RC2: 'Comment on egusphere-2025-5263', Anonymous Referee #2, 19 Dec 2025

The paper analyses an eight-year time series of active satellite measurements of low cloud frequency of occurrence over the Arctic, thus extending previous work to longer time series. An existing method is used to distinguish four different types of low clouds, present their spatio-temporal distribution, and analyze the main drivers responsible for the distribution. In general, the data record and the topic of the study are very interesting, as our knowledge on Arctic clouds is still limited.

The manuscript builds on a study previously submitted to AMT, which I have reviewed. In general, I find the manuscript (especially its first half) much improved with respect to reorganisation and readability. The manuscript now also includes an investigation of the coupling of clouds to the surface, which I had suggested in my initial review. Unfortunately, the exact method by which the authors derive the concept of "coupling" is not described in detail. Here, the main question is whether this has been done on the individual cloud profile scale or whether the 7-day averaging has been applied. For the latter, I believe no sensible statement can be made. Such analysis may help explain why the authors find that ice clouds are more frequently coupled to the surface than liquid clouds. I have strong difficulties identifying a physical mechanism which could lead to this finding. Here, and also in other cases, I miss a clearer, physically oriented analysis that digs into the data to identify specific conditions/regions/times when such a process takes place. Ideally, typical cases could be extracted that can then subsequently be presented in detail for a solid interpretation. Indeed, moving the paper from a more measurement-focused (AMT) to a more physics-oriented journal (ACP), I would have expected a stronger focus on the physical mechanisms leading to the observed cloud distributions.

We thank the reviewer for the careful reading of the manuscript and for the constructive comments. We appreciate the positive assessment regarding the improved organization and readability of the revised manuscript, as well as the acknowledgment of the added cloud–surface coupling analysis, which was suggested in the reviewer's initial review of our previous version submitted to the ACP journal (not AMT).

We fully agree that, in this previous version, the methodology used to diagnose cloud–surface coupling was not described in sufficient detail, and that this lack of clarity made the interpretation of the results difficult. In response to this concern, we have substantially revised both the methodology and the analysis. First, we have added a dedicated subsection in the Methods section that explicitly describes how cloud–surface coupling is diagnosed. The coupling state is now determined at the individual cloud-profile scale, following the approach of Sotiropoulou et al. (2014) and the simplified formulation of Gierens et al. (2020). For each cloud profile, the potential temperature structure between the cloud base (or liquid layer base for liquid-containing clouds) and the surface is analyzed, and the coupling criterion is applied independently to each profile. Figure 1 provides an illustrative example of a DARDAR granule along a satellite track, showing the vertical distribution of cloud types together with the diagnosed cloud–surface coupling state for individual cloud profiles. Importantly, no temporal averaging is applied prior to the coupling diagnosis. The daily and regional statistics presented in the manuscript therefore represent an aggregation of individually diagnosed coupling states, rather than a coupling inferred from *temporally averaged thermodynamic profiles. Please find below, the paragraph added to the method to describe the calculation of the coupling of clouds with the surface :*

"The cloud–surface coupling state is determined from the thermodynamic structure of individual cloud profiles. Building on the work of Gierens et al. (2020), who introduced a simplified version of the coupling algorithm originally proposed by Sotiropoulou et al. (2014), we analyze the vertical profile of the potential temperature (θ) from the cloud liquid layer base to the surface. The cumulative mean of θ is computed for each individual cloud profile over this layer and compared to the local θ profile. A cloud profile is classified as decoupled from the surface if the difference between the mean θ and the instantaneous θ exceeds 0.5 K at any level. Cloud profiles that do not exceed this threshold are considered to be related to surface-coupled clouds. For ice-only clouds, the procedure is carried out using the base of the ice cloud, rather than the base of the liquid layer. The coupling state is therefore diagnosed on a profile-by-profile basis and subsequently aggregated in time and space for the statistical analyses presented in this study, consistent with the methodology applied in previous observational studies (e.g.,Griesche et al., 2021)."

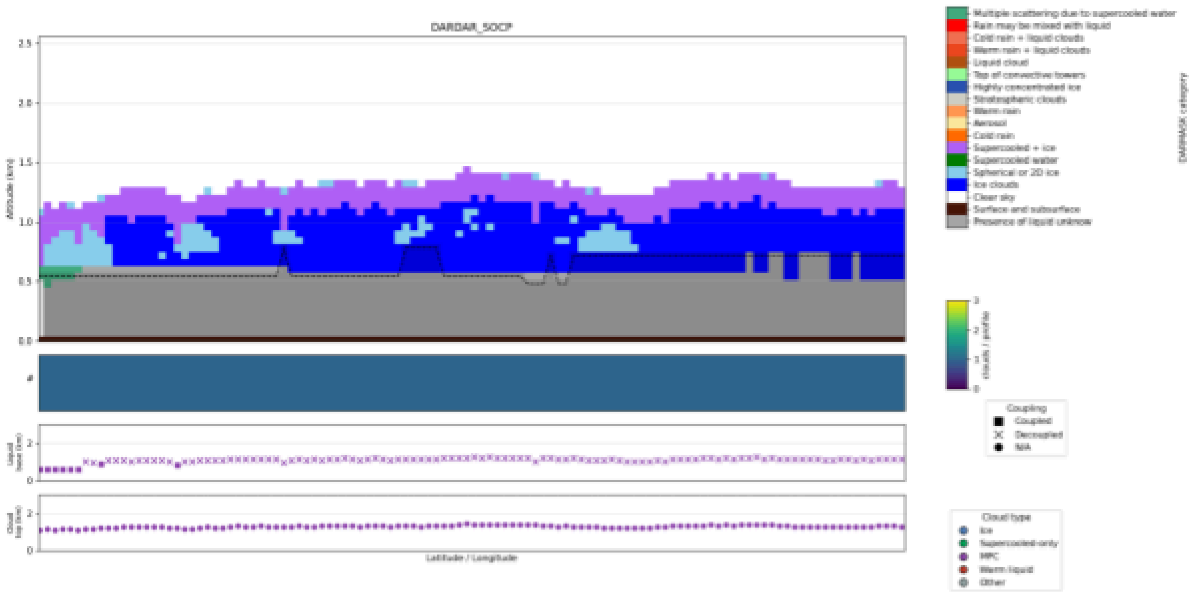

Figure 1. Vertical cross-section of cloud classification derived from the DARDAR-SOCP treatment along a satellite track. The top panel shows the vertical distribution of hydrometeor classes as a function of altitude (km), with colors indicating the different DARDAR-MASK categories (legend on the right). The black dashed line indicates the altitude of the radar clutter, below which data are excluded from the analysis. The second panel displays the number of cloud layers detected in each vertical profile along the track.The third panel shows the altitude of the liquid cloud base (km). Symbols indicate the diagnosed cloud–surface coupling state: squares correspond to coupled clouds, crosses to decoupled clouds, and circles to cases where the coupling state is not available (N/A).The bottom panel presents the cloud-top height (km) together with the identified cloud type for each profile, distinguishing ice clouds, supercooled-liquid-only clouds, mixed-phase clouds (MPCs), warm liquid clouds, and other cloud types.

Second, we fully acknowledge the reviewer's concern regarding the use of 7-day temporal averaging. As pointed out, such averaging can obscure synoptic variability and lead to ambiguous physical interpretations. In response, we have reprocessed the entire dataset using a daily temporal segmentation, which better preserves synoptic-scale variability while still providing sufficient sampling for robust statistics. All coupling, cloud occurrence, and regression analyses presented in the revised manuscript are now based on this daily framework.

Third, following the difficulties encountered by the reviewer in identifying a physically robust mechanism explaining why ice clouds appeared more frequently coupled to the surface than liquid clouds, we carefully updated our method (as mentioned above) and reprocessed the entire 8-year DARDAR.

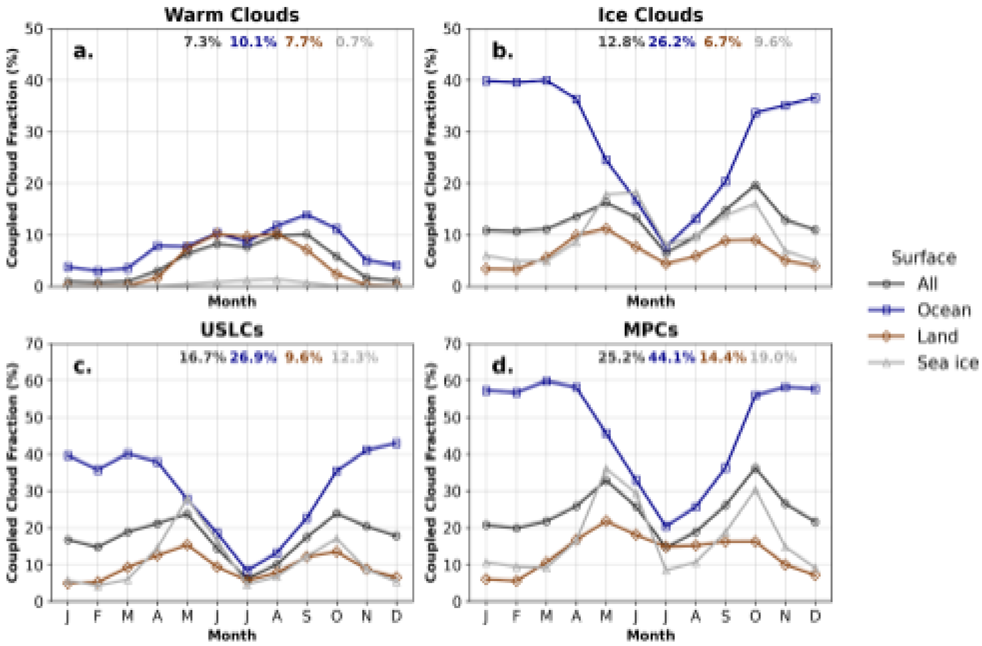

Figure 2: Monthly evolution of low-level coupled cloud fractions over different surface types (ocean, land, sea ice, and all surfaces). Panels show (a) warm clouds, (b) ice clouds, (c) USLCs, and (d) MPCs.

The updated analysis, illustrated in the revised Figure 2, is now more physically consistent with these previous observational studies. In particular, the new results show that mixed-phase clouds (MPCs) are more frequently coupled to the surface than purely liquid clouds (USLCs) across all surface types, and especially over open ocean and sea ice. This behavior is in line with the interpretation that coupling favors cloud regimes with enhanced ice production. While our analysis relies on spaceborne observations with coarser vertical resolution than the ground-based sensors used by Griesche et al. (2021), it provides a pan-Arctic, climatological perspective that complements their site-specific studies.

Regarding the expectation of a more physics-oriented analysis appropriate for ACP, we agree that stronger links between observations and physical interpretation are desirable. Within the limitations of spaceborne active remote sensing and large-scale statistical analysis, we have strengthened the manuscript by (i) clarifying what the coupling metric physically represents, (ii) separating observational results from interpretation more clearly, and (iii) reframing the multiple linear regression and coupling analyses as diagnostic tools rather than mechanistic explanations. While a focus on detailed case studies would indeed be valuable, this lies beyond the scope of the present pan-Arctic, “climatological study” and would require complementary high-resolution or in situ observations.

In addition, several of my other points of criticism, e.g. blind-zone, orographic effects, are not addressed in the newly submitted version. Furthermore, I suggested the inclusion of further parameters into the MLR analysis to relate more to physical processes, e.g. subsidence, in-cloud temperature, airmass characteristics. Furthermore, I was very skeptical about the seven-day averaging performed before calculating the correlations. This could be the cause of artificial correlation and requires further sensitivity studies. Furthermore, I recommend the use of machine learning techniques instead of the linear approach.

We agree that the impact of the near-surface blind zone is a critical limitation of CloudSat–CALIPSO observations and that it must be explicitly addressed. Following the reviewer's comment, we have revised the entire analysis to define cloud altitude relative to the local surface (above ground level, AGL) rather than mean sea level. This correction makes cloud occurrence over high-elevation land surfaces directly comparable to that over the ocean and resolves the spurious absence of clouds previously observed over regions such as central Greenland.

In addition, the analysis no longer relies on a fixed lower-altitude threshold (e.g., 500 m). Instead, the lowest usable altitude is now defined dynamically using the CloudSat radar clutter height for each individual profile. Cloud occurrences are therefore computed between the clutter height and 3000 m AGL. This adaptive approach explicitly accounts for surface-dependent radar contamination and is particularly important over elevated and heterogeneous terrain.

Surface type	Mean clutter height (km)	Median clutter height (km)
Ocean	0.810	0.660
Sea Ice	0.803	0.660
Land	0.901	0.833

Table 1. Statistical data on clutter altitude based on surface type (ocean, sea ice, and surface)

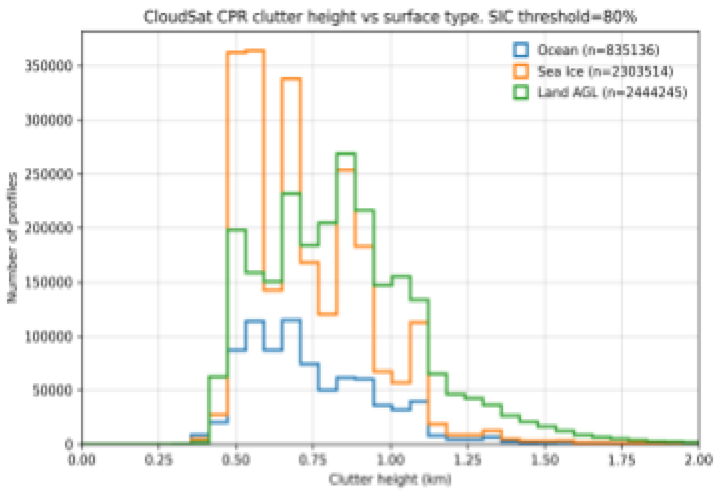

Figure 3: Surface-dependent variability of CloudSat CPR radar clutter height over ocean, sea ice, and land. n corresponds to the total values of analyzed profiles.

To document and justify this methodological revision, we performed a dedicated statistical analysis of the CloudSat CPR radar clutter height as a function of surface type (ocean, sea ice, and land). The results (Fig. 5 and Table 2) show that clutter heights are lowest and more narrowly distributed over open ocean and sea ice (median of 660 m and mean of 810 m), whereas they are consistently higher and more widely distributed over land (median of 833 m). The pronounced tail toward higher clutter heights over land highlights the strong influence of surface elevation and terrain complexity and demonstrates that the use of a fixed lower-altitude threshold would be inappropriate, particularly over regions such as Greenland.

We fully agree that orography can strongly affect cloud occurrence and that an inappropriate height reference can lead to misleading results over elevated terrain. In response, we have *revised the entire analysis to express cloud altitude relative to the local surface rather than mean sea level. By restricting the analysis to clouds located between the clutter height and 3000 m AGL, the results over mountainous regions, including Greenland, become physically meaningful and directly comparable to those over oceanic regions. We emphasize, however, that the present study does not explicitly diagnose orographic lifting processes; therefore, the revised manuscript avoids process-based interpretations related to orographic forcing and clearly states this limitation.*

In order to evaluate the impact of the blind zone, comparisons with ground-based data from the Cloudnet network have been made. Indeed, Cloudnet observations benefit from multi remote sensing instruments (radar, lidar, see detailed description of data here: https://cloudnet.fmi.fi/), and provide a "Classification product" including different cloud types (see Hogan and O'Connor (2004) and https://cloudnet.fmi.fi/product/classification for details), very comparable to those from DARDAR used in our study. The Cloudnet Classification product from Ny-Alesund (Norway, 78.923°N, 11.922°E) and Hyytiälä (Finland, 61.844°N, 24.287°E) Arctic sites has been used because they are the only ones, in the Arctic region, that are available when CALIPSO and CloudSat were in operation (June to December 2016 at Ny Alesund, and March to August 2014 at Hyttiala). Thus, we can compare time-synchronized data.

To ensure representative occurrences comparable to ground-based observations, a square of 5° of latitude by 5° of longitude (± 2.5° in both latitude and longitude), centered over each ground site location has been chosen to calculate occurrences from DARDAR data.Results are shown on the two figures below. Figure 4 presents the results for the Ny-Alesund site, and Figure 5 for the Hyttiala site. On each figure, occurrences of total (a), cold (b), warm (c), ice (d), mixed-phase (e) and cold liquid containing (f) clouds in the altitude range up to 3000 m above ground are presented. Weekly (blue colors) and monthly (green colors) occurrences have been computed. Ground-based occurrences are displayed in thick straight lines. Occurrences from DARDAR observations are presented for the old (dotted lines) and the new (thin straight lines) processings.

