

We thank the Reviewers for their suggested revisions to the manuscript. We have adjusted the scope and focus of our manuscript according to your suggestions. Both Reviewers had significant and valid concerns about our direct calculation of the cloud feedback parameter from our data, and limitations of the MIXCRA algorithm which should be included in the presentation of our results. We discuss how our revised manuscript addresses these concerns in a broad overview here and then respond to individual Reviewer comments below. Our resubmitted manuscript includes a substantial revision, consisting of the removal of figures 1, 2, 3, 4, and 8, expansion of section 3.1, and a more careful presentation of the results considering the limitations of the combination of AERI observations and the MIXCRA algorithm that we use.

In order to provide adequate context for our analyses, we explore the contents of our cloud property dataset in a comprehensive manner in an expanded version of section 3.1 (revised manuscript, Sections 3.1, 3.2, 3.3). This includes classification of all MIXCRA retrievals to put into perspective the subset of clouds that we study (revised manuscript, Figure 1) a climatological overview of all MIXCRA retrieved cloud properties (revised manuscript, Figure 2), and an investigation into the relationship between sea-ice regime and cloud properties (revised manuscript, Figure 3). We retain the cloud phase investigation from the original manuscript (Table 1).

We have removed the cloud radiative effect (CRE) and cloud feedback analyses, which includes the removal of Figures 3 and 4 from the original manuscript. Prior to any further discussion of these analyses, we would like to address a mistake in the original submission. Inadvertently, the same, incorrect, 95% confidence intervals were plotted for all feedback values in Figure 4, indicating no statistical significance to any of the slopes in the presented regressions between surface cloud radiative effect and globally averaged surface temperature anomalies. We apologize for this mistake.

In further investigation of this mistake and considering the Reviewer's comments, we have determined that the level of filtering we were originally performing on our cloud fraction anomaly timeseries resulted in a smoothed timeseries that is not representative of the original timeseries. Reducing the strength of this filter impacts the magnitudes of the resulting feedbacks in a non-negligible way and reduces the variability in the CRE that can be explained by global surface temperature variations. Additionally, the fully un-filtered cloud fraction data is unsuitable for a cloud radiative kernel (CRK) cloud feedback analysis, due to a signal that is dominated by internal variability and short timescale noise. Therefore, we have removed the CRE and cloud feedback sections of our original manuscript (original manuscript, Section 3.2 and Figures 3 and 4).

We agree that the presentation of our results in our original manuscript was not accompanied by adequate caveats surrounding the subset of clouds that we analyze. To address this, we include explicit discussions of the limitations of the MIXCRA algorithm and

often remind readers of the subset of clouds that we analyze, specifically in the revised section 3.1, particularly L281-289, L322-331, and elsewhere in the manuscript on L40-52, L60-64, L184-189, L339, L341, L357-359, L382, L409-410, L414, L428, L446, L455-457, L460-469, L470, L502, L557-558, L569-570, L585, L595, L616, L630-636, and Appendix C, among other locations throughout the manuscript. Additionally, we have further investigated the impacts of these limitations on our dataset and the conclusions that can be drawn from our data. This includes clarification on the importance of clouds with liquid water path (LWP) below a threshold of 60 gm^{-2} due to the large changes seen in their CRE with changes in their cloud properties (Appendix A of the revised manuscript). Additionally, we perform an analysis showing that there is no change in the rate at which clouds surpass this 60 gm^{-2} threshold, indicating no long-term shift in the population of clouds that we study into LWP regimes that cannot be probed by the MIXCRA algorithm (Figure 5 of the revised manuscript). To align with these clarifications, we have shifted our quality control threshold of our data to limit ourselves to clouds with an LWP less than 60 gm^{-2} , a change from our previous limit of 100 gm^{-2} . These investigations can be found in the revised manuscript in Figures 1 and 5, Appendix C, and Appendix D, as well as in our response to comments 8-9 of Reviewer 1.

Our item-by-item responses are included below labeled as “Reply” and bolded to distinguish them from the Reviewer comments.

Reviewer 1:

Review of: “Insights into the low-level single-layer stratiform cloud optical depth feedback based on two decades of observations at the North Slope of Alaska.” by Coulbury et al.

General remarks

1. The manuscript analyzes observations of cloud properties by the Atmospheric Emitted Radiance Interferometer (AERI) at Utqiagvik, North Slope of Alaska. The data base extends to about 20 years which allows the authors to investigate long term trends in cloud properties. Different aspects are covered by the analysis ranging from simple trends in cloud optical thickness, changes of the cloud radiative effect, the cloud feedback to surface temperature and identifying controlling factors for cloud property changes. Although limited to a single specific Arctic location, in general, an improvement of our understanding of these cloud processes by observational constrains would be valuable for arctic climate modelling. However, the study lacks of significant issues that I will explain in detail below. Most evident is that most results are

not statistical significant. Still the authors attempt to interpret the calculated numbers. These challenges in interpretation are increased by the selection bias introduced by the AERI retrieval and not considering the changing ocean/sea ice conditions at Utqiagvik. In combination with the low confidence of the results, I doubt that any robust conclusions can be drawn from this study. I also do not see, how this can be improved by simple changes of the manuscript.

Reply: As discussed in the introduction to this response document, we have removed the cloud feedback analysis which lacked statistical significance due to overfiltering of the data and the excess noise in the unfiltered dataset rendering it unsuitable for a cloud feedback analysis. We instead shift our focus to simple linear trends as well as the way in which cloud optical depth (COD) changes with temperature on shorter timescales (Sections 3.3 and 3.4 of the original manuscript, now Sections 3.5 and 3.6 of the revised manuscript), which has been shown to serve as a proxy for the long-term cloud optical depth feedback (Gordon and Klein 2014).

As for the limitations of the MIXCRA algorithm and the influence of sea-ice conditions, see responses to comments 8-9 and 12 of Reviewer 1.

- **Gordon, N. D. and Klein, S. A.: Low-cloud optical depth feedback in climate models, *Journal of Geophysical Research: Atmospheres*, 119, <https://doi.org/https://doi.org/10.1002/2013JD021052>, 2014.**

2. Therefore, I have to reject the manuscript. I do not see a way how to adjust the study to make it reasonable. The authors first have to investigate how their measurement approach affects the results. But still it is questionable, if data from a single station/location and using only a 20 year time series can show significant trends and correlations. Maybe including other Arctic stations (still only a limited number and often in specific local environments) might help. But this is not easy to achieve. Another option might be to resubmit a new manuscript that focus on one of the aspects of Sections 3.1-3.6 and elaborates this in detail. E.g. showing a 20 year data set of CRE without trend analysis or correlations would alone be valuable. The seasonal cycle still could be studied in a more extensive way than in current Fig. 3. The authors could also explore how CRE estimates from different instruments data sets (many are available at NSA, radar, MWR,...) compare. This would address also the limitations and potential selection bias of the AERI based CREs. These are just some ideas to reduce the frustration caused by my review. But the authors may have their own ideas.

Reply: While we appreciate the Reviewer’s suggestions surrounding a bulk CRE analysis, we choose to focus on the COD and its impact on the cloud feedback due to its large uncertainty and the suggestions of previous manuscripts that the COD feedback may be an important factor in clarifying model representations of Arctic amplification (Gettleman and Sherwood, 2016; Tan et al, 2016; Taylor et al, 2022; Tan et al, 2022). Bulk CRE measurements don’t provide insights into the cloud property changes that impact this CRE, and focusing on the COD helps to diagnose model biases at the process-level. We retain our focus on the COD and how it changes with time and temperature at the Department of Energy’s North Slope of Alaska (NSA) site to bring clarity to this highly uncertain aspect of the Arctic atmosphere.

However, the cloud feedback and CRE analysis have been removed as per the introduction to this document. We instead limit our investigation of changes in COD to analyses that are more firmly grounded in the limitations imposed by the AERI instrument and MIXCRA algorithm. This includes the detection of statistically significant simple linear trends (revised manuscript, Section 3.4, Figures 4 and 5) which show how cloud properties change with time over the 21 years of our dataset. Additionally, this includes an analysis of how the natural logarithm of the COD is related to temperature, as per analyses conducted in Tseloudis et al, 1992; Gordon and Klein, 2014; Tan et al, 2019; and Terai et al, 2019. We would like to clarify that this analysis relating the natural logarithm of the COD to temperature is not a presentation of trends, but rather an investigation of the relationship between these properties as a function of the temperature of the atmospheric column that a given cloud exists in (revised manuscript Section 3.5 and 3.6 and Figures 6, 7, and 8).

- **Gettelman, A. and Sherwood, S. C.: Processes Responsible for Cloud Feedback, Current Climate Change Reports, 2, <https://doi.org/10.1007/s40641-016-0052-8>, 2016.**
- **Tan, I., Storelvmo, T., and Zelinka, M. D.: Observational constraints on mixed-phase clouds imply higher climate sensitivity, *Science*, 352,224–227, 2016.**
- **Taylor, P. C., Boeke, R. C., Boisvert, L. N., Feldl, N., Henry, M., Huang, Y., Langen, P. L., Liu, W., Pithan, F., Seias, S. A., and Tan, I.: Process Drivers, Inter-Model Spread, and the Path Forward: A Review of Amplified Arctic Warming, *Frontiers in Earth Science*, 9,<https://doi.org/10.3389/feart.2021.758361>, 2022.**
- **Tan, I., Barahona, D., and Coopman, Q.: Potential Link Between Ice Nucleation and Climate Model Spread in Arctic Amplification, *Geophysical Research Letters*, 49, <https://doi.org/10.1029/2021GL097373>, 2022.**

- Tseloudis, G., Rossow, W. B., and Rind, D.: Global Patterns of Cloud Optical Thickness Variation with Temperature, *Journal of Climate*, 5, 1992.
- Gordon, N. D. and Klein, S. A.: Low-cloud optical depth feedback in climate models, *Journal of Geophysical Research: Atmospheres*, 119, <https://doi.org/https://doi.org/10.1002/2013JD021052>, 2014.
- Tan, I., Oreopoulos, L., and Cho, N.: The Role of Thermodynamic Phase Shifts in Cloud Optical Depth Variations With Temperature, *Geophysical Research Letters*, 46, <https://doi.org/10.1029/2018GL081590>, 2019.
- Terai, C. R., Zhang, Y., Klein, S. A., Zelinka, M. D., Chiu, J. C., and Min, Q.: Mechanisms Behind the Extratropical Stratiform Low-Cloud Optical Depth Response to Temperature in ARM Site Observations, *Journal of Geophysical Research: Atmospheres*, 124, 2127–2147, <https://doi.org/10.1029/2018JD029359>, 2019

Major comments

Significance of results

3. Most detected trends are weak and statistically uncertain. E.g. in Fig. 4 the confidence interval for all results are at least a factor of two larger than the magnitude of the detected feedback. To me, this means, that not even the sign (positive and negative feedback) can be estimated with sufficient certainty. With such high uncertainties, nothing can be concluded from the results. E.g.: L321 - 324 can not be stated.

Reply: We appreciate the Reviewer’s concerns, but we would like to clarify that Figure 4 of the original manuscript does not plot trends as the Reviewer states, rather the relationship between globally averaged surface temperature anomalies and surface CRE anomalies. However, this is a moot point as the analysis has been removed from the resubmitted manuscript.

4. The values of CRE in Fig. 3 are very low compared to literature of cloud radiative effects (e.g., Shupe and Intrieri, 2004). Is this due to the filtering for thin low clouds in the data set? Then, what do we learn, if only clouds with low CRE are analysed? Additionally, the trends presented in Fig. 4 are of similar magnitude than the climatological CRE in Fig. 3. Does this mean, a 1 K temperature change causes the CRE to almost double? This seems to be unrealistic given that we already observed a strong increase of Arctic temperatures.

Reply: One reason that we choose to focus on the COD of low and optically thin clouds is that small changes in their COD result in large changes in their surface CRE (Turner et al 2007b). Hence the filtering for thin and low clouds is justified given that clouds that are outside of the detection capabilities of the MIXCRA algorithm see only small changes in their CRE with cloud property changes. However, this is also a moot point as the analysis has been removed from the resubmitted manuscript.

- **Turner 2007b: Turner, D. D. and Coauthors: Thin Liquid Water Clouds: Their Importance and Our Challenge, Bulletin of the American Meteorological Society, 88: 177-190, <https://doi.org/10.1175/BAMS-88-2-177>, 2007b**

5. In L328-335 the authors confirm, that their results are not significant. If this is the case, the authors should not even try to interpret their results. The authors also add, that their analysis can not be considered as long-term feedbacks due to the limited time period (L333). Here the authors also contradict themselves in their discussion:
6. "This indicates that much of the variance.... can be explained by factors other than globally averaged surface temperature." is followed by "...it is important to consider how cloud changes, as mediated by global surface temperature trends, are impacting the radiative budget at the Arctic surface".
7. If temperature does not explain cloud changes, then there are no cloud changes as mediated by global temperature trends.

Reply: We appreciate the reviewer's concerns, however this analysis has been removed from the revised manuscript.

Limitation and impact of cloud type

8. The significance of the results is further reduced by the limitations of the AERI/MIXCRA retrieval of cloud properties. As mentioned by the authors, the retrieval will converge only for low, optically thin, single-layer clouds. Thus, only a subsection of clouds are studied. This makes interpretation challenging or even impossible, because observed trends can be due to a trend of cloud properties but also due to a trend in the retrieval performance. Two issues:
 - I) The data is automatically limited to $COD < 50$. What if a climate trend pushes a cloud with $COD = 49$ into $COD = 51$? Then this cloud is removed from your analysis.
 - II) Similar the convergence of MIXCRA might change with increasing temperatures or changing cloud properties. What if this will mostly affect thicker clouds and less thin clouds. This also might induce an artificial

signal in your trend analysis. As illustrated in Fig. 1 and discussed by the authors in L300, there is a seasonality in the retrieval performance. What if there is also a climate trend of the retrieval performance over 20 years? To me, this makes it challenging to interpret any result of the analysis. It might simply be biased by the retrieval and the selection of a subrange of clouds. It makes me also doubt if Fig. 5-7 can be used to derive any conclusions. Of course these are all limitation of the approach presented in the manuscript. If the trend signal would be higher than the uncertainties in estimating cloud properties, CRE, etc. this would be OK. But given the fact, that already the trends are not statistically relevant, the uncertainty introduced by the observations and retrieval limitations will make any conclusion questionable.

Reply: While it is true that a subsection of clouds are studied, low-level optically thin stratiform clouds with a small liquid water path (less than 60 gm^{-2} in this manuscript, but often as low as 20 gm^{-2}) have a vast body of literature dedicated to them and are widely regarded as an important aspect of the atmosphere and therefore worth studying in isolation (Marchand et al 2003, Shupe and Intrieri 2004, Turner 2005, Turner 2007a, Turner 2007b, Turner 2007c, Lee and Penner 2010, Wood 2012, Terai et al 2019, Stauffer et al 2025). Particularly at the NSA site, a large portion of clouds have been shown to have a LWP less than 60 gm^{-2} (Turner et al 2007c). Interest in these clouds is motivated by multiple factors. Setting aside the valuable microphysical information that is available when these clouds are considered, investigation of these clouds is merited given that for even small changes in their liquid water path, large changes in the upwelling top of the atmosphere (TOA) and downwelling surface flux fields are observed (Turner 2007b, and Fig. A1). These sensitivities also vary based on the effective radius of liquid particles in the cloud (Fig. A1). The microphysical properties of low-level, optically thin clouds, and changes of these properties, have a significant impact on the surface and TOA radiative budgets at the NSA site. We clarify these points in the revised manuscript on L40-50, L186-189, and L324-326, which reference Turner 2007b and Appendix A of the manuscript.

As for the use of the AERI and MIXCRA retrieval, all instruments have limitations, and it is not always possible to compensate for the limitations of one instrument by introducing data from another instrument. The limitation of AERI retrievals to low-level, optically thin clouds is a known aspect of this instrument, and we have further emphasized this limitation in the revised manuscript (revised section 3.1, specifically L281-289, L322-331, and elsewhere in the manuscript on L40-52, L60-64, L184-189, L339, L341, L357-359, L382, L409-410, L414, L428, L446, L455-457, L460-

469, L470, L502, L557-558, L569-570, L585, L595, L616, L630-636, and Appendix C, among other locations throughout the manuscript). However, the demarcation of the optical depths of these clouds into liquid and ice contributions, and the other detailed microphysical information that come with MIXCRA retrievals, is an invaluable aspect of an investigation of Arctic clouds, particularly considering that these clouds are frequently mixed-phase.

We acknowledge the reviewer’s concerns that there may be a trend in the subset of clouds we study moving into an optically thicker regime. We respond to this concern in two ways. First, there is no trend in the rate at which clouds over the NSA site are exceeding a liquid water path (LWP) of 60 gm^{-2} . This can be seen Fig. 1 of this response document, which is Fig. 5 of the revised manuscript, which represents the application of the Liu et al 2022 trend detection framework to the daily saturation rate, or percent of all microwave radiometer (MWR) measured LWP in a given day that exceed 60 gm^{-2} . The details of this analysis can be found in the revised manuscript (Section 3.4 and Fig. 5).

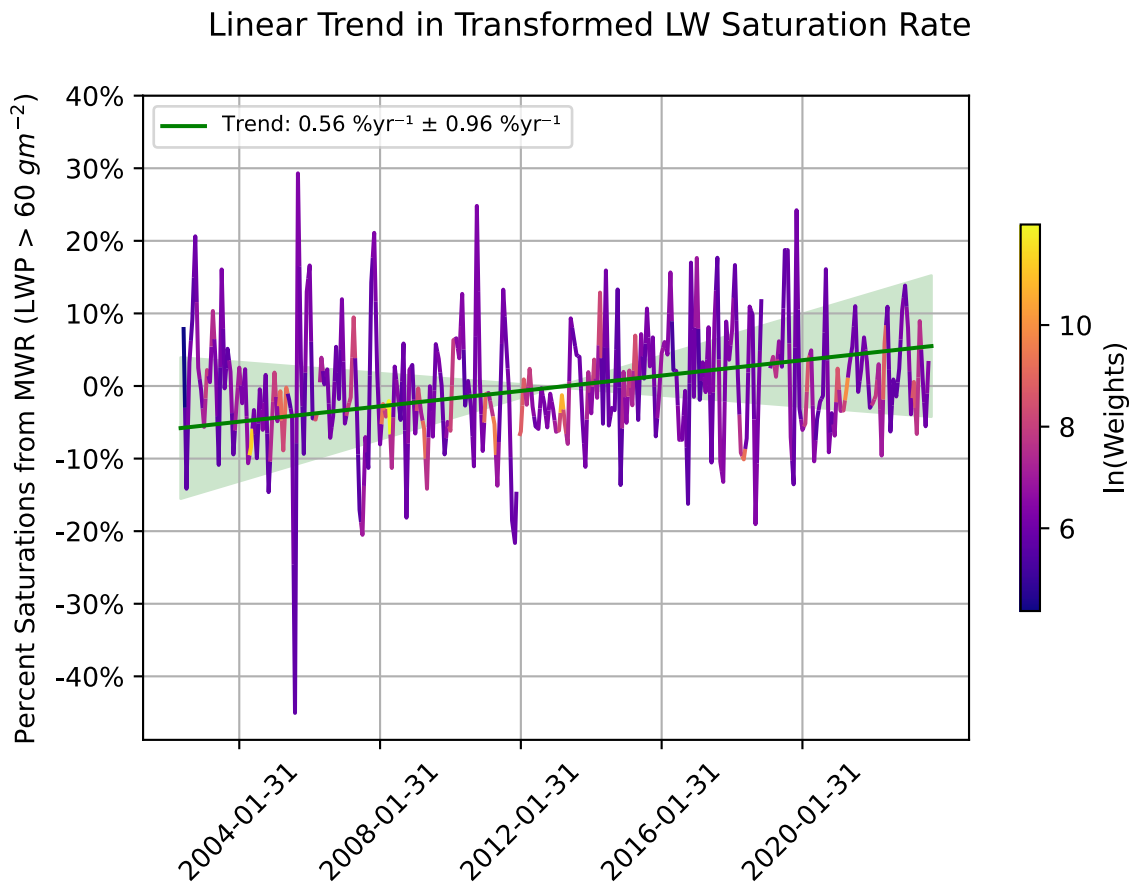


Figure 1: The linear trend in the daily saturation rate as evaluated using the Liu et al 2022 trend detection framework. The green envelope represents the 95 % confidence interval of the regression.

