Replies to comments of Review #2

We would like to thank the reviewer for their very positive feedback and appreciate their time for reading and commenting on the submitted manuscript. The replies to the referees' comments are given in this document and structured as follows:

Referee's comments in italic – line numbers according to initially submitted manuscript
Authors' responses in roman – line numbers according to adjusted manuscript.
Citations from the initial and the adjusted manuscript are given in bold.

Please note that we also implemented some minor text revisions in addition to the changes made in response to the reviewer's comments. For these changes, we refer to the tracked changes file.

Review of "Bias in satellite-derived cloud radiative effect over Arctic sea ice relative to aircraft measurements during ARCSIX," egusphere-2026-2210, by Becker et al.

This is a very thorough application of advanced aircraft cloud microphysics and atmospheric radiation measurements toward evaluating and improving satellite surface radiation budget retrievals over the Arctic. While satellite remote sensing is necessary globally, satellite-based surface radiation estimates are critical over the entire Arctic Ocean which has very few surface-based data sets and which is experiencing dramatic sea ice losses in recent decades. The sea ice decline portends a substantial increase in solar energy entering the open water column, which will ultimately have implications throughout the Arctic climate system. The primary conclusion of this study is that low biases in surface albedo parameterizations used in the satellite retrieval algorithms introduce large enough errors in surface radiation budget (SRB) and cloud radiative effect (CRE) retrievals that the satellites often estimate a cloud cooling effect during spring and summer when a cloud warming effect actually occurs over sea ice. This is an important conclusion that merits publication in Atmospheric Chemistry and Physics.

The manuscript is essentially sound and well organized, and should be acceptable for publication after the authors address a few issues:

1. *In the abstract, lines 11-15, it would be good to make this conclusion quantitative. How large is the satellite surface albedo bias? What are the values (W/m^2) of the actual cooling effect and the erroneous satellite warming effect?*

We added this information to the abstract. The two sentences discussing the CRE and the albedo bias now read: "**The simulations based on aircraft measurements reveal that clouds warm the surface by 5–20 W m^{-2}, depending on season, whereas satellite-based CRE estimates suggest a cooling effect of 10–25 W m^{-2}. This discrepancy is primarily caused by a negative bias of up to 0.18 in satellite-derived surface albedo.**" (lines 10–12)

As the abstracts of ACP articles "should have fewer than 250 words", we tightened the abstract elsewhere, but without reducing its informational content. We refer to the tracked changes file for these modifications.

2. *Line 37. The SRB equation is incomplete. It should include terms for the turbulent fluxes (sensible and latent heat) and a surface conduction term. Orders of magnitudes (or ranges for the*

Arctic Ocean) should be given in the text, all of which will indicate that the radiative flux terms are the largest.

It is true that the turbulent and conductive flux densities contribute to the energy budget at the surface. However, our equation only accounts for the surface radiation budget (SRB) by intention. Thus, the equation is complete from a radiative point of view. To consider the reviewer's suggestion anyway, we mentioned the orders of magnitudes of all components in the sentence before the equation: "**Depending on season, each of the former three components is typically on the order of up to 20 W m^{-2} in the Arctic, while the surface radiation budget (SRB) clearly dominates the surface energy budget, especially in summer, with a 5–10 times higher magnitude (Persson et al., 2002). The SRB is quantified by the net irradiance F^{net}, with:**" (lines 36–39)

3. *In Figure 1, where do the sea ice concentration values come from? (This will be important, below).*