We note that the last cloud type (CLCC for cold liquid containing clouds) has been computed only for this evaluation work. Indeed, the supercooled liquid class is not included in the Cloudnet classification product. So, the USLCs class could not be directly evaluated. Instead, and to be coherent with the Cloudnet product, the cold liquid containing clouds including the USLCs or MPCs cloud types have been computed from DARDAR data. As expected, since the real clutter altitude is sometimes greater than the 500 m previous threshold (see details below), the new DARDAR processing presents lower occurrences values than the old processing, but not systematically, and not for all cloud types.

		Cloud type					
		Total	Warm	Cold	Ice	MPC	CLCC
Ny Alesund	Average	0,3	1,3	-2,1	5,2	0,1	-5,8
	σ	16,5	4,5	16,0	23,6	9,4	7,6
Hyttiala	Average	0,2	5,3	-1,7	-2,9	3,4	-2,3
	σ	8,4	5,5	10,8	8,1	7,1	8,2
Total	Average	0,2	3,3	-1,9	1,1	1,7	-4,0
	σ	12,6	5,2	13,1	17,5	8,2	7,8

Table 2: Averages and standard deviations of the differences between ground-based and space-based cloud occurrences for Ny Alesund site, Hyytiala site and both.

When comparing ground-based and space-based occurrences, a general good consistency is observed. The weekly and monthly variabilities are very similar on both observations for the two observation sites. Differences are observed in terms of values of occurrences, in particular on the weekly occurrences. These differences can come from the blind zone which may affect the space-based products. This could impact the occurrences with systematic higher occurrences from ground. But they also may be due to the representativity of the 5x5° box compared to the site location. In order to quantify the differences, we calculated their average (for the monthly occurrences only) in the table below:

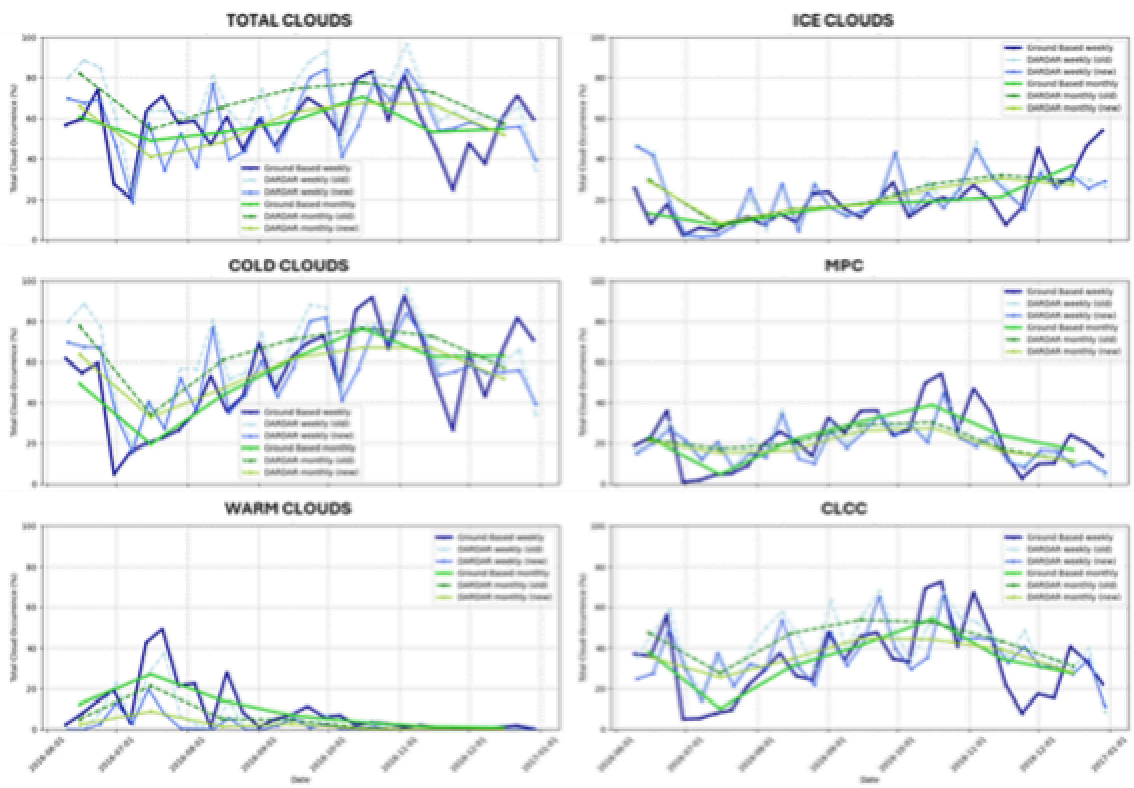

Figure 4: Comparison of DARDAR occurrences with ground-based site at Ny Alesund

The averaged differences remain very small, with only some %, and especially well distributed around zero (from -5.8% to +5.2%, as seen also in the figures), meaning that no bias is present, thus no under or overestimation of occurrences seems to be made. The standard deviations show non-negligible values (up to 23 %). So, the main source of uncertainties comes probably more from the spatial representativity of the data (comparison of 5x5° box to one location), than from the blind zone.

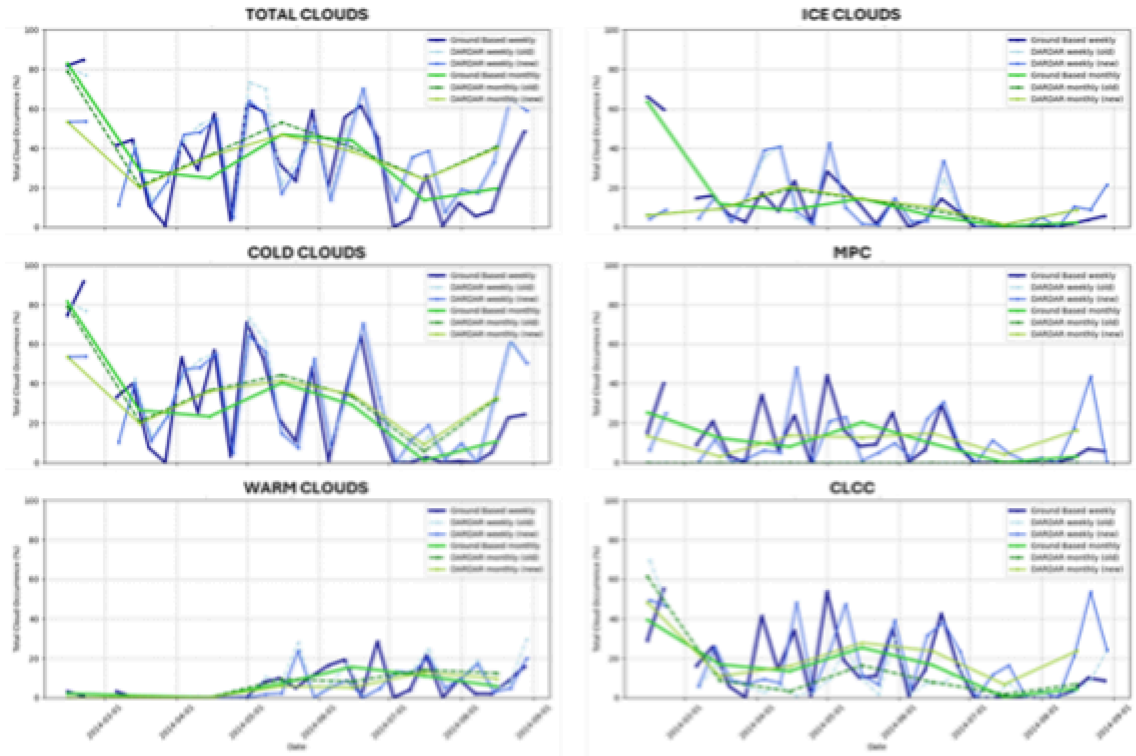

Figure 5: Comparison of DARDAR occurrences with ground-based site at Hyytiala

In conclusion of these comparisons, the cloud occurrences presented in this paper have been evaluated from ground based observations at Ny Alesund and Hyttiala sites to estimate the effect of the blind zone near the ground on space observations. Time synchronized data and similar cloud products have been compared. The results show a good agreement between the two datasets, with some differences, but no systematic bias. This leads to the conclusion that the impact of the ground clutter on the low altitude cloud occurrences from DARDAR presented in the paper remains limited.