This rate was calculated using the LWP reported by the MWR at the NSA site, which can measure the LWP of clouds above the saturation point at which MIXCRA can no longer adequately retrieve this property (approximately 60 gm^{-2}). The temporal resolution of the MWR retrieval is comparable to that of the MIXCRA at one measurement every 20 seconds. The MWR retrieved LWP has a larger uncertainty than that of the MIXCRA, however, this uncertainty is convolved into the trend detection framework by calculating the saturation rate three times, once with the reported LWP value, once by adding the MWR reported uncertainty to all LWP values, and once by subtracting this uncertainty. This provides an upper and lower bound for the saturation rate based on the MWR reported uncertainty, which is then ingested into the trend detection framework as a measurement uncertainty in the daily saturation rate. Using the MWR means that all clouds are represented in this analysis. As can be seen, there is a small positive trend, but it is not statistically significantly different than zero over the course of the dataset, indicating that there is no interannual climate trend that is depleting the population of clouds we are able to study with the combined AERI observations and MIXCRA algorithm. This is clarified in the revised manuscript on L460-469 in the following way:

“There is no trend in the daily saturation rate, or rate at which clouds exceed a LWP of 60 gm^{-2} , of all clouds over the NSA site during the years covered by the MIXCRA retrieved cloud property dataset (Fig. 5). This conclusion is based off of LWP measurements made by the MWR located at the NSA site from 2002 to 2023, therefore it represents measurements of all clouds at the NSA site, not just low-level, optically thin, stratiform clouds. While a potential increase is seen in this rate, it is less than the magnitude of the 95 % confidence interval, so it is not statistically significantly different than zero. This indicates that there is no long-term shift in the population of optically thin Arctic clouds to CODs that cannot be probed by the combination of AERI observations and the MIXCRA. Therefore the statistically significant increase in COD with time as seen in Fig. 4 represents a shift in the COD of clouds within the optically thin regime to larger COD, and is not indicative of a change in the rate at which clouds shift into or out of this regime.”

There is no trend in the success rate of the MIXCRA algorithm with time in our dataset. This can be seen in Fig. 2b, which represents the application of the Liu et al 2022 trend detection framework to the percent of all monthly performed retrievals that survive the quality control process discussed in the manuscript. As with all trend detections performed with the Liu et al 2022 framework, the seasonal cycle and noise at a lag of 1 month has been removed from this dataset, resulting in negative values. Fig 2a is the raw dataset of monthly retrieval success, to provide context to the

transformation process that is performed on the data prior to application of the trend detection framework.

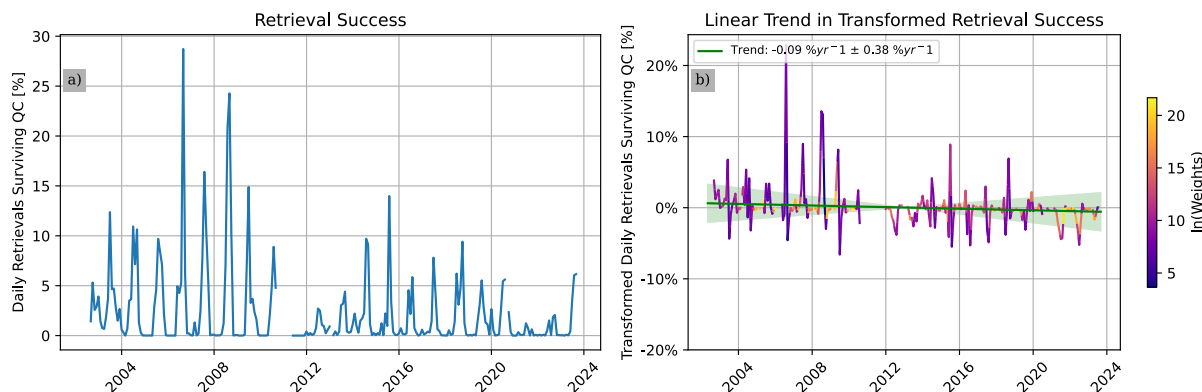


Figure 2: A timeseries of the percent of AERI retrievals that are processed by the MIXCRA algorithm and survive all quality control in each month (panel a). The linear trend in the monthly MIXCRA retrieval success rate as evaluated using the Liu et al 2022 trend detection framework, after the noise and seasonal cycle have been removed. The green envelope represents the 95 % confidence interval of the linear trend.

There is a slight negative trend in the transformed timeseries but it is well within the 95 % confidence interval indicating that it is not statistically significantly different than zero. This plot is included in the revised manuscript as Fig. D1. This is discussed in the revised manuscript on L332-337 in the following way:

“A potential source of bias in this dataset, and one that is particularly relevant when considering the claims about long-term trends that we purport to make, would be a shift in the efficacy of the MIXCRA retrieval process with time. There is not, however, any detectable trend in the rate at which the MIXCRA algorithm successfully retrieves cloud properties over the 21 years of our dataset (Fig. D1). This indicates that, of the many statistically significant relationships and trends presented in this dataset, none of them are biased by a long-term increase or decrease in the ability of the MIXCRA algorithm to probe the microphysical properties of low-level, optically thin, stratiform clouds.”

We hope that this assuages the reviewer’s concerns about climate trends in the retrieval performance

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- Shupe, M. D. and Intrieri, 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, [https://doi.org/10.1175/1520-0442\(2004\)017<0616:CRFOTA>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<0616:CRFOTA>2.0.CO;2), 2004.

- **Turner, D. D.: Arctic Mixed-Phase Cloud Properties from AERI Lidar Observations: Algorithm and Results from SHEBA, Journal of Applied Meteorology, 44(4):427-444, 44, <https://doi.org/10.1175/JAM2208.1>, 2005**
- **Turner, D. D.: Improved ground-based liquid water path retrievals using a combined infrared and microwave approach, Journal of Geophysical Research: Atmospheres, 112, <https://doi.org/10.1029/2007JD008530>, 2007a.**
- **Turner, D. D., Vogelmann, A. M., Austin, R. T., Barnard, J. C., Cady-Pereira, K., Chiu, J. C., Clough, S. A., Flynn, C., Khaiyer, M. M., Liljegren, J., Johnson, K., Lin, B., Long, C., Marshak, A., Matrosov, S. Y., McFarlane, S. A., Miller, M., Min, Q., Minimis, P., O’Hirok, W., Wang, Z., and Wiscombe, W.: Thin Liquid Water Clouds: Their Importance and Our Challenge, Bulletin of the American Meteorological Society, 88, 177 – 190, <https://doi.org/10.1175/BAMS-88-2-177>, 2007b**
- **Turner, D. D., Clough, S. A., Liljegren, J. C., Clothiaux, E. E., Cady-Pereira, K. E., and Gaustad, K. L.: Retrieving Liquid Water Path and Precipitable Water Vapor From the Atmospheric Radiation Measurement (ARM) Microwave Radiometers, IEEE Transactions on Geoscience and Remote Sensing, 45, 3680–3690, <https://doi.org/10.1109/TGRS.2007.903703>, 2007c.**
- **Lee, S. S. and Penner, J. E.: Comparison of a global-climate model to a cloud-system resolving model for the long-term response of thin stratocumulus clouds to preindustrial and present-day aerosol conditions, Atmospheric Chemistry and Physics, 10, 6371–6389, <https://doi.org/10.5194/acp-10-6371-2010>, 2010**
- **Wood, R.: Stratocumulus Clouds, Monthly Weather Review, 140, 2373 – 2423, <https://doi.org/10.1175/MWR-D-11-00121.1>, 2012**
- **Terai, C. R., Zhang, Y., Klein, S. A., Zelinka, M. D., Chiu, J. C., and Min, Q.: Mechanisms Behind the Extratropical Stratiform Low-Cloud Optical Depth Response to Temperature in ARM Site Observations, Journal of Geophysical Research: Atmospheres, 124, 2127–2147, <https://doi.org/10.1029/2018JD029359>, 2019.**
- **Stauffer, C. L., Tan, I., and Matrosov, S. Y.: Aerosol and Meteorological Influences on Mixed-Phase Stratiform Clouds at North Slope of Alaska, Geophysical Research Letters, 52, <https://doi.org/10.1029/2025GL114815>, 2025**
- **Liu, L., Huang, Y., Gyakum, J. R., Turner, D. D., and Gero, P. J.: Trends in Downwelling Longwave Radiance Over the Southern Great Plains, Journal of**

9. All this makes me wonder, why the study is limited to AERI measurements? Why not all data from the NSA are used? Observations at Utqiagvik offer a whole range of cloud and atmosphere remote sensing. Another approach would be to measure CRE directly independent to any retrieval algorithm. A recent study by Lubin et al. (2026) used microwave radiometer and broadband solar and thermal-IR fluxes from pyranometer and pyrgeometer to analyse trends in cloud properties at Utqiagvik. It seem necessary to argue, why the authors did not include these independent data in their analysis. The results of this manuscript also needs to be contextualize with respect to Lubin et al. (2026).

Reply: As discussed above in response to comment 2 of Reviewer 1, we appreciate the suggestion to measure bulk CRE but the thrust of this manuscript is to address issues with model representations of cloud microphysical properties, parameterizations, and the processes that impact the cloud feedback, not an investigation of the total cloud feedback itself. We apologize if our original manuscript was not adequately clear on this point. Additionally, we are interested in the COD of these low-level clouds, and its decomposition into contributions from each phase, because we would like to contribute to investigations of model disagreement in the projection of the Arctic climate due to process-level biases in the representation of Arctic mixed-phase clouds and their microphysical properties. While we agree that investigations of bulk CRE are interesting in the context of long-term trends in Arctic amplification, the goal of this type of analysis is distinct from those in our manuscript.

The choice to limit the scope of our manuscript to AERI observations is motivated by the high fidelity of AERI measurements and the auto-calibration of the AERI instrument such that long-term trends can be measured from its observations (Liu et al 2022, Gero and Turner 2011). It is difficult to maintain the calibration and sensitivity of active remote sensors over long time periods, an issue which the AERI solves by constant calibration against blackbodies of known temperature included within the instrument. The MIXCRA algorithm convolves information from the AERI instrument, radiosonde launches, and a ceilometer to retrieve not only the COD, but the contributions to this COD from ice and liquid particles in the cloud. This also motivates our use of AERI observations and the MIXCRA algorithm as we would like to

study long term changes in COD in the context of changing contributions from ice and liquid components of mixed phase clouds, and shifts between ice and liquid clouds individually. No other instrument is able to provide this data, particularly in the context of optically thin and/or near-surface clouds which are of utmost importance in determining the surface radiative budget. Our intention was not to produce a comprehensive review of cloud data produced by the NSA site, but rather to add a data product to this list and demonstrate some possible uses of this dataset, considering its novel length.

As for Lubin et al (2026), from our understanding, that manuscript uses MWR measured LWP and PWV to provide context to total radiation trends found at the NSA site. Their focus is not on low-level, optically thin stratiform clouds, nor do they purport to provide information on COD, IWP, or effective radius. This being said, we acknowledge that it is necessary to situate our data on LWP against other sources in the field, and as such we have added the following paragraph to our manuscript on L454-459:

“A recent study using observations from the NSA site investigated trends in the LWP with time and found statistically significant positive trends for some months of the year over the period from 2001 to 2024 (Lubin et al., 2026). The clouds considered in this manuscript are a small subset of the clouds considered in that analysis as we only analyze low-level, optically thin, stratiform clouds (Fig. C1). We also found a positive trend in the LWP of the low-level, optically thin, stratiform clouds that we consider, however due to the smaller pool of observations that we draw from, this trend was not statistically significantly different than zero (not shown).”

- Liu, L., Huang, Y., Gyakum, J. R., Turner, D. D., and Gero, P. J.: Trends in Downwelling Longwave Radiance Over the Southern Great Plains, *Journal of Geophysical Research: Atmospheres*, 127, <https://doi.org/10.1029/2021JD035949>, 2022.
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- Lubin, D., Zou, X., Mülmenstädt, J., Vogelmann, A., Cadeddu, M., and Zhang, D.: Surface radiation trends at North Slope of Alaska influenced by large-scale circulation and atmospheric rivers, *Atmospheric Chemistry and Physics*, 26, 295–311, <https://doi.org/10.5194/acp-77026-295-2026>, 2026.

Cloud controlling factors

10. I don't agree, that the authors can detect cloud controlling factors. The authors simple look at correlations by a multi-linear-regression. A correlation does not tell anything about causes and consequences. E.g. higher T850 may cause a higher COD, but it can also be that a higher COD causes a higher T850. The strong correlation of cloud optical thickness and OCPHILIC might not be related to aerosol-cloud interactions. It is known, that the production of organic particles is less in presence of sea ice. What if less sea ice leads to more clouds but also to more organics? This also will provide a nice correlation but OCPHILIC does not control the clouds. And the same holds for most other parameters/correlations.
11. The authors also miss to address the uncertainties of all measured quantities used in Section 3.5. and how this will affect the derived correlations. Significance is only quantified by confidence of the regression. And often this significance is limited. The authors state themselves: L439: "this impact could....", L440: "This could...", L441 "... but a clear analysis of this relationship is precluded by a low correlation and large error." or L443: "highly uncertain". Reads for me like a lot of speculation and no clear conclusions.

Reply: We are aware that correlation does not imply causation. However, in the current literature a cloud controlling factor (CCF) analysis refers to a multiple linear regression, as in Ceppi and Nowack (2021), Klein et al (2017), Myers et al (2021), Naud et al (2023), Tan et al (2024), Stauffer et al (2025), and Zelinka et al (2026). The reason that multiple linear regression is an acceptable method of investigating cloud controlling factors, despite only presenting sensitivities from correlations, is because the factors used in the CCF analysis are known controls on cloud properties, typically established in a causal sense from model studies. This is also true for our CCF analysis. We do not purport to prove conclusively new physical controls on clouds, and in our original manuscript we discussed all of our results in the context of sensitivities of cloud properties to external variables. All of this said, for simplicity, we removed this analysis from the manuscript. We would prefer that the emphasis of this manuscript be placed on the statistically significant relationships presented therein, and do not want to confuse readers. We expect that a future manuscript will be written that uses our dataset to perform a CCF analysis.

- **P. Ceppi, & P. Nowack, Observational evidence that cloud feedback amplifies global warming, Proc. Natl. Acad. Sci. U.S.A. 118 (30) e2026290118, <https://doi.org/10.1073/pnas.2026290118> (2021).**
- **Klein, S.A., Hall, A., Norris, J.R. et al. Low-Cloud Feedbacks from Cloud-Controlling Factors: A Review. *Surv Geophys* 38, 1307–1329 (2017). <https://doi.org/10.1007/s10712-017-9433-3>**

- Myers, T.A., Scott, R.C., Zelinka, M.D. *et al.* Observational constraints on low cloud feedback reduce uncertainty of climate sensitivity. *Nat. Clim. Chang.* **11**, 501–507 (2021). <https://doi.org/10.1038/s41558-021-01039-0>
- Naud, C. M., Elsaesser, G. S., & Booth, J. F. (2023). Dominant cloud controlling factors for low-level cloud fraction: Subtropical versus extratropical oceans. *Geophysical Research Letters*, **50**, e2023GL104496. <https://doi.org/10.1029/2023GL104496>
- Tan, I., M.D. Zelinka, Q. Coopman, B.H. Kahn, L. Oreopoulos, G. Tselioudis, D.T. McCoy, and N. Li, 2024: Contributions from cloud morphological changes to the interannual shortwave cloud feedback based on MODIS and ISCCP satellite observations. *J. Geophys. Res. Atmos.*, **129**, no. 8, e2023JD040540, doi:10.1029/2023JD040540.
- Stauffer, C. L., Tan, I., and Matrosov, S. Y.: Aerosol and Meteorological Influences on Mixed-Phase Stratiform Clouds at North Slope of Alaska, *Geophysical Research Letters*, **52**, <https://doi.org/https://doi.org/10.1029/2025GL114815>, 2025.
- Zelinka, M.D., Myers, T.A., Qin, Y. *et al.* Recent cloud trends and extremes reaffirm established bounds on cloud feedback and aerosol-cloud interactions. *Commun Earth Environ* (2026). <https://doi.org/10.1038/s43247-026-03461-8>

12. I also wonder why the surface albedo/sea ice cover is not considered in the analysis as a major parameter characterizing Arctic environments. The impact of sea ice on cloud properties is only briefly discussed, almost neglected, in the manuscript. This starts with L50-51, where only thermodynamic parameter are considered to change cloud properties. I would doubt, that this fully holds for Arctic environments. Sea ice is a major component that regulates the conditions at the surface. E.g., sea ice cover changes the water vapor supply (latent heat flux) which is a major control of boundary layer clouds (e.g., Saavedra Garfias et al. 2023). And the location of Utqiagvik is prone to seasonal changes of sea ice cover. This is recently shown by a study of Saavedra Garfias and Kalesse-Los (2025) for surface-coupled clouds observed at Utqiagvik. This may also explain some of the results. E.g., L7-8: Why the COD changes are unsymmetric in season? Could this be linked to sea ice? Spring and Autumn experience a more significant change in sea ice cover than summer and winter. That's why I think, that Section 3.5 can not be presented without including sea ice cover in the analysis and reasoning.

Reply: We acknowledge that the sea ice cover surrounding the NSA site is important in characterizing the Arctic atmosphere and may have an important control on the cloud properties recorded in our dataset. We initially did not include the sea ice

cover in our cloud controlling factor analysis as we believed it to be a co-linear predictor with factors such as relative humidity and surface temperature. This was not adequately expressed in the initial manuscript and we apologize for this.

We have added a plot to our manuscript in which monthly averaged MIXCRA retrieved cloud properties are binned by the sea-ice cover in a semicircle of radius approximately 80 miles around the NSA site. The exact area used can be seen in Appendix F of the revised manuscript. Each bin contains months for which the sea-ice cover falls within a given quintile, such that one fifth of all recorded months are contained in each bin. Sea-ice percent thresholds for each quintile are contained in the tick labels for panel a). This plot is included here (Fig. 3) and in the revised manuscript (Fig. 3 of the revised manuscript).

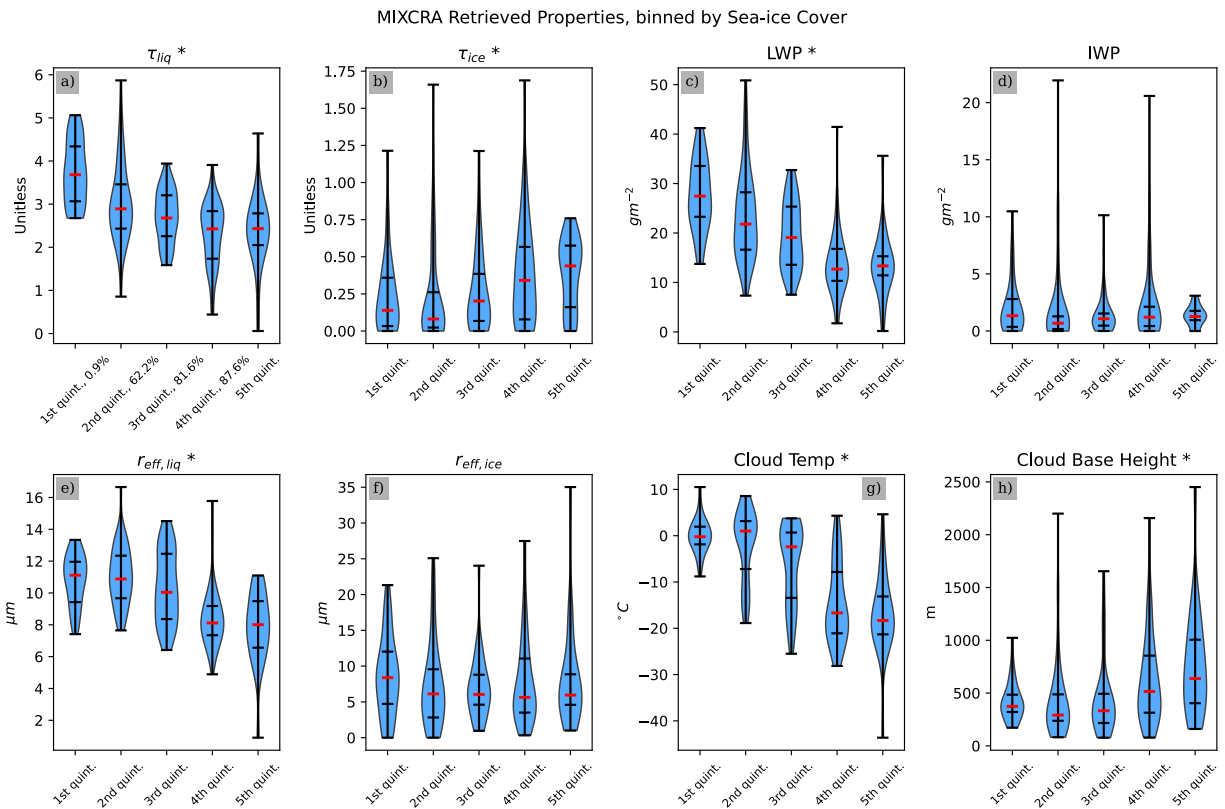


Figure 3 Monthly averaged values of six cloud properties for low-level, single-layer, optically thin stratiform clouds from April 2002 to August 2023 over the NSA site, binned by sea-ice concentration surrounding the NSA site. Each sea-ice bin represents a quintile of the full sea-ice concentration distribution. The upper bounds of these quintiles are provided in the tick marks for panel a). Each violin plot contains all averages for a given sea-ice bin, with lines representing the median; 25th, and 75th percentiles; and minimum and maximum values. The blue envelope of each violin plot represents the probability density of the distribution of monthly averaged values. Panels containing a star in their title indicate properties for which the distributions of the lowest sea-ice quintile and the highest sea-ice quintile are statistically significantly different. All properties except for the CBH are retrieved by MIXCRA. The CBH uses cloud radar and micropulse lidar observations as per Stauffer et al 2025.

This figure is discussed in the following way in the revised manuscript on lines 382-412:

“In addition to a seasonal investigation of the properties of low-level, optically thin, stratiform clouds over the NSA site, we also present these cloud properties in the context of the sea-ice concentration surrounding (Fig. F1) the NSA site. Hourly sea-ice concentration data from the MERRA-2 reanalysis dataset (Global Modeling and Assimilation Office (GMAO), 2015) is spatially averaged and divided into five quintiles, with an equal number of hours in each group. These quintiles have upper bin edges of 0.9 %, 62.2 %, 81.6 %, 87.6 %, and 100 % sea-ice concentration (Fig. 3). All monthly averaged MIXCRA-retrieved cloud properties are then sorted into one of these quintiles based on the area averaged sea-ice concentration in the given month. Considering the distributions of monthly averaged MIXCRA-retrieved cloud properties as binned by sea-ice quintile, and how these distributions change between quintiles, will give a sense of how cloud properties change with the broader sea-ice regime characterizing the ocean surrounding the NSA site.

The median values of the distributions of monthly averaged liquid COD, LWP, reff,liq, and cloud temperature generally decrease with increasing sea-ice concentration (Fig. 3). The median of the highest sea-ice quintile distribution for these properties is less than that of the lowest sea-ice quintile, a result that is statistically significant at the 95 % confidence level. These relationships are expected. Smaller liquid COD, LWP, reff,liq, and colder cloud temperatures are expected in high sea-ice months given the seasonal cycle seen in Fig. 2 and the fact that high sea-ice months typically occur in the winter and spring, and low sea-ice months typically occur in the summer and autumn. Additionally, as suggested by Saavedra Garfias and Kalesse-Los (2025), these relationships may be due to open sea-ice areas being local sources of moisture, which is crucial for the development of Arctic clouds (Tan et al., 2023).

Increasing median values of ice COD and cloud base height are seen with increasing sea-ice concentration, and the median values of the ice COD and cloud base height in the highest sea-ice quintile distribution are greater than that of the medians in the lowest quintile, a result which is significant at the 95 % confidence level. The increasing CBH with increasing sea-ice fraction may be explained by decreasing surface based moisture sources with fewer open ice areas in high sea-ice conditions. Increasing ice COD with increasing sea-ice may not be due to sea-ice concentrations, but rather the lower temperature of the clouds in these high sea-ice months, as seen in Fig. 3. At temperatures below -15 °C, ice nucleating particles that would not otherwise have been activated at warmer temperatures have been observed

to form ice particles (Kanji et al., 2017; Wilson et al., 2015), which would result in an increased ice COD.

The relationships between cloud properties and sea-ice concentration that we present here are not causative. However, the decrease with increasing sea-ice concentration observed in the LWP, reff,liq, and cloud temperature is in agreement with analysis performed by Saavedra Garfias and Kalesse-Los (2025), despite the differences in methodology, and the analysis of a larger subset of Arctic mixed-phase clouds in that manuscript. The methodology applied in Saavedra Garfias and Kalesse-Los (2025) accounts for the coupling of clouds to sea-ice conditions based on upstream advection of water vapour, and the agreement between our and their results indicates some control of sea-ice concentration on those cloud properties.”

- Tan, I., Sotiropoulou, G., Taylor, P. C., Zamora, L., and Wendisch, M.: A Review of the Factors Influencing Arctic Mixed-Phase Clouds: Progress and Outlook. In *Clouds and Their Climatic Impacts*, American Geophysical Union, <https://doi.org/10.1002/9781119700357.ch5>, 2023.
- Saavedra Garfias, P. and Kalesse-Los, H.: Observed modulation of wintertime Western Arctic mixed-phase cloud properties by sea ice conditions, their long-term variabilities and trends, *EGUsphere*, 2025, 1–35, <https://doi.org/10.5194/egusphere-2025-2327>, 2025.
- Kanji, Z. A., Ladino, L. A., Wex, H., Boose, Y., Burkert-Kohn, M., Cziczo, D. J., and Krämer, M.: Overview of Ice Nucleating Particles, *Meteorological Monographs*, 58, 1.1 – 1.33, <https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0006.1>, 2017.
- Wilson, T. W., Ladino, L. A., Alpert, P. A., Breckels, M. N., Brooks, I. M., Browse, J., Susannah, B. M., Carslaw, K. S., Huffman, J. A., Judd, C., Kilhau, W. P., Mason, R. H., McFiggans, G., Miller, L. A., Najera, J. J., Polishchuk, E., Rae, S., Schiller, C. L., Si, M., Temprado, J. V., Whale, T. F., Wong, J. P. S., Wurl, O., Yakobi-Hancock, J. D., Abbatt, J. P. D., Aller, J. Y., Bertram, A. K., Knopf, D. A., and Murray, B. J.: A marine biogenic source of atmospheric ice-nucleating particles, *Nature*, 525, 234–238, <https://doi.org/10.1038/nature14986>, 2015

Cloud radiative effect

13. The authors approach to calculate CRE following Zhou et al. (2022) might introduce significant uncertainties. In Zhou et al. (2022) I don't see an evaluation of the method for high latitudes. How confident are you, that your application to NSA is providing reliable CRE?
14. The approach by Zhou et al. (2022) is build for a fast evaluation of climate models. In this study a 20 year time series at a single location is used. For a single location I

assume that it is possible to apply more precise methods to calculate CRE, e.g. run a radiative transfer code tailored for your location and using all observations that are available. NSA provides 6-hourly radiosonde data, cloud base from ceilometer,.... Everything to run a radiative transfer model is available. What is the benefit of using Zhou et al. (2022) instead? What uncertainties do the authors expect from this method?

15. The manuscript also does not reveal how changes of the local surface albedo in Utqiagvik are treated in the calculation of CRE. The solar component of the CRE strongly depends on surface albedo. As surface albedo (snow, sea ice, ocean) changes a lot at Utqiagvik (seasonally and likely also climate trends are obvious), this needs to be considered.

Reply: We originally used the CRK method and kernels provided by Chen Zhou as it was, as the reviewer notes, fast. We could have input atmospheric profiles into a radiative transfer model and measured the CRE from the perspective of the surface at the NSA site in this manner. However, the kernels provided by Chen Zhou serve as look-up tables from the perspective of the surface, considering the cloud base height. Additionally, these kernels were already developed using observations and so were compatible with our observational dataset of COD and cloud fraction. That being said, we have removed the cloud feedback analysis from our revised manuscript as discussed in the introduction to this document.

Linear trend

16. In Fig. 9 I simply can not identify such a strong trend (red line) by eye. Especially when extreme month are weighted less, the trend should not exceed the majority of data points. It might help to show the unfiltered and filtered time series to convince the readers. But I still would doubt, that a statistically significant trend will become visible.

Reply: We would like to note that extreme months are not weighted less. Months with larger standard deviation and fewer points are deweighted (L273-275, L463-363 of the original manuscript). Therefore it is not an issue that the trend exceeds the majority of data points. We would also like to note that we did not filter this data. It has been transformed from the original timeseries, but this transformation constitutes only a de-seasonalization and a de-noising process, not any sort of high or low pass filtering. This is clarified in the revised manuscript on lines (L194-205) in the following way:

“In this framework, the data is first averaged at a monthly resolution and then transformed by denoising and removal of the seasonal cycle. As discussed in detail in

Appendix A of Liu et al. (2022), the noise at a timestep t in the dataset is assumed to be of the form written in Eq. A3 of Liu et al. (2022)

$$N_t = \phi N_{t-1} + \epsilon_t,$$

where ϵ_t is random white noise with zero mean, and ϕ is the autocorrelation coefficient of the noise. This noise is therefore assumed to be autoregressive at a lag of 1 month. The noise at every timestep N_t is calculated and subtracted from the deseasonalized data to produce a transformed dataset, in which a linear trend is sought. This transformed dataset is then assigned a weight in each month. The value of this weight is based on two factors, the number of observations in a given month, and the standard deviation of the values in that month. A larger standard deviation and fewer observations both serve to decrease the weight assigned to a month. In this way the trend is based off of monthly values for which there is high confidence. Therefore, monthly averages based off of highly variable observations or very few observations contribute less to the detected trend.”

To provide additional context to the weighting process applied as part of the linear trend detection, the transformed timeseries of MIXCRA retrieved total COD is now color coded by the weight assigned to each month (Figure 4 of the revised manuscript). The natural logarithm of the weight is plotted to aid in visual comparison between weights. Data points exceeded by the trend, particularly in the early and late periods of the total COD timeseries for which statistically significant trends are detected, have low weights.

- Liu, L., Huang, Y., Gyakum, J. R., Turner, D. D., and Gero, P. J.: Trends in Downwelling Longwave Radiance Over the Southern Great Plains, *Journal of Geophysical Research: Atmospheres*, 127, <https://doi.org/10.1029/2021JD035949>, 2022.

17. If this can not be convincingly shown for the COD time series. I would also question if trends in Section 3.3 can be identified. Could it be, that the problem results from using monthly data in combination with your filtering?

Reply: We would once again like to note that the Reviewer is incorrectly interpreting Sections 3.3 and 3.4 of the original manuscript (3.5 and 3.6 of the revised manuscript) as trends; they are not. Rather, they plot binned correlations between monthly averaged cloud properties against binned atmospheric temperatures, as discussed in the introduction to this document. Additionally, the cloud properties in sections 3.3 and 3.4 of the original manuscript are not filtered. Many of the slopes

presented in Figures 5, 6, and 7 of the original manuscript (revised manuscript Figures 6, 7, and 8) are statistically significant and agree with existing literature on the relationship between cloud optical depth and temperature, including literature using more temporally limited data from the NSA site (Terai et al (2019), Tseloudis et al (1992), Tan et al (2019), Gordon and Klein (2014)).

- Terai, C. R., Zhang, Y., Klein, S. A., Zelinka, M. D., Chiu, J. C., and Min, Q.: Mechanisms Behind the Extratropical Stratiform Low-Cloud Optical Depth Response to Temperature in ARM Site Observations, *Journal of Geophysical Research: Atmospheres*, 124, 2127–2147, <https://doi.org/10.1029/2018JD029359>, 2019.
- Tseloudis, G., Rossow, W. B., and Rind, D.: Global Patterns of Cloud Optical Thickness Variation with Temperature, *Journal of Climate*, 5, 1992
- Tan, I., Oreopoulos, L., and Cho, N.: The Role of Thermodynamic Phase Shifts in Cloud Optical Depth Variations With Temperature, *Geophysical Research Letters*, 46, <https://doi.org/10.1029/2018GL081590>, 2019.
- Gordon, N. D. and Klein, S. A.: Low-cloud optical depth feedback in climate models, *Journal of Geophysical Research: Atmospheres*, 119, <https://doi.org/10.1002/2013JD021052>, 2014.

18. Fig. B1 also does not look convincing. The smoothed CF anomaly time series does not represent the full time series in my view. Any issue with the fourier transformation? However, if the authors want to go for a 21 year trend, annual averages should be sufficient. Then you would not struggle with filtering monthly variability.

Reply: As discussed above, the CF anomaly data used in our cloud feedback analysis was oversmoothed, and as such this analysis has been removed.

List of specific comments

19. Abstract L10: Are these parameter measured data or reanalysis data? Mention the source of the data in your abstract.

Reply: These parameters are a mix of observations and reanalysis data, as discussed in L260-263 of the original manuscript. However, the CCF analysis has been removed and the abstract has been re-written.

20. Abstract L11-12: Is this the same conclusion as stated in L3-4 ? Are the conclusion given above also significant and from the same long data set? I suggest to restructure the abstract.

Reply: We acknowledge the lack of clarity and the abstract has been rewritten to reflect the substantial revisions performed to the document. The conclusion in L3-4 was referencing our $\ln(\tau)/dT$ analysis in which COD observations are binned by the temperature of the low-atmosphere and then linear regressions are performed between the natural logarithm of COD against the column averaged temperature in each bin (revised manuscript Sections 3.5 and 3.6). This elucidates how COD changes with temperature above the NSA site, which has been shown to be timescale invariant and has been used as a proxy for the COD feedback (Tseloudis et al, 1992; Gordon and Klein, 2014). In the rewritten abstract, this is referenced on L9-12 in the following way: “We investigate how the natural logarithm of COD changes with temperature in our dataset, with increases seen at column averaged temperatures between $-14\text{ }^{\circ}\text{C}$ and $-4\text{ }^{\circ}\text{C}$ annually. Additionally, increases with temperature are seen in the spring and autumn seasons, while decreasing COD with increasing temperature is seen in the winter. Our results align with current literature.”

Lines 11-12 of the original manuscript were discussing the statistically significant linear trend detected in COD with time over the course of the dataset (Section 3.4 of the revised manuscript). This is referenced on L5-6 of the revised abstract in the following way: “Trends in cloud microphysical properties over the 21 years of this dataset are sought, with an increase of 0.044 year^{-1} found in the total COD, statistically significantly different than zero at the 90 % confidence interval”

- **Tseloudis, G., Rossow, W. B., and Rind, D.: Global Patterns of Cloud Optical Thickness Variation with Temperature, *Journal of Climate*, 5, 1992**
- **Gordon, N. D. and Klein, S. A.: Low-cloud optical depth feedback in climate models, *Journal of Geophysical Research: Atmospheres*, 119, <https://doi.org/10.1002/2013JD021052>, 2014.**

21. L82: Section title: R_{eff} is also retrieved via MIXCRA.

Reply: We chose not to include this in the 2.2 Section Title as the focus of our manuscript is the COD and the effective radius is not central to the conclusions made in the paper.

22. L86- L254: I would emphasize that this effective radius represents the entire cloud layer. You do not retrieve a height resolved profile of R_{eff} . Thus your R_{eff} represents the entire cloud. Folloe up question: Is this definition of R_{eff} considered in estimating LWP/IWP? What profiles are assumed for the cloud particle sizes?
In this respect, Eq. 5 refers to homogeneous cloud layers, neglecting the increase of

particle size and LWC with altitude. This might be OK, when your assumption on the cloud vertical profile in the MIXCRA retrieval is the same. Then your R_{eff} corresponds to a homogeneous cloud with droplets of this size. If you have different assumptions on the cloud profile, this could result into biases.

Reply: We are aware that the passive AERI instrument is incapable of retrieving vertical profiles of R_{eff} and that it represents an average across the column but weighted more towards the cloud base. To answer your question, R_{eff} is considered in estimating both IWP and LWP as explained in Turner 2005:

The equations for the LWP reproduced from Eq. 8 of Turner 2005 is

$$W = \frac{2 r_e \rho \tau_{\text{vis}}}{3},$$

where W is the LWP, r_e is the effective radius of liquid particles, τ_{vis} is the visible cloud optical depth, and assuming a gamma size distribution. This equation is also used for IWP when the ice particles are assumed to be spheres, discussed on lines L117-130 of the revised manuscript. As we are studying low-level, optically thin, stratiform clouds, we assume that the clouds are vertically homogenous in particle size and water content.

- Turner, D. D.: Arctic Mixed-Phase Cloud Properties from AERI Lidar Observations: Algorithm and Results from SHEBA, *Journal of Applied Meteorology*, 44(4):427-444, 44, <https://doi.org/10.1175/JAM2208.1>, 2005.

23. L93: LBLDIS: explain acronym

Reply: Acknowledged, LBLDIS is a fusing of Line-By-Line Radiative Transfer Model (LBLRTM) and DIScrete Ordinates Radiative Transfer (DISORT) code. This has been spelled out on L114-116.

24. Section 2.2: The MIXCRA description is quite lengthly and detailed. On the other hand, the motivation of the manuscript puts the focus on cloud feedback analysis not on retrieval description. The analysis done in the manuscript also does focus on climate analysis and not on the evaluation of the MIXCRA results. Although it is important, that measurement uncertainties and limitations are provided, I don't think such a detailed MIXCRA description is not needed and available publication can be cited here.

Reply: We acknowledge that the MIXCRA description is detailed. While we certainly do a significant amount of analysis on the dataset, we felt that a thorough description of the retrieval was merited to contextualize our results and also to provide an updated description of the MIXCRA code. No recent description exists, and it has changed somewhat since the original paper describing it was published in 2005 (Turner (2005)). Lines 123-140 of the original manuscript, which contained a detailed description of the equations that underpin the optimal estimation framework, have been removed and replaced with citations to Turner (2005) and Rodgers (2000) to shorten this section.

- **Turner, D. D.: Arctic Mixed-Phase Cloud Properties from AERI Lidar Observations: Algorithm and Results from SHEBA, Journal of Applied Meteorology, 44(4):427-444, 44, <https://doi.org/10.1175/JAM2208.1>, 2005.**
- **Rodgers, C. D.: Inverse methods for atmospheric sounding: theory and practice, vol. 2, World scientific, 2000.**

25. L111: "dual phase". The most common phrase is "mixed-phase cloud". Or does "dual phase" mean something different?

Reply: Dual phase and mixed phase are the same, we employed dual-phase as that is the language used in the original Turner (2005) description of MIXCRA. We have updated this to mixed-phase throughout the manuscript for clarity.

- **Turner, D. D.: Arctic Mixed-Phase Cloud Properties from AERI Lidar Observations: Algorithm and Results from SHEBA, Journal of Applied Meteorology, 44(4):427-444, 44, <https://doi.org/10.1175/JAM2208.1>, 2005.**

26. L119: What is RU?

Reply: Radiance Units. The term Radiance Units has been added after RU to clarify this point (L139-140).

27. L167: This equation could be repeated and included here.

Reply: Acknowledged. It has been included (Eq 4).

28. L172: With respect to the cloud radiative effect, averaging COT might cause trouble because the relation between e.g. transmitted radiation and COT is not linear. Averaging COT likely overestimates the total cloud radiative effect, especially for low COT. (See your statement in L175-176)

Reply: All individual retrievals are binned according to the process discussed in L193-198 of the original manuscript, such that COD is not averaged monthly for this analysis. This is now a moot point as the CRE results have been removed in the revised manuscript.

29. L205: Your trend analysis is based on only 20 years of data. You tried to remove internal variability, especially an oscillation of 9 year period was removed. You argue that this might be related to PDO. Can you prove this? Otherwise you might also remove some of the natural trend. A 9 year period only fits twice into your entire time series. Depending on the phase of this oscillation, it might significantly contribute to the total trend, when not removed. A non-perfect or over-emphasised filtering might still affect your analysis. Can this be quantified?

30. It might be my impression, because the applied methods do not fall into my major expertise. But to make your approach trustworthy, I strongly suggest to add some illustration of your method by example plots (E.g., the histograms discussed along section 2.3.1. or the regressions discussed in L250.)

31. L206: What is PDO?

32. L213 and Eq. 3: Cloud fraction was written as CF before. It is somehow misleading when the anomaly of cloud fraction is represented by ΔC and not ΔCF .

33. Eq. 3: Are the quantities ΔCRE and the kernel $\delta R/\delta C$ also binned? If yes, I would suggest to add the dependencies, e.g., $\Delta CRE(COD, CBP)$. Otherwise it looks as if your CRE anomaly only depends on cloud fraction anomaly. This seems to be too simple.

Reply: We appreciate comments 30-34. The PDO is the pacific decadal oscillation. However, none of these lines remain in the revised manuscript as the cloud feedback and power spectral density analysis have been removed from the revised manuscript.

34. L221-224: This reads as if you analyzed MODIS data in your study. I guess, this only refers to the Tan et al. (2019) study.

Reply: Acknowledged, reference to the MODIS data used in Tan et al. (2019) has been removed from our manuscript.

- **Tan, I., Oreopoulos, L., and Cho, N.: The Role of Thermodynamic Phase Shifts in Cloud Optical Depth Variations With Temperature, Geophysical Research Letters, 46, <https://doi.org/10.1029/2018GL081590>, 2019.**

35. L288: Can you mention the method Zhang et al. (2019) used to derive cloud properties. We know, that cloud properties can differ depending on the retrieval method (active/passive remote sensing...).

Reply: Zhang et al (2019) use a high spectral resolution lidar and a Ka-band radar to determine cloud properties, as mentioned on L285 of the original manuscript. They use the methodology presented in Zhang et al (2017) to detect the presence of mixed-phase clouds. We clarify this point on L429-430 of the revised manuscript.

- **Zhang, D., Vogelmann, A., Kollias, P., Luke, E., Yang, F., Lubin, D., and Wang, Z.: Comparison of Antarctic and Arctic Single-Layer Stratiform Mixed-Phase Cloud Properties Using Ground-Based Remote Sensing Measurements, Journal of Geophysical Research: Atmospheres, 124, 10 186–10 204, <https://doi.org/10.1029/2019JD030673>, 2019**
- **Zhang, D., Z. Wang, T. Luo, Y. Yin, and C. Flynn (2017), The occurrence of ice production in slightly supercooled Arctic stratiform clouds as observed by ground-based remote sensors at the ARM NSA site, J. Geophys. Res. Atmos., 122, 2867–2877, doi:10.1002/2016JD026226.**

36. L307: add "...by the cloud"... also the surface emits and reflects.

Reply: Acknowledged, however this section has been removed from the manuscript.

37. Fig. 1: "Climatology" what does it mean? Are "monthly averages" plotted? If yes, use the more specific name.

Reply: Acknowledged, Figure 1 has been replaced by Figure 2 of the revised manuscript, which is a violin plot of monthly averages.

38. Fig. 2: Does the plot show total numbers? A relative fraction is also interesting. Or add the number of failed retrievals.

Reply: Acknowledged, Figure 2 has been replaced by Figure 1 of the revised manuscript which shows the number of failed retrievals along with the reason for their failure.

39. Fig. 5: How annual values can differ from winter values, when low temperatures were only observed during winter?

Reply: Low temperatures were not only observed during winter, it is simply that annual bins were only reported if they contained 80 or more points, while seasonal bins were included when containing 40 or more points. Therefore each of the annual bins from -15C and colder is influenced by winter months, but also by spring and autumn months that exist in bins too cold to have 40 or more spring or autumn

exclusive months in them. This is discussed on Lines 347-351 of the original manuscript. Additionally, the error bars between the annual and winter months overlap significantly. These bars were plotted over top of one another in Figure 5 of the original manuscript, and have been offset from one another in the revised manuscript to aid in visualization. We have changed the thresholds for reporting a point to 100 in the annual average and 25 in the seasonal average to aid in visualization of the competing influences of multiple seasons on the annual average. A more detailed discussion of this is provided on lines L487-498.

40. Fig. 7: Y-axis labels are missing.

Reply: Acknowledged, units have been added to the y-axis and x-axis.

41. Fig. 8: Why this analysis was not split into season?

Reply: Removing points from the overall regression reduced statistical significance. However, this figure is removed from the revised manuscript.

42. Section 3.6: Why authors started with the most challenging analysis of CRE and cloud feedback and end with the most simple analysis trend in optical thickness? I suggest to sort the manuscript by starting with simple analysis.

Reply: Acknowledged, the revised manuscript is re-organized.

43. L530: I could not find the data set. Doi ist not working. The data set also need to be included in the bibliography.

Reply: Our apologies, the original link was broken but we were told that an updated version (which was verified to work) was sent to reviewers. This may not have been the case. An updated link has been placed in the Data Availability statement and can be found here:

https://zenodo.org/uploads/17833181?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6IjNiMGVjOTk0LTcyMTQtNDJmNy05MmUzLWQwM2Q5NDE4MGZiNiIsImRhdGEiOiNt9LCJyYW5kb20iOiJhNDEyNWUwNmMwZDNlZjc0NjFjOTM5OGM5NDI0ZGFmZiJ9.9VG9NFm9pnX5qfUGscloSiA6imlLGu7ph5wZZv2nEd6BRYbTttwWOld4jc_3PhrbyU-VioQnQawqwWdjs6deiQ

44. L700: Tan et al. (2024) is listed twice in your bibliography.

Reply: Acknowledged, this edit will be made. Thank you for your review!

Reviewer 2:

Review of egusphere-2025-6553: "Insights into the low-level single-layer stratiform cloud optical depth feedback based on two decades of observations at the North Slope of Alaska" by C. Coulbury et al.

This paper introduces a new data product comprising retrievals of cloud optical depth (COD) and effective radius (r_{eff}) of liquid water and ice components in mixed-phase clouds. The retrievals are based on longwave spectral zenith radiance measurements from the Atmospheric Emitted Radiance Interferometer (AERI) which has been continuously deployed at the US Department of Energy Atmospheric Radiation Measurement (ARM) Facility at the North Slope of Alaska (NSA) for 21 years. A rigorous retrieval algorithm based on high resolution radiative transfer simulations called MIXCRA (Mixed-phase Cloud Retrieval Algorithm) uses an optimal-estimation approach to simultaneously retrieve the COD and effective radii and their retrieval uncertainties. The manuscript first describes the AERI instrument and its operational history at the NSA site, and then provides a detailed description of the retrieval algorithm. Subsequent sections provide a brief climatological description of the retrieval results (3.1), determination of the cloud radiative effect (CRE) and an attempt to identify a cloud feedback in the context of Arctic amplification (3.2), a discussion of COD variability with temperature in a climatological context (3.3 and 3.4), variability in COD with non-cloud properties called cloud controlling factors (CCF) (3.5), and finally a detection of linear trends in COD over the entire time series (3.6).

This set of cloud retrievals, for single-layer optically thin clouds in the high Arctic, is a potentially valuable contribution and *Atmospheric Chemistry and Physics* is an appropriate journal for introducing this data product. The authors may want to consider contributing this data product as an ARM Value Added Product (VAP), though some differentiation would be required from the existing AERIOE VAP (which may only treat liquid water clouds). I believe these results can be published in *ACP* in some form along the lines of this manuscript's earlier sections.

