Reply to reviews.

We thank both reviewers for their time and comments. Replies are given in a point-by-point way below.

Reviewer 1: Review of "Observed modulation of wintertime Western Arctic mixed-phase cloud properties by sea ice conditions, their long-term variabilities and trends" by Pablo Saavedra Garfias and Heike Kalesse-Los.

In this study, the authors provide observational evidence that Arctic cloud properties are strongly related to sea ice concentration (for coupled cases). The analysis also present the long-term trends of Arctic cloud properties, and reveals that the evolution of cloud properties presents cyclical characteristics. The results are interesting and the paper is generally well written, my specific and minor comments are listed below for the authors to consider.

Specific comments:

1. More physical explanations would be helpful to better understand the relationships between the cloud properties and SIC.
    a. For example, for coupled cases, LWP and IWP both increase as SIC decreases, but the cloud depth decreases as SIC decreases. That means a shallower cloud may have a higher LWP and IWP, which is hard to understand. Is this finding statistically robust, and is there an explanation?
    b. In addition, the IWP increases as SIC decreases, and the cloud top temperature also increases as SIC decreases, which suggests the IWP is higher in a warmer and shallower cloud. This is also difficult to understand and inconsistent with previous studies. Some explanation is necessary.

    Reply a): Yes, the finding is statistically robust for coupled cases. Please note though that a cloud depth decrease with SIC decrease is not generally valid but only for coupled cases and in High pressure conditions, thus only a subset of wintertime MPC is affected. Higher LWP and IWP in shallower clouds (and decreasing SIC) is realized by increased liquid- and ice r_eff (see Fig. 5 in latest version of manuscript).

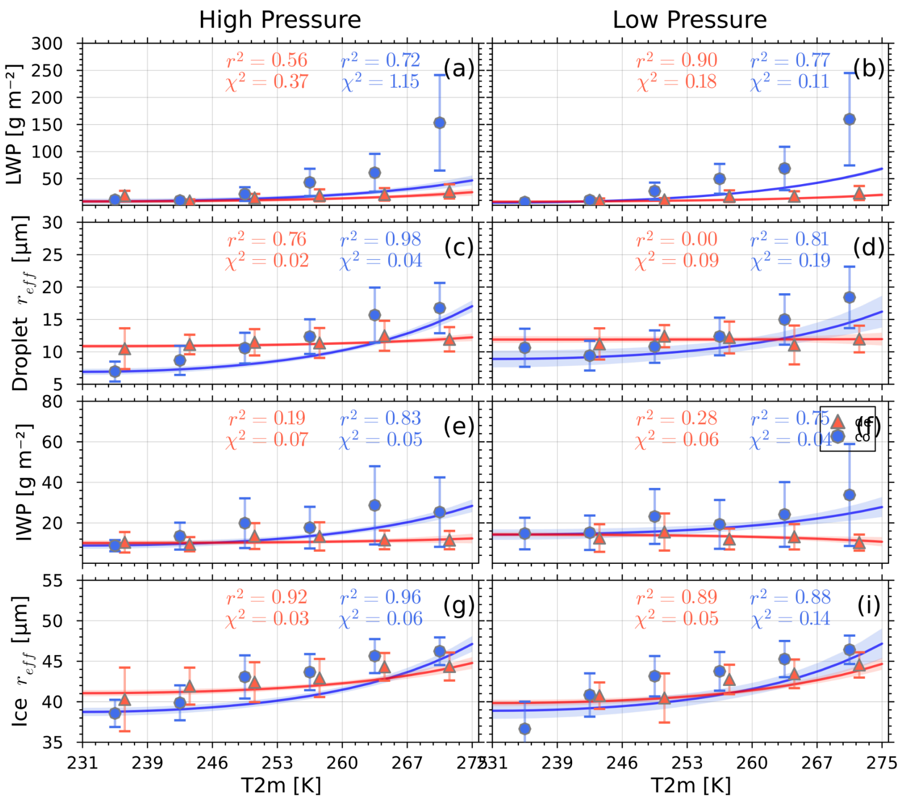
    Reply b): These observations are correct. Our findings indicate that the lower atmosphere temperature (represented by T2m) drives some of the MPC's micro- and macro-properties, cloud-top temperature (CTT) included. This is supported by the figures below (see answers to point 2.) where micro- and macro-properties are shown as a function of T2m (like Figs. 5 and 6 in latest version of manuscript), where a high correlation is evident, mainly for coupled cases. The physical explanation is given by the fact that in-cloud temperature lapse-rate also increases considerably as SIC decreases (Fig. 5 (g, i) in latest version of manuscript), which means that although CTT increases, still within freezing temperature ranges, there is a larger temperature gradient within thinner clouds as SIC decreases. Cesana et al. (2024) found that ice cloud cover and SIC are positively correlated within a pan-Arctic perspective. When their results are constrained to the wintertime months (Table 2 in Cesana et al., 2024), the correlation changes sign and a decrease in SIC is on par with an increase in ice cloud cover and even stronger negative correlation with mixed-phase cloud cover. Although we only focus in MPC, Cesana et al. (2024) findings are in agreement with our results. Furthermore, in-situ measurements in Svalbard have suggested that a warming Arctic favors the increase of highly active ice nucleating particles, thus favoring the formation of ice-containing clouds (Tobo et al., 2024). Similarly, Schäfer et al. (2025) using Arctic wintertime MPC simulations found an increase in cloud ice with a warming climate due to increase of ice-nucleating particles and the rime splintering process and secondary ice production. These recent studies are aligned to our findings at NSA.