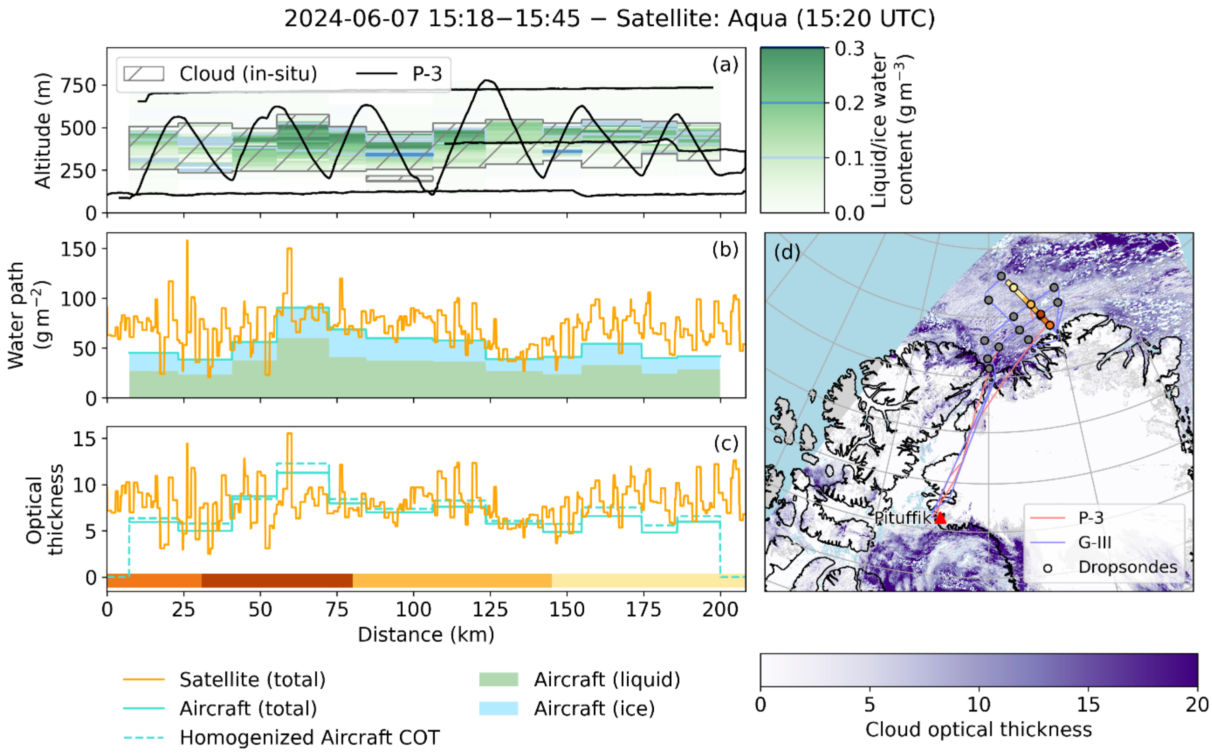
The sea ice concentration shown in Figure 1 was derived from AMSR-2 89 GHz observations (Spreen et al., 2008). We added this information to the main text: "**...; the flight tracks are illustrated in Fig. 1 together with the mean sea ice concentration from the Advanced Microwave Scanning Radiometer 2 (AMSR-2, Spreen et al., 2008).**" (lines 143–144). Additionally, we complemented the caption of Fig. 1 by the reference "**(Spreen et al., 2008).**".

4. *Figure 2 is somewhat unclear. In panel (b) are they stacked aircraft liquid and ice water paths that add up to the total water path? Or do they represent separate traces with the ice water path actually larger than the liquid water path? The blue and white legend just to the right of panel (b) appears to belong to panel (d). Maybe it should be moved underneath panel (d). The color bar at the bottom of the panel (c) plotting area is described as indicating periods of applicable dropsondes (line 243). Is there any significance to the colors?*

The liquid and ice water path in panel (b) are stacked and together add up to the total water path. We agree that this does not necessarily become clear, because the turquoise line on top of the blue area, representing the total water path, is not well visible. Therefore, we made the colored areas fainter such that the TWP line becomes clearer. Additionally, we clarified this issue in the figure caption: "**(b) Total CWP from aircraft and satellite observations, where the former is split into LWP and IWP (stacked bars) ...**".

There is no physical significance of the colors in panel (c), but each color represents a different dropsonde profile (the spatially closest one) that is used for simulation at the corresponding data points. The launch locations of these dropsondes are indicated by the identically colored dots in panel (d). Actually, the last sentence of the figure caption should make this clear. Nevertheless, we revised this sentence slightly: "**Dropsonde profiles represented by colored dots serve as simulation input for the data points of the cloud wall segments highlighted with identical color in (d) or at the bottom of (c).**" Additionally, we revised the corresponding sentence in the text: "**For the example case, Fig. 2d shows the dropsonde locations as colored dots and highlights the wall segments with the color of the assigned profile, which is repeated at the bottom of Fig. 2c.**" (lines 244–245).

We also tried to consider your further suggestions and updated the figure. The new version is shown here:



5. *Line 186. What is meant by "among manifold other in situ cloud probes"? Does it mean several other cloud probes? Or cloud probes on the aircraft's intake manifold?*

We mean that the aircraft was equipped with several other cloud probes besides the ones considered for the analysis. Accordingly, we replaced "**among manifold**" by "**beside several**" in the relevant sentence (lines 188–189).

6. *Line 189. Please clarify the sentence as "determine the size of large particles up to 1280 mm. with a resolution of 10 mm..."*

Thanks for this suggestion. Based thereon, we modified the sentence as follows: "**The 2D-GRAY is an optical array probe producing gray-scale images, which are used to determine the size of cloud particles up to 1280 µm at a resolution of 10 µm.**" (lines 191–193)

7. *Line 270. "Cloud-induced modifications of the spectral albedo are not corrected for..." This needs some clarification. Surface albedo measured under clouds will be larger than under clear skies, because clouds substantially attenuate near-infrared irradiance compared with the equivalent cloud-free atmosphere (for recent examples, see Lubin et al., 2023, Journal of Climate, JCLI-D-22-0731.1). The correct spectral surface albedo to use as the boundary condition in a radiative transfer model (for clear or cloudy conditions) is the surface albedo measured under clear skies.*

It is true that the <u>broadband</u> sea ice albedo in the Arctic is usually larger under cloudy compared to cloud-free conditions, because the extinction of the spectral downward irradiance by the clouds is stronger in the near-infrared than in the visible wavelength range. As the broadband albedo α_{BB} is a weighted average of the spectral albedo α_λ over wavelength λ and the spectral downward irradiance $F_\lambda^\downarrow$ serves as weighting function, with

$$\alpha_{\mathrm{BB}} = \frac{\int \alpha_\lambda \cdot F_\lambda^\downarrow \, \mathrm{d}\lambda}{\int F_\lambda^\downarrow \, \mathrm{d}\lambda},$$

this effect gives a higher weight to the relatively large spectral albedo in the visible range and increases the broadband albedo. However, this broadband albedo change is implicitly considered when calculating the CRE, because we use an albedo spectrum as simulation input. The downward irradiance resulting from the simulations depends on the presence or absence of clouds anyway. Therefore, also the broadband albedo derived from the simulations differs between cloudy and cloud-free state.

Nevertheless, there is a second effect modifying the spectral albedo between cloudy and cloud-free conditions. This is the neglected effect we are referring to in the manuscript. Due to the scattering geometry at the surface, the hemispherically integrated amount of reflected radiation (upward irradiance) and, thus, the albedo depends on the hemispherical distribution of the incident radiation (downward irradiance). This distribution is determined by solar zenith angle (SZA) and diffuse fraction of the downward irradiance. As the illumination is diffuse under clouds, there is an SZA-dependent change in spectral albedo between cloudy and cloud-free conditions. Mostly, the spectral albedo is lower under Arctic clouds, especially in the near-infrared or for darker ice surfaces (see Fig. 3 in Stapf et al., 2020). However, we did not correct the spectral albedo measured under cloudy conditions for this effect, as a correction might be erroneous and because the albedo difference in the visible wavelengths, where the spectral weighting is highest, is relatively low, at least over snow-covered sea ice (Fig. 3 in Stapf et al., 2020).

The associated sentence in the manuscript is replaced by the following passage: "**Although the diffuse- versus direct-dominated illumination modifies the spectral albedo between cloudy and cloud-free conditions (Stapf et al., 2020), this effect is neglected here because its strength is difficult to quantify and would have induced additional uncertainties. In contrast, the effect of the spectrally non-uniform extinction of the downward irradiance by clouds, which usually increases the broadband surface albedo in cloudy conditions (e. g., Lubin et al., 2023), is implicitly considered by the simulations.**" (lines 273–277)

8. *Paragraph comprising lines 277-292. This is the most important clarification needed, as it has a direct bearing on the most important conclusion. In this description of how the satellite algorithms treat the surface albedo over sea ice, there is no mention of how the sea ice concentration is specified. If I were to naïvely design a satellite cloud and SRB retrieval algorithm for use over sea ice, I would start with passive microwave sea ice concentration retrievals from SSM/I etc., available basically since the start of the modern satellite era (and sometimes estimating sea ice type), and then parameterize the albedo as a mixture of open water and ice (and maybe ice type based on well-known field measurements by Grenfell, Perovich and others). Perhaps some refinements could involve reanalysis estimates of recent precipitation. Do these algorithms do anything like this - involving an actual observation of sea ice? Or are they just some sort of climatological parameterization? I don't see how "a rough melt parameterization that depends on the day of the year" (line 280) has any realism without a defensible value of the sea ice concentration. It is important to understand exactly how the satellite retrievals' handling of sea ice works, because the spectral albedos they use (Figures 3 and 6) are substantially too low.*

The albedo product used for the satellite retrievals considers sea ice concentration, which is obtained from GEOS-IT and interpolated onto the pixel grid of each satellite granule. The surface albedo is then calculated as a linear combination of sea ice and open ocean albedos, weighted by the sea ice concentration. The inclusion of the sea ice concentration is mentioned in our manuscript: "**For pixels with mixed surface type coverage, the albedo additionally accounts for the sea ice concentration from the GEOS product for instrument teams (GEOS-IT).**" However, we agree that the description on the surface albedo can be improved in the text (see below).