1. However, the climate-change-related analysis, beginning in the latter half of Section 3.2 and extending through Section 3.5, has a conceptual flaw. These AERI-based retrievals are a subset of all clouds at the NSA site that is arbitrarily defined by limitations of the observing technique. Specifically, thin clouds with liquid water path in

the approximate range 1-40 g m⁻², corresponding to COD < ~5, will show spectral variability in their emitted zenith radiance that can be harvested by MIXCRA to retrieve COD and r_{eff} . Clouds with larger LWP will radiate as blackbodies in the middle infrared and cannot be explored with AERI except to measure an effective cloud base temperature in the mid-IR window. Furthermore, higher cloud layers must be filtered and these scenes excluded from the data product, because the retrieval algorithm cannot separate out emitted longwave contributions from the higher layers. The result is that this data product represents a small fraction of high Arctic clouds during summer, although possibly a larger fraction during winter and early spring. This limitation is compounded by what the authors describe as more frequent quality control filtering by the algorithm during winter (lines 299-301 and Figure 2). It is not meaningful to draw conclusions related to Arctic amplification or large-scale Arctic change from this limited data product, and such conclusions (e.g., Figures 3-7) might be misleading to readers who are theoreticians and modelers rather than observationalists.

Reply: While it is true that our dataset represents retrieved cloud properties from a subset of the total clouds at the NSA site, we do not purport to make conclusions related to large-scale Arctic change as a whole, but rather discuss the contribution of this specific subset of clouds to Arctic amplification in the context of the fact that our observations are limited to the NSA site. Additionally, we hope to provide a resource that can be used to improve the model representation of this particular type of Arctic cloud, given their widespread appearance and influence on the climate system (Shupe and Intrieri, 2004; Terai et al, 2019). This is in part because of the large changes in surface fluxes that result from small changes in the cloud properties of low-level, optically thin, stratiform clouds (Figure A1 and Turner et al, 2007b)). Reviewer 1 had similar concerns on the limitations placed on our analysis by the subset of the clouds that we analyze. An in depth discussion of this point including analyses showing that there is not a long-term shift in the population of thin clouds to clouds that cannot be probed by the MIXCRA algorithm as well as no trend in the rate at which the MIXCRA algorithm converges over the course of the dataset can be found in our response to comments 8-9 of Reviewer 1 and in Figures 1 and 2 of this document (Figures 5 and D1 of the revised manuscript).

However, we acknowledge that the finer points of these distinctions may be rather opaque to theoreticians and modelers, however clear they may be to observationalists. Therefore, further care has been taken in the revised manuscript to point out the limitations of the AERI observations and MIXCRA algorithm, and we place special emphasis on the fact that these conclusions cannot be taken to be

representative of all clouds in the entire Arctic region (revised section 3.1, specifically L281-289, L322-331, and elsewhere in the manuscript on L40-52, L60-64, L184-189, L339, L341, L357-359, L382, L409-410, L414, L428, L446, L455-457, L460-469, L470, L502, L557-558, L569-570, L585, L595, L616-618, L630-636, and Appendix C, among other locations throughout the manuscript).

- **Shupe, M. D. and Intrieri, 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, [https://doi.org/10.1175/1520-0442\(2004\)017<0616:CRFOTA>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<0616:CRFOTA>2.0.CO;2), 2004.**
 - **Terai, C. R., Zhang, Y., Klein, S. A., Zelinka, M. D., Chiu, J. C., and Min, Q.: Mechanisms Behind the Extratropical Stratiform Low-Cloud Optical Depth Response to Temperature in ARM Site Observations, *Journal of Geophysical Research: Atmospheres*, 124, 2127–2147, <https://doi.org/10.1029/2018JD029359>, 2019.**
 - **Turner, D. D., Vogelmann, A. M., Austin, R. T., Barnard, J. C., Cady-Pereira, K., Chiu, J. C., Clough, S. A., Flynn, C., Khaiyer, M. M., Liljegren, J., Johnson, K., Lin, B., Long, C., Marshak, A., Matrosov, S. Y., McFarlane, S. A., Miller, M., Min, Q., Minimis, P., O’Hirok, W., Wang, Z., and Wiscombe, W.: Thin Liquid Water Clouds: Their Importance and Our Challenge, *Bulletin of the American Meteorological Society*, 88, 177 – 190, <https://doi.org/10.1175/BAMS-88-2-177>, 2007b.**
2. However, this data product pertaining to thin single-layer clouds potentially has considerable value. Mixed-phase cloud microphysics is an immensely complex topic area and the clouds treated by these MIXCRA retrievals can serve as numerous examples, over 21 years and in all seasons, of the simplest and most straightforward Arctic clouds. It may be beneficial for researchers to examine these case studies to have a basis for trying to understand more complicated scenarios.
 3. To that end, I suggest that this manuscript be re-worked to emphasize and expand on Section 3.1. Figure 1 and Table 1 are a good start. Additional questions might include: What are the altitude ranges of these clouds as a function of season? Are there some mid-level or higher layers that are distinct from the presumably more numerous low-level clouds? What is the variability in r_{eff} for liquid and ice? Also, what fraction of *all* NSA stratiform clouds is represented by this data product, in all seasons? It may be appropriate to present some basic linear trends as in Section 3.6, although the limitations of these trend detections should be discussed.

Reply: We thank the reviewer for the interesting suggestions and questions. We have greatly expanded Section 3.1 to provide additional context to the contents of the

MIXCRA dataset, and the subset of clouds that we consider with our retrievals. This expansion includes violin plots of all MIXCRA retrieved cloud properties as binned by month of the year and sea-ice concentration in the ocean surrounding the NSA site, as well as cloud base height measurements made by collocated cloud radar and micropulse lidar from times when a successful MIXCRA retrieval was performed (Figures 2 and 3 of the revised manuscript). All points here are discussed in the revised manuscript in Section 3.2, but to respond to the reviewer's specific questions, there is little variation in the altitude ranges of clouds with season, with slightly higher cloud bases observed in the spring and late fall than in the summer. Cloud base height under high sea-ice concentration conditions is statistically significantly higher than the cloud base height under low sea-ice concentration conditions at the 95 % confidence level. Weak bimodality exists in the January distribution of cloud base height, but for the most part these distributions are smooth, indicating that there are not frequently distinct high and low cloud layers. Higher variability is seen in the effective radius of ice particles than liquid particles, and the liquid effective radius follows a much clearer seasonal cycle than the ice effective radius. The percent of all hours for which a stratiform cloud was detected during which a successful MIXCRA retrieval was performed varies with month, with over 50 % of all stratiform hours containing a MIXCRA retrieval in July, and fewer than 10 % in February (Appendix C of the revised manuscript).

Additionally, Figure 2 of the original manuscript has been replaced by Figure 1 of the revised manuscript which shows the percent of all MIXCRA retrievals removed by various quality control conditions. This adds additional context to the subset of all clouds that we are able to study using the MIXCRA algorithm.

4. Next, instead of attempting generalizations involving CRE, CCF and cloud feedbacks, perhaps this paper could emphasize smaller but useful timescales. Specifically, the authors imply a high time resolution with a measurement cadence of several minutes. Are there any continuous segments lasting multiple hours or even a few days? If so, are there changes in the COD, r_{eff} , and phase partitioning that appear consistent with current conceptions of a "classical" Arctic mixed-phase cloud lifecycle (e.g., Morrison et al., 2012, *Nature Geoscience*; Sedlar et al., 2021, *ACP*; Jimenez et al., 2025, *ACP*)? Are there any summertime segments resembling case studies observed at other well-instrumented high Arctic locations such as ASCOS (e.g., Birch et al., 2012, *ACP*). Adding some other NSA measurements or VAPs to elucidate these segments would be helpful. An example or two might entice other investigators to further explore this new AERI data product.

Reply: While we appreciate the reviewer's suggestion, we feel that an analysis of this type is outside the scope and goal of the manuscript, as we would like to emphasize the length of the given dataset and the interannual variability of COD changes to temperature across decades in connection to the previous literature on this topic. Additionally, Figures 6, 7, and 8 of the revised manuscript represent a fundamental thermodynamic relationship that applies to both long and short timescales (Tseloudis 1992, Gordon and Klein 2014). This relationship, and the match between the relationship found in our manuscript and previous similar analyses, is significant and represents an important development in our ability to constrain model representations of the COD feedback, which we would like to emphasize.

That being said, there are many continuous observational segments lasting multiple hours which could be used as interesting case studies and compared to temporally limited observational campaigns. In order to advertise these periods and encourage the use of our dataset, we explicitly mention them in the conclusion section as a possible use case of this dataset in applications to shorter timescales (L636-641).

- Tseloudis, G., Rossow, W. B., and Rind, D.: Global Patterns of Cloud Optical Thickness Variation with Temperature, *Journal of Climate*, 5, 1992
- Gordon, N. D. and Klein, S. A.: Low-cloud optical depth feedback in climate models, *Journal of Geophysical Research: Atmospheres*, 119, <https://doi.org/10.1002/2013JD021052>, 2014.

5. Finally, this set of AERI retrievals should be archived and publicly available by the time of the manuscript's publication, if not as an ARM Facility VAP, then in any FAIR repository. Maybe NSF's Arctic Data Center, or any university library digital collection that provides DOIs for researchers' data sets would do. The link given in the manuscript (10.5281/zenodo.17833181) just takes me back to the manuscript.

Reply: Our apologies, the original link was broken but we were told that an updated version (which was verified to work) was sent to reviewers. This may not have been the case. The correct link has been placed in the Data Availability statement and can be found here:

https://zenodo.org/uploads/17833181?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6IjNiMGVjOTk0LTcyMTQtNDJmNy05MmUzLWQwM2Q5NDE4MGZiNilsImRhdGEiOnt9LCJyYW5kb20iOiJhNDEyNWUwNmMwZDNIJzjc0NjFjOTM5OGM5NDI0ZGFmZiJ9.9VG9NFm9pnX5qfUGscloSiA6imlLGu7ph5wZZv2nEd6BRYbTttwWOld4jc_3PhrbyU-VioQnQawqwWdjs6deiQ

If possible, we would like for this data to be included as an ARM Facility VAP, as the reviewer suggested.

6. In summary, if the manuscript is given a major revision to emphasize the retrieval algorithm and a general survey of the data product, with perhaps some time series case studies, it could be a well-cited contribution.

Thank you for your review!

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