Regarding long-term trends, the cloud top temperature increase is statistically significant only for L-pressure systems (Fig. B1 (f)), and IWP and ice r_eff do not have a statistically significant trend for L-pressure (Fig. S2 (b, d)), thus IWP is higher only for coupled MPC cases with the trend estimated by considering an effect by a 2.9 years oscillation e.g. ENSO (Fig. S5 (b)), which suggest influences by low latitude circulation patterns which are well known to affect the Arctic atmosphere through atmospheric teleconnections that influence not only sea ice but also e.g. IWP (Tan et al. 2023, Lubin et al., 2026).

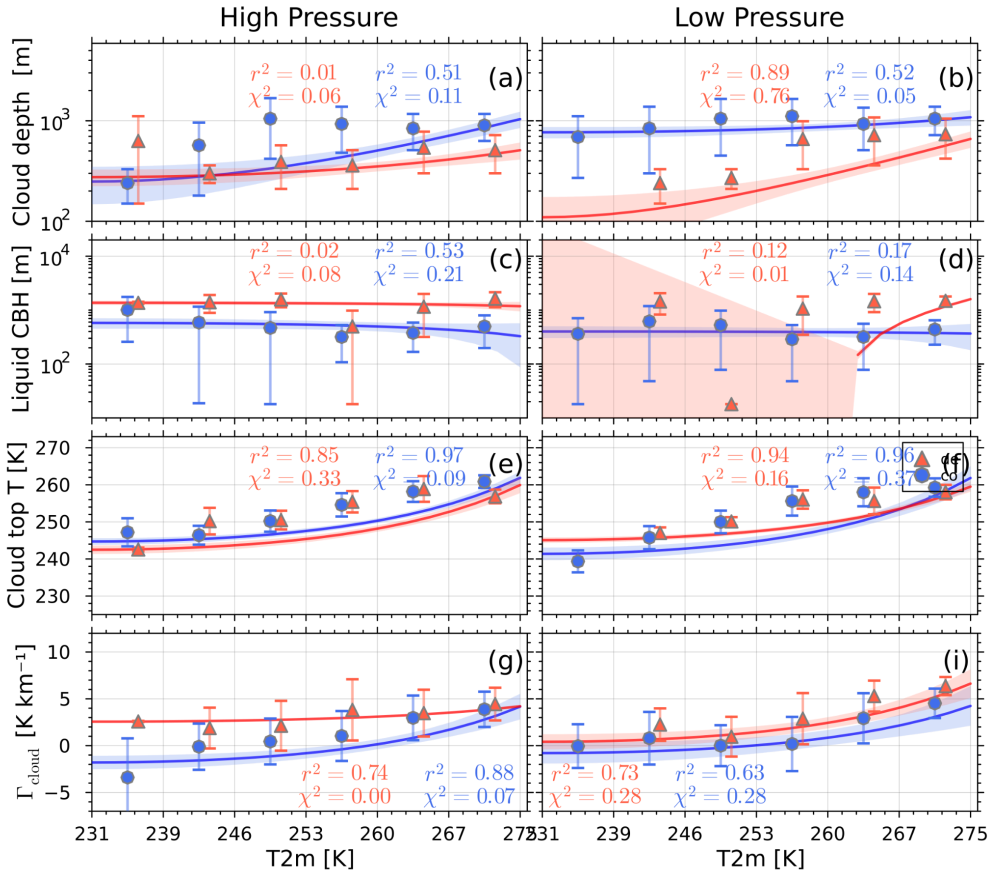
- Cesana, G. V., Pierpaoli, O., Ottaviani, M., Vu, L., Jin, Z., and Silber, I.: “The correlation between Arctic sea ice, cloud phase and radiation using A-Train satellites”, Atmospheric Chemistry and Physics, https://doi.org/10.5194/acp-24-7899-2024, 2024
- Tobo, Y., Adachi, K., Kawai, K. et al. Surface warming in Svalbard may have led to increases in highly active ice-nucleating particles. Commun Earth Environ 5, 516 (2024). https://doi.org/10.1038/s43247-024-01677-0
- Schäfer, B., David, R. O., Hodnebrog, Ø., & Storelvmo, T. (2025). Response of an Arctic mixed-phase cloud to ice-nucleating particle perturbations and warming. Geophysical Research Letters, 52, e2024GL114467. https://doi.org/10.1029/2024GL114467
- Tan, I., Sotiropoulou, G., Taylor, P.C., Zamora, L. and Wendisch, M. (2023). A Review of the Factors Influencing Arctic Mixed-Phase Clouds: Progress and Outlook. In Clouds and Their Climatic Impacts. https://doi.org/10.1002/9781119700357.ch5
- 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-26-295-2026, 2026.

