Responses to reviewer's comments about the manuscript, entitled "Enhanced MOIDS-derived ice physical properties within CoLM revealing bare ice-snow-albedo feedback over Greenland" (EGUSPHERE -2025-230)

General comments

This paper examines the extent to which accounting for the physical properties of ice in areas of exposed bare ice on the Greenland ice sheet affects the albