Advances in CALIPSO (IIR) cirrus cloud property retrievals – Part2:
Global estimates of the fraction of cirrus clouds
affected by homogeneous ice nucleation

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General:
The manuscript contains a new global climatology of cirrus clouds derived from satellite observations. It is an impressive work with very extensive analyses of various properties of cirrus, as cloud ice particle number concentration (N_i), effective diameter (D_e), ice water content (IWC), shortwave extinction coefficient (α_{ext}), optical depth (τ), and cloud radiative temperature. The study includes innovative data analyses that lead to new perspectives and a deeper understanding of cirrus clouds. In particular, the observations are analyzed to determine whether the cirrus formed homogeneously or heterogeneously. Further, the fraction of hom-affected cirrus clouds is determined and τ distributions are used to establish a proxy for cloud net radiative effect (CRE) of the hom affected cirrus. Finally, a conceptual model of cirrus cloud characterization is proposed. Altogether, this study has the potential to become a new standard work on cirrus properties.

Unfortunately, however, I have some concerns, which I will list in the following. I know that the authors are experienced scientists with many publications and therefore write their articles the way they like it best. Nevertheless, I would like to add some comments, because I feel that otherwise the extensive and thorough study may not get the attention it deserves.

(G 1) It took me quite a while to work through the long, sometimes complicated text and the equally complicated figures. To my opinion, the interesting, but complex results could be presented more simply and shorter to make them easier for the reader to understand. Otherwise, I fear readers will be discouraged from reading the article.

So, overall, I think it might be good to consider shortening the main part of the paper and only showing the most important figures in that part. Everything else could be moved to the Appendix or Supplementary Material.

(G 2) I have some suggestions for simplifications - but not for the text, for that I can only ask the authors to go through the manuscript again and simplify and shorten the descriptions.

For example, I recommend

(a) to introduce a small table with abbreviations, which contains for example:

T_r *:* cloud layer radiative temperature, approximately in the middle between T_{top} und T_{bottom}

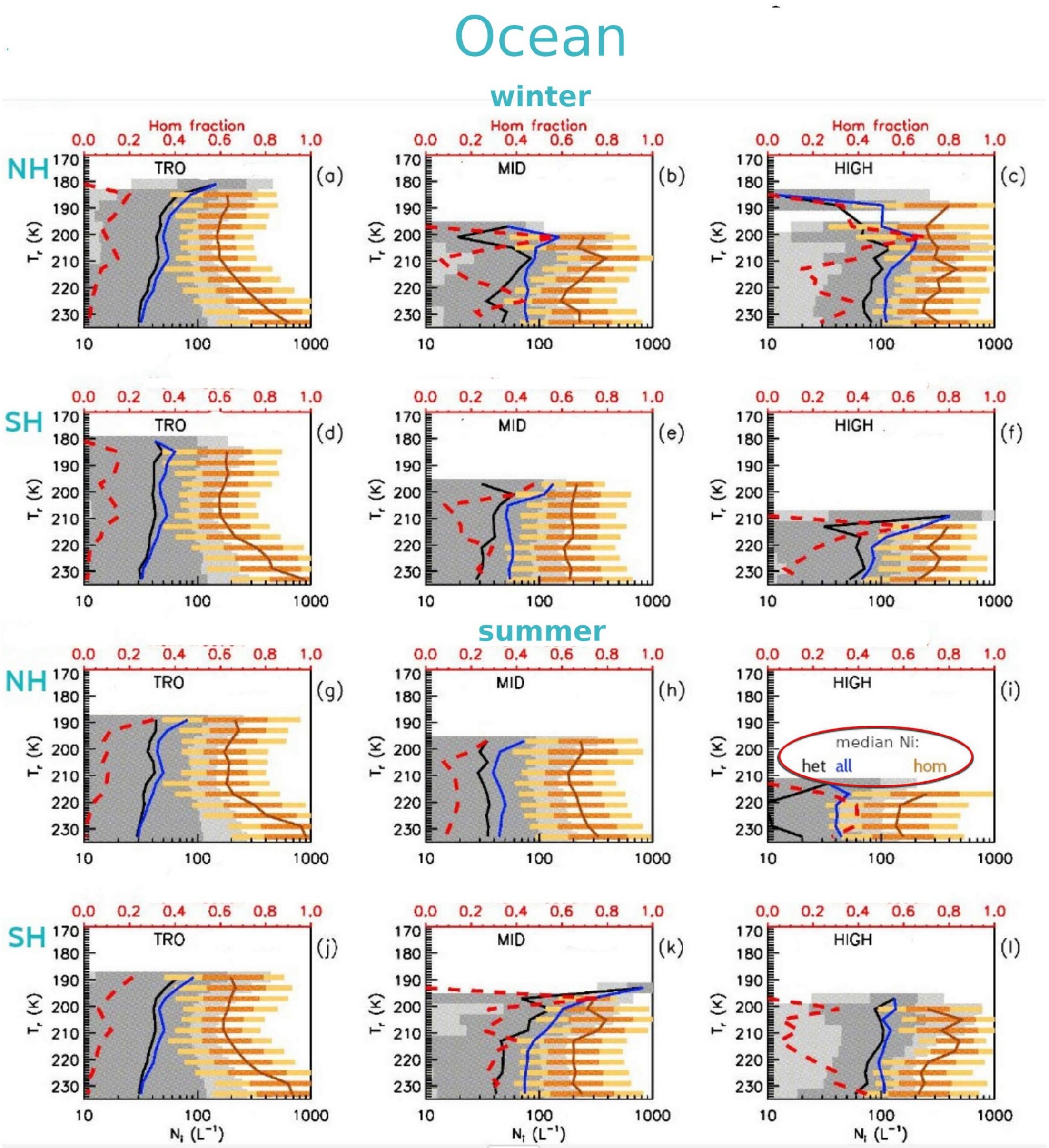
IAB: CALIOP 532 nm layer integrated attenuated backscatter