2. SIC is well correlated to temperature according to Fig. 1, while all the cloud properties are plotted as a function of SIC in Fig. 5. I'm wondering if all the cloud properties are really directly controlled by SIC, or are they actually controlled by temperature, especially for the cloud top temperature and lapse rate.

Reply: We assume the reviewer is referring to Fig. 3, not Fig. 1. Yes, the time series in Fig. 3 shows a correlation between SIC and temperature. Although it is correct that temperature is strongly correlated with the MPC variables and acts as a driver, we are interested in how changes in SIC modulates the MPC variables. The driving mechanism is that open sea ice warms the lower atmosphere, thus temperature controls the MPC properties. The fact that increase of T2m is correlated with SIC decreases (as in Fig. 3) indicates that more latent and sensible heat fluxes are released to the lower atmosphere, favorable for convection, and when the surface is coupled to the clouds it drives the increase of the MPC parameters. Our findings show (Figures below) that the cloud property relationships with respect to T2m are different than the relations with SIC and that the relationship between MPC properties and T2m is stronger for coupled cases especially for LWP, IWP, droplet r_eff (first figure below). Interestingly, for CTT, the 2m temperature controls the relationship well for both coupled and decoupled cases. The lapse-rate only has a strong relationship with 2m temperature, in L-pressure situations, while for H-pressure only the coupled cases show a dependency with 2m temperature (second figure below).



Similar to Fig. 5 in the manuscript but as function of T2m (instead of SIC)

