IST with the background mean plus one and two standard deviations are obtained from the NRB signal between 25 km and 30 km.

Line 336: color scale is missing for Fig. 4

Reply: We have provided the color code only to portray the difference between days.

Lines 347-348: how does this statement match the main purpose of the manuscript, which is the diurnal cycle retrieval?

Reply: Thank you for pointing out this mistake. We have modified it in the revised manuscript. We mean here that the cirrus clouds occurrence presented from 15:00 IST on day one to 11:00 IST on day two. However, it is noted that many cirrus clouds

especially very thin and subvisible types go undetected because they are thin clouds. Such thin cirrus clouds may not be detected during the daytime due to the limitation of the instrument.

Lines 410-411: how to tell the increase in sedimentation load from other reasons for the descending? What is the proof of this statement?

Reply: Thank you to the Reviewer for the clarification. Generally, the cirrus clouds during the winter season are either thin or subvisible (Sivakumar et al., 2003; Sunilkumar et al., 2003) as this season is free from any deep convection. Sedimentation occurs due to a decrease in the temperature close to the tropopause. Our observation indicates that the cirrus clouds are not always laminar and descend even in winter. Such descending cirrus during the winter season could be due to increases in sedimentation (Nair et al., 2012). However, the optically thicker clouds while descending, as shown in Figure R4 appear related to gravity settlement due to increased load by sedimentation. A detailed analysis of the descending type of the cirrus clouds is being carried out, which we are planning to report in a separate study.