It is important to note that we did not directly calculate the sea ice albedo here. Instead, this study used the surface albedo data assumed in the MODIS/VIIRS cloud products, which were provided by the algorithm team. Their parameterization of the sea ice albedo does not directly involve observations of sea ice, but only statistics of satellite observations over permanent snow/ice. Different ice types are only broadly considered using a season-dependent albedo scaling to account for sea ice melt ("rough melt parameterization"), but are not based on field measurements. Furthermore, a parameterization of snow grain size using precipitation data is not applied. Our purpose here is not to improve the representation of sea ice albedo in the MODIS/VIIRS cloud products, but to evaluate the existing spectral albedo assumptions against data from ARCSIX and to determine the implications on calculations of cloud radiative effects. Nevertheless, we appreciate the reviewer's suggestion for considering field observations, which could serve as a starting point for further studies. Concrete investigations using ARCSIX observations are already planned by the science team. That said, the results of this study can provide guidance for improving the sea ice albedo assumptions in cloud retrievals, which we discuss in the conclusion of the manuscript (see below).

To clarify the description of the albedo product, we revised the first half of the paragraph as follows: "**Currently operational satellite products do not retrieve multi-spectral surface albedo values over sea ice. Therefore, and to be consistent with the MODIS and VIIRS cloud products applied for the CRE calculation, this study uses the same pixel-level albedo data that are specifically assumed in the MOD06/MYD06 and CLDPROP cloud retrievals. These data were provided by the MODIS/VIIRS cloud product algorithm team and comprise the following features. Over land surfaces, the albedo values are directly taken from the kernel-based MODIS MCD43 product, while operational MCD43 data are not available over sea ice and ice-free ocean. Hence, the spectral sea ice albedo within each MODIS channel is represented by a five-year average of MCD43 white-sky albedo data over permanently snow-covered land surfaces (Moody et al., 2007). To account for sea ice melt, these statistical values are multiplied by a scaling factor that depends on the day of the year and is constant throughout all channels. While this scaling factor equals unity outside the melt season, it is reduced to 0.8 from June through August. During 10-day transition periods in late May and early September, the scaling factor linearly changes from unity to 0.8 and vice versa. The surface albedo assumed for the MODIS and VIIRS cloud products explicitly accounts for sea ice concentration by linearly combining the sea ice albedo described above and the open ocean albedo, which is assumed to be 0.05 and lambertian. This sea ice concentration data is taken from the GEOS product for instrument teams (GEOS-IT).**" (lines 282–294)

The discussion regarding the issues of surface albedo representation added to our revised conclusions section reads as follows: "**Representing the sea ice albedo by spatially invariant, season-dependent statistical values, similar to the approach applied in Kay and L'Ecuyer (2013), to parameterize sea ice melt does not account for regionally distinct effects or specific synoptic conditions that differ interannually. Although an underestimation of sea ice albedo is not unique to this study and was similarly noticed in CERES observations and different**

climate models (Huang et al., 2022; Kim and Taylor, 2026), the present study quantifies the radiative impact of the surface albedo uncertainty, which has implications on the accuracy of the surface albedo feedback and, thus, the strength of Arctic amplification. Additionally, satellite retrievals of cloud properties suffer from the surface albedo misrepresentation. These implications demand an improvement of the satellite-derived albedo over snow-covered areas to accurately represent spatial and temporal surface albedo variability. Jiao et al. (2019) developed a dedicated snow kernel to complement kernel-based retrievals of spectral surface albedo. Although their approach is not yet operational, it yields improved albedo values over snow surfaces as compared to current retrieval methods (Ding et al., 2019). In this sense, the ARCSIX field observations have immense potential for improving the representation of snow metamorphism, sea ice melt, or melt pond formation for more accurate estimates and predictions of sea ice properties." (lines 559–670)

Added literature:

- Persson et al. (2002): https://doi.org/10.1029/2000JC000705
- Spreen et al. (2008): https://doi.org/10.1029/2005JC003384
- Kay and L'Ecuyer (2013): https://doi.org/10.1002/jgrd.50489
- Jiao et al. (2019): https://doi.org/10.1016/j.rse.2018.11.001
- Ding et al. (2019): https://doi.org/10.3390/rs11131611