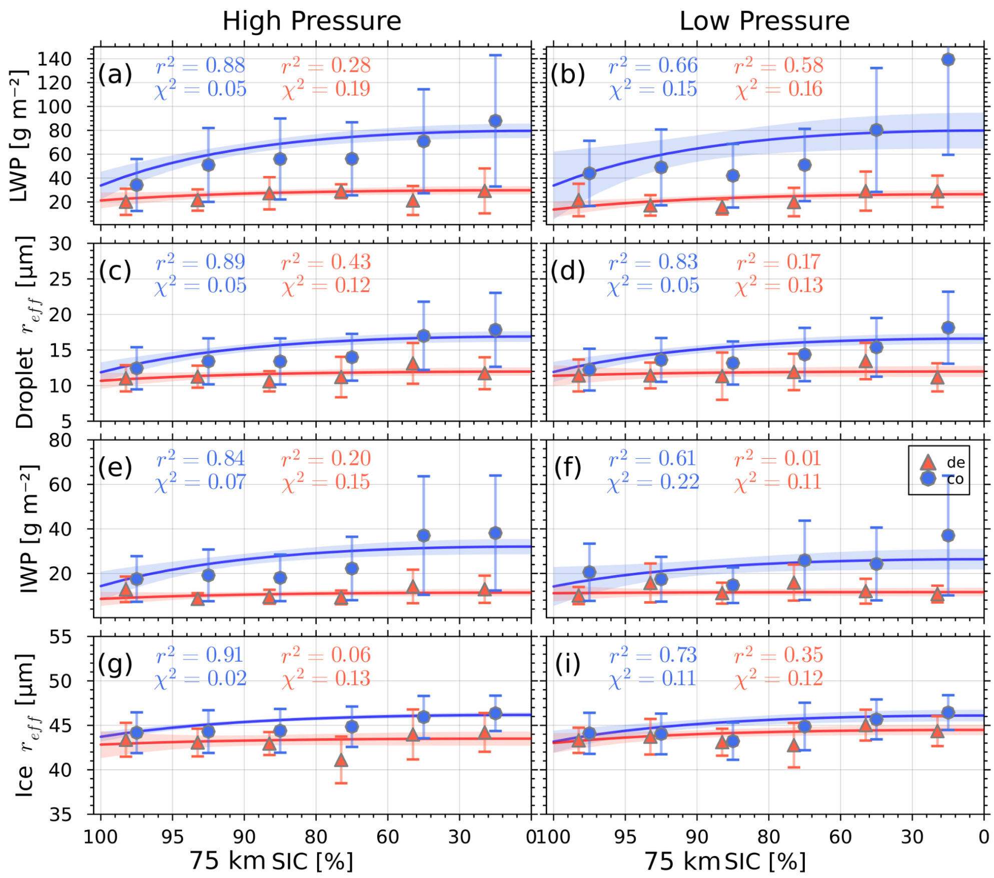


Similar to Fig. 6 in the manuscript but as function of T2m (instead of SIC)

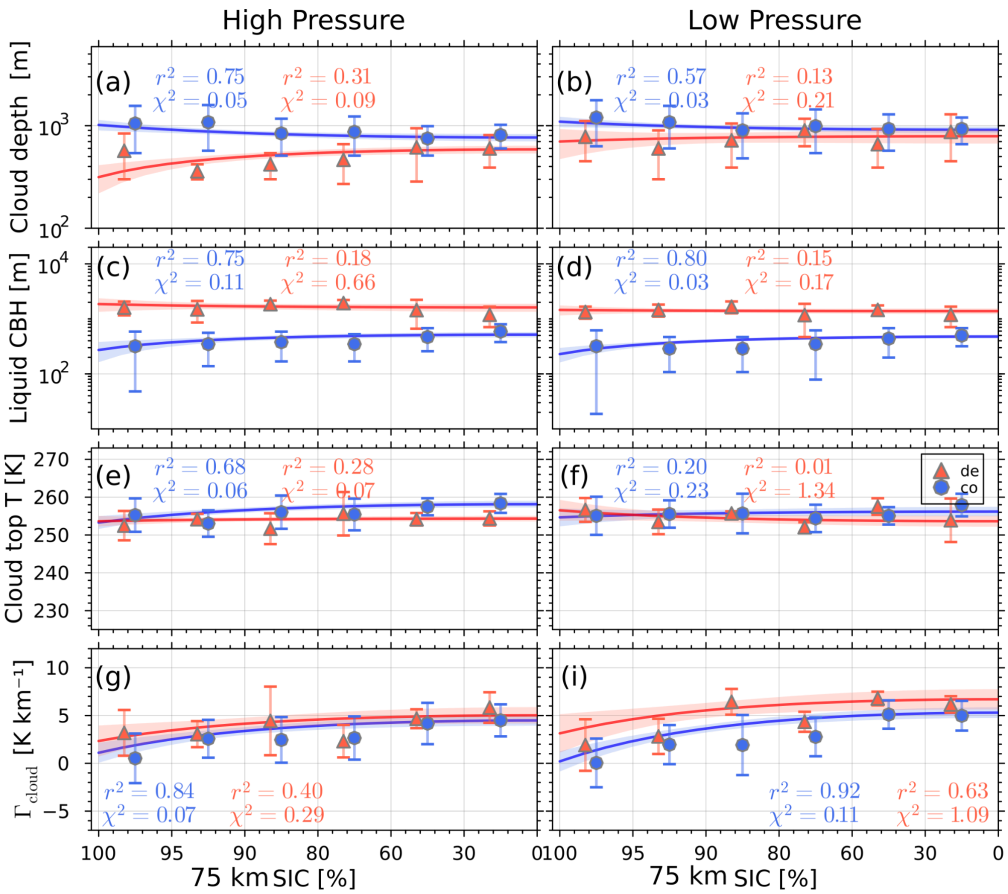
Minor comments:

1. A radius of 50 km and a conical sector of ±3 degrees is used for the upstream area. How are the results sensitive to the choice of radius and conical sector?

   Reply: The results were replicated for an extended radius of 75km and results added in appendix C and as supplementary material S3. In appendix C the results for LWP trends under different SIC ranges for 50km and 75km are compared in a table. Their corresponding plots are also added to the supplement material S3. We found that for coupled cases the MPC properties versus SIC and time series trend are robust results, with a slight improvement in the statistical significance. Two exceptions are to highlight: first, the cloud top temperature under L-pressure, where the difference between coupled and decoupled disappears and no relationship with SIC is evident anymore. Second, the decoupled LWP time series under H-pressure and for SIC<95% has its trend switched from positive (+6.2 g m^{-2} decade^{-1} , in 50km SIC) to negative (-24.0 g m^{-2} decade^{-1}, in 75km SIC), the corresponding plots are in the supplementary material section S3. Generally, the main differences found in results when changing SIC from within 50 to 75km is obtained for MPC properties classified as decoupled (see figures below), with the statistics supporting the conclusion that decoupled MPC properties are not correlated with SIC. Moreover, we found that changing the radius from 50 to 75km, slightly moves the SIC distribution from a median of 95% to 96%, respectively.



Similar as Fig. 5 in the main manuscript but for a SIC averaged within 75 km.



Similar as in Fig. 6 in the main manuscript but for a SIC averaged within 75 km.

2. Figure 2c and d. The observed LWP is high at 2-4 UTC, but the cloud is mostly classified as ice.

Reply: The observation is correct. The following has been added to the manuscript lines 122-128: “Furthermore, one of the main short-comings of the Cloudnet target classification is that cloud liquid detection is solely based on a valid lidar signal. In Fig 2., at 2-4 UTC, the lidar signal is fully attenuated by liquid within the lowest range gates of the ceilometer. Thus, higher supercooled liquid-layers remain undetected and all pixels without valid lidar signal are classified by Cloudnet as ice. More sophisticated cloud radar Doppler spectra-based tools such as introduced in Kalesse-Los et al., 2022 (https://amt.copernicus.org/articles/15/279/2022/) and Schimmel et al., 2022 (https://amt.copernicus.org/articles/15/5343/2022/) would be able to detect liquid beyond full lidar signal attenuation. However, their application would require novel training on the NSA dataset which is beyond the scope of this study. As a takeaway, the amount of MPC detected by Cloudnet used here has a low bias whereas ice-only clouds are overestimated”.

3. Line 237. The argument of “plateau where the property levels off” is probably based on the fitted model. For many properties, there is no “plateau” according to the actual observational data.

    Reply: Correct. The sentence was deleted.

4. Figure 5c and 4g. It is obvious that the model used to fit the data is not the best one for the decoupled cases in these two figures.

    Reply: Correct. An explanatory sentence was added to the manuscript (Line 266): “This empirical model has been chosen to best fit the *coupled* cases, thus when the fit is not the best for decoupled cases it is an indicator for the difference between coupled/decoupled cases. For decoupled cases, only few cloud properties have a clear relation with SIC. For many variables no correlation was found. ”

5. Line 290. If there is an inversion in the cloud layer, it may be inappropriate to calculate the lapse rate using the equation in Line 283. Have you tried to calculate the lapse rate using the temperatures at any two adjacent altitudes in the cloud, and then average over the entire cloud layer?