In the revised manuscript, we propose to show these results in a new section (2.2 Comparison with ground-based data), but in a simpler way to keep focus on the aim of the paper (cloud occurrences results and impact of environmental parameters). Only monthly occurrences are kept, as well as the new DARDAR processing. All the detailed results presented in this answer will be added in a supplement material.

We appreciate the reviewer's suggestion to include additional predictors more directly linked to physical processes, such as subsidence, in-cloud temperature, or air-mass *characteristics. Unfortunately, the set of environmental variables that can be robustly and consistently collocated with the DARDAR product is limited by the availability of the ECMWF-AUX dataset. Several of the suggested parameters are either not available in this dataset or cannot be defined unambiguously at the cloud level using spaceborne observations alone. To avoid introducing poorly constrained or inconsistent predictors, we therefore chose to restrict the MLR analysis to parameters that are well defined, physically interpretable, and uniformly available across the entire eight-year pan-Arctic dataset. This limitation is now explicitly stated in the manuscript.*

We fully share the reviewer's concern regarding the use of 7-day temporal averaging and its potential to introduce artificial correlations by mixing distinct synoptic regimes. In response, we have completely revised the temporal segmentation of the analysis. The entire dataset has been reprocessed using a daily temporal resolution, and all cloud occurrence statistics, coupling diagnostics, and regression analyses are now based on 1-day data. This change substantially reduces temporal smoothing and improves the physical interpretability of the statistical relationships.

We acknowledge that machine-learning techniques can offer powerful alternatives to linear regression when exploring complex, non-linear relationships. However, the primary objective of the present study is to identify and interpret first-order, physically consistent relationships between cloud occurrence and large-scale environmental parameters. In this context, a multiple linear regression framework provides transparency and facilitates physical interpretation, whereas machine-learning methods would require a substantially different experimental design, additional predictors, and a separate validation strategy. We therefore consider such approaches to be beyond the scope of the present study, but we agree that they represent a promising direction for future work.

As already mentioned above the second part of the manuscript is rather difficult to read with many repetitions in sections 4 (Summary and Discussion) and 5 (Conclusions). Especially, section 4 includes several comparisons with the results of other studies. However, here, often rather different regions and time frames are compared which would need to be considered. While of course of interest, it might be better to focus only on speculating on the physical mechanisms of a few key findings with more in-depth analysis rather than the presented rather long list.

We thank the reviewer for this comment regarding the structure and readability of the second part of the manuscript. We agree that, in the previous version, Sections 4 (Summary and Discussion) and 5 (Conclusions) contained redundancies and that the discussion included an overly long list of comparisons with previous studies that were sometimes based on different regions and time periods, making the interpretation difficult.

In response, we have substantially revised both the Discussion and the Conclusions. Repetitions between Sections 4 and 5 have been removed, and the structure has been clarified to ensure a clearer separation between the presentation of results, their interpretation, and the main conclusions. The Discussion now focuses on a reduced number of key findings, which are discussed in more depth, rather than on an exhaustive comparison with the literature.

In addition, we have carefully revised the interpretation of the results to remove speculative statements and to clearly distinguish observationally supported conclusions. Comparisons with previous studies are now used primarily to place our results in context, while explicitly acknowledging differences in spatial coverage, time periods, and observational approaches where relevant.

We believe that these revisions significantly improve the clarity, focus, and physical consistency of the manuscript, and make the Discussion and Conclusions more accessible and coherent.

I do not provide a more detailed review as it is clear that still substantial revisions are needed before the paper can be published.

We thank the reviewer for this assessment of the revised manuscript. We appreciate the positive feedback regarding the improved organization, readability, and the inclusion of cloud–surface coupling, which directly followed the reviewer's earlier suggestions. For a more detailed description of the methodological revisions and additional analyses addressing these points, we refer the reviewer to our responses to Reviewer #1.