IAB < 0.01 sr -1 = ~ 0.01 < τ < ~ 0.3 optically thinner cirrus – thin - subvisible cirrus*
IAB > 0.01 sr -1 = ~ 0.3 < τ < ~ 3 optically thicker cirrus – opaque cirrus

* subvisible cirrus (τ < 0.03), thin cirrus (0.03 < τ < 0.3)

(b) to use either the τ ranges throughout the manuscript to identify the cirrus type, or (I think even better) the name (subvisible cirrus, thin cirrus, opaque cirrus), IAB doesn’t give an intuitive impression on the type.

(c) to simplify the figures:
I strongly recommend revising all figures so that the recurring headings above each panel be incorporated into a general figure title, so that only the specific information appear above the panels (in the current version it is hard to find out the differences between the panels). Further, I would also include information that is now somehow hidden in figure captions in the Figure title.
As an example of the simplification of the figures here **Figure 18 (**I modified the figure for my own understanding):



(G 3) Retrieval of liquid origin cirrus

Line 110 ff: *… cirrus clouds with T_{base} warmer than 235 K (and T_r colder than 235K), hereafter called liquid origin cirrus. …*
This method is an approximation that may underestimate liquid origin cirrus clouds somewhat (overestimating in situ cirrus) since cloud condensate from below the 235 K isotherm may be advected across this isotherm upwind of the CALIOP nadir view when there is no cloud at nadir below this isotherm.'

This method sorts not only liquid origin as in-situ origin cirrus, but likely also in-situ origin as liquid origin, as explained in the following: Warm conveyer belts (but also convective systems) consist from bottom to top of layers of liquid, mixed-phase and cirrus clouds. The mixed-phase clouds appear in the cirrus region as liquid origin clouds, but above these, in-situ cirrus usually also form due to the lifting of the air masses. An example is shown by Luebke et al. (2016) (see Figure below, top panel). The vertical structure of liquid origin and in-situ origin cirrus is clearly recognizable.

If these clouds were classified as described in this paper (i.e. if the clouds reach down to temperatures warmer than -38C they are liquid origin cirrus), the whole in-situ origin cirrus umbrella would be misclassified as liquid origin cirrus.

I would recommend doing some case studies to test the classification. A trajectory analysis, as done for example by Luebke et al. (2016), would be best suited for this. This is the most reliable method to classify cirrus of in-situ and liquid origin. I think it is crucial to check the classification method, as all results on in-situ origin and liquid origin cirrus depend on the correctness of the sorting - and my concern is that many of the in-situ cirrus at the top of WCBs, MCS or convective cells will be classified as liquid origin.

A. E. Luebke et al.: Cirrus origins **5799**

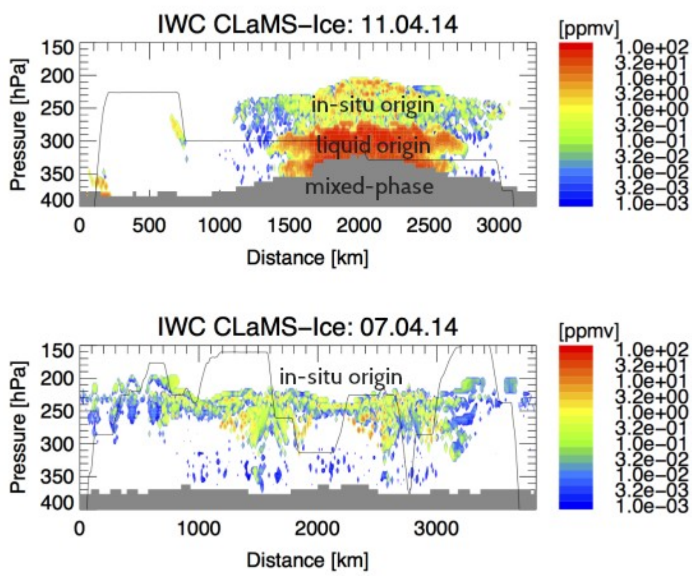


Figure 4. Examples of CLaMS-Ice simulations from ML-CIRRUS showing a liquid origin cloud sample (top) from the 11 April flight and an in situ origin sample (bottom) from the 7 April flight. The flight path is illustrated by the black line and represents the pressure at which the aircraft was flying (y axis) and the distance since take-off (x axis). The colors in each plot represent the simulated IWC (orange: high IWC, blue: low IWC). Grey areas indicate $T > 238$ K and do not contain simulated clouds.

(G 4) Hom-affected and het-only cirrus clouds (Sections 3.2 and 3.3 etc.)

E.g. Line 293ff: *Characteristic in all plots* (Figure 12 and subsequent figures) *is a broad region on the left side (relatively low α_{ext}) where Ni < 30 L^{-1}, apparently corresponding to het only. To the right of this region is a gradient of increasing N_i, culminating in values of N_i > 2000 L^{-1}. This gradient region is likely produced by varying degrees of hom activity.*

I am not convinced by this classification and would interpret this central point of the paper differently, as I will explain in the following.

I agree that there are two cirrus regimes, as described in Krämer et al. (2016, 2020). Here α_{ext} (color coded by N_i) is used to make this visible. The region of high α_{ext} and N_i (‚hom acitivity‘) corresponds approximately to the area of high IWC and Ni in Fig. 6 (top panel) of Krämer et al. (2020). In this region, both in-situ and liquid-origin cirrus clouds are present. For the in-situ cirrus clouds, the interpretation that they are formed by hom (of soluble aerosol particles) is correct, but not for the liquid-origin cirrus. Hom (of cloud drops) can occur within liquid origin cirrus clouds, but is rather rare outside the tropics. The predominant freezing mechanism of liquid origin cirrus is het, nevertheless, they can have high N_i .

The region with low α_{ext} and N_i is defined here as ‚het only‘. However, I think the composition of the cirrus clouds in this region are much more complex. First to mention, in this region there are also also both in-situ and liquid origin cirrus present. Further, the in-situ origin cirrus could have formed either hom or het, since hom also produces only few ice crystals at warm temperatures and low updrafts. But, most importantly, the concentration of hom cirrus with initially high N_i (and thus α_{ex}) decreases quite rapidly in the warming phases of the ubiquitous mesoscale temperature fluctuations where the environment is subsaturated (Jensen et al., 2024). This means that they are moving from the hom affected regime to what is now defined as het only. This can be seen also in Fig. 6 (bottom panel) of Krämer et al. (2020) - the thinner the cirrus (and the lower N_i) the more frequent the cirrus clouds are in a subsaturated environment.
The fact that the cirrus clouds with low α_{ext} and N_i are in a subsaturated environment is also indicated by the decreasing D_e to the left of D_{max} (Figures 15 and 16), because under this condition, the thinner the cirrus clouds and the lower the N_i, the smaller the ice particles.
In an at least saturated or supersaturated environment, the ice particles would be larger with decreasing Ni, i.e. there would be no maximum in D_e, but an increase, maybe with a change of the slope during the transition from one to the other regime .
In summary, I believe that this region is a mixture of in-situ origin cirrus clouds of different ages, which could have formed either het or hom, and aged liquid origin in the dissolution stage.
I recommend reconsiding the naming and the discussion of the ‘het only’ cirrus regime.

What I wonder (although I know it would be a lot of work) is whether this analysis would be better done separately for in-situ and liquid origin cirrus (the derivations presented in section 3.2 only apply to in-situ cirrus anyway)? Especially for in-situ cirrus, the interpretation of the freezing mechanisms would be much clearer, now the liquid origin probably blurs their features.

Specific comments:

(S 1) Line 35f: *… liquid origin cirrus associated with cloudy air advected from lower levels (T>235 K) that often contains liquid cloud droplets.*

I don't think cirrus of liquid origin often contains liquid droplets - they are usually completely glaciated by the Wegener-Bergeron-Findeisen process when they enter the cirrus temperature regime (< -38C; see Costa et al., 2017, their Figure 15). Only at high vertical velocities (as in convective cirrus), or in the absence of INPs (e.g. in the Arctic), liquid droplets can rise to temperatures as low as -38 C, where they freeze homogeneously.

(S 2) Line 51f: *However, hom resulting from cloud droplet freezing dominated ice production in the lower part of cirrus clouds at all latitudes.*

This is not consistent with the measurements of Costa et al. (2017), see point (2).

(S 3) All kinds of studies are cited in the introduction, but not with a specific focus. Then it is said - even without focus - what is in the paper.

(S 4) Line 130-132: *When only clouds with τ>~S0.3 are sampled over oceans* (solid red lines)*, liquid origin cirrus clouds prevail at mid- and high latitude (60 % and 70 %, respectively), but not in the tropics (32%).*

I think these numbers 60, 70 and 32% can be derived from those in the respective panels by taking the difference to 1, right? That is not easy to understand - please mention it in the text or write both numbers (for in-situ and liquid origin) in the panels.

When all clouds are considered (solid blue lines)*, the percentage of in situ cirrus increases by 18 to 25 % and they always prevail.*

I can’t find these numbers in the panels …

(S 5) Line 132ff: *For these blue curves, it is seen that the liquid origin cirrus prevail at Tr larger than about 227 K, which is ~ 6 K higher than shown in Luebke et al., 2016 (their Fig. 13) and Dekoutsidis et al., 2023 (their Fig. 4). …*

Note that the analysis of Luebke et al. (2016) and Dekoutsidis et al. (2023) are based on the same field experiment (ML-Cirrus) and represent only the meteorological conditions that prevailed during that time.
I would recommend to compare the in-situ / liquid origin fractions with the analysis of Wernli et al. (2016), which covers 10 years of ERA5 data.

(S 6) Line 175: *Global maps for each season are shown for median Ni, De, IWC, and Tr using the cloud sampling criteria described in section 2.1 and IAB ≥ 0.01 sr-1 (i.e., ~ 0.3 < τ < ~ 3,* thick cirrus*)* …

Please introduce the cirrus category ‚thick cirrus‘, also in the Figure captions (or even more simply as the title of the figures: ‚Median Ni / De / IWC / Tr , Tr < 235 K, thick cirrus (~ 0.3 < τ < ~ 3)‘, then only the time of year appears above the individual panels.

(S 7) Line 193ff (Figure A3):

- **panel b:** I wonder why the in-situ D_e is of comparable size to that of liquid origin? I think it should be smaller, because in-situ ice particles cannot grow as large as ice particles of liquid origin.
- **panel e:** I wonder why the in-situ N_i of thick cirrus (red curves) increases at warm T - could this be a misclassification?
- **panel f and h** (IWC and IWP): I wonder why the in-situ IWC and IWP (red curves) is of comparable size to the liquid origin ones? I think they should be smaller. Misclassification?