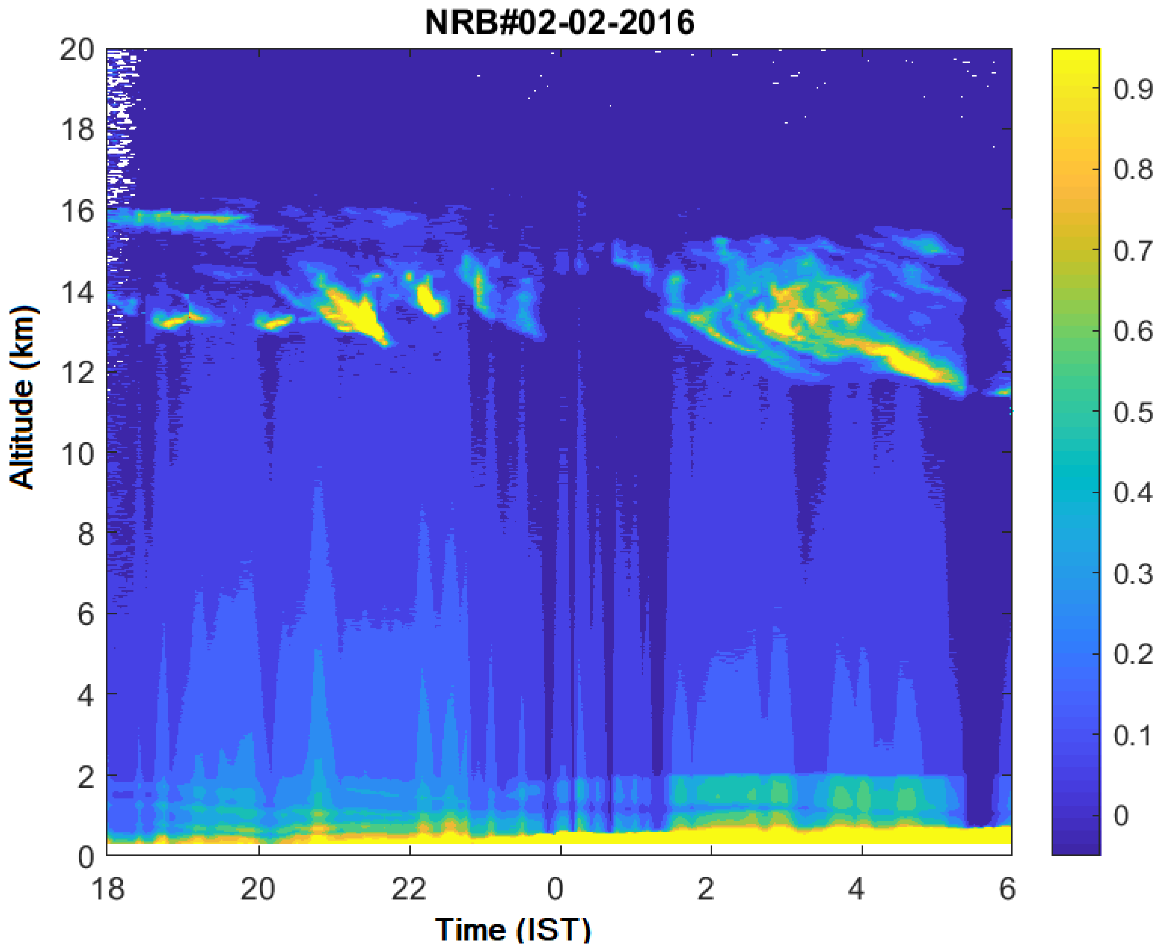

Figure R4: Time height section of the NRB signal observed during a typical winter season (02 February 2016)

Sivakumar, V., Bhavanikumar, Y., Rao, P. B., Mizutani, K., Aoki, T., Yasui, M. and Itabe, T.: Lidar observed characteristics of the tropical cirrus clouds, Radio Sci., 38(6), n/a-n/a, doi:10.1029/2002RS002719, 2003.

Sunil Kumar, S. V., Parameswaran, K. and Krishna Murthy, B. V.: Lidar observations of cirrus cloud near the tropical tropopause: General features, Atmos. Res., 66(3), 203–227, doi:10.1016/S0169-8095(02)00159-X, 2003.

Nair, A. K. M., Rajeev, K., Mishra, M. K., Thampi, B. V. and Parameswaran, K.: Multiyear lidar observations of the descending nature of tropical cirrus clouds, J. Geophys. Res. Atmos., 117(17), 1–9, doi:10.1029/2011JD017406, 2012.

Lines 434-439 and elsewhere: sometimes, the term POC (percentage of occurrence of cirrus) is used as some cloud type: “the lower layer of POC”, “the POC has a limited vertical extent”, and so on. Strictly speaking, the POC has no vertical extent, it’s just a percentage. This misusage is misleading. Please, fix it throughout the whole manuscript.

Reply: Thank you to the Reviewer for pointing out this mistake. We have fixed this issue in the revised manuscript.

Lines 562-564: where is the proof of this relation? What are the values of Pearson’s correlation coefficients for the interannual variation and ENSO or QBO strength?

Reply: We have added the information on the relationship between the POC and convection (OLR), POC anomalies, and ENSO and QBO indices. The POC is negatively correlated with OLR. That is, the deeper is the convection, the higher is the occurrence of the cirrus clouds. To understand the interannual variations of the POC, we have obtained the POC anomalies by subtracting the annual cycle calculated over the period 2016-2018. We have taken a four-month lag in POC anomalies for ENSO (POC anomalies lagging ENSO). It is observed that the POC anomalies lagged at four-month is positively correlated with the ENSO index significant at a 95% confidence level. It indicates that occurrence enhances during the El Nino years and decreases during the La Nina years. The POC anomalies positively correlated with the QBO index significant at a 95% confidence level. It indicates the POC enhancement during the westerly phase and decrement during the Easterly phases. Though POC shows a strong interannual variation in connection with the ENSO and QBO, it needs a thorough investigation with longer-term datasets.

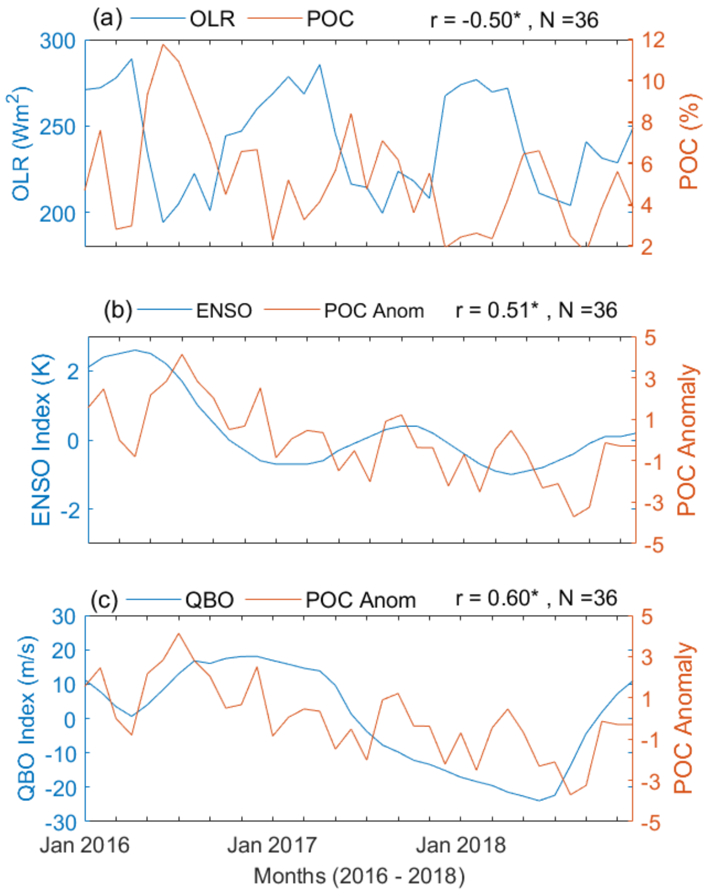

Figure R5: The time series of (a) the POC and OLR (b) a four-month lagged ENSO index (the Niño 3.4 SST anomalies) and POC anomalies (c) the QBO indices (the zonal wind at 50 hPa) and POC anomalies. The correlation coefficient (r) and the number of months (N) are also shown. The asterisk indicates that the correlation coefficient is significant at a 95% confidence level.

Line 618: please, add the uncertainty values to each occurrence rate value here and elsewhere.
Reply: We have calculated the overall percentage of the occurrence by taking the ratio of the total number of cirrus clouds observed to the total number of observations for every 5 min and 30 m altitude intervals over the period 2016-2018. The monthly (seasonal, annual) percentage occurrences are thus calculated by counting the total hours of the cirrus occurrence divided by the total hours of the observations during a given month (season or year). As the percentage of the occurrence is calculated by dividing the total hours of the cirrus observations divided by the total hours of the MPL observations, there is no uncertainty in the measurement. Note that the cirrus occurrence here and in the rest of the manuscript is not the averaged one.

Lines 623-624: please, see the comment to lines 347-348 above
Reply: We have modified the sentence of lines 347-348 in the revised manuscript.

Other comments:

Line 30: “have net warming” –please, reformulate

Reply: We have modified this sentence in the revised manuscript.

Line 353: “is of its first in kind”–language issues
Reply: Corrected the sentence in the revised manuscript.

Line 299: “shaper and colder” –I didn’t get what is meant here
Reply: Sorry for the typo. It is sharper and colder. We mean that, in this case, the tropopause is sharper and colder compared to the previous case.

Line 498: “at” is missing in “POC is higher altitude”
Reply: Corrected

Line 506: please, change “May month” to “month of May” or just to “May”
Reply: Thank you for the excellent suggestion. We have corrected it in the revised manuscript.

Line 525: “11778 hours lidar was operated”, please rephrase
Reply: We have rephrased the sentence as “lidar was operated for11778 hours” in the revised manuscript

Line 599: “at relatively higher altitudes”: please, change either to “at relatively high altitudes” or to “at higher altitudes” depending on what you want to say here

Reply: We have changed the sentence as suggested in the revised manuscript.

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