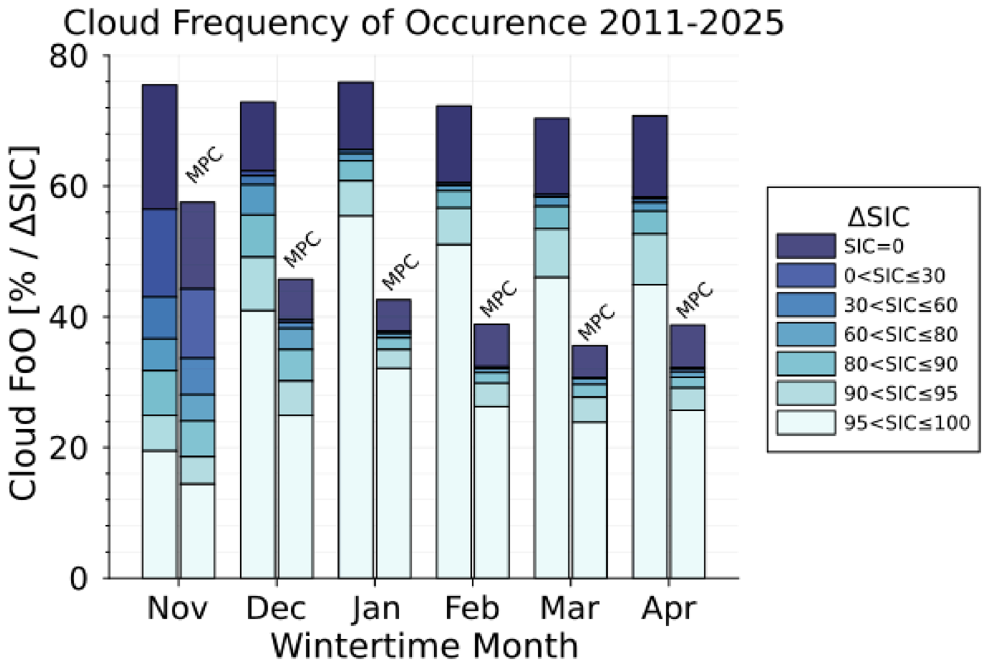
    Reply: The lapse-rate has been calculated by integrating the temperature profile between bottom and top cloud layer, the equation has been corrected (Line 314).

6. Another important macro-property is the cloud occurrence frequency. Is it affected by SIC?

    Reply: The cloud occurrence frequency (FoO) is definitely an important cloud macrophysical property and was added to the manuscript in Fig. 3 and Lines 240-251 . Total cloud occurrence (Figure below, left bars) is derived from all clouds considered in the manuscript (cloud top height ≤ 3 km) from wintertime 2011 to 2015. With MWR-LWP > 0 g/m2 or IWP > 0 referring to cloud liquid and cloud ice detections. The FoO shown below is based on cloud events in a month versus total days in a month.

    Our findings show that even though the total (left bars in figure below) cloud FoO is roughly constant at about 75% throughout the wintertime, there is a dependency on SIC for the distribution of cloud FoO during the different winter months. For MPC (right bars in figure below) the FoO shows a reduction from start to end of winter from about 56% in November to about 40% in April, with the largest contribution from SIC>95% happening in January. It is important to note that the SIC shown is the average within the semi-cone (50 km radius and 6° wide) with the azimuth being determined by the water vapour transport (WVT). The fact that for every month there are occurrences of SIC=0%, indicates the constant presence of polynyas and leads during wintertime along the SIC semi-cone around the NSA site. The absolute values for total cloud cover and MPC are in line with other studies such as Shupe et al., 2011 reporting an annual total cloud FoO of around 80% at NSA and Shupe et al, 2006 reporting a MPC FoO of around 40% at NSA in fall.

- Shupe, M. D., Matrosov, S. Y., and Uttal, T.: Arctic mixed-phase cloud properties derived from surface-based sensors at SHEBA, J. Atmos. Sci., 63, 697–711, 2006.
- 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, https://doi.org/10.1175/2010JAMC2467.1, 2011.



7. Line 463. I think the analysis of long-term ice properties should be mentioned in the text in Section 3.2.3.

Reply: Thanks for the suggestion. A paragraph on cloud ice properties are now mentioned at the end of Section 3.2.3, Line 460 :

> "Regarding ice cloud properties, coupled IWP does not have a statistically significant trend at L-pressure conditions, similarly Ice r_eff does not show any significant trend (Fig. S2 (b, c, d)) when the moving average method is used. IWP only has a significant trend when the method *ii* is used for trend determination. In that case IWP exhibits a positive trend at L-pressure affected by a 2.9 years oscillation e.g. ENSO (Fig. S5 (b)), and at H-pressure a 10.8 years oscillation e.g. ENSO/PDO (Fig. S4 (b)) which suggest effects due to weather patterns."

Anonymous Referee #2

nominated 05 Aug 2025, accepted 11 Aug 2025, report 10 Oct 2025

In this manuscript, the authors analyze observations from the ARM North Slope of Alaska site and try to relate the local cloud observations to the sea ice concentration (SIC) upstream. While the research question could be of interest, the study is not performed in a rigorous way, at least not based on the information provided, and therefore, the results can not be trusted. Even if the analysis is correct, the way they are presented only provides an incremental step in the understanding of the Arctic system. The authors need to collaborate with experts on atmospheric processes in the boundary layer, clouds and the large-scale circulation to formulate relevant questions and design of the analysis.

Reply: We thank the referee for taking the time to review the manuscript and consider its comments thoughtfully. We agree that the manuscript "provides an incremental step in the understanding of the Arctic system". The manuscript is part of the large research consortium AC3 (www.ac3-tr.de) which is comprised of multiple experts on many theoretical and experimental topics related to the Arctic system, and the manuscript was shared with the entire consortium for internal review before submission to ACP which is a standard procedure in AC3. Valuable comments were received and incorporated. Therefore, we consider that the research reported in the manuscript is aligned with relevant questions of the Arctic system.

1. The manuscript is full of uncertainties of what is actually done in the analyses, here, I only mention a few. First, Table 1 lists all datasets and the time resolution varies from 1 s to 1 day. In the following analysis, there is no information on what time resolution of the data is used. It seems like the data points in Figure 3 are monthly although the caption says weekly averages.

Reply: We apologize for the confusion regarding the time resolution. Table 1 indicates the temporal resolution of every instrument separately, but for the analysis the synergy is performed at 1 minute resolution as indicated in the text following the PSG23 method. We added a sentence to clarify that information (Lines 231-233) without the need for the reader to look for the PSG23 method.

2. Turning to Figure 2, what is the resolution of the data points that are behind this analysis? It is also very strange to have a so non-linear SIC division, does the distribution really support that? How can the confidence interval be so small when the bars show 50% of the data points? In this figure, I see no motivation for the chosen function – it could just as well be fitted with a straight line. To me it suggests that you have decided that the cloud parameters should be a function of the SIC and then you do your best to divide the dataset in such a way that you think that is what you see. The relationship is much more complex than that and the seasonality in the airmasses entering the Arctic over the season have a strong cycle, thus the temperature has a strong cycle and so has the LWP and IWP along with the SIC.

Reply:

- There seem to be questions regarding the data resolution used for visualization purposes only, thus we added the clarification in every Figure's caption if applicable. In Fig. 2 the temporal resolution of the used data is as indicated in Table 1.
- In Fig. 2 no SIC is shown, we assume the Reviewer refers to Fig.3 panel (c). It seems that the Reviewer is confused with the time series showing wintertime only, thus what is called by the Reviewer as "non-linear division" it is the jump from April to November, the distribution of SIC depends therefore in the time frame chosen to

define wintertime, this clarification was added to the figure's caption. Again, for visualization purposes the data are re-sampled to weekly resolution.

- We assume the Reviewer refers to Fig. 4 (Fig. 5 in latest version of manuscript) where the fitting curve is shown. The motivation is to find a function that not only fits better the data (unlike a simple linear line) and has a physical explanation to the SIC-cloud parameter relationship. The Reviewer's comment does not take into account the unphysical explanation that would imply if a simple linear fit is performed since the SIC-cloud relationship cannot increase indefinitely but it needs to level-off to values where no sea ice is found.The relationship is definitely much more complex, thus a non-linear fit explains the data behaviour the best.
- The following Reviewer's remark "the seasonality in the airmasses entering the Arctic over the season have a strong cycle, thus the temperature has a strong cycle and so has the LWP and IWP along with the SIC" is correct. Reviewer 1 had a similar remark (1 b), please see our response to that question).

3. In conclusion, the study is not well motivated, nor well performed and the results, if they are correct, are not of interest to the community. Statements towards the end of the conclusion section illustrate my point. "This study put into consideration empirical mathematical models derived from long-term observations as parameterization for the modelling of atmospheric boundary layer MPC ascribed to Arctic sea ice conditions. We suggest that the sea ice-atmospheric feedback processes that are represented in Arctic weather and climate models certainly should aim to mirror the complexity of relationships that the present study has uncovered. This implies the consideration of not only small-scale horizontal moist air mass transport that serves as physical link between sea ice openings and clouds downstream, but also weather patterns, atmospheric circulation processes, intra- and multi-decadal climate oscillations, and teleconnections between the Arctic and lower latitudes."

Reply: We disagree with the reviewer assessment here. The reviewer does not show any concrete point to conclude that the results are not correct, yet it is implied in its comment above. Moreover our conclusion is aligned with the interest of other research that also found that large-scale atmospheric circulation plays a significant role in the observed trends at NSA (for example Lubin et al. 2026).

- 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-26-295-2026, 2026.