(S 8) Line 237f: *... two different τ categories: ~ 0.01 < τ < ~ 0.3 (IAB < 0.01 sr-1) and ~0.3<τ<~3 (IAB>0.01sr-1); henceforth categories 1 and 2.*

Instead of categories 1 and 2, you could say 'thin cirrus’ and ‚thick cirrus', which is more specific and informative.

(S 9) Line 251f: … *highest* (IWC) *values in* (geometrically) *thinner clouds in Category 2 for a given Tr, were not anticipated.*

Possibly the higher IWC, especially at warmer temperatures in the geometrically thinner cirrus clouds, indicates that these are young cirrus which have not yet lost any ice particles through evaporation in temperature fluctuations (see Jensen et al., 2023). During aging ice particles are lost by evaporation and sedimentation, so the geometrical thickness increases and the IWC decreases.

(S 10) Line 253ff: *For a given T_r, D_e tends to be quasi-constant, although usually decreasing for the thinnest clouds in both categories, possibly due to entrainment. But this D_e decrease could also be due to hom in Category 2* (thick cirrus)...

It could also be that the larger ice crystals in geometrically thicker cirrus clouds, especially in the tropics at warm temperatures, indicate liquid origin cirrus clouds. I think that is more likely than the occurrence of hom.

(S 11) Line 440ff: *Most evident when comparing Figs. 15 and 16 for $\alpha_{ext} < 0.3\ km^{-1}$ (where het is expected to prevail) is that median N_i is higher over land (up to a factor of 10), presumably due to higher INP concentrations over land. ...*

Or stronger updrafts → enhanced hom over land ?

…. higher INP over land (which can also be enhanced by stronger updrafts) may be producing a “Twomey effect” in het cirrus clouds over land.

This is very speculative (over-interpreted?) .... to make this hypothesis more information about INP and updrafts would be necessary.

(S 12) Line 476f: *When D_e > sensitivity limit, we set the sample as het-only.*

Here I have strong concerns, as outlined in point **G 4**.

(S 13) Line 550ff: *Also of interest are the seasonal changes in hom fraction between 30°N and 60°N in Fig. 20. Relative dust contributions of the world's main dust source regions are … more likely to reach cirrus cloud levels in the UT due to ascent within frontal systems, orographic uplift, and dry convection. ...*

As in point S 11, seasonal changes in hom fraction might also be due to changes in updrafts and not only to be related to INP.

(S 14) Line 575, Figure 22: I wonder if it wouldn't be easier to understand if LO and IS were the same color (LO grey, IS red) and hom / het the color shades ? And then to plot LO (het/hom) over IS (het/hom).

(S 15) Line 604f: *Interpreting these w regimes as het and hom regimes, respectively (which was not done in Krämer et al., 2016) ….*

It has been discussed by Krämer et al. (2016) that het dominates in slow updrafts with low IWCs and hom in fast updrafts with high IWCs, see their Figure 6 and corresponding text.

(S 16) Line 650, Figure 25: Considering point G 4, does this scheme fit?

I'll stop commenting here (but have read the rest of the paper); I think there are enough points to be revised, after which the remaining parts could have changed. So I will wait for the next version of the manuscript.

References:

Costa, A., Meyer, J., Afchine, A., Luebke, A., Günther, G., Dorsey, J. R., Gallagher, M. W., Ehrlich, A., Wendisch, M., Baum gardner, D., Wex, H., and Krämer, M.: Classification of Arctic, midlatitude and tropical clouds in the mixed-phase temperature regime, Atmospheric Chemistry and Physics, 17, 12 219–12 238, https://doi.org/10.5194/acp-17-12219-2017, 2017.

Jensen, E. J., Kärcher, B., Woods, S., Krämer, M., & Ueyama, R. (2024). The impact of gravity waves on the evolution of tropical anvil cirrus microphysical properties. Journal of Geophysical Research: Atmospheres, 129, e2023JD039887. https://doi.org/10.1029/2023JD039887

Wernli, H., M. Boettcher, H. Joos, A. K. Miltenberger, and P. Spichtinger (2016), A trajectory-based classification of ERA-Interim ice clouds in the region of the North Atlantic storm track, Geophys. Res. Lett., 43, 6657–6664, doi:10.1002/2016GL068922.