Response to reviewer comments for acp-2020-186

"Finely laminated Arctic mixed-phase clouds occur frequently and are correlated with snow"

Emily M. McCullough, Robin Wing, and James R. Drummond

Thank you to the two anonymous reviewers for their prompt feedback. We have addressed the comments made by the reviewers, and the paper has been improved as a result.

Comments from Reviewer 1 and Reviewer 2 are in black.
Replies from the Authors are in blue.

Reviewer 1:

Review of "Finely laminated Artic mixed-phase clouds occur frequently and are correlated with snow" by McCullough, Wing, and Drummond. This study by McCullough et al. is one of few studies presenting very high-resolution observations of clouds. This study reveals that laminated features in Artic clouds are not uncommon and attempts to quantify the relative occurrence of this phenomenon. It also estimates correlations between the occurrence of laminated clouds and the occurrence of precipitation, which could help improve our understanding of the formation mechanism of these laminations and/or of the impact of these laminations on precipitation.

Although I believe answers to these questions would make a great contribution to the field of atmospheric science, I have several issues with this manuscript as it now stands. For reasons detailed below, I would recommend this manuscript be rejected, but I would encourage the authors to resubmit.

———————- Highlights ———————-
-Science
This study is one of few studies presenting very high-resolution observations of clouds.
-Figures
The figure presented through the manuscript are impeccable. The authors have used appropriate font size, color contrast, labels, and legends.

———————- Major comments ————————

R1_1- Lack of precision in the identification of laminated clouds and in the use of certain terminology

This manuscript relies on manual inspection of plots to create a climatology of the occurrence of laminated clouds. Manual inspection is a highly subjective way to classify observed scene and an impossible one to reproduce. I believe it is imperative for published science to be 100% reproducible. I would recommend the authors start from the vague rules they provide in P 5 L 15-19 to create a precise, programmable set of rules defining what are laminated clouds.

We have attempted to make this study in the most reproducible way possible through as strict criteria as necessary, without anything stricter than required. We recognize that manual inspection is subjective and can be difficult to reproduce. However, this study is specifically the investigation of specific features as identified by humans in the lidar image plots, and the naked eyeball has an incredible ability to access patterns. Therefore we defined as precisely as possible a set of rules for the inspectors to follow to identify the features. In other words, we came up with a programmable set of instructions - but for human computers rather than electronic computers.

A limited check found that person-to-person results were quite consistent. We provided 3 human "test classifiers" each with the same two month-long test sets of CRL image plots to classify (April 2016 and April 2019; 57 days total). These were accompanied by four additional training images, which included 2 examples of what we meant by 'laminated', and 2 examples of non-laminated days. Individually, the three test classifiers reported 7, 4, and 2 days as false negatives, 0 days as false positives, and correctly identified all remaining days. Taking the most common response for each day in any cases of disagreements between the three test classifiers, the daily laminated vs. non-laminated classification results matched as follows with the results found by our group using the strict quantitative criteria: 30 days were correct positives, 0 days were false positives, 24 days were correct negatives, and 3 days were false negatives. Thus, 54/57 days were correctly classified. Of the days which were false negatives, all three test classifiers were able to see the laminations pointed out by the main classifier after the test was complete. The standard colour-scale plot provided to test observers washed out the laminations in some images, making them harder to see, while during the detailed investigation, the main classifier was able to adjust the colour scale at will. We determined inspection by eye to be the optimal approach for the purposes of the investigations in this paper.

For the manuscript, we have provided criteria which are as precise as possible and stated in formal language. Future researchers can reproduce our classification for their needs.

As a last resort, I would ask the authors to provide all figures as supplemental material each one labelled according to their scene classification. I believe "Available upon request from the corresponding authors" is simply not sufficient in this case.

We will provide a set of images, and a spreadsheet identifying which days were assigned each classification.

If the rules defined in P 5 L 15-19 were more precisely defined and implemented I would agree they could be appropriate to identify laminated clouds.

See response above.

That being said, they would not be sufficient to identify mixed-phased or multi-layer conditions which the authors claim to study as stated in the manuscript and in the title.

Many aspects of this comment were be addressed in McCullough2019. We examined a sample of the clouds with the laminated morphology (as described in the present paper) more thoroughly using depolarization and colour ratio data from CRL, and temperature and humidity data from radiosondes.

Mixed phase: McCullough 2019 found that mixed-phase clouds, in which the brighter layers were likely liquid droplets, and the dimmer layers were probably ice and/or aerosol, but more likely ice particles, was the most likely explanation for the laminated phenomena.

Multi-layer: Regardless of particle phase, the laminated clouds are definitely multi-layer of some sort; the laminations are themselves the layers. We see the alternating brighter-and-dimmer stripes *within* the cloud, and these are not separate layers *of* clouds.

Mixed-phase: According to work by Shupe and others, additional information besides photon count is helpful to assess cloud microphysical phase. Thus, the authors statements throughout the manuscript and in the title that "the clouds observed over this 3.5-year climatology are mixed-phase" is not strongly supported. This work would benefit for example from using depolarization information.

McCullough2019 did an assessment of particle phase using depolarization, as described in the previous response. Thus at least some subset of the laminated clouds are mixed-phase (and we suspect most or all of them to be mixed-phase). Therefore, the results in the present paper will be of interest to other people who study mixed-phase clouds, and we have framed the original introduction with this in mind.

We agree that the support for each laminated cloud being mixed-phase is not strongly presented in the present paper, but feel that given the results in McCullough 2019, in the same journal, an explicit reiteration of the detailed particle phase results is not critical for this particular manuscript.

CRL does not have depolarization measurements for every day included in the study. Further, the depolarization results can be ambiguous in any case (aerosols for instance can have a wide range of depolarization values. Likewise, oriented plate and columnar ice crystals). We do however have many examples of the laminated morphology. And this 2nd paper on the topic of laminated clouds, it is still in the realm of an exploratory investigation: Figuring out which aspects of the visual morphology is worth studying in more detail in order to learn something new about the clouds.

We have rewritten the introduction to reduce the emphasis on mixed-phase clouds to accommodate this comment.

Multi-layer: Multi-layer clouds are generally defined as clouds containing multiple liquid layers. Given this, to sustain their claim that the statistics presented in this study pertain to multi-layer clouds, the authors should probably perform a phase classification to distinguish between liquid and ice which both can produce high photon counts.

We believe these to be mixed phase clouds, as per McCullough 2019.

We have defined specifically what we mean by multi-layer clouds. The term multi-layer has been used in a variety of ways in the recent literature. Even the term "mixed-phase cloud" is nuanced: a mix of phases over what spatial scales?

Still, R1's comment brings up a more interesting question: What would be the implication of laminated clouds which turned out not to be mixed-phase? Particularly, given that the laminated clouds shown here are generally correlated with precipitation. We have seen reports of laminated structures of haze (see references in McCullough2019), but the cloud examples shown here are clearly not just haze. It's also possible to have variations in number density of particles (either liquid or solid or both) which would map to variations in returned photon count. We can follow up on this idea in future studies.

Moreover, I would argue that the types of cloud presented in Fig. 3a and in Fig. 3d are quite different ...

They do look different. We chose these examples to demonstrate that the laminations are not confined to one cloud morphology type. The internal processes/composition of the small scale features within each of these clouds may however not be so different.

We are interested in the laminated visual features, not those exclusive to any particular cloud type.

yet the authors consider them together in their statistics ...

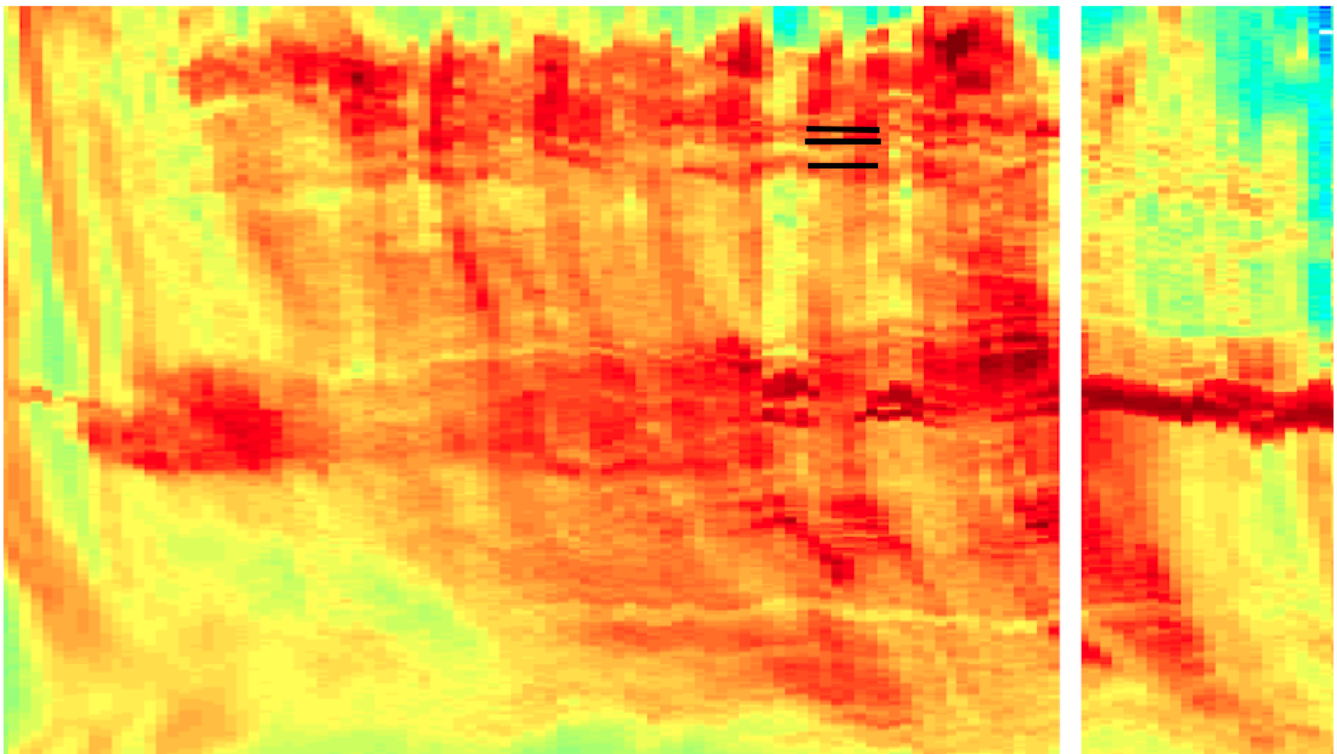
They both show the same lamination features, at the small scales we are interested in, regardless of their context.

At first glance, I would label the cloud in Fig. 3d as a “traditional multi-layer clouds”, and I would certainly need to be convinced that the cloud in Fig. 3a is a “multi-layer” clouds.

We encourage R1 to zoom in on the plots to see the multiple thin layers within a single cloud, which lead to the label of ``multi-layer" clouds. There is sufficient resolution in the discussion paper to do so. We have provided some zoomed-in examples below, and have edited Figure 1 in the paper to be more clear about which layers are the laminations.

Figure 3d: It is possible that R1 is interpreting the three thicker layers of clouds in Fig 3d. to be the criteria we're following to identify "multi-layer". And it is true that perhaps those 3 layers would be sufficient if classifying clouds by multi-layer or not, at those size-scales, was our goal.

We are focused on the much smaller features: See the marked black lines in Illustrations 1 and 2 in this response document, which zoom in on the same region of Fig. 3d that is presented in the paper's Fig 1. These much thinner layers, "laminations", are also and separately sufficient to classify the cloud as "multi-layer", regardless what else is going on in the rest of the cloud. The laminations are layers which are all within one contiguous section of cloud. So one contiguous cloud region might have both "multi-layer" sections and sections for which other descriptors may be appropriate.



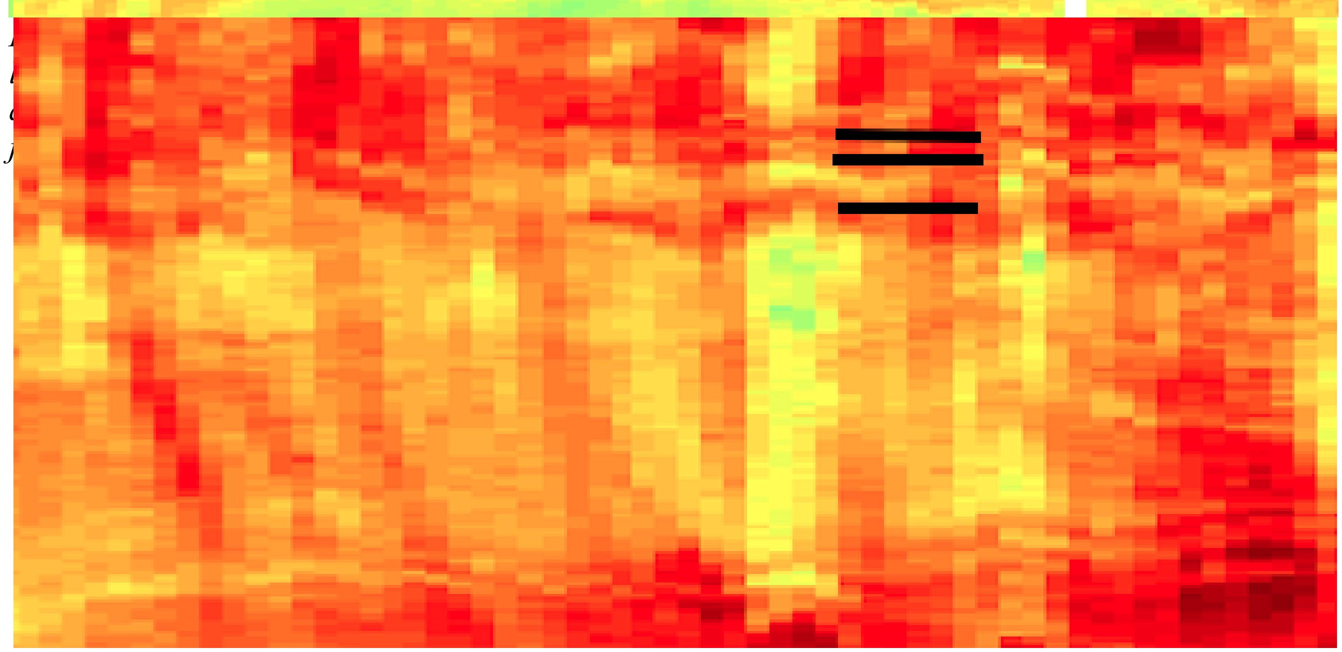


Illustration 2: Further zoom-in of Fig 3d / Fig 1 from the paper. Same black lines as in Illustration 1 identify one example of the scale of laminations that we are interested in.

Figure 3a: Similarly, in Figure 3a, 1600 UTC, we see lots of overall thicker horizontal layers within the cloud, at all sorts of scales. We are interested in the very finest ones. See the zoom-in images in Illustrations 3, 4, 5 of this document. We can see that there are layers ("laminations") within contiguous cloudy regions, thus making the overall cloud type, at least at this scale and location/time, "multi-layer".

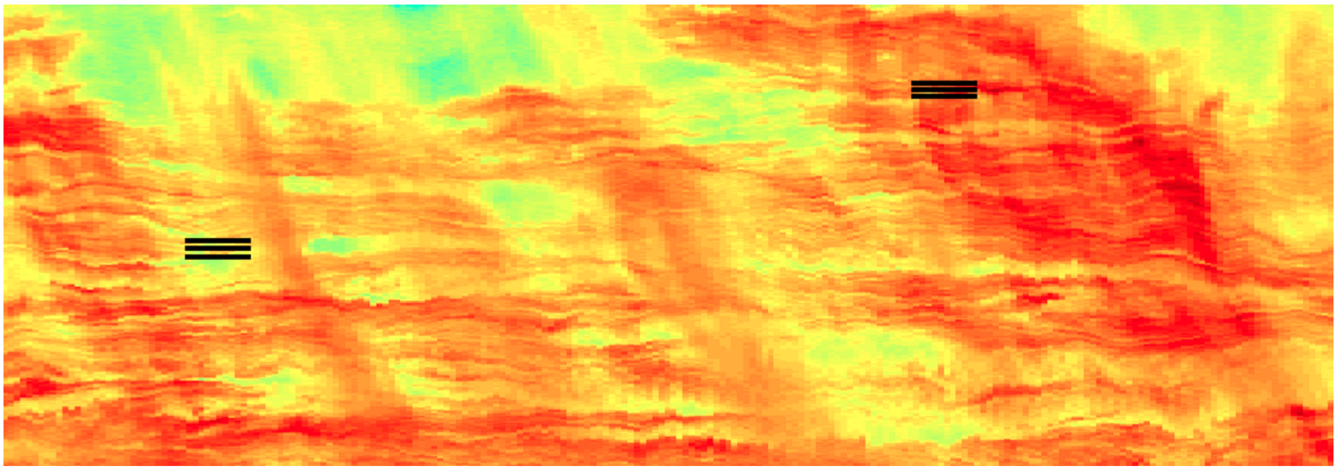


Illustration 3: Zoom-in of Figure 3a. Black lines show two examples of sets of 3 laminations each.

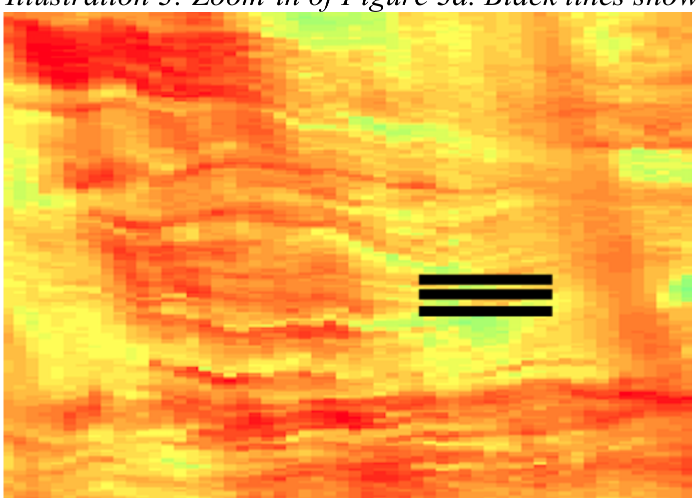


Illustration 5: Further zoom-in of Fig. 3a/ Illustration 3, showing left example of laminations in Illustration 3.

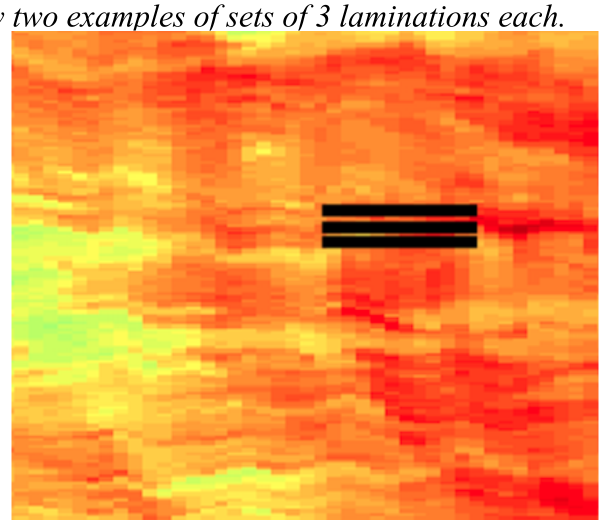


Illustration 4: Further zoom-in of Fig. 3a/ Illustration 3, showing right example of laminations in Illustration 3.

Of course, this study would also be valuable if it was simply describing clouds in general(i.e., without multi-layer statements). That being said, this approach would require a rewriting of the introduction which claims that part of the uniqueness of this study is that it focuses on multi-layer clouds.

We feel that "multi-layer clouds" is an applicable descriptor given that the laminations are all layers in single sections of cloud. We have rewritten the introduction to emphasize these points.

R1_2- Statistical bias caused by the scene classification methodology

This study is based on the analysis of entire days (i.e., 24-hrs) of observations. I believe this was done to keep data size manageable for manual inspection.

Yes. Plus, if we get large correlations at this resolution (which we do!), it tells us there's information in our 24h resolution study (and there is). For example, we can address questions such as: "If we see this type of laminated feature, did it snow that same day?" and this study, even at 24 h resolution, answers "Yes, it probably did, and moreover it probably did not snow on days where the laminated features are absent, even if they are cloudy." This is sufficient to indicate that laminations are probably features either directly or indirectly relevant to the microphysical processes related to precipitation which are occurring in the clouds.

This however creates an issue related to data gaps. The authors attempt to address this issue by defining "interpretable" days. That being said, they do not use this method consistently. For instance, as this classification now stands, a day with only 30 min of laminated clouds is interpretable even if 23.5 hrs of data are missing, but a day with 22 hrs of nonlaminated clouds and 2 hours of missing data is non-interpretable. This methodology is sure to make all relative statistics presented in the current study biased high toward laminated conditions.

We have removed all language regarding fully interpretable days.

Of course the answers will be biased in any framework which includes gaps of data of the kind "data missing not at random". Our missing data is irregular, often related to the very features we're trying to study (laminations correlated with snow... and snow can cause the lidar to be closed.).

We follow the method consistently as it is written. Whether the method is biased in an unhelpful way depends on what question we're trying to address:

We are interested in the particular question:
"If we count the minimum number of days per year that we see laminated clouds, is this very many?" with the follow-on question of "and therefore do we need to care that these show up in the CRL data and/or Eureka environment, when considering scientific queries regarding the clouds themselves?".

As R1 points out, our method probably discards more non-laminated days than laminated ones based on the "fully interpretable" criteria. But also, we will *not* count as "no laminations" any day which is missing data and could have them. So for the top row of our pie charts in Fig 4 in the discussion paper for example, we've got in fact the minimum number of days/year which display laminated clouds.

We have changed the presentation of the data in the manuscript to make things clearer:
- Pie charts are removed
- Plotted each day with Laminated, Non-Laminated, and Undetermined results.
- This allows us to indicate the minimum and maximum possible number of laminated days per year (or per month, for monthly plots)

We have also introduced the strict vs. inclusive criteria for non-laminated days in the correlations with weather:
- The strict version is analogous to the "fully interpretable" scenes from the discussion paper. No undetermined days were included.
- The inclusive version takes R1's comment into interpretation, and indicates the maximum amount

which our correlations could be biased based on rejecting the undetermined days. It does this by including all undetermined days as non-laminated (even though some of them surely *would* be laminated if we could see them properly!)

I believe it would be fairer first to remove days with > 1-hr of missing data, then days with low-level cloud obstruction.

Our question was "Do these laminations show up on enough days that we have to care about them at CRL and/or at Eureka?" Which means we don't want to exclude any days where they exist. Therefore, we did not remove any days which met the laminated cloud criteria, even if they had > 1h of data missing otherwise.

I would consider the rest of the scenes as interpretable. Then I would classify those as clear or cloudy and I would further classify the cloudy ones as laminated and non-laminated. This would ensure that laminated and non-laminated conditions are estimated using the same sample size of "interpretable" cases and would generate unbiased relative frequency of occurrences.

We have attempted to clarify the procedures such that readers should be able to draw conclusions.

Many of our times with missing and/or obscured data (which directs days into Undetermined sky scene classifications) occur precisely because a day has a certain type of weather - which is what we're trying to study.

Most days with laminations are in fact missing multiple hours of data - because it snows! (Major finding of Investigation C as shown in the updated manuscript)

The full set of plots now included as supplementary material should make it more clear the kind of time coverage that is available for CRL lidar. We have many measured days per year, but there are a variety of gaps as well.

I would also recommend that the authors use 1-h scenes rather than 24-h scenes. This would correspond better with the time resolution of the weather reports and would likely increase the number of interpretable scenes.

What R1 says is true. That would make the time resolutions more similar. However:
- This is not manageable, because of the large dataset involved.
- There are nuances here where maybe the cloud exists, then the snow falls in the next hour. An hourly correlation would miss all of this information. We would not get a coincidence, even if the cloud were causing the snow.
- We could do such an hourly study on a subset of data at a later time, for a later paper. We could take into account the number of hours between onset of laminated features and onset of snow, for example.
- We have strong correlations at the daily resolution level. Before carrying out the daily tests, we had no idea whether laminations would be correlated with weather at all - and now that we know there *are* strong correlations, we can think about other higher temporal resolution studies we might like to pursue.

———————- Minor comments ———————-
- Abstract: The abstract could be written in such a way as to be much more insightful. For example, "P 1 L 10-11" would be more informative if some actual correlation coefficients were given. Also, it

would be more informative if information about part II of investigation A was provided; for instance, are there notable monthly differences in the occurrence of laminated clouds? P1 L 2-4: This sentence is very long. Please consider rewriting it. P 1 L 6:" the expression "interpretable days" is not defined in the abstract thus creating confusion for anyone who has yet to read the complete manuscript.

The abstract has been rewritten to address this comment.

- Number of tables: Have the authors consider putting some of their tables in an appendix or perhaps submitting some of them as supplemental material?

We have removed almost all of the tables. Now that we provide the whole dataset as supplementary material, they are less needed than they were for the discussion paper. Further, the new stacked bar charts are easier to read.

- Introduction: I would encourage the authors to shorten their introduction and to be more focused on what makes their study unique which is the fact that they provide very high-resolution observations of clouds and put them in context with precipitation occurrence. For example, I would remove P 1 L 15-17, L 23-25, P 2 L-1-4, and in particular L 8-13 (Anyway "measurements which parameterize" is an incorrect statement since measurements do not "parameterize" they are "used to evaluate" or "used to construct parameterizations").

Done. Introduction has been rewritten.

I think your best statement in the introduction is P 3 L 3-5

Introduction has been rewritten.

I think the introduction would benefit from more background information on previous studies focused on high-resolution observations of mixed-phased clouds such as those conducted by Verlinde and coauthors.

There was more extensive reference to these papers in McCullough2019, but we have added some to the introduction of the present manuscript as well. The layers studied by Verlinde are 10 times larger than those studied here, and are based on aircraft campaigns of short duration.

- Organization: Figure 1 is presented in the introduction before any information has been provided about the sensor used to record the information presented. I encourage the authors to move this figure after or within the methods section.

We disagree, although we respect also the preference of R1. If we don't put the figure very early on, people get the wrong idea about what kind of "layers" and what size scales we're discussing. The methods section does not describe the manner of creating the plot for Figure 1, only its interpretation. We have adjusted Figure 1 to be more clear, which might help. No doubt the figure may move during typesetting in any case.

- Spelling and grammar: There are several spelling and grammar errors throughout the manuscript. For one, the word "occurrence", which is written at least three different ways: "occurance", "occurrance", and "occurence". I would encourage the authors to run a spell check before resubmitting their manuscript.

Apologies from the authors for not having caught all of these before submitting the paper. These have been corrected.

Reviewer 2:

General Comment: Arctic mixed-phase clouds play an important role in the Earth's energy and water budgets. However, its morphology is complex, and the occurrence of each cloud type is still unclear. This manuscript focuses on laminated mixed-phase clouds and its relationships with weather conditions using lidar data from multi-year observations. The manuscript is well organized, and figures and tables are very clear. The dataset and analysis technique are unique and interesting. Although the analysis method is well described and the limitations of the technique are considered the discussion, I have a few concerns in the method and definition, which might affect the conclusions. The concerns below should be addressed before the manuscript is accepted for publication.

Major comments

1. I have questions and concerns about definitions of the "laminated clouds" focused in this study. The manuscript stated "we focus on a different type of mixed-phase cloud which contains layers of ice and liquid throughout the volume of the cloud." Is this same as "ice (precipitating) cloud in which more than one liquid layers were embedded"? Because "Arctic mixed-phase clouds" implies that ice particles and liquid particles coexist and temperatures are below the freezing temperature in the cloud depth, so the liquid particles can be supercooled liquid droplets. However, the analysis of the study seems to also include rain precipitating clouds, where the temperature could be greater than 0C. Please give more detailed descriptions of the target clouds in terms of this and the temperature information of the target cases.

We looked for the morphology as visualized by the CRL plots. We did not concern ourselves about whether any of our identified-as-laminated clouds fit any other criteria for inclusion.

We have now removed most mentions of mixed-phase clouds from the manuscript.

The temperatures at the altitudes of the clouds, even the summer clouds (e.g. see the August example from McCullough2019) are below 0C, in general, and do not preclude mixed-phase cloud formation. Rain can come from mixed-phase clouds. And the rain detection is done at ground level.

2. I have a question about the third criterion for "Laminated." Based on the criterion, the laminated cloud can include three thin cloud layers (i.e. quasi-horizontal stripes) in the 75 m depth. I felt that this is too narrow. If the depth between the first layer and the third layer exceeded 75 m, was the cloud not included? Why was this criterion used to define laminated clouds? What kind of clouds did you want to include/exclude by this criterion?

The purpose of this paper is to look specifically at these fine-scale features. This study began in McCullough2019 as an exploration. It was not motivated by wanting to understand some particular type of cloud, nor a particular cloud in a particular environment. We were looking at the data and noticed that there were lidar plots in which it "looked as though someone had scratched their fingernails across the bottom few km of the plots", particularly when cloudy. We of course had seen this here and there in single plots before, but looking at the whole dataset, it seemed to be a prevalent feature, and we decided to examine the features in more detail.

First, we looked to see what kind of size scale was applicable. Looking for the most narrow features we could find, we saw some that are a single height bin in extent (i.e. 7.5 metres top to bottom of one stripe). We saw many that are a couple of height bins in extent. Ones much wider in extent than 2 or 3 height bins just didn't look quite the same. At that stage, these were quite qualitative comments, and we were not determining strict criteria for any purpose.

The literature review for McCullough2019 showed that laminated features on the 10 metre scale hadn't been published on before (closest related work was at size scales 10x as large as our max resolution). So that's where the interesting things were to us: We could see something new. Then the rest of McCullough2019 investigated what these features could be (depolarization combined with backscatter and temperature plots indicates that mixed phase clouds is a reasonable interpretation).

McCullough2020 is now following up to see whether they happen often enough at CRL that they are significant and whether we can say anything related to the larger atmosphere at Eureka by studying them.

To count these properly, we needed some precise criteria to use. So we tried to find criteria which matched what we would identify intuitively as a laminated morphology. We had to pick a set of criteria which could strictly include or exclude certain days, for reproducibility (as R1 also makes the case for in their comments) and for comparisons in future to other lidars. Yes, it may exclude some in which the layers are more widely spaced. In practice, we often see such features on the same day as more finely laminated clouds, so there are not too many days where this is the case.

We didn't mind excluding some of the larger-spaced features, because this study's strength is in investigating the small scale layers, because very little work is published regarding features of this scale.

As CRL's resolution is 7.5 m in height, if we allow for only features which are visible at our maximum resolution, but not lower (i.e. each stripe is confined to a single altitude bin), we see: stripe, gap, stripe, gap, stripe which makes up therefore 5 bins of 7.5 metres = 22.5 metres. But this would be quite a strict criteria, and would miss many of the days which we'd say have the same morphology.

If we allow each stripe to instead be spread out over 3 height bins, as in it is partly filling the lower bin, then fully fills the middle bin, then is fading out again over the course of the 3rd bin, a minimum of 9 bins of 7.5 metres are then required to visualize 3 layers. Setting the cutoff at 10 bins of 7.5 metres, 75 metres, allows for a little more spacing than that (i.e. can have a gap between the stripes), but still probes for features which we will see in high resolution CRL data, but which would not be visible if we binned to much lower resolution.

So to answer the question:
- We are trying to include all the clouds which "look like the morphology we're trying to investigate"
- We are trying to exclude all the clouds which "look like something else"

And of course, there will be a bit of overlap in the two groups.

In effect, we're using the size scale as a description, not as a cutoff value for size above which no stripes in clouds are important.

We tested the robustness by setting wider criteria, and increased the maximum vertical extent for 3 layers to: 150 metres.

The results in the paper have not materially changed.

3. What was the thickness of the “quasi-horizontal stripes”? How did you define the quasi-horizontal

stripes (i.e. what is the vertical gradient of the lidar backscatter)? Was this definition same as one by O'Connor's et al. (2004) for ceilometer' cloud base height? O'Connor, Ewan J., Anthony J. Illingworth, and Robin J. Hogan. "A Technique for Autocalibration of Cloud Lidar." Journal of Atmospheric & Oceanic Technology 21, no. 5 (2004).

No, the criterion is not the same as in O'Connor. We examined the plots of log(range-scaled counts) by eye, generally on the colour scales indicated as in Figures 1 and 3: 10^5.5 to 10^10.5. We zoomed in so that we could see the narrowest stripes, if they were there, and then if we could see the stripes (subject to criteria given: stripes being about a factor of 10 brighter than surrounding areas of the cloud, 3 stripes within 75 metres (150 m for revised manuscript), within a cloud, lasting for 0.5 h), the day counted as laminated. Due to variations in laser power, thickness of cloud, etc, the absolute gradients can vary.

Refer to McCullough2019 for a representative example of the profiles, including amplitudes. Plots at a standard colour scale have also been produced as supplementary material for the revised paper.

4. I have a concern about the way to count laminated cloud day. If my understand was correct, the laminated cloud day was counted when the laminated condition lasted 0.5 h at least within 24 hours. Yes, this is correct. Based on this definition, it is possible that the most of time could be non-laminated condition in a day that was classified as "laminated day". Yes, this is correct. Is this reasonable to select laminated days? We think that it is. My concern is that if "non laminated day" was counted using a definition that non-laminated condition was lasted >0.5 h, many laminated days selected in the manuscript could be counted as "non-laminated day." In that case, the results obtained in the present study could be opposite. Is the conclusion also affected by the criterion and selection? Of course the conclusion is affected. We tried to be very clear about the criteria so that the reader would know precisely what the conclusions were.

We have addressed a similar comment for R1 by implementing:
- Removal of language referring to fully interpretable days
- Lower and upper bounds on the possible number of laminated clouds per year are now indicated
- Strict and Inclusive versions of the correlation plots are now included

5. While the minimum duration of laminated condition was 0.5 h, the weather condition used in the study was based on the daily reports which provide only a few condition categories per day. How did you ensure the correlation of these different time resolution data?

We find large correlations, and therefore there is information in the comparison of the data. We have not found any literature about these laminated clouds or their correlation, on any time scale, with weather, wind, temperatures, etc. We probed the last two a little bit in McCullough2019, but weather for the first time here.

Because we'd already classified the CLR data by day, it was sensible to classify the weather by day, too. And the daily reports provide *all* the classification categories per day, with the exception of some particular gaps between 0000 and 0200h during some months, when no weather observations are made. If the weather/precipitation changes between hourly observations, the observers make an extra observation and record this as weather which happened that hour.

We summed together any and all weather types which were recorded at any time during each day. Some of the weather types were only present for a short period that day - they get recorded just like whatever the dominant weather type was. The reports give more than one type of weather at each report. They're inclusive, rather than picking a "best descriptor".

See response to R1 comment regarding increasing the time resolution of the comparisons to 1h instead of daily.

6. Based on the classification method, I think that the "Undetermined (obscured)" category implies a low-level thick mixed-phased cloud. I am curious about this category and wondering if this category was included in Investigation B, how this category was correlated with the weather conditions.

We are also curious about the correlation of these clouds with weather, but have not correlated the weather on all Undetermined days as of yet, since it was not so relevant to the laminated clouds. This would be worth doing if those low-lying clouds are of interest, and by this comment, it sounds as though they are (at least to R2, so probably to more readers as well) so we may pursue this in future.

This category includes clouds, fog, ice fog, and anything atmospheric in general which can obscure any part of the lidar scene. Sometimes this is clouds which are at higher altitudes, but have high optical depth. We have reworded parts of the paper to make it more clear that the obscuring clouds are not necessarily actually that low in altitude - they can be, but aren't always.

The set of plots now included in supplementary material makes this more clear.

7. On p. 13, Pearson's r correlation analysis: Please discuss the variability of r values over the years. What is the reason of the variability?

We have 4 values (one per year) of r calculated for each combination of weather and clouds. There is both statistical and geophysical variation which contributes to the differences in r from year to year. More observations are required in order to speculate about the variability in r. We have added text to explain this in the results and discussion sections.

8. Discussion for Investigation A: Please more discuss about the seasonality of the occurrence in terms of meteorological conditions, environment, etc. Figure 5 shows clear seasonal variability in each year except 2017; there is a peak at May and April. What is the reason of the seasonal variability? Why does 2017 show different variability from other years?

Most of the variability is down to having few measurements in many months. (e.g. In 2017 we had few measurements in most months than we had for other years).

We may also have geophysical variation, but we have insufficient measurements to explore this fully.

We do have bias from missing data periods which are made clear in the paper, but which does not affect the conclusions that we are drawing from the results - but which also means that we must be cautious about over-interpreting the monthly results.

The new stacked bar chart expressions for these data make it much more clear that how the minimum and maximum possible number of laminated days varies by month/year. It is now much easier to see that 2017 does not disagree with the other years, per se, but it does have much less data, and therefore less ability to pin down the occurrence frequency to a small possible range of values.

9. Lines 10-11 on p. 17: Same as comment #4, the laminated cloud case was identified when the laminated condition lasted only for 0.5 h. The most of time might be non-laminated condition. If “non-laminated cloud day” was counted as a day where non-laminated condition lasted for >0.5 h, the result could say “non laminated clouds may form an even larger component of the atmosphere at Eureka.” Please carefully mention/discuss considering the limitation of the analysis technique. I have the same comment a statement on lines 18-19 on p.18.

We are in complete agreement. We already know that clouds, in general, are important in the atmosphere. We therefore questioned whether these laminated features show up frequently, or hardly ever. It was less a question of finding out whether they were more common than non-laminated clouds, and more a question of finding out how often laminations happen, and whether they might be important. We have reworded the paper to take R2's perspective into account.

10. Please also discuss about the seasonal variabilities in terms of meteorological conditions, environment. etc.

We have added text which shows instead why the monthly variation in laminated cloud occurrence frequency is more related to missing data.

Minor comments

1. Lines 21-22 on p.13: The occurrences in November and December show large variability in Figure 5. Therefore, this sentence can mislead the readers. This sentence should be rephrased carefully.

This section was rewritten.

2. Figure1: Please specify the laminated cloud regions identified by the definitions.

Done.

3. Line 10 on p. 13: Remove “is.”

This section was rewritten.

Finely laminated Arctic mixed-phase clouds occur frequently and are correlated with snow

Emily M. McCullough[1,*], Robin Wing[2], and James R. Drummond[1]

[1]Department of Physics and Atmospheric Science, Dalhousie University, 6310 Coburg Rd., PO Box 15000, Halifax, NS, B3H 4R2, Canada

[2]LATMOS/IPSL, OVSQ, Sorbonne Universités, CNRS, Paris, France

Correspondence to: Emily McCullough (e.mccullough@dal.ca)

Abstract.

Finely laminated (multi-layer) ~~clouds, which are strongly correlated with precipitation events, have been detected in 3.5~~ Arctic clouds were studied using 4 years of high resolution ~~measurements of Arctic mixed-phase clouds using~~ lidar measurements and local meteorological reports. This study focuses on layers which are 7.5 to 30 m thick. The layers are quasi-horizontal, stacked at least 3 layers high within 150 m, located within any type of cloud from 0 to 5 km altitude, and persist for at least 0.5 h.

Identification of laminated days was made using measurements from the Canadian Network for the Detection of Atmospheric Composition Change (CANDAC) Rayleigh-Mie-Raman lidar, located at Eureka, Nunavut (79.6° N, 85.6° W).

~~Laminated clouds occur on 52% of~~ Laminated clouds were found on 18 - 88% of all days (and on 34 - 87% of all measured cloudy days~~with 24 h measurement coverage from 0-5 km altitude, and on 62% of cloudy interpretable days. There is an average of 70 laminated cloud days detected per year, with no full year having fewer than 52 detections. Given CRL does not measure on all days of the year, it is probable that the true occurence~~). More frequent measurements from March, April and May show with more precision that laminated clouds occur on about 50 - 75 % of all days during the spring season. The frequency of laminated clouds ~~at Eureka is much higher~~to non-laminated clouds is generally consistent year to year.

~~A study was conducted using local weather reports~~ Local weather reports were obtained from the nearby Environment and Climate Change Canada (ECCC) weather station. Days with laminated clouds are strongly correlated with snow precipitation (r = 0.63), while days with non-laminated clouds (r = -0.40) and clear sky days (r = -0.43) are moderately anti-correlated with snow precipitation.

1 Introduction

Arctic clouds generally warm the surface by trapping and re-emitting upwelling infrared radiation, except in summer when they contribute a slight cooling by emitting more radiation to space than they reflect back to the surface (Nott and Duck, 2011; Intieri et al., 2002). ~~Shupe et al. (2011) describe a 70% annual average cloud fraction at Eureka, with cloud fractions of 50% (in May) to 80% (September through March), measured during a 2005-2009 study period. High interannual variability was noted in the monthly distribution of cloud occurrence, but the total annual cloud occurance was constant to within ±1%.~~ During the

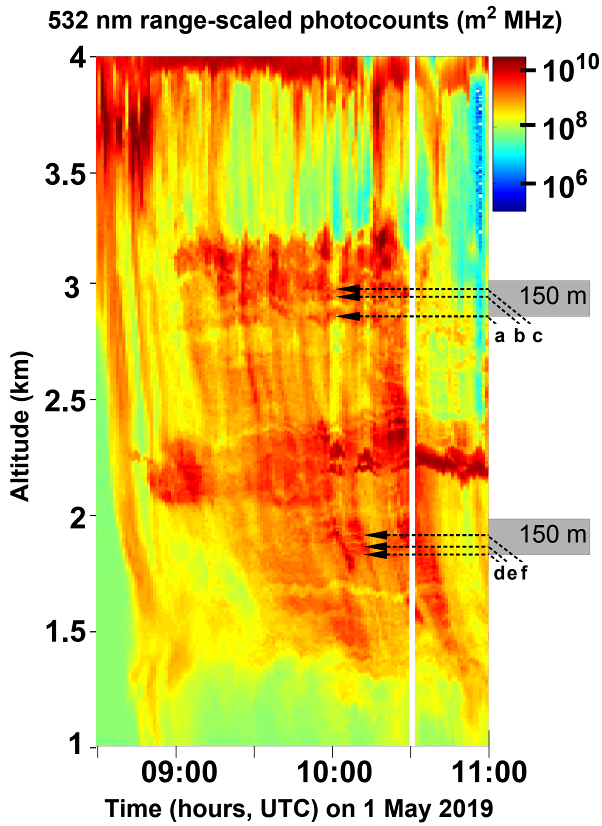


Figure 1. Thin laminated layers within an Arctic cloud with fall streaks also visible. 532 nm range-scaled counts from the CRL lidar at Eureka, Nunavut, on 1 May 2019. This is an excerpt of the plot in Fig. 3d. The laminations discussed in this paper are the numerous, tiny, quasi-horizontal features. Two example sets (a,b,c) and (d,e,f) are shown with dotted arrows. For each set, the distance from the bottom edge of the lower layer (a and d) to the top edge of the upper layer (c and f) is less than 150 m (grey boxes). The laminated scenes last more than 0.5 h duration. Given the criteria (>2 laminations, <150 m extent, >0.5 h), these examples lead to the classification for 1 May 2019 as "Laminated".

Arctic polar night, in the absence of incoming solar radiation, clouds can dominate the radiation budget, so understanding their radiative impact is essential (e.g. Noel et al. (2006); Cess et al. (1990, 1996); Platt et al. (1998)). ~~Given the sensitivity of the~~ The atmospheric radiation balance is sensitive to cloud particle phase. Therefore, warm clouds (which are exclusively liquid), cold clouds (which are exclusively ice, but with multiple formation processes including homogenous and heterogeneous freezing), and the rather more complex mixed-phase clouds, should all be characterized.

~~Mixed-phase clouds are ubiquitous in the Arctic. Over the Arctic as a whole, satellite measurements show occurance frequency from 30% during winter to 50% during the rest of the year, but the spatial distribution is not uniform. Specific locations, e.g. Svalbard, show up to 90% occurance at low altitudes for parts of the year (Mioche et al., 2015). Multi-year ground- and ship-based measurements in Alaska show 41% average occurrance frequency throughout the year (59% frequency when clouds were present), increasing to 70% in the fall.~~ There is a ~~25% annual average fraction of mixed-phase clouds at Eureka (Shupe, 2011). Therefore, mixed-phase clouds are an important component of the Arctic radiative budget.~~

~~Mixed-phase clouds involve a complex interaction of three phases of water (vapour, liquid, and ice) coexisting in the same cloud, and are particularly challenging to model. Models in the 1980s and 1990s were not capable of adequately predicting particle size spectra within clouds, and those which predicted cloud height, depth and water content were hoping to benefit from further measurements which parameterize the cloud optical properties in terms of liquid and ice water content (Heymsfield and Platt, 1984; Sun and Shine, 1995). Numerous studies measuring liquid water path (LWP) have since been undertaken (e.g. Turner (2005); Bühl et al. (2016)). Mixed phase clouds are now known to contain little liquid water, but this small amount, in all seasons, has a dominant effect on local cloud-surface radiative interactions (Luke et al., 2010; Shupe and Intieri, 2004), top-of-atmosphere radiation budgets (Korolev et al. (2017), after Dong and Mace (2003) and Zuidema et al. (2005)) and global climate (Tan et al., 2019).~~

~~Numerous shortcomings in climate and weather models and reanalysis products have been attributed to an inadequate representation of mixed phase clouds, and/or the presence of supercooled liquid within these clouds. Tan et al. (2019) shows that in a global climate model in which the amount of CO_2 is doubled, the global mean surface temperature is underestimated if the amount of supercooled liquid is underestimated in mixed phase clouds. Korolev et al. (2017) provides an overview citing several examples including: 1. Large errors in the annual mean downwelling solar absorbed radiation at the Arctic surface (cloud albedo and optical thickness of the cloud will differ based on the liquid to ice ratio in the cloud, even for the same total condensed water content), 2. Biases in the Arctic wintertime temperature inversion in many CMIP5 models, 3. Errors in the the development of precipitation and the lifetime of clouds (these depend on the ice phase specifically), and 4. Numerous questions remaining about the cloud-aerosol indirect effects in mixed phase clouds (because a change in aerosol number is related to a change in liquid droplet concentrations, glaciation effects, riming effects, and so on). Emphasis is placed on a~~ need for data in a large variety of surface, meteorological, and cloud conditions in the Arctic, including studies which examine the inhomogeneity of clouds at small scales (~~i.e.~~e.g. spatial distribution of ice vs. liquid at scales as small as 10^{-1} m) ~~.~~

~~More recent weather prediction models have begun to include~~ (Korolev et al., 2017). Numerous shortcomings in climate and weather models and reanalysis products have been attributed to an inadequate representation of the distribution of~~the various phases of water within the mixed phase cloud (Forbes and Ahlgrimm, 2014). Vertical resolution has a large effect on~~

~~mixed phase cloud model results. Barrett et al. (2017) use a vertical single-column model of mixed phase altocumulus cloudsto perform resolution sensitivity studies. The low resolution model runs (500 m vertical resolution) reproduce only 12% of the mean supercooled liquid water content which is present in the high resolution (50 m) run, and thus were unable to reproduce the supercooled liquid layer (~200 m thick) which is typical at the top of these clouds. The Barrett et al. (2017) model includes both ice and liquid~~ , for example, supercooled liquid within mixed phase clouds. Such shortcomings include: Underestimation of global surface temperature (Tan et al., 2019); errors in the microphysical process rates ~~, and the difference in results between model runs is attributed to the dependence of microphysical process rates~~ which depend on vertical gradients of cloud properties ~~. Models with simpler microphysics (no ice explicitly modeled) had less bias in total amount of supercooled water, but because they are not representing the clouds' vertical structure correctly (liquid layer atop ice), they still underestimate the radiative impact of the supercooled liquid (Barrett et al., 2017). The Barrett et al. (2017) results are expected to apply to Arctic boundary layer~~ (Barrett et al., 2017); and errors in the development of precipitation (Korolev et al., 2017). Increasing model resolution from 200 m to 50 m in one study was just sufficient to allow the representation of the 200-m thick supercooled liquid layer that tops many mixed-phase clouds (Barrett et al., 2017). Clearly, observations at yet higher resolution are required to elucidate any finer features of these clouds~~as well. Therefore, it is important to have both models and observations at high vertical resolution (tens, rather than hundreds of metres) for Arctic clouds~~.

~~Recent observational studies have been done on mixed phase clouds with supercooled liquid tops above ice-dominated cloud volumes (Morrison et al. (2012); Shupe et al. (2008), the same type of cloud modeled by Barrett et al. (2017)), and these are referred to as "single-layer~~ Some mixed-phase clouds contain layers of ice and liquid throughout the volume of the cloud, and are named variously "multi-layer" clouds in the Mioche et al. (2015) nomenclature, and "multilayered" clouds in, e.g., Vassel et al. (2019) (Note that Vassel et al. (2019) uses "multilayer" (without a hyphen) instead for situations with two separate clouds, neither of which is necessarily a mixed-phase ~~clouds" by, e.g. Mioche et al. (2015). Such single-layer mixed-phase stratiform clouds were observed by Boer et al. (2009) to occur with <5% frequency in spring, 5-8% frequency in summer, and 5-12% frequency infall at Eureka, with most winter clouds being glaciated instead.These clouds are not the focus of the present paper.~~

~~Instead, we focus on a different type of mixed-phase~~ cloud~~which contains layers of ice and liquid throughout the volume of the cloud. This type of mixed phase cloud has been less commonly studied, goes by a variety of names in the literature[1] including "multi-layer clouds" (Mioche et al., 2015)~~, with a clear visible interstice in between). Recent examples of multi-layer cloud studies are e.g. Verlinde et al. (2007, 2013), and Rambukkange et al. (2006)~~, which look at layers <~~. These all describe detailed aircraft-based multi-instrument case studies made during the Mixed-Phase Arctic Cloud Experiment (M-PACE). Lidar (7.5 m x 2.5 s), radar (45 m x 3-4 s), and in-situ measurements were all employed. For Verlinde et al. (2013), the total study duration was 12 h on 6 October 2004. During that period, up to six distinct liquid cloud layers were identified, each between

[1]~~Cloud type nomenclature is not uniquely defined in the literature, in particular when layered and mixed-phase clouds are considered together. The clouds in our paper, with layers throughout the volume of a single cloud, are named "multi-layer" in the Mioche et al. (2015) nomenclature. However, this type of cloud is instead named "multilayered" in e.g. Vassel et al. (2019). In contrast, Vassel et al. (2019) uses "multilayer" (without a hyphen) for situations with two separate clouds (neither of which is necessarily a mixed-phase cloud) with a clear visible interstice in between. These "multilayer" clouds are the focus of Vassel et al. (2019) itself, and, e.g. Curry et al. (1988), but are not the topic of McCullough et al. (2019), nor of our present paper.~~

100 - 200 m thick, ~~and McCullough et al. (2019), with layers <10 m thick~~between 0 and 4.5 km altitude. Higher cloud layers precipitated ice into lower liquid layers, which usually contained drizzle. In this way, and via changes to the radiative heating profile, the layers interacted with one another over the clouds' lifetime.

Lidar is an excellent tool for studying ~~mixed phase~~ clouds as it produces vertical profiles of the atmosphere, including during the dark periods of polar night. With depolarization capability, the lidar can constrain the phase of the hydrometeors (liquid vs. ice), and thus represent the vertical distribution of ice and water within the cloud as well (Schotland et al., 1971; Sassen, 2005; Bourdages et al., 2009; McCullough et al., 2017)~~, the importance of which is described by Korolev et al. (2017). McCullough et al. (2019) showed measurements from~~. Ground-based lidars can operate for longer periods of time (days, months, years) than airborne lidars (typically flights of a few hours). Therefore, we use ground-based lidar measurements from a Canadian High Arctic station to pursue a study of polar clouds.

Measurements in this paper use the Canadian Network for the Detection of Atmospheric Change (CANDAC) Rayleigh-Mie-Raman lidar (CRL) at the Polar Environment Atmospheric Research Laboratory (PEARL; located at Eureka, Nunavut in the Canadian High Arctic (79.6° N, 85.6° W)). ~~The laminations described in McCullough et al. (2019) are at least as thin as the detection limit of the lidar (~~CRL has a measurement resolution of 7.5 ~~m), which is~~ m and is well-suited to exploring Arctic clouds at small scales, like those needed to investigate multi-layer clouds.

In McCullough et al. (2019), we began an exploratory investigation of our lidar data at its measurement resolution, and we detected laminated features with layers <10 m thick. These are an order of magnitude ~~thinner than layers previously described in the literature~~smaller than those described by Verlinde et al. (2007, 2013) and Rambukkange et al. (2006). An example of ~~such~~ a laminated cloud of this sort is shown in Fig. 1~~.~~

~~A cursory investigation in McCullough et al. (2019) indicated that laminated clouds occur throughout the year. Several questions arose: Are laminated clouds a significant feature at Eureka? How often do the laminated clouds occur? Are laminations ubiquitous, and therefore part of the background state of the local atmosphere, or are they infrequent events which perturb (or are the result of perturbations to) the background state? Therefore the need for a statistical investigation was indicated.~~

~~Questions relating to the makeup~~; profiles of a similar example are shown in Fig. 2 of McCullough et al. (2019), demonstrating that the laminations are coherent horizontal structures within a cloud. The regions between laminations generally exhibit range-scaled signals between 35 % and 70 % lower than the signals of the laminations ~~themselves was investigated initially in McCullough et al. (2019) by looking at the~~ immediately above and below.

The initial investigation in McCullough et al. (2019) indicated that laminated clouds occur throughout the year. Case studies using the full suite of CRL wavelengths, as well as depolarization and radiosonde measurements of relative humidity over ice and water, and windspeeds~~. Together, these measurements indicated that the~~, revealed some of their properties. The laminations are associated with thermal/convective stability ~~, precipitation, and that regions~~ and precipitation. Regions of high lidar backscatter are generally associated with low linear depolarization parameter, and vice versa, with some interruptions to this pattern. Therefore, it is likely that the laminations themselves are collections of either liquid droplets or horizontally-oriented plate ice particles (high backscatter, low depolarization), and the regions between laminations are aerosols or randomly-oriented frozen particles (lower backscatter with higher depolarization). The laminations could also be related to the particle size and number density distributions ~~.~~ (similar to the comparably-sized layers of cloud droplet concentrations (tens of metres) found by Hobbs and Rangno (2008) during airborne campaigns over the Beaufort Sea).

Mixed-phase clouds are not the only target for high-resolution lidar measurements, and indeed are not the only type of cloud investigated in the present paper. They are mentioned specifically for several reasons: a. Eureka, Nunavut, our study site, has a 25% annual average fraction of mixed-phase clouds (Shupe, 2011), and therefore a significant portion of the clouds measured in this paper are likely to belong to the mixed-phase class; b. Previous detailed case studies of several of the example days from this paper, using backscatter and depolarization, have demonstrated that at least some of the clouds in this paper are very likely to be mixed phase McCullough et al. (2019), and c. Mixed-phase clouds are ubiquitous in the Arctic in general, and as such are a topic of broad interest in the scientific community which can be effectively investigated by the high resolution lidar methods used in the present paper, and in McCullough et al. (2019).

The work carried out in McCullough et al. (2019) gave rise to questions regarding several topics: Are laminated clouds a significant feature at Eureka? How often do the laminated clouds occur? Are laminations ubiquitous, and therefore part of the background state of the local atmosphere, or are they infrequent events which perturb (or are the result of perturbations to) the background state? Such questions indicated a need for a statistical investigation. Further questions regarded precipitation: How are the laminated clouds correlated with precipitation? If we can quantify what kind of precipitation, or none, the laminated clouds are ~~correlated with, this can further constrain our interpretation of the laminations themselves. We will~~ associated with, we can learn more about ~~what is the clouds are producing, and thereby learn more about the~~ the conditions and microphysical processes occuring within the cloud. Therefore, an investigation linking laminations to surface weather was also indicated.

The ~~two goals for the current paper are~~current paper is organized into three investigations with specific goals designed to address these topics:

Investigation A: Determine whether cloud laminations are a significant feature in the atmosphere at Eureka by determining the frequency ~~, relative frequency,~~ and monthly distribution of laminated clouds throughout the year. This is expressed as a minimum and maximum possible occurrence frequency.

Investigation B: Determine ~~any~~ what fraction of measured days which contain any clouds are affected by laminations.

Investigation C: Determine any correlation with meteorological conditions at Eureka, which will help improve our understanding of the makeup of, and processes within, laminated clouds.

To accomplish these goals, we quantitatively examine ~~3.5~~ 4 years of measurements (January 2016 through ~~June~~ December 2019). The datasets used are the CRL 532 nm range-scaled photocounts, and weather data from Environment and Climate Change Canada (ECCC) meteorological reports.

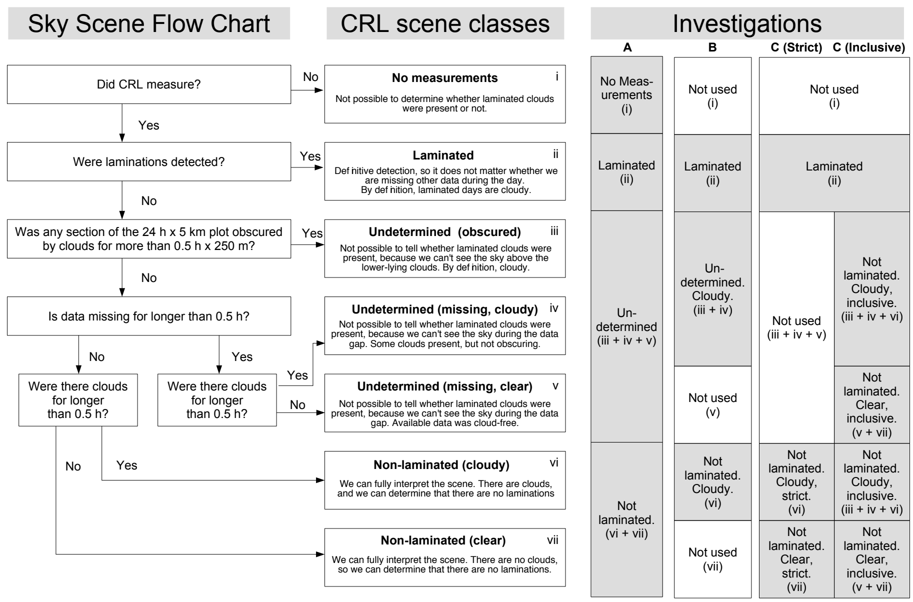


Figure 2. Flow chart (left section) for the classification of CRL sky scenes into classes labelled i through vii (centre section). Full criteria for the classifications are given in the text. The right section of the figure indicates which combinations of sky scene classes are grouped together and used for each investigation.

2 Method

2.1 ~~Identification~~ Classification of ~~laminated~~ days using CRL plots

Measurements were made with CRL at 1 min × 7.5 m resolution up to 12+ km altitude. Plots of range-scaled 532 nm photocounts were produced for each 24 h UTC day from 0 to 5 km altitude at the measurement resolution (no further vertical integration). Shupe et al. (2011) have shown that the annual mean lowest cloud bottoms at Eureka are at 1.75 km altitude, while mean highest cloud tops are at 4.5 km, exceeding 5 km only in August. Therefore, the altitude range used in the CRL study, up to 5 km, is deemed sufficient to encompass most clouds at Eureka.

The CRL plots were examined by eye to determine whether laminated clouds could be detected~~at any time during that day~~. This paper focuses on laminated features within any clouds that CRL can see, and not on a particular type of cloud. Days without ~~laminations are further sub-classified. We desired to differentiate between days for which we can definitively show the presence or non-presence of laminations, and~~ laminated clouds were further classified such that the goals of investigations A, B, and C could all be met using various combinations of the CRL sky classes. General insight into the classification requirements for each investigation is given first. A summary of the scheme, and its application to the investigations, is in Fig. 2. The specific quantitative criteria for each of the sky classes are then given.

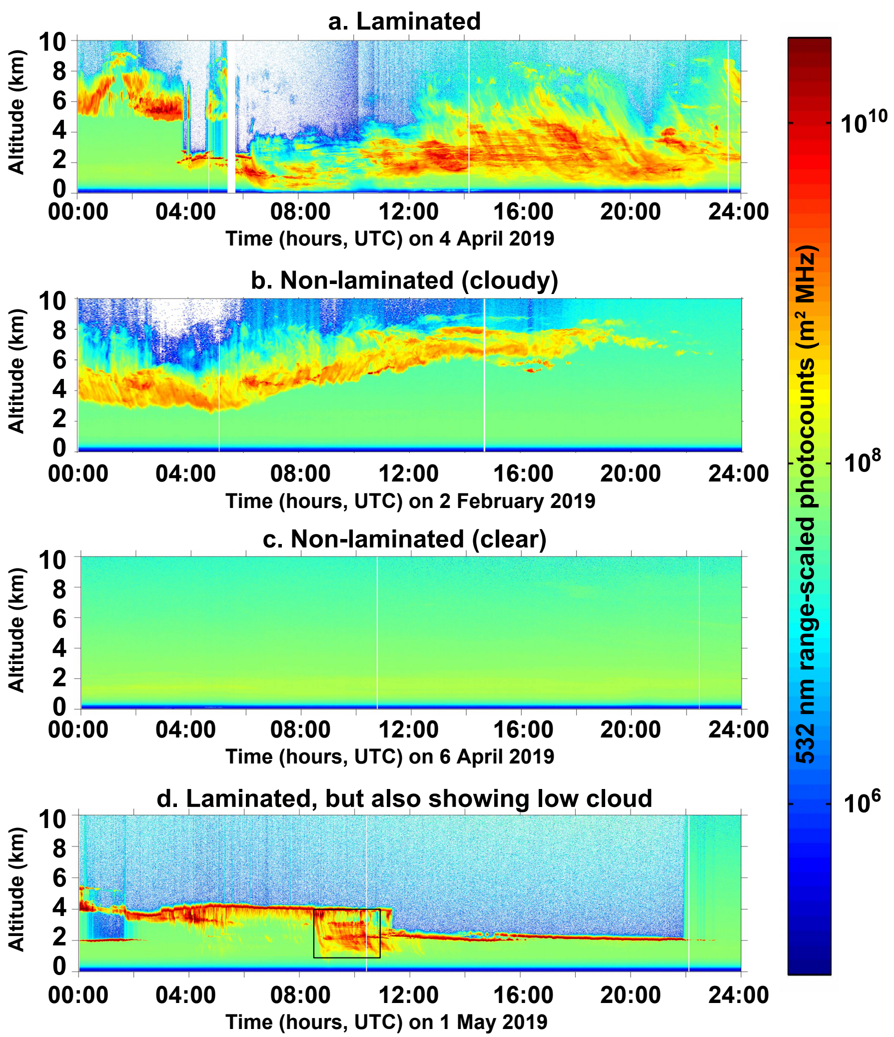


Figure 3. 532 nm range-scaled photocount plots associated with sky scene categories in Fig. 2. 1 min x 7.5 m resolution, 0 - 10 km shown for context. Panel a: “Laminated”. Laminations are visible 07:00 - 24:00 UTC. The white vertical bar is a gap in the measurements. Even if this gap had exceeded 0.5 h duration, it would not impact our classification because laminations are definitively seen. On a non-laminated day (e.g. Panels b,c), a gap > 0.5 h would cause reclassification to “Undetermined (missing, cloudy)” and “Undetermined (missing, clear)”, respectively. Panel b: “Non-laminated (cloudy)”. There are clouds below 5 km which do not obscure other altitudes in the scene up to 5 km, and none of the clouds are laminated. Panel c: “Non-laminated (clear)”. There are no clouds, and therefore no laminated clouds. There are aerosol signatures visible below 1 km all day, and at 18 UTC at 8 km do not impact our classification. Panel d: “Laminated”. Laminated cloud is visible at 10:00 UTC (The 3 layers visible at this scale are not the laminations - the laminations are the finer features visible in the expanded excerpt in Fig. 1.) There is also low-lying cloud identified 12:00 UTC - 22:00 UTC on this day, but because laminations have been detected, the day counts as “Laminated”. If there were no visible laminations present, we would classify the day as “Undetermined (obscured)” instead. Black box expanded as Fig. 1.

2.1.1 Classification requirements for each investigation

Classification requirements for Investigation A

For Investigation A, the goal is to determine how often the laminated clouds occur in the Eureka atmosphere. We can determine the lower and upper bounds on the occurence frequency based on our observations. We require sky scene classes which give the minimum and maximum possible number of days containing laminated clouds in the time period of interest (per year, or per month, for example).

The minimum possible number of days on which the Eureka atmosphere contained laminated clouds is something we can find directly. If we detect laminated clouds on a particular day, then we can state that the day contains laminated clouds. The sum of these days provides the minimum possible number of laminated cloud occurence days at Eureka in the time period of interest.

The maximum possible number of days on which the Eureka atmosphere contained laminated clouds is equal to the total number of days in the time period of interest, minus the number of days for which ~~CRL may not have been sensitive to laminations even if they were present above the lidar. This makes it possible to describe the relative occurrence frequency~~ we can definitively state that there were no laminated clouds. In order to state that there were no laminated clouds present in the atmosphere for a particular day, we must be able to fully discern all features for that entire 24 h x 5 km day in the CRL data, and find no instances of laminated clouds therein.

The ~~sky scene classification scheme is described below. There are 6 categories, with lower case roman numerals corresponding to the categories in the flow chart in Fig. 2. Corresponding example plots~~ remainder of the days in the time region of interest will hold some uncertainty, and are classified as undetermined. We don't see laminated clouds in the plot for that day, but it is possible that this is due to one or more contributions of measurement bias. For these days, we cannot definitively state that there were laminated clouds (because we did not see them), nor that there was a definite absence of laminated morphology in the atmosphere that day (maybe the lidar was not measuring at that time, or thick clouds obscured the lidar's view of clouds at higher altitudes which might have hosted laminations). Days with zero hours of CRL measurements are classed separately as "No Measurements" from the days with at least some CRL measurements, "Undetermined", so that we can make calculations both including, and excluding, days with no measurements.

Classifications required: "Laminated", "Non-laminated","No Measurements", "Undetermined".

Classification requirements for Investigation B

Investigation B concerns just the measurements which contain clouds. "Cloudy" in this context means: Is there at least one cloud large enough, and in the right altitude range, such that the day could meet the criteria for being "Laminated" if there happened to be laminated features within the cloud? The specific criteria are given in ~~Fig. 3. The categories are: i.~~Sec. 2.2.

The Laminated class is by definition cloudy, so needs no subdivision. The Non-laminated class can be subdivided into Non-laminated (cloudy) and Non-laminated (clear). The Undetermined class can be divided as well: "Undetermined (obscured)" is for days which had at least part of the scene obscured by atmospheric phenomena (e.g. regions above clouds; these days may also be missing some hours of measurement, but are by definition cloudy), "Undetermined (missing, cloudy)", for days which had no obscuring features, but which do have some missing hours of data, and which have clouds meeting the quantitative cloud criteria, and “Undetermined (missing, clear)” for days which do not meet the quantitative thresholds for being considered cloudy in this paper.

For Investigation B, we exclude all No Measurement days, so these also need to be identified as a class. The maximum and minimum values are found in investigation B by variously including and excluding the class which are undetermined, but cloudy, from the total of the Non-laminated days.

Classifications required: “~~No measurements”. This category is for days on which CRL made no measurements at all, and therefore it is not possible to determine whether laminated clouds are present or not . ii. “~~Laminated”~~. This category identifies days, with any number or quality of measurements, which show a definitive detection of laminated clouds. The~~ , “Non-laminated Cloudy”, and “Non-laminated Clear”, “Undetermined Cloudy”, and “Undetermined Clear”.

This is a first investigation into the relative occurrence frequency of laminations within clouds, and therefore the results of Investigation B can be considered as the motivation to pursue, or not, studies of: lamination occurrence frequency within a certain class of cloud at Eureka (e.g. only studying mixed-phase clouds), or frequency on a per-cloud basis, or any number of other avenues. Each of these would require a more detailed classification of clouds in the CRL data either by type (requiring more than just CRL data), or by extent (where does one cloud start and another end?). Even classifying a whole day as “cloudy" or “not cloudy" or “clear" introduces biases: How cloudy is cloudy enough? What do you do when each of your days has a different number of hours of measurement? Further, many of the days with less than 24 ~~h lidar scene counted as laminated if there were laminated clouds for any part of the day~~h of measurements are missing data for reasons related to the weather - precisely the phenomena we are studying. Therefore, we keep to the most inclusive criteria that is practical, in the context of this paper, for considering a day to be “cloudy”.

Classification requirements for Investigation C

Investigation C determines any correlation between laminated clouds and meteorological conditions at Eureka. Clear and cloudy non-laminated scenes are also tested for correlation in this study.

As for Investigations A and B, two limiting cases are sought for correlation results: (1) The strict case, which only includes days for which we have definitive measurements in “Laminated” and “Non-laminated” classes. All “Undetermined” and “No Measurement” days are excluded from the correlation tests. (2) The inclusive case, which additionally includes all “Undetermined” classes as though they are non-laminated. ~~The criteria used to identify laminated clouds were:~~

Classifications required: ‘No Measurement”, “Laminated”,“Undetermined cloudy”, “Undetermined clear”, “Non-laminated Cloudy”, ”Non-laminated Clear”.

These limiting cases allow us to check whether our criteria for rejecting the “Undetermined” days from consideration for the “Non-laminated” category are too strict, and unduly inflating the correlation of laminated days with certain types of reported weather. This is a concern because, according to the criteria in Section 2.2, a day with a up to 23.5 missing hours with laminations would be “Laminated”, while the same scene with no laminations would be “Undetermined(missing)”, rather than “Non-laminated”.

2.2 Quantitative criteria for CRL sky classifications

Refer to the flow chart in Fig. 2 for the classification process. Each day is assigned to a unique classification category. The classes are numbered i through vii. Corresponding example plots are given in Fig. 3.

Definition of "cloudy"

This definition is used in several of the individual class criteria. For the purposes of this paper, "cloudy" is determined according to the following criteria:

(i) At least one cloud had least 0.5 h continuous duration, and either

(iia) extinguished the lidar beam above the cloud, or

(iib) subtended at least 250 m in height, between 250 m and 5 km altitude.

Typical values to consider the lidar beam "extinguished" are signals less than in the CRL data set.

i. No Measurements

Days with less than 0.5 h of CRL measurements are assigned to the "No Measurements" class.

ii. Laminated

Laminations are regions within clouds which show very fine quasi-horizontal stripes. We examined many examples of plots exhibiting such stripes to get an idea of what specific quantitative characteristics the laminations had, and then developed classification criteria based on these.

(i) The laminated region occurs in a cloud, and not only in a region of aerosol, dust, fog, etc. Typical signal values are approximately

(ii) Defined edges of the cloud were visible; range-scaled-photocounts value was higher than surrounding non-cloud values by a factor of approximately 10 or higher.

(iii) There were a minimum of three quasi-horizontal stripes, about equal in thickness, stacked one on top of the other, with maximum total extent of ~~75~~ 150 metres from the lower edge of the first stripe to the upper edge of the third stripe.

(iv) The laminated condition lasted for a minimum duration of 0.5 h.

~~Note that "Laminated" days are by definition cloudy. They are also considered to be "fully interpretable scenes" despite possibly having measurement gaps in time or altitude, because we can unambiguously determine that laminated clouds were present on these days. iii. "Undetermined~~

An example of laminated clouds is given in Fig. 3a. We found very few cases which were difficult to classify as laminated or not. There were not very many days (fewer than 10 in the 4 year dataset) which had, for example, laminated-type features which did not meet the extent criteria, or which lasted for shorter than 0.5 h. Therefore, we consider that the criteria appropriately encompass the phenomenon that we are exploring.

iii. Undetermined (obscured)

In the “undetermined (obscured)” ~~. This category is for scenes in which low altitude clouds obscured at least 1~~category we don’t see laminated clouds in the plot for that day, but there are sections of the sky scene which we cannot properly categorize because they have been obscured. Therefore, we cannot categorically state that there was a total absence of laminated clouds in the atmosphere. Sources of obscuration include low altitude clouds, and clouds at high optical depth which extinguish lidar returns from altitudes higher up. See, e.g., Fig. 3d. The criteria are:

(i) Clouds or other atmospheric phenomena obscured a contiguous region of the sky at least 0.5 h ~~of measurements for altitudes above those clouds. Laminated clouds were not detected during the measurement, but it is not possible to interpret the entire 24 h $\times$ 5 km sky scene , and therefore it is not possible to determine whether laminated clouds are present or not in the regions not represented in the lidar plot.~~ in duration.

~~iv.“Undetermined (missing > 1 h data) ”. This category, like category iii, has no detections of laminated clouds. Because part of~~ (ii) The obscured region subtends at least 250 m in vertical extent above 250 m altitude.

(iii) There is no restriction on the nature, location, or duration, of the obscuring phenomena themselves. Common examples are: Fog, low altitude clouds, clouds of high optical depth. In the context of this paper, all obscuring phenomena tend to meet the criteria for being clouds, except for the minimum altitude restriction of 250 m. Therefore, all Undetermined (obscured) days are considered “cloudy”.

iv. Undetermined (missing, cloudy)

In the “undetermined (missing, cloudy)” category we don’t see laminated clouds in the ~~24 h scene is missing, it is not possible to determine whether laminated clouds present in the atmosphere on this dayduring the times that the lidar was not running.~~ plot for that day, and there are no obscuring cloud features. There are times during the day during which we have no CRL measurements. The interpretable sky that is available does have clouds. The criteria are:

~~v. “Non-laminated (cloudy)” . No laminations were detected on these days. The entire 24 h $\times$ 5 km scene was visible, and no more than 1 h of measurements were missing nor obscured throughout the day . At least one cloud of duration~~ (i) There was at least one contiguous measurement gap at least 0.5 h ~~or longer was present. The~~ in duration.

(ii) The criteria for “cloudy” are met, but none of the clouds obscure any part of the lidar scene as per the criteria for class ii.

v. Undetermined (missing, clear)

In the “undetermined (missing, clear)” category we don’t see laminated clouds in the plot for that day. There are times during the day during which we have no CRL measurements. The interpretable part of the day is ~~considered “fully interpretable” because we can determine unambiguously that although there were clouds present, there were no laminated clouds.~~ cloud-free. The criteria are:

~~vi. “Non-laminated (clear) ”.~~ (i) There was at least one contiguous measurement gap at least 0.5 h in duration.

(ii) The criteria for “cloudy” are not met.

vi. Non-laminated (cloudy)

A particular day is “non-laminated (cloudy)” if we can fully interpret the entire sky scene, clouds are present, and we find no laminations:

(i) The entire 24 ~~h × ~~h x 5 ~~km scene was visible, and no more than 1 h of measurements were missing nor obscured throughout the day. These days can include such features as aerosol layers, dust, etc., but no clouds, and may be more appropriately described as cloud-free. By definition, cloud-free days cannot contain laminated clouds. The day is considered “fully interpretable” because we can determine unambiguously that there were no laminated clouds present.~~ km sky scene is present and interpretable

(ii) The criteria for “cloudy” are met.

~~As indicated in the list, three categories are considered to be fully interpretable: i. Laminated (which is by definition cloudy), v.~~ An example of a non-laminated (cloudy) day is given in Fig. 3b.

vii. Non-laminated (clear)

“Non-laminated ~~(cloudy), and vi. Non-laminated~~ (clear)~~. These categories all unambiguously describe the (non-)laminated status of the atmosphere on that day. The remaining three categories are not fully interpretable, and therefore lead to indeterminate results: iii. Undetermined (obscured), v. Undetermined (missing >1 h data) , and i. No measurement. While we did not detect laminations in these indeterminate scenes, it is possible that there were laminations present those days. For this reason, the lamination statistics in this paper indicate minimum occurrence frequency.~~”, means essentially cloud-free; aerosols and clouds too small to meet the criteria for hosting laminations may still be present. We can fully interpret the entire sky scene, and find no laminations, nor any clouds. An example of a non-laminated (clear) day is given in Fig. 3c.

~~Flow chart describing the classification of CRL sky scenes into three interpretable categories: ii. Laminated, v. Non-laminated (cloudy), and vi. Non-laminated (clear), and several undetermined categories: i. No measurements, iii. Undetermined (obscured), and iv. Undetermined (missing > 1 h data).~~

(i) The entire 24 h x 5 km sky scene is present and interpretable

(ii) The criteria for “cloudy” are not met.

~~532 nm range-scaled photocount plots associated with sky scene categories in Fig. 2. 1 min x 7.5 m resolution, 0 - 10 km shown for context. Panel a: “Laminated”. Laminations are visible 07:00 - 24:00 UTC. The white vertical bar is a gap in the measurements. Even if this gap had exceeded 1 h duration, it would not impact our classification because laminations are definitively seen. On a non-laminated day (e.g. Panels b,c), a gap > 1 h would cause reclassification to “Undetermined (missing > 1 h data)”. Panel b: “Non-laminated (cloudy)”. There are clouds below 5 km which do not obscure other altitudes in the scene up to 5 km, and none of the clouds are laminated. Panel c: “Non-laminated (clear)”. There are no clouds, and therefore no laminated clouds. There are aerosol signatures visible below 1 km all day, and at 18 UTC at 8 km do not impact our classification. Panel d: “Laminated”. Laminated cloud is visible at 10:00 UTC (The 3 layers visible at this scale are not the laminations - the laminations are the finer features visible in the expanded excerpt in Fig. 1.) There is also low-lying cloud identified 12:00 UTC - 22:00 UTC on this day, but because laminations have been detected, the day counts as “Laminated”.~~

~~If there were no visible laminations present, we would classify the day as “Undetermined (obscured)” instead. Black box expanded as Fig. 1.~~

2.3 Weather from ECCC

Publicly available meteorological reports from Environment and Climate Change Canada (ECCC, formerly Environment Canada (EC)) were used ~~for context such that we might~~ to investigate the conditions at the ground ~~which are consistent with laminated clouds as~~ when laminated clouds are identified by CRL.

The ECCC weather data are recorded by human weather observers at Eureka. The data are generally reported hourly, with between 22 and 24 observations being made per day. For each day of ECCC meteorological data, we identified a positive detection for any type of weather which was reported at any time during that day, and non-detection for any weather which did not occur that day. Table 2 gives all reported weather conditions for 2016-2019, and the number of days on which each was reported.

For analysis in this paper, we have grouped the ECCC standard weather observations into categories, as in Table 1. ~~The first two categories in the table, “All Precipitation” and “All~~ For example, our “Snow” ~~are combinations of the categories lower in the table. The subsequent categories are grouped logically by type of weather and are all independent of one another.We have excluded three types of reported weather from consideration : “Dust”, which only appeared on one measured day in 2017, and~~ category includes ECCC weather conditions “snow”, “moderate snow”, etc. The “All Precipitation” category is a combination of the “Snow” and “Rain” categories, including all ECCC weather conditions therein.

Weather types reported for two or fewer days between 2016-2019 are either included in one of the combined weather categories (e.g. “snow showers” in “Snow”), or excluded from consideration if they would have required making a new category of their own (e.g. “Smoke”).

“Clear or mainly clear”, and “Cloudy or mostly cloudy”, ~~descriptors which are only used in the absence of any other type of weather occurring that hour. For example, an hour with “~~are also excluded from consideration in this paper. These categories are not reported for all hours in which these conditions occur; rather, they are reported only for observation hours during which no other reportable weather occurred. (e.g. “Cloudy” would not be reported in addition to “snow” ~~will not be listed also as “cloudy” in the ECCC weather data, despite clouds being required~~ for a particular hour, even though clouds are required to be present in order for the snowing condition to be reported ~~. “Ice Pellets” (2 instances)and “Snow Grains” (4 instances) have been included in the “All Snow” category, but excluded from consideration otherwise.~~ by ECCC).

2.4 Correlation of CRL laminations with ECCC weather

Pearson product-moment correlation coefficients, r, and the associated significance values, p, were calculated for the three CRL ~~fully interpretable~~ categories (Laminated, Non-laminated cloudy, and Non-laminated clear), and our weather categories listed in Table 1.

The Pearson’s r is expressed as the covariance of two random variables divided by the product of the standard deviation of each variable X and Y, as in: r $= cov(X,Y)/\sigma_X * \sigma_Y$.

Table 1. ECCC reported weather conditions were grouped together for comparison in this paper.

Weather category	ECCC weather conditions included
All Precipitation	~~snow, moderate snow, snow showers, snow grains, snow pellets, rain, rain showers, drizzle, ice pellets~~ Snow and R
~~All~~ Snow	snow, ~~moderate snow , snow showers, snow~~ snow grains, snow pellets, ~~ice pellets, blowing snow Snow~~ snow showe
Blowing Snow	blowing snow
~~Fog fog~~ Rain	rain, rain showers, moderate rain, drizzle, freezing drizzle, freezing rain
Ice Crystals	ice crystals
Fog	fog
Freezing Fog	freezing fog
Excluded from ~~manuscript~~ study	~~clear or~~ smoke, haze, blowing sand, dust, ice pellet showers, ice pellets, clear, mainly clear, cloudy~~or~~ , mostly clou

The interpretation of r is discussed at length in Cohen (1988) as being useful only in a relative sense; context is required in order to state whether a particular value of r is "small" or "large". Thus, all r values reported here are ~~most~~ only useful when compared with one another. The convention suggested by Cohen (1988) is what we will follow for descriptors in this paper: $r = 0.1$ is *small*, $r = 0.3$ is *medium*, and $r = 0.5$ is *large*. We are working with a 95% (2σ) confidence interval, so we take r values having p ≤ 0.05 to be significant.

We use r to express how the behaviour of the local weather conditions from ECCC varies with ~~the cloud determination made by the lidar~~ lidar classifications.

In our study, daily results were compared. A certain type of weather may be noted for a particular day, but may not have occurred at the same time as the laminated clouds, ~~if neither~~ nor lasted the entire day. Consequently, there will be some ~~amount of~~ noise expected in the final result, and the correlations are thus intended as minimum correlation amplitudes ~~. We seek the combinations of lidar cloud morphology and reported weather condition which have higher correlations than other combinations have~~in both the strict and inclusive cases outlined in Section 2.1.1. Tables of correlation coefficient r were colour-coded for ease of interpretation, in the style of a corrgram, or correlogram.

3 Results for Investigation A: Frequency and distribution of laminated clouds throughout the year

~~Comparisons are also expressed in this paper as relative percentages, showing how much more likely snow is to occur on a day with laminated clouds than it is on a day with non-laminated clouds, for example, as this is an intuitive way to understand the results.~~

4 ~~Results and Discussion for Investigation A: Frequency and distribution of laminated clouds throughout the year~~

3.1 ~~Yearly frequency results~~

~~Occurance of laminated clouds for each year, a. Considering all days of the year (see note below table about 2019*), b. Considering only the interpretable days, and c. Considering only the interpretable cloudy days. 2016 2017 2018 2019 2019* All yearsa. Considering~~

3.1 Yearly Results

Figure 4a shows the yearly CRL scene classification considering all days of ~~the year N = 366 N = 365 N = 365 N = 365 N = 181 N = 1277Laminated 61~~ all years from 2016 through 2019. Known-Laminated days (~~17 %) 52 (14 %) 84 (23 %) 46 (13 %) 46 (25%) 243 (19.0 %) Non-laminated (cloudy) 40 (11 %) 24 (7 %) 52 (14 %) 34 (9 %) 34 (19 %) 150 (12 %) Non-laminated (clear) 24 (7 %) 15 (4 %) 17 (5 %) 17 (5 %) 17 (9 %) 76 (6 %) Undetermined (obscured by low cloud) 58 (16 %) 49 (13 %) 71 (19 %) 26 (7 %) 26 (14 %) 204 (16 %) Undetermined (missing > 1 h data) 45 (12 %) 55 (15 %) 48 (13 %) 13 (4 %) 13 (7 %) 161 (13 %) No measurement 135 (37 %) 170 (47 %) 93 (26 %) 229 (63 %) 45 (25 %) 443 (35 %) b. Considering only interpretable days N = 128 N = 91 N = 153 N = 97 N = 97N = 469~~Laminated~~61 (48 %) 52 (57 %) 84 (55 %) 46 (47 %) 46 (47 %) 243 (52 %)~~; blue) are at the bottom of each bar in the plot. The height of these bars indicates the lowest possible percentage of days per year which are laminated: 18 ± 4 %, as indicated by the thick black "Minimum possible" line in the plot. Days which have been positively identified as Non-laminated ~~cloudy 40 (31 %) 24 (26 %) 52 (34 %) 34 (35 %) 34 (35 %) 150 (32 %) Non-laminated clear 24 (21 %)~~ extend downward from the top of the plot (red and orange bar segments). This defines the location for the "Maximum possible" thick black line, at 88 ± 2 % of days.

Days without any CRL measurements are then excluded from consideration (by removing the lightest grey "No Measurements" category). The results are given in Figs. 4b and c. The minimum possible number of measured laminated days is 67 ± 15 ~~(17~~ days (29 ± 3 %)~~17 (11 %) 17 (18 %) 17 (18 %) 76 (16 %) c. Considering only cloudy interpretable days N = 101 N = 76 N = 136 N =~~. The maximum possible number of measured laminated days is 183 ± 28 days (80 ~~N = 80 N = 393Laminated61 (60~~ ± 3 %)~~52 (68 %) 84 (62 %) 46 (57%) 46 (57%) 243 (62 %) Non-laminated cloudy 40 (40 %) 24 (32 %) 52 (38 %) 34 (43 %) 34 (43 %) 150 (38 %)~~

~~Frequency of laminated clouds compared to other sky scene classifications from CRL.~~

~~The sky scene classification of each day of the year for 2016 through 2019 according to the 6 categories in Sec. 2.2 is represented by the pie charts in Fig. ??a and Table ??a. A total of 834 dayswere measured by CRL from 2016 through June 2019 (present date at writing of this manuscript). There are definitive laminated cloud detections on 243 of these days, which averages to 70 days per year. This includes 61, 52, and 84 days per full year (2016, 2017, 2018), and 46 detections in the 2019 half-year. Excluding the half-year (in case a non-uniform distribution of laminated clouds throughout the year is relevant), the average is 66 days per year. Therefore, a minimum of approximately 20 %of the days of the year have laminated clouds. There may be additional laminated clouds occurring in any of the undetermined categories (grey colours in Fig. ??), which occupy two thirds to three quarters of each year .~~

~~In Table ??b and Fig. ??b, only the fully interpretable days are considered. The sky may be cloudy or clear, but the full 24 h x 5 km scene is visible and interpretable for each of these days. Laminated clouds are detected on 47 % to 57 % of the the measurement days each year for which we have appropriate data to be able to detect them if they are present.~~

~~Finally, a subset of the interpretable days is examined: Only those which are cloudy are included in Table ??c and Fig. ??c. Laminations are detected on between 57 % and 68~~ The yearly results show that, overall, laminations are present every year, with a minimum possible detection threshold of about 18 %, and potentially present in the atmosphere on up to 88 % of ~~the cloudy days for which we have appropriate data to be able to detect them if they are present.~~ days. This points to these laminated clouds being a recurring feature of the Arctic atmosphere.

~~Monthly bar charts as of 30 June 2019. Measurements are ongoing. Colours correspond with those in Fig. ??. Percentages are with respect to all (28 to 31) days in each month. Only the interpretable days are shown in upper panels, for clarity.~~

3.2 Monthly Results

3.3 ~~Monthly frequency results~~

~~Monthly distribution of measurements. Totals are the sum for all measured days in each named month for the 3.5 year study period. Total number of interpretable days is the sum of the first three rows of the table. Total number of cloudy interpretable days is the sum of the first two rows of the table. Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Laminated 1 9 52 44 36 24 10 8 14~~ Figure 5 shows the same data as in Fig. 4a, broken down by month. The distribution of CRL measured days throughout the year is not consistent between years, nor throughout any single year. Funding circumstances preclude the lidar from full operations during December and January in particular, but also at other times of year. Hot weather at Eureka precludes full operations during the summer. The lidar must be closed if laboratory temperatures exceed certain thresholds, and also if local wind speeds exceed 20 ~~19 7 Non-laminated (cloudy) 4 22 29 22 17 11 12 5 3 5 15 5 Non-laminated (clear) 2 7 13 12 18 3 4 5 1 3 6 2 Laminated % of interpretable days 14.3 23.7 54.8 56.4 50.7 63.2 38.4 44.4 77.8 71.4 47.5 50.0 Laminated % of cloudy interpretable days 20.0 29.0 63.8 66.7 67.9 68.6 45.5 61.5 82.3 80.0 55.9 58.3~~

~~The sky scene classification is plotted monthly in Fig. ??, and the monthly values for all years combined are given in Table ??, to explore the distribution~~ knots. Lidar maintenance must be carried out, usually in February and/or October/November, leading to further downtime. Therefore, the "No Measurements" category is data missing not-at-random. The monthly distribution plots are provided here more as a source of context for the yearly plots than as a study of the variation in occurence frequency of laminated clouds throughout the year. ~~Laminated clouds can and do occur at all times of year. Indeed, February 2016 is the only measured month in 3.5 years that shows no laminations, and that particular February there were only 4 interpretable daysmeasured.~~

~~Monthly detection rates~~ With the unique exception of August 2016 (which only had 2 measured days), all months with any CRL measurements at all, between 2016-2019, contained at least one detection of laminated clouds~~are seen in Fig. ??. We can see the number of laminated cloud days which were definitively detected in each month. The true occurence frequency of laminated clouds is therefore likely to be higher as measurements were not made on every day of each month, and not all measured days were interpretable - therefore this is a minimum number understood to exist in the atmosphere at Eureka. March, April, and May have definitive detections of laminated clouds on 25 % to >~~.

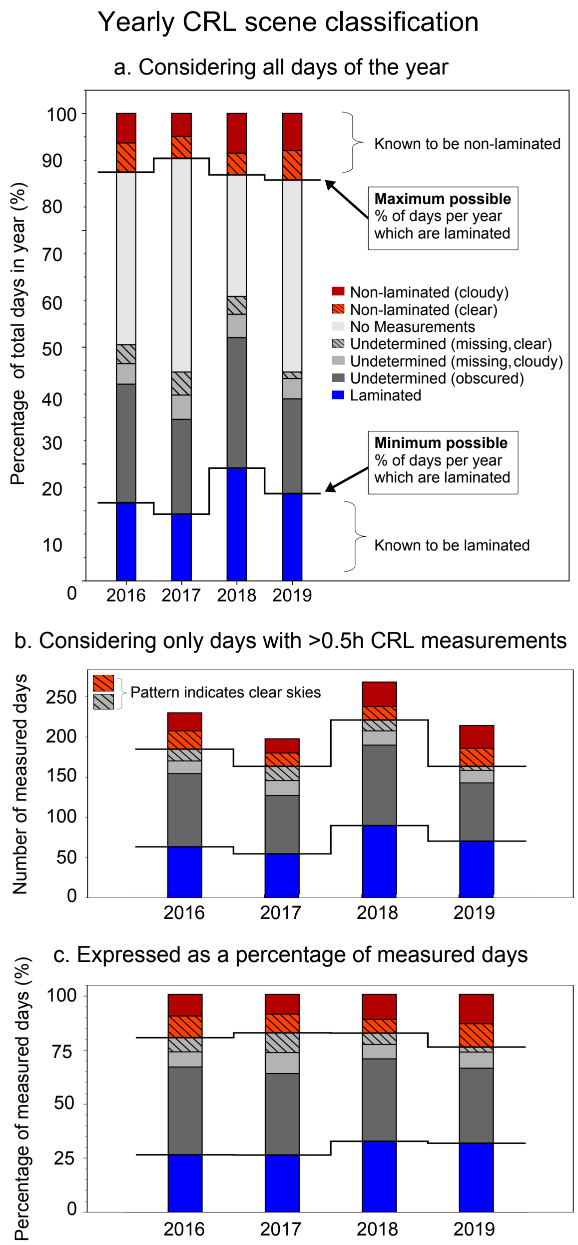


Figure 4. CRL sky scene classifications for each year. All days of each year are represented in panel a. Known-laminated days (Laminated; blue) are at the bottom of the plot. The thick black line directly above the blue bars indicates the lowest possible percentage of days per year which may hold laminated clouds. Known-non-laminated days (red for cloudy; orange with pattern for clear skies) are at the top of the plot. The thick black line directly below these segments indicates the maximum possible percentage of days per year which may hold laminated clouds. The centre portions of the plot contain the undetermined categories of data (shades of grey). Panels b and c consider only days with at least 0.5 h of CRL measurements (i.e. lightest grey "No Measurements" is excluded). Patterned orange and medium grey bars indicate clear sky days.

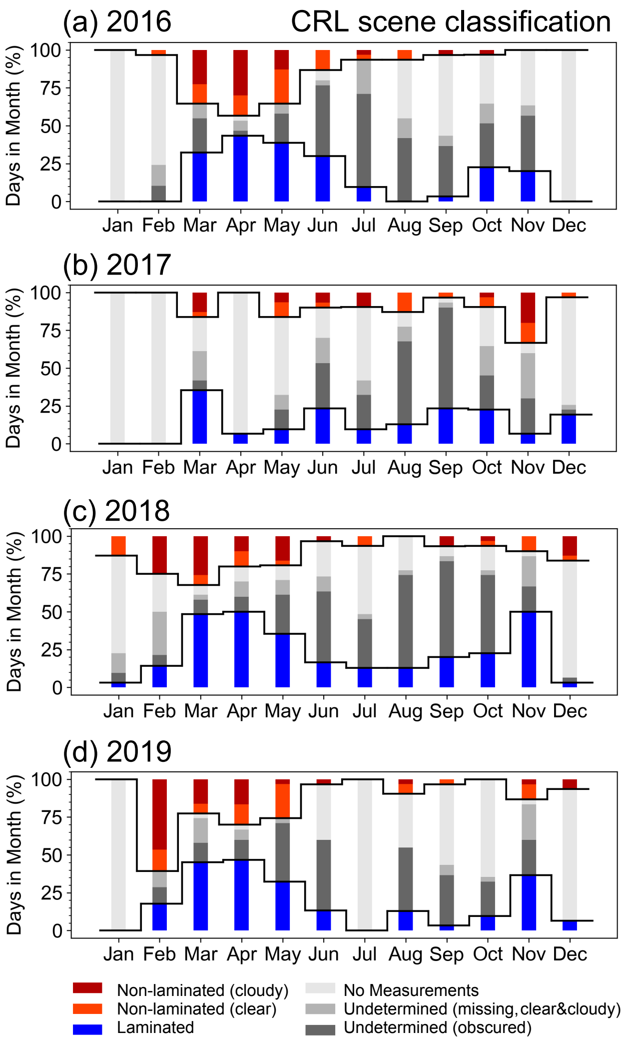


Figure 5. Monthly bar charts for all years indicating the distribution of laminated clouds and other CRL sky scenes throughout the year. The Undetermined (missing) cloudy and clear categories have been combined together for these plots.

The strongest conclusions we are able to draw happen in the spring, when years 2016, 2018, and 2019 have excellent measurement coverage. Not only was CRL operating for more than 28 days per month, but most of these days had 24 h x 5 km sky scenes which were fully interpretable as Laminated, Non-laminated (cloudy) or Non-laminated (clear). Few days during these times of year had measurements which had Undetermined classifications. For the best measurement months, laminated clouds occur on between 50 to 75 % of all days~~of each month. October and November show similar detection rates. June , July, August and September, as well as any Decembers, Januaries, and Februaries which have more than a couple of measurement days , show somewhat lower numbers of detections, generally 5 % to 20 % of all days of the month.~~ .

June and July generally have measurements on more than half of the days per month, but most of these days result in Undetermined categorizations. Therefore we cannot draw strong conclusions for these months.

~~Removing the effect of the number of measurement days, we find that relative detection rates for laminated clouds vary between 14 % and 78 % of all interpretable days, and between~~ August-October each year contain many cloudy days which obscure parts of the sky scene at higher altitudes. For these months, we have positive lamination detections which set an observational floor of about 20%~~and 82 % of all cloudy interpretable days , depending on the month~~, even assuming all of the Undetermined days to be truly non-laminated in the atmosphere.

~~Considering all interpretable measured days, January and February have the fewest days with laminated clouds, at 14.0 %~~ November shows results similar to the springtime, with up to 30 to 50 % of days having positive lamination identifications. December and January have so few CRL measurements as to be uninterpretable for this study. February 2019 has good coverage, and ~~23.0 % respectively. July and August have about double as many detections, at about 40 %. November, December, and May show yet slightly higher rates, exhibiting laminated clouds on about 50~~ laminations on about 25 % of all ~~interpretable measured days. March and April are the first months for which any measured interpretable day is more likely than not to show laminated clouds; they show about 55 % each. In June, the frequency increases by another 10 % to 63.2 %. September and October show the highest values of the year, between 70 % and 80 % occurence frequency; during this~~ days. February 2016, 2017 and 2018 however do not have sufficient measurement days to conclude whether this is a general feature of February at Eureka, or whether 2019 is somehow different.

The 2017 dataset has fewer fully interpretable days than any other year in the study. It is also missing long series of data in the springtime months (e.g. April, with only 2 measurements days). While the measurements we have for 2017 do not contradict the overall conclusions we draw from 2016, 2018, and 2019, they are not on their own strong enough to explore in detail.

Overall, laminations are present throughout the year. Most examples have been identified in the spring and late fall, but they are not absent at any time of year~~there are laminated clouds on about three-quarters of all fully interpretable measured days~~. Therefore, we conclude that laminations are a persistent feature of the atmosphere at Eureka.

~~The values when considering only cloudy interpretable days are uniformly larger, by a factor of 1.1 to 1.4, than the values when clear interpretable days are included. Again, January and February have the lowest detection rates for laminated clouds, representing approximately 20 % and 30 % of all cloudy interpretable days , respectively and July has the next higher value at 45 %. November and December both have occurance frequencies greater than half, above 55 %each. March, April, May,~~

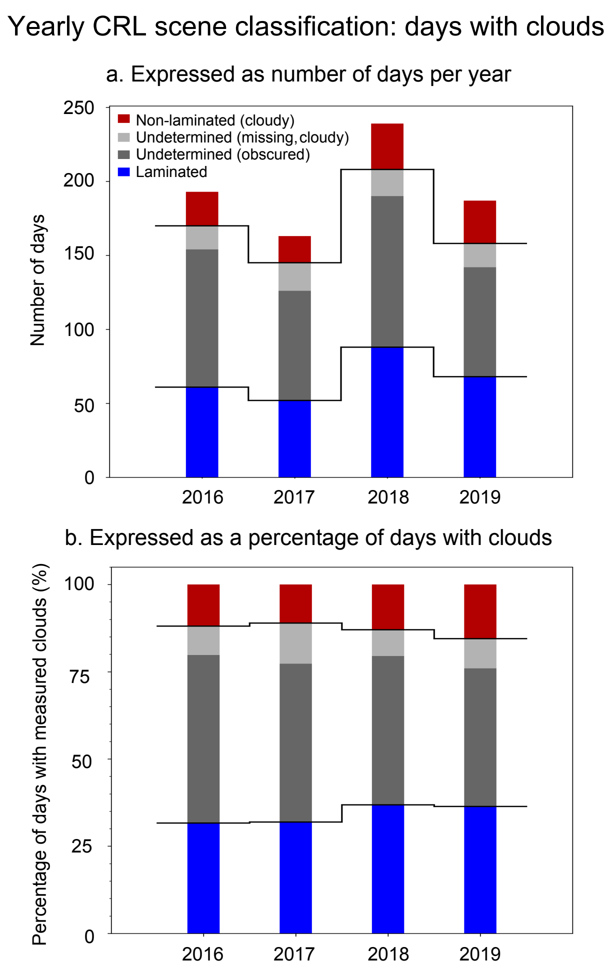


Figure 6. Yearly bar charts for all years, only including days with > 0.5 h continuously of either clouds with high optical depth , or clouds 250 m in vertical extent, which are above 250 m altitude.

~~June, and August all have values between 60 % and 70 %. September and October have the highest relative frequencies when considering only cloudy interpretable days , at over 80 %each.~~

4 Results for Investigation B: Fraction of days with clouds which are laminated

Figure 6 retains only days which contain at least some cloud, according to the classification criteria in Section 2.1.1. These days are not necessarily more cloudy than clear; they only require a cloud be present which is big enough, and present for long enough, that if it were laminated, the laminations could be detected.

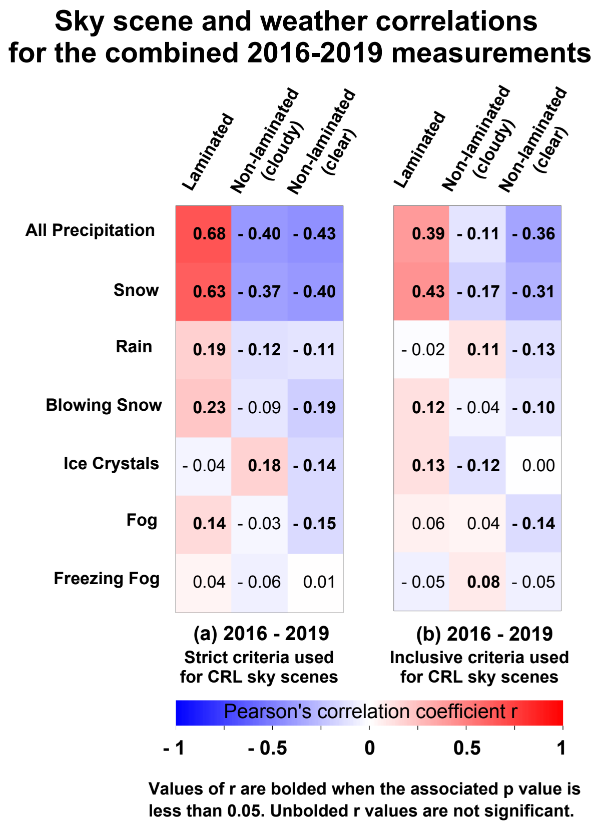


Figure 7. Correlation for 2016-2019 combined between Laminated, Non-laminated (cloudy), and Non-laminated (clear) skies from CRL and weather categories from ECCC. Pearson's r correlation coefficient is plotted in colour with each value identified. Red indicates a strong positive correlation, white indicates no correlation, and blue indicates a strong negative correlation. Values in bold are significant at 2σ. Panel (a) uses strict criteria for including days in the CRL Non-laminated categories; Panel (b) includes Undetermined days with the Non-laminated data.

In fig. 6a, the total height of each bar gives the number of cloudy days per year. The black line above the blue bar segments gives the minimum possible number of laminated cloud days per year: 67 ± 15 (34 ± 3 %). The black line below the red bar segments gives the maximum possible number of laminated cloud days per year: 170 ± 27 (87 ± 2 %).

5 Results for Investigation ~~B~~C: Correlation of laminations with weather

5.1 ~~CRL cloud lamination - ECCC weather correlation results~~

~~Considering only the three fully interpretable categories, laminated, non-laminated cloudy, and non-laminated clear, there were a total of 128, 91, 153, and 97 measurement days for 2016, 2017, 2018 and 2019 respectively, to use in the comparisons with~~

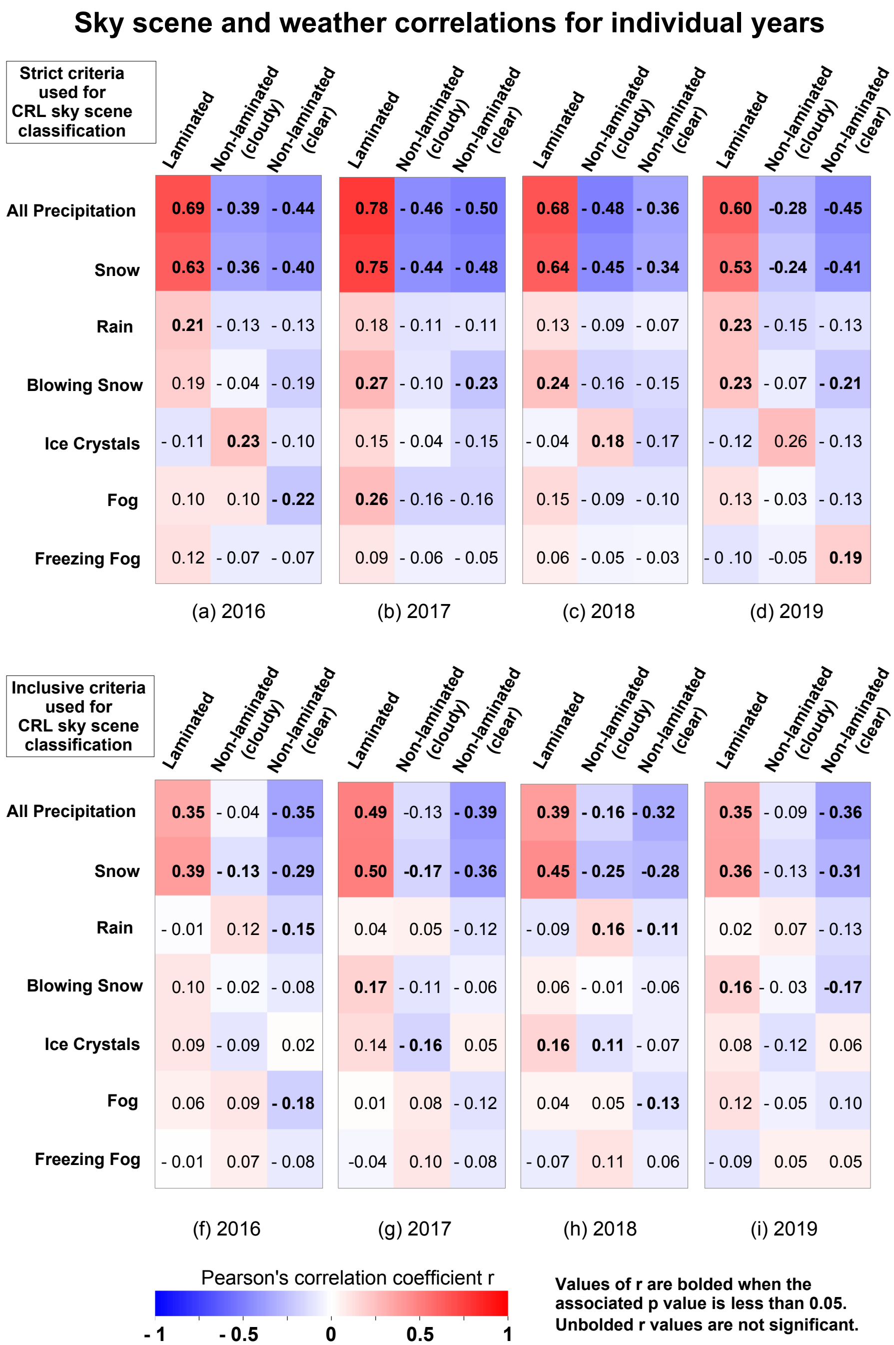


Figure 8. Correlation between CRL sky scenes and ECCC weather categories for individual years. a,b,c,d follow strict criteria, and e,f,g,h follow inclusive criteria, as for Fig. 7.

~~the 8~~ For investigation C, days with no CRL measurements (“No Measurements”) were excluded. Laminated, Non-laminated (cloudy), and Non-laminated (clear) days were compared with each of the seven categories of ECCC weather data.

The Pearson’s r correlation values were calculated ~~for each of the combinations discussed in~~ as described Sec. 2.4. ~~The correlation results are provided in Fig. ??.~~ Correlation scores can vary between $r = -1$ (complete anti-correlation) and $r = 1$ (complete positive correlation). In Fig. ~~??~~7, stronger correlations are highlighted with darker shades of red or blue and significatant values of r are in bold.

~~Correlation between Laminated, Non-laminated (cloudy), and Non-laminated (clear) skies from CRL and weather categories from ECCC. Pearson’s r correlation coefficient is plotted in colour with each value identified. Red indicates a strong positive correlation, white indicates no correlation, and blue indicates a strong negative correlation. Values in bold are significant at~~ ~~2σ.~~ The correlation plots in Fig. 7 give the results for 2016-2019 combined. The left panel (a) shows the version using the strict criteria: Laminated, Non-laminated (cloudy) and Non-laminated (clear) all have their definitions as described in Section 2.2. No Undetermined days are included in this panel.

~~In all years, the highest correlation values were between laminated clouds and snow. Three years, 2016, 2017, and 2018, yielded alarge correlation, with r values of~~ Laminated clouds have large positive correlations with All Precipitation (0.68) and with Snow (0.63~~, 0.67, and 0.56~~). Much smaller positive correlations are seen with Rain, Blowing Snow, and Fog. Other weather conditions did not have significant correlations with laminated clouds. Non-laminated cloudy days were negatively correlated, with medium strength, with All Precipitation (-0.40) and with Snow (-0.37). Small correlations were seen with Rain (negative) and ~~2019 yielded a medium correlation of 0.42, however, we have yet to include end of year measurements in this total. Snow was significantly negatively correlated with non-laminated cloudy and clear sky scenes in all years, with medium negative correlation values~~Ice Crystals (positive).

~~Blowing snow was also positively, but weakly, correlated with laminated clouds , with r values of 0.23 for 2017 and 0.26 for 2018, the only two values which were significant. 2016~~ Clear days also showed medium negative correlations with All precipitation (-0.43) and ~~2019 show weakly positive but, non-significant correlations . Blowing snow is has significant small negative correlations with non-laminated cloudy days in 2018, and with non-laminated clear days in 2019.~~

~~The combined All Snow category produces correlations which are much weaker (in 2016), slightly stronger (in 2017) , and slightly weaker (in 2018 and 2019)than the correlation with snow alone. All Snow is likewise negatively correlated with non-laminated cloudy and clear days , with small to medium correlations~~with Snow (-0.40). Small negative correlations were recorded with Rain, Blowing Snow, Ice Crystals, and Fog.

~~The combined category with all precipitation (snow and rain together) retains a significant positive, and medium-to-strong, correlation of 0.67, 0.7, 0.58 and 0.46 for each year. This combined value which is no doubt dominated by the high number of snow days as compared to rain days, is nonetheless higher in each case than the correlation value for snow alone.~~

~~Rain displayed correlations of about 0.2 for each year, but this correlation was only significant for 2016; this insignificant correlation is likely due to the low number of rainy days at Eureka which do not also display low altitude clouds.~~

~~Ice crystals and freezing fog displayed no significant correlations for any year. Foghad a significant positive correlation with laminated cloudy days in 2017.~~

The ~~correlation plots of Fig. ?? provide clear evidence of the relationship between snow and laminated versus non-laminated clouds. A more intuitive way to explore this result is to examine the relative occurance frequencies of each combination. Table ?? in Appendix A gives the number and percent of laminated, non-laminated cloudy, and non-laminated clear days on which each type of weather occurred for at least 1 h . Combined all-year values are given in Figure ?? and Table ?? for combinations which have significant Pearson's r correlation values in at least one year.~~

~~Percent of days for which each type of weather was reported for at least 1 h, for each of the three fully interpretable sky scene categories. Bars show results for all years 2016 - 2019 combined, as in Table ??. Points are data from individual years, as in Table ??, coloured according to correlation significance in Fig. ??. Black points show significant correlation between the sky scene classification and the weather for that year, and grey points show no significant correlation.~~

~~Number of all fully interpretable days for which each type of weather was reported for at least 1h, with percentage in brackets. All years 2016 - 2019 combined. Only weather with at least one significant correlation (Fig. ??) are included. See Table ?? for individual years and remaining weather categories.~~ ~~Laminated~~ right panel (b) has more inclusive criteria for the Non-laminated ~~Cloudy~~ categories. Effectively, all Undetermined days which had at least 0.5 h of measurements are here included in Non-laminated ~~Clear % % % Number of interpretable days N = 243 N = 158 N = 76 All Precipitation 173 (71 %) 24 (15 %) 1 (1 %) All Snow 170 (70 %) 33 (21 %) 2 (3 %)Snow 161 (66 %)22 (14 %) 1 (1 %) Blowing Snow 55 (23 %)19 (12 %) 2 (3 %) Fog 49 (20 %)17 (11 %) 5 (7 %) Rain 18 (7 %) 2~~ categories. Thus, Non-laminated (~~1 %) 0 (0 %)~~ cloudy) additionally includes: Undetermined (missing) days which contain clouds, and all Undetermined (obscured) days, since these are by definition also cloudy. Non-laminated (clear) additionally includes: Undetermined (missing) days which are clear.

~~Precipitating snow occurs about 5 times more often on days with laminated clouds compared to days with non-laminated clouds. Rain occurs 7 times as often. Blowing snow and fog each occur about twice as often on laminated cloud days. The details are as follows.~~

~~All Precipitation,which includes rain and precipitating snow,is 4.7 times more likely to occur on laminated cloudy days than it is on non-laminated cloudy days (71 % and 15 % occurence frequency,respectively). Precipitating snow,with 183 measured days,dominates this effect,and is itself 4.7 times more likely to occur on laminated cloudy days (66 % occurence frequency) than it is on non-laminated cloudy days (14 % occurence frequency).~~

~~The contribution of rain to the All Precipitation category is small: only 20 measured days. This small number of rain days is also responsible for the insignificant correlation r values in Fig. ??. Nevertheless, the relative occurence frequency values for rain remain interesting and would benefit from more study once further years' data are available. Rain occurs 7 times more often during laminated cloudy days (7 %) than it does during non-laminated cloudy days (~~Under the inclusive criteria, the overall pattern of results is the same as for the strict criteria. Laminations are still most strongly correlated with All Precipitation (0.39), which is dominated by Snow (0.43), and more weakly correlated with other weather categories. Non-laminated (cloudy) shows small negative correlations with All Precipitation (-0.11) and with Snow (-0.17), and Non-laminated (clear) shows medium negative correlations with All Precipitation (-0.36) and with Snow (-0.31). The correlation strengths for the inclusive case are smaller in all cases than for the strict case, which makes sense given our selection criteria. As for the strict case, the correlations between laminated clouds and snow, in particular, and laminated clouds and all precipitation, more generally, are both (1) stronger and (2) positive as compared to the correlations between Non-laminated categories and such weather, which is (1~~%; only 2 days over the entire 3.5 year study period).~~) weaker, and (2) negative.

~~Considering the All Snow category (precipitating and blowing), laminated days (70 % occurence frequency)are 3.3 times more likely to display any type of snow than non-laminated cloudy days are (21 % occurence frequency). During the study period, there were similar numbers of non-laminated cloudy days having blowing snow (19 days) and precipitating snow (22 days),but the totals are vastly different for laminated days: 55 blowing snow days,compared to 161 precipitating snow days. Therefore,precipitating snow is primarily responsible for the correlations in the All Snow category as well. Blowing snow occurs twice as often on laminated cloudy days (23 %)as it does on non-laminated cloudy days (12 %), which is an effect less than half the size of that for precipitating snow.~~ Figure 8 gives the same kinds of correlation plots separated out by year. The results show the same pattern year by year as we find for the combined-years calculations. Panels a,b,c,d contain the strict criteria. Panels e,f,g,h have the inclusive criteria. An identical pattern is observed to that in Fig. 7: The strongest positive correlations are between laminated clouds and All Precipitation and Snow. Negative correlations are between all Non-laminated categories and All Precipitation and Snow. Other weather categories have some significant values, all of these other correlation values are smaller in amplitude than the All Precipitation and Snow already mentioned.

~~Fog showed significant correlation in 2017, with an r value larger than that found for the significant 2016 correlation for rain. However, while rain showed a 7-fold difference in occurance frequency between laminated and non-laminated cloudy days, fog shows only a 2-fold difference (20 % versus 11 %), which is a result more akin to that of blowing snow~~For the individual years, particularly for the more inclusive criteria version (e,f,g,h), there are more insignificant correlation results than there are for the strict version (a,b,c,d) and for the combined-years versions (a and b). Nevertheless, all years, in every test, have results which support the overall pattern observed in Fig 7.

6 Discussion

6.1 Discussion for Investigation A

Investigation A seeks to quantify the laminated clouds in the Arctic atmosphere: How often do the laminated clouds occur, and are they therefore likely to have an important or significant effect on the overall state of the atmosphere at Eureka?

The finding that laminated clouds occur on an annual average a minimum of ~~70 daysper year, which accounts one-fifth of the year,~~ about 18 % of all days, indicates that laminated clouds do occur with sufficient frequency that they are relevant to our overall understanding of the atmospheric conditions. This could be a small, but frequent, perturbation, or its impact may be much larger; this result is sufficient motivation to continue further studies. This minimum occurrence frequency is found despite a relatively high number of unmeasured days per year, and an additional number of days which are not fully interpretable by the criteria laid out in Section 2.2. It is almost a certainty that the true occurence frequency of laminated clouds at Eureka is ~~much~~ higher - and thus that they have ~~an even~~ a stronger impact on the atmosphere than might be estimated using the value of ~~70 days per year. These laminated clouds are not stochastic, infrequent features - rather, they are part of the general situation.~~

~~More importantly for cloud-specific studies, approximately 50 % to 60~~ calculated here, with the maximum possible occurence frequency being 88 %. Approximately 29 % to 80 % of all fully interpretable days, cloudy and clear, exhibit laminated clouds. ~~Therefore, they are present on more than half of all measured days. Further, any fully interpretable cloudy day is much more likely than not to exhibit laminated clouds, with a relative occurence frequency of approximately 60 % to 70 %. This is a finding that cannot be ignored when probing the microphysical processes and the dynamics within clouds between 0 and 5 km at Eureka~~These laminated clouds are not stochastic, infrequent features - rather, they are part of the general situation.

~~Regarding the distribution~~ The monthly examination of laminated clouds ~~throughout the year, it is expected that the results are~~ is primarily useful for context, rather than for detailed statistical monthly interpretations. The results are highly influenced by the small number of measurements made during some months.

March, April, and May have the highest number of measured days, principally because of the ACE/OSIRIS Arctic Validation Campaign which occurs annually during polar sunrise (see for example Kerzenmacher et al. (2005), Adams et al. (2012), Griffin et al. (2017) and references therein), and measurements tend to be easily continued following the campaign each year. Further, these months tend to have very few closures longer than 1 h (because there were few days with high winds, rain, etc., which could damage the lidar if it were to attempt measurements), so we can be confident that CRL is getting an accurate picture of the sky. In these three months, laminated clouds are measured on ~~about~~ between 50 % ~~of all interpretable days, and on more than 50~~ to 75 % of all ~~cloudy interpretable~~ days. This is a clear indication that laminations in Arctic ~~mixed-phase~~ clouds at Eureka are an integral component of the atmosphere during the spring season.

Summer months, June, July, August, and September, have frequent fog and cloud at low altitudes which ~~obscures~~ obscure the sky scene above~~, as determined by this study. (Shupe et al. (2011) notes low level clouds on average 40 % of the time, and 20 % of the time in summer)~~. These obscuring scenes occur on at least 55 % of all summer days, and on 80 % of the measured summer days. The whole year has obscured scenes on at least 37 % of days, and on 59 % of the measured days. Laminated days are included in these totals. 43 % of all summer days are in the Undetermined (obscured) category. If there are hidden laminated clouds above the optically thick fog and clouds, we may be ~~severely~~ under-counting lamination events especially during summer. ~~Even so, of the fully-interpretable days in these months, there is a better than 50 % chance of seeing laminated clouds. Therefore, we expect that laminated clouds may form an even larger component of the atmosphere at Eureka during summer than the values measured here are capable of showing.~~

October and November generally display more laminated than non-laminated clouds on interpretable days, and display laminated clouds on at least ~~30~~ 20 % of all days of the month (measured or not).

December, January, and February each year have zero to few measured days for CRL because of funding and operational constraints of the Polar Environment Atmospheric Research Laboratory. Therefore, although the ~~“~~percent of days with laminations ~~”~~ in Fig. ~~??~~ 5 is a small number, it is based on so few measurements that it is not yet a particularly significant finding. Better estimates of the mothly laminated cloud frequency would be possible with increased funding to operate CRL during the December to February period each year.

Cloud laminations seem to be a ubiquitous feature of the lower troposphere at Eureka, and the 3.5 studied years are very similar to each other, so we infer that 3.5 years of measurements is of ample duration to act as a case study when making more detailed investigations as to the nature of the laminations.

6.2 Discussion for Investigation B

~~Prior to the correlation analysis, we were unsure whether snow, blowing snow, or both together, would be correlated with laminated cloudy days. The All Snow category was included in this study due to a practical aspect of weather observation at Eureka station, which may allow the Snow and Blowing Snow categories to become somewhat conflated: The weather conditions (snow, blowing snow, ice crystals etc.) are reported using observations made at EurekaWeather Station, at 10 m above sea level. The windspeeds are recorded at the airport runway, which is 1.8 km to the Northeast, and 73 m higher in elevation, than the weather station's instrument compound. Due to ECCC's reporting criteria, blowing snow is not able to be reported when the windspeed is less than a minimum value. There is the possibility of a confounding variable in the blowing snow category arising from local wind speed. Note that CRL lidar is located 180 m to the Northwest of the weather station's instrument compound. McCullough et al. (2019) established no relationship between laminated clouds and wind speed. Changes in the reporting methods may account for some of the relative increase in the number of blowing snow cases year by year. Therefore, the All Snow category was included in the study, to group these two cases together, in addition to studying each separately. Blowing snow is often reported on days which also report snow, so sometimes the All Snow category will be affected more than other times.~~ Importantly for cloud-specific studies, any fully interpretable cloudy day is likely to exhibit laminated clouds, with a relative occurence frequency of approximately 34 % to 87 %. This is a finding that will likely be useful when probing the microphysical processes and the dynamics within clouds between 0 and 5 km at Eureka.

~~From the results in Section ??, we see that it istruly the precipitating snow, rather than the blowing snow, which is correlated with laminated clouds~~

6.3 Discussion for Investigation C

The correlation analysis between CRL sky classifications and ECCC weather yielded the same results for both the combined 2016-2019 dataset and the individual years datasets, and for both strict and inclusive criteria used to identify Non-laminated days. Precipitating snow is the individual type of weather most strongly correlated with laminated clouds for strict criteria. The combined All Precipitation category is also strongly correlated with laminations. The correlations with these two weather types with all Non-laminated categories is, conversely, negative in sign. This is ~~also~~ consistent with the finding from McCullough et al. (2019)~~that laminations occur in a variety of wind conditions, high winds being required for blowing snow.~~. No other individual weather types have such strong correlations with the CRL scene types tested.

McCullough et al. (2019) made a preliminary report of several cases of coincident laminated clouds and rain, however the more quantitative analysis coving the full ~~3.5~~ 4 year period indicates ~~only a small positive correlation with rain~~that only 2016 and 2019 had any significant correlations of rain with laminated clouds, and these were small positive correlations only significant when using the strict criteria for classification. Rain has more than one formation mechanism in clouds. Raindrops can form directly from water vapour (condensing droplets, conceivably from convective clouds with vertical mixing, in which we would expect no persistent laminations) or can form indirectly, from melting snowflakes (possibly from laminated clouds, which we have shown to be strongly correlated with precipitating snow). This confounding variable may contribute to the ~~weak~~ small correlation of rain with cloud laminations in some years. Perhaps only certain kinds of raindrops which have formed via specific processes are correlated with laminated clouds. Adding more years' data into this study might reveal more significant small correlations of rain with laminated clouds, or rule them out. This same discussion can be applied to the All Precipitation category~~, already discussed - it~~. It makes sense that if only some kinds of rain are correlated with laminations, that the All Precipitation category ~~will~~ may be less well correlated with laminations than the Snow category is, in some circumstances. Certainly, the ~~stronger~~ larger correlation with snow is enough to explain many instances of cloud laminations in cold conditions.

Snow and rain are formed in clouds, so it is not surprising that these forms of precipitation have significant negative correlation with clear/cloud-free sky conditions. More interestingly, snow is also significantly negatively correlated with Non-laminated cloudy conditions. Precipitating snow is ~~5 times~~ more likely to occur on a cloudy day if the clouds exhibit laminations than if the clouds are non-laminated. Rain is ~~7 times~~ also more likely if the clouds are laminated, compared to if they are not, but to a much lesser degree. This points to formation mechanisms of snow, and perhaps rain as well, in relation to cloud appearance in high resolution lidar data. This contrast in correlation values between laminated and non-laminated clouds, in otherwise identical sky conditions (fully sensed up to 5 km for 24 h, with clouds visible), is a key result of this ~~paper~~analysis: The precipitating snow is correlated with laminated clouds, and is negatively correlated with non-laminated clouds. This finding leads to interesting questions regarding the types of the clouds that the laminations occupy. McCullough et al. (2019) demonstrated with depolarization measurements that many of the laminated clouds are mixed-phase clouds.

Blowing snow has significant small correlations with CRL sky scene classifications in three of the years studied, but these correlations are all smaller the medium and large correlations for the Snow and All Precipitation categories. Therefore, we conclude that while measuring instances of precipitating snow is likely important for understanding laminated clouds, blowing snow is not likewise a necessary condition for study. One practical aspect of weather observation at Eureka station may allow the Snow and Blowing Snow categories to become somewhat conflated: The weather conditions (snow, blowing snow, ice crystals etc.) are reported using observations made at Eureka Weather Station, at 10 m above sea level. The windspeeds are recorded at the airport runway, which is 1.8 km to the Northeast, and 73 m higher in elevation, than the weather station's instrument compound. Due to ECCC's reporting criteria, blowing snow is not able to be reported when the windspeed is less than a minimum value. There is the possibility of a confounding variable in the blowing snow category arising from local wind speed. Note that CRL lidar is located 180 m to the Northwest of the weather station's instrument compound. McCullough et al. (2019) established no relationship between laminated clouds and wind speed. Changes in the reporting methods may account for some of the relative increase in the number of blowing snow cases year by year.

Ice Crystals, Fog, and Freezing Fog show correlations which are only significant for some years with the CRL sky scenes. Ice Crystals are better correlated with Non-laminated (cloudy) than they are with Laminated skies; perhaps this is because of the types of clouds included in the Non-laminated (cloudy) category. This category, even under the strict criteria named here, is actually quite inclusive in terms of what kinds of clouds are required for "cloudy", and how small they can be. Future studies may wish to further restrict the qualifications that a particular cloud, or day, must reach in order for the day to be classified as "cloudy".

6.4 Horizontal variability of mixed phase clouds

One interesting possibility to follow up on is the horizontal variability within mixed phase clouds. It is possible that the laminations ~~, which arises~~ (as a term describing visual features of lidar image plots~~,~~) may in fact arise from ~~a geophysical feature which is in fact~~ geophysical patches or clusters of liquid droplets or ice crystals, rather than a contiguous ~~layer~~layers. As the feature passes by the lidar during the ~~1 min~~ one minute integration time, this could have the effect of spreading out the horizontal extent of the feature from the perspective of the lidar. A patch of hydrometeors which is present for part of the ~~1 min~~ one minute time bin is displayed as present during that entire ~~1 min~~one minute. Therefore, discrete horizontal features may appear connected in the lidar data. For CRL, any gaps smaller than approximately 1 m in horizontal extent will not be resolvable at 5 km altitude from the lidar, due to the divergence of the laser beam, even for a single laser shot. When integrating for 1 min, at the 2 to 15 m/s windspeeds found at 5 km in McCullough et al. (2019), gaps smaller than approximately 120 to 900 m become undetectable.

The small scale horizontal variability of clouds has been shown by García et al. (2012) and more recently by Ruiz-Donoso et al. (2019) to be an important consideration when calculating the total upwelling and downwelling radiation budgets. Therefore, a 3-D approach will eventually be necessary to understand the complete impact of laminated clouds on the radiation budget.

The Wegener-Bergeron-Findeisen (WBF) process, whereby ice crystals grow using vapour supplied from liquid droplets in the same cloud, is one example of a process which can result in patchy features (Tan and Storelvmo, 2016). The entire cloud does not glaciate at a uniform rate. Instead, clusters of ice particles and clusters of liquid droplets are formed. The horizontal size of these clusters can be as large as a few kilometers (Korolev et al., 2003; Field et al., 2004) or, in the Arctic, as small as 10 m (Chylek and Borel, 2004). Global circulation models which inappropriately assign a homogenous mixture of ice and liquid throughout an entire cloud volume can experience a WBF process which is too efficient, and lasts for timescales six orders of magnitude shorter than those observed (Tan and Storelvmo, 2016). With our vertically-resolved measurements, we access information about one dimensional size of this patchy process, but, as described above, CRL is insensitive to horizontal inhomogeneity smaller than ~100 - 900 m at 5 km altitude.

Combining the lidar with other instruments as was done in Ruiz-Donoso et al. (2019) would be one way to access 3-D cloud information. Combining CRL measurements with windspeed information can provide some upper limits on the horizontal spacing between laminated cloudy regions, but the zenith-pointing lidar is ~~effectively~~ essentially a 1-D tool. Therefore in this paper we have focused on the vertical information.

~~Despite the scientific motivations for considering the possibility of patches versus laminations, the results in this paper are not changed. If it is~~ If the case that the laminations are from a collection of discrete patches, the patches ~~still need to~~ should be confined to relatively contiguous, closely stacked (<~~10~~30 m thick), altitude levels for timescales of hours. Thus, we may be discussing laminations of pocket-containing and non-pocket-containing layers, rather than laminations of homogenous regions, but the laminations persist. ~~Therefore, while investigating these features at higher time resolution is interesting, the possibility that some patchy features are being interpreted as laminations does not undermine the results found in the current paper.~~

6.5 Future work

~~There is a reasonable way forward for improving the completeness of the study for Investigations A and B, should better statistics be desired.~~

Classifying each day is labour intensive. Adding a few months' worth of campaign data from 2009 through 2013 would not suffice to build up a climatology~~, so that is not a goal of this paper~~. We will nonetheless continue measurements to see whether the results here are part of a trend, and whether there is something else we did not account for in the data or interpretation, for example the total snowfall for the year.

In Section 2.2, the Undetermined categories place a tight restriction on data quality. The days for which there was only an hour or two of low-lying cloud, and no visible laminations, are all combined together in the Undetermined (obscured) category with days containing 24 h of low-lying cloud. Likewise, days missing an hour or two of data are in the same category as those missing 23 h, the Undetermined (missing~~>1 h data~~, clear/cloudy) category. For many of these days, it may be reasonable to guess, or interpolate, the sky conditions during the missing hours. When the sky has been clear for a number of hours before and after the missing data, and the winds have not changed, it is likely that the sky during the missing hours was clear, too.

In this study, as long as the laminations and a particular kind of surface weather occur on the same day, it was not necessary that the laminations occur precisely at the same time as that weather in order for the coincidence to be counted. Future studies of a subset of data could reduce the uncertainty in the results by using the hourly resolution of the ECCC data, and ~~redoing~~ reprocessing the CRL sky scene classification hourly to match. Nevertheless, the results are strong enough using the daily approach that this has not yet been necessary in order to conclude that snow, and no other meteorological condition, is the weather most strongly correlated with laminated clouds.

Further, there is a Millimeter Wavelength Cloud Radar (MMCR, Moran et al. (1998)) colocated with CRL. While it cannot detect the laminations (insufficient resolution), it can determine whether a cloud was present that could have hosted laminations. If the MMCR shows totally clear sky, then laminations are highly unlikely. Likewise, if it shows only clouds with a morphology inconsistent with laminations. Therefore, we can likely improve the statistics in this paper, and reduce the number of days falling into one to two of the "Undetermined" categories, if we loosen the data quality criteria or include insight from colocated instruments.

Given the strong results from the existing database studied in this paper (laminated clouds being ubiquitous throughout the year at Eureka; strong correlation between precipitating snow and laminated clouds), we are interested in following up on the precipitation-formation processes within these clouds. To that end, we will be selecting several representative case studies on snowing laminated cloud days to examine in detail with such measurements as lidar depolarization, radar, radiosonde, and other colocated instruments at Eureka. We are also interested to seek out results from other polar lidars to see whether the same laminated features are present at those locations as well, and how their appearance and correlations with surface weather compare to those found here at Eureka.

Different measurement methods which are able to classify individual clouds by their cloud types (e.g. mixed-phase vs. cirrus vs. other) can be used to determine what type of cloud is most frequently the host of the laminated features. A statistical study restricted to just a singular cloud type would then be possible.

7 Conclusions

Key conclusions from Investigation A: ~~Frequency of laminations:Cloud laminations are found to be a significant feature in the CRL measurements.~~ Laminations occur often at Eureka. There are laminated clouds on ~~52~~ 18 to 88 % of all ~~interpretable days, and on 62 % of interpretable cloudy days~~days. The relative frequency of laminated clouds to non-laminated clouds is generally consistent year to year, within the ~~3.5~~ four year study carried out. ~~There is a minimum average of 70 laminated cloud days detected per year, with no~~ No studied full year ~~having~~ had fewer than 52 detections~~.~~, and it is probable that the true occurence frequency of laminated clouds at Eureka is much higher.

Key conclusions from Investigation B: ~~Correlation of laminations with weather~~Between 34 and 87 % of days with any clouds which were elegible for classification as Laminated (if they were to show signs of laminations) are actually laminated.

Key conclusions from Investigation C: Precipitating snow is strongly correlated with laminated clouds, and is anti-correlated with non-laminated clouds. ~~Precipitating snow is 5 times more likely to occur on a day with laminated clouds as compared to a day with non-laminated clouds.~~ This can help constrain our understanding of the composition of, and precipitation processes within, laminated clouds.

8 Data availability

~~CRL data used in this paper~~

CRL data: A standardized set of range-scaled photocounts plots has been submitted to the data repository. A spreadsheet identifying the sky scene classification of each day is provided as supplementary material. Further CRL measurement data is available upon request from corresponding author (e.mccullough@dal.ca). ~~ECCC data~~

ECCC data is available at:

https://climate.weather.gc.ca/historical_data/search_historic_data_e.html~~. Parameters used are: StationID 53598, and station name "EurekaA". The data is available in CSV and XML format. The values used in this paper were last verified accessed 18 August 2019 from the ECCC website~~; Last verified 6 June 2020. Search parameter used is: Station Name "Eureka".

The three links to Station "Eureka A" are all applicable to this project. They link to sites with different Climate ID numbers assigned Meteorological Service of Canada, and the weather observations for these sites are all made near the CRL lidar. New Climate ID numbers are assigned when stations discontinue observations, even if other observations continue at the same location, with the same site name.

~~Note that on some of the data pages~~ First link: Climate ID 2401203. Data from 2016 Feb 22 at 15:00 UTC through current date in June 2020. 2401203 is located at longitude: -85.81, latitude: 79.99.

Second link: Climate ID 2401208. No early Feb 2016 data, but also no weather recorded for most/all days. 2401208 is located at longitude: -85.81, latitude: 79.99; not used for this paper.

Third link: Climate ID 2401200. Data from Jan 2016 through Feb 25 at 12:00 UTC. More hours record weather, but each record holds fewer values (e.g. ~~for the 2016 data), there are three stations listed: The first two are both named “Eureka A”, and the third is “EurekaClimate”. The second link to “Eureka A” is the correct path to the 2016 data used in this paper. 2017-2019 dataare accessed in a similar manner.~~ the version from 2401203 may say “Blowing Snow, Fog” and have an entry only every 3 h, while 2401200 records something every hour, but for that particular entry lists only “Blowing Snow”. 2401200 is located at longitude: -85.93, latitude: 79.98.

Since the bulk of the 2016-2019 ECCC weather data set was recorded at station 2401203, we have used those values preferentially for this paper for dates in Feb 2016 for which more than one record is available.

Until early 2016, both weather observations and temperature, etc, were all recorded at or in close proximity to the Weather Station building at Eureka. After that, some equipment moved up to the airport runway, which is 1.8 km to the Northeast, and 73 m higher in elevation, but the weather observations are still made at the Weather Station. The Weather Station is closer in both distance and altitude to the CRL lidar.

There is a mechanism for downloading monthly CSV files of hourly observations, and these are the data used for this project.

If we wanted to use the ground temperatures, etc, as well, it would be best to use: 2401203 before mid-Feb 2016 for both temperatures, humidity, etc, AND weather reports; 2401208 after mid-Feb 2016 for temperatures, humidity, etc; 2401200 after mid-Feb 2016 for weather reports only.

See https://climate.weather.gc.ca/glossary_e.html#climate_ID for further information about interpreting the historical climate data.

Appendix A: Supplementary tables about Weather~~and interpretable CRL days~~

Table 2. Number of ~~all fully interpretable~~ days ~~for~~ during 2016-2019 on which each type of ECCC weather condition was reported for at least ~~1h for a~~1 hour. ~~2016, b. 2017, c. 2018, and d. 2019. Note that in 2016, blowing snow occurred only on~~ The second column removes any days ~~when there was also precipitating snow,~~ for which ~~is why the number of All Snow days matches the number of Snow days, despite the 15 days in the Blowing Snow category~~there were no CRL measurements.

ECCC reported weather name	
~~a. 2016~~ Snow	
~~All Precip~~ Snow Grains	
~~All Snow 39 (64 %) 7 (18 %) 1 (4 %)~~ Snow Pellets	
~~Blowing Snow~~ Snow Showers	
~~Fog~~ Moderate Snow	
~~Rain~~ Moderate Snow Grains	
~~Ice Crystals~~ Blowing Snow	
~~Freezing Fog~~ Rain	
~~Ice Pellets~~ Rain Showers	
~~c. 2018~~ Moderate Rain	
~~All Precip~~ Drizzle	~~60 (71 %)~~
~~Blowing Snow~~ Freezing Drizzle	
~~Fog 16 (19 %) 6 (12 %) 0 (0 %)~~ Freezing Rain	
Ice Crystals	
Fog	
Freezing Fog	
~~Ice Pellets~~ Smoke	
~~Snow Grains~~ Haze	
Blowing Sand	~~Laminated Non-laminated Non-laminated Cloudy Clear b. 2017 N = 52 N = 24 N = 15 All Preci~~
~~Rain~~ Dust	
~~Freezing Fog~~ Ice Pellet Showers	
Ice Pellets	
~~d. 2019~~ Clear	
~~All Precip~~ Mainly Clear	
~~All Snow~~ Cloudy	
~~Snow~~ Mostly Cloudy	
~~Blowing Snow~~ No Value	

Author contributions. E. M. McCullough: Operation and maintenance of the lidar. Data analysis. Writing of analysis MATLAB code. Manuscript preparation. R. Wing: Contributions to statistical interpretations. Contribution to manuscript preparation. J. R. Drummond: Deputy Principal Investigator of PEARL laboratory. Contribution to manuscript preparation.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This research is currently supported by the Natural Sciences and Engineering Research Council, Environment and Climate Change Canada and the Canadian Space Agency.

PEARL has been supported by a large number of agencies whose support is gratefully acknowledged: The Canadian Foundation for Innovation; the Ontario Innovation Trust; the (Ontario) Ministry of Research and Innovation; the Nova Scotia Research and Innovation Trust; the Natural Sciences and Engineering Research Council; the Canadian Foundation for Climate and Atmospheric Science; Environment and Climate Change Canada (ECCC; who also provided the radiosonde data); Polar Continental Shelf Project; the Department of Indigenous and Northern Affairs Canada; and the Canadian Space Agency. This work was carried out during the Canadian Arctic ACE/OSIRIS Validation Campaigns of 2016, 2017, 2018, and 2019, which are funded by the Canadian Space Agency, Environment and Climate Change Canada, the Natural Sciences and Engineering Research Council of Canada, and the Northern Scientific Training Program. This particular project has also been supported by NSERC Discovery Grants and Northern Supplement Grants held by James R. Drummond, Robert J. Sica, and Kaley A. Walker, the NSERC CREATE Training Program in Arctic Atmospheric Science (PI: Kim Strong). Thomas J. Duck was the initial Principal Investigator of CRL lidar, and contributed helpful comments regarding early drafts of the paper.

In addition, the authors thank the following groups and individuals for their support during field campaigns at Eureka: PEARL site manager Pierre Fogal; Canadian Arctic ACE/OSIRIS Validation Campaign project lead Kaley A. Walker, CRL operators: Graeme Nott, Chris Perro, Colin P. Thackray, Jason Hopper, Shayamila Mahagammulla Gamage, Jon Doyle; Canadian Network for the Detection of Atmospheric Change (CANDAC) support scientist Alexey Tikhomirov; CANDAC operators: Mike Maurice, Peter McGovern, John Gallagher, Alexei Khmel, Paul Leowen, Ashley Harrett, Keith MacQuarrie, Oleg Mikhailov, and Matt Okraszewski; and the Eureka Weather Station staff. Thanks to members of CANDAC for their helpful discussions.

References

Adams, C., Strong, K., Batchelor, R. L., Bernath, P. F., Brohede, S., Boone, C., Degenstein, D., Daffer, W. H., Drummond, J. R., Fogal, P. F., Farahani, E., Fayt, C., Fraser, A., Goutail, F., Hendrick, F., Kolonjari, F., Lindenmaier, R., Manney, G., McElroy, C. T., McLinden, C. A., Mendonca, J., Park, J.-H., Pavlovic, B., Pazmino, A., Roth, C., Savastiouk, V., Walker, K. A., Weaver, D., and Zhao, X.: Validation of ACE and OSIRIS ozone and NO_2 measurements using ground-based instruments at 80° N, Atmospheric Measurement Techniques, 5, 927–953, 2012.

Barrett, A. I., Hogan, R. J., and Forbes, R. M.: Why are mixed-phase altocumulus clouds poorly predicted by large-scale models? Part 2. Vertical resolution sensitivity and parameterization, Journal of Geophysical Research: Atmospheres, 122, 9927–9944, 2017.

Boer, G. D., Eloranta, E., and Shupe, M.: Arctic mixed-phase stratiform cloud properties from multiple years of surface-based measurements at two high-latitude locations, Journal of the Atmospheric Sciences, 66, 2874–2887, 2009.

Bourdages, L., Duck, T. J., Lesins, G., Drummond, J. R., and Eloranta, E. W.: Physical properties of High Arctic tropospheric particles during winter, Atmospheric Chemistry and Physics, 9, 6881–6897, 2009.

Bühl, J., Seifert, P., Myagkov, A., and Ansmann, A.: Measuring ice- and liquid-water properties in mixed-phase cloud layers at the Leipzig Cloudnet station, Atmospheric Chemistry and Physics, 16, 10 609–10 620, 2016.

Cess, R., Potter, G., Blanchet, J., Boer, G. J., del Genio, A., Deque, M., Dymnikov, V., Galin, V., Gates, W., Ghan, S., Kiehl, J., Lacis, A., Le Treut, H., Li, Z.-X., Liang, X.-Z., Mcavaney, B., Meleshko, V., Mitchell, J., Morcrette, J.-J., Randall, D., Rikus, L., Roeckner, E., Royer, J., Schlese, U., Sheinin, D., Slingo, A., Sokolov, A., Taylor, K., Washington, W., Wetherald, R., Yagai, I., and Zhang, M.-H.: Intercomparison and interpretation of climate feedback processes in 19 atmospheric general circulation models, Journal of Geophysical Research, 95, 16 601–16 615, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.467.4030&rep=rep1&type=pdf, 1990.

Cess, R. D., Zhang, M. H., Ingram, W. J., Potter, G. L., Alekseev, V., Barker, H. W., Cohen-Solal, E., Colman, R. A., Dazlich, D. A., Genio, A. D. D., Dix, M. R., Dymnikov, V., Esch, M., Fowler, L. D., Fraser, J. R., Galin, V., Gates, W. L., Hack, J. J., Kiehl, J. T., Treut, H. L., Lo, K. K.-W., McAvaney, B. J., Meleshko, V. P., Morcrette, J.-J., Randall, D. A., Roeckner, E., Royer, J.-F., Schlesinger, M. E., Sporyshev, P. V., Timbal, B., Volodin, E. M., Taylor, K. E., Wang, W., and Wetherald, R. T.: Cloud feedback in atmospheric general circulation models: An update, Journal of Geophysical Research: Atmospheres, 101, 12 791–12 794, 1996.

Chylek, P. and Borel, C.: Mixed phase cloud water/ice structure from high spatial resolution satellite data, Geophysical Research Letters, 31, 1–4, 2004.

Cohen, J.: Statistical Power Analysis for the Behavioural Sciences, Lawrence Erlbaum Associates, 2nd edn., 1988.

Curry, J. A., Ebert, E. E., and Herman, G. F.: Mean and turbulence structure of the summertime Arctic cloudy boundary layer, Quarterly Journal of the Royal Meteorological Society, 114, 715–746, 1988.

Dong, X. and Mace, G. G.: Arctic Stratus Cloud Properties and Radiative Forcing Derived from Ground-Based Data Collected at Barrow, Alaska, Journal of Climate, 16, 445–461, 2003.

Field, P. R., Hogan, R. J., Brown, P. R. A., Illingworth, A. J., Choularton, T. W., Kaye, P. H., Hirst, E., and Greenaway, R.: Simultaneous radar and aircraft observations of mixed-phase cloud at the 100 m scale, Quarterly Journal of the Royal Meteorological Society, 130, 1877–1904, 2004.

Forbes, R. and Ahlgrimm, M.: On the Representation of High-Latitude Boundary Layer Mixed-Phase Cloud in the ECMWF Global Model, Monthly Weather Review, 142, 3425–3445, 2014.

García, S. G., Trautmann, T., and Venema, V.: Reduction of radiation biases by incorporating the missing cloud variability by means of downscaling techniques: a study using the 3-D MoCaRT model, Atmospheric Measurement Techniques, 5, 2261–2276, 2012.

Griffin, D., Walker, K. A., Conway, S., Kolonjari, F., Strong, K., Batchelor, R., Boone, C. D., Dan, L., Drummond, J. R., Fogal, P. F., Fu, D., Lindenmaier, R., Manney, G. L., and Weaver, D.: Multi-year comparisons of ground-based and space-borne Fourier transform spectrometers in the high Arctic between 2006 and 2013, Atmospheric Measurement Techniques, 10, 3273–3294, 2017.

Heymsfield, A. and Platt, C.: A parameterization of the particle size spectrum of ice clouds in terms of the ambiant temperature and ice water content., Journal of the Atmospheric Sciences, 41, 846–855, 1984.

Hobbs, P. and Rangno, A. L.: Microstructures of low and middle-level clouds over the Beaufort Sea, Quarterly Journal of the Royal Meteorological Society, 124, 2035–2071, 2008.

Intieri, J. M., Shupe, M. D., Uttal, T., and McCarty, B. J.: An annual cycle of Arctic cloud characteristics observed by radar and lidar at SHEBA, Journal of Geophysical Research, 107, 5–1–5–15, 2002.

Kerzenmacher, T. E., Walker, K. A., Strong, K., Berman, R., Bernath, P. F., Boone, C. D., Drummond, J. R., Fast, H., Fraser, A., MacQuarrie, K., Midwinter, C., Sung, K., McElroy, C. T., Mittermeier, R. L., Walker, J., and Wu, H.: Measurements of O3, NO2 and Temperature during the 2004 Canadian Arctic ACE Validation Campaign, Geophysical Research Letters, 32, 1–5, 2005.

Korolev, A., McFarquhar, G., Field, P., Franklin, C., Lawson, P., Wang, Z., Williams, E., Abel, S., Axisa, D., Borrmann, S., Crosier, J., Fugal, J., Krämer, M., Lohmann, U., Schlenczek, O., Schnaiter, M., and Wendisch, M.: Mixed-Phase Clouds: Progress and Challenges, Meteorological Monographs, 58, 2017.

Korolev, A. V., Isaac, G. A., Cober, S. G., Strapp, J. W., and Hallett, J.: Microphysical characterization of mixed-phase clouds, Quarterly Journal of the Royal Meteorological Society, 129, 39–65, 2003.

Luke, E. P., Kollias, P., and Shupe, M. D.: Detection of supercooled liquid in mixed-phase clouds using radar Doppler spectra, Journal of Geophysical Research, 115, 1–14, 2010.

McCullough, E. M., Sica, R. J., Drummond, J. R., Nott, G., Perro, C., Thackray, C. P., Hopper, J., Doyle, J., Duck, T. J., and Walker, K. A.: Depolarization calibration and measurements using the CANDAC Rayleigh–Mie–Raman lidar at Eureka, Canada, Atmospheric Measurement Techniques, 10, 4253–4277, doi:10.5194/amt-10-4253-2017, https://www.atmos-meas-tech.net/10/4253/2017/, 2017.

McCullough, E. M., Drummond, J. R., and Duck, T. J.: Lidar measurements of thin laminations within Arctic clouds, Atmospheric Chemistry and Physics, 19, 4595–4614, 2019.

Mioche, G., Jourdan, O., Ceccaldi, M., and Delanoë, J.: Variability of mixed-phase clouds in the Arctic with a focus on the Svalbard region: a study based on spaceborne active remote sensing, Atmospheric Chemistry and Physics, 14, 2445–2461, 2015.

Moran, K. P., Martner, B. E., Post, M. J., Kropfli, R. A., Welsh, D. C., and Widener, K. B.: An Unattended Cloud-Profiling Radar for Use in Climate Research, Bulletin of the American Meteorological Society, 79, 443–455, 1998.

Morrison, H., de Boer, G., Feingold, G., Harrington, J., Shupe, M. D., and Sulia, K.: Resilience of persistent Arctic mixed-phase clouds, Nature Geoscience, 5, 11–17, 2012.

Noel, V., Chepfer, H., Haeffelin, M., and Morille, Y.: Classification of ice crystal shapes in midlatitude ice clouds from three years of lidar observations over the Sirta observatory, Journal of the Atmospheric Sciences,, 63, 2978–2991, 2006.

Nott, G. J. and Duck, T. J.: Review lidar studies of the polar troposphere, Meteorological Applications, 18, 383 – 405, 2011.

Platt, C., Young, S., Manson, P., Patterson, G., Marsden, S., and Austin, R.: The optical properties of equatorial cirrus from observations in the ARM pilot radiation observation experiment, Journal of the Atmospheric Sciences, 55, 1977–1996, 1998.

Rambukkange, M., Verlinde, J., Eloranta, E., Luke, E., Kollias, P., and Shupe, M.: Fine-scale horizontal structure of Arctic mixed-phase clouds, in: American Meteorological Society's 12th Conference on Cloud Physics, BNL-79883-2008-CP, Madison, WI, 2006.

Ruiz-Donoso, E., Ehrlich, A., Schäfer, M., Jäkel, E., Schemann, V., Crewell, S., Mech, M., Kulla, B. S., Kliesch, L.-L., Neuber, R., and Wendisch, M.: Small-scale structure of thermodynamic phase in Arctic mixed-phase clouds observed by airborne remote sensing during a cold air outbreak and a warm air advection event, Atmospheric Chemistry and Physics Discussions, 2019, 1–31, 2019.

Sassen, K.: Lidar: range-resolved optical remote sensing of the atmosphere, chap. Polarization in lidar, no. 2 in Springer Series in Optical Sciences, Springer Science+Business Media Inc., 2005.

Schotland, R., Sassen, K., and Stone, R.: Observations by lidar of linear depolarization ratios for hydrometeors., Journal of Applied Meteorology, 10, 1011–1017, 1971.

Shupe, M., Daniel, J., de Boer, G., Eloranta, E., Kollias, P., Long, C., Luke, E., Turner, D., and Verlinde, J.: A focus on mixed-phase clouds: The status of ground-based observational methods, Bulletin of the American Meteorological Society, pp. 1549–1562, https://www.researchgate.net/profile/Pavlos_Kollias/publication/258300377_A_Focus_On_Mixed-Phase_Clouds/links/54099fa20cf2187a6a705ce6.pdf, 2008.

Shupe, M. D.: Clouds at Arctic Atmospheric Observatories. Part II: Thermodynamic Phase Characteristics, American Meteorological Society, pp. 645–661, doi:10.1175/2010JAMC2468.1, 2011.

Shupe, M. D. and Intieri, J. M.: Cloud Radiative Forcing of the Arctic Surface: The Influence of Cloud Properties, Surface Albedo, and Solar Zenith Angle, Journal of Climate, 17, 616–628, 2004.

Shupe, M. D., Walden, V. P., Eloranta, E., Uttal, T., Campbell, J. R., Starkweather, S. M., and Shiobara, M.: Clouds at Arctic Atmospheric Observatories. Part I: Occurrence and Macrophysical Properties, Journal of Applied Meteorology and Climatology, 50, 626–644, 2011.

Sun, Z. and Shine, K. P.: Parameterization of Ice Cloud Radiative Properties and Its Application to the Potential Climatic Importance of Mixed-Phase Clouds, Journal of Climate, 8, 1874–1888, 1995.

Tan, I. and Storelvmo, T.: Sensitivity study on the influence of cloud microphysical parameters on mixed-phase cloud thermodynamic phase partitioning in CAM5, Journal of the Atmospheric Sciences, 73, 709–728, 2016.

Tan, I., Storelvmo, T., and Delinka, M. D.: Observational constraints on mixed-phase clouds imply higher climate sensitivity, Science, 352, 224–227, 2019.

Turner, D. D.: Arctic Mixed-Phase Cloud Properties from AERI Lidar Observations: Algorithm and Results from SHEBA, Journal of Applied Meteorology, 44, 417–444, 2005.

Vassel, M., Ickes, L., Maturilli, M., and Hoose, C.: Classification of Arctic multilayer clouds using radiosonde and radar data in Svalbard, Atmospheric Chemistry and Physics, 19, 5111–5126, 2019.

Verlinde, J., Harrington, J. Y., McFarquhar, G. M., Yannuzzi, V. T., Avramov, A., Greenberg, S., Johnson, N., Zhang, G., Poellot, M. R., Mather, J. H., Turner, D. D., Eloranta, E. W., Zak, B. D., Prenni, A. J., Daniel, J. S., Kok, G. L., Tobin, D. C., Holz, R., Sassen, K., Spangenberg, D., Minnis, P., Tooman, T. P., Ivey, M. C., Richardson, S. J., C. P. Bahrmann, S. M., DeMott, P. J., Heymsfield, A. J., and Schofield, R.: The mixed phase Arctic cloud experiment, Bulletin of the American Meteorological Society, pp. 205–211, 2007.

Verlinde, J., Rambukkange, M. P., Clothiaux, E. E., McFarquhar, G. M., and Eloranta, E. W.: Arctic multilayered, mixed-phase cloud processes revealed in mullimeter-wave cloud radar Doppler spectra, Journal of Geophysical Research, 118, 199–13,213, 2013.

Zuidema, P., Westwater, E. R., Fairall, C., and Hazen, D.: Ship-based liquid water path estimates in marine stratocumulus, Journal of Geophysical Research: Atmospheres, 110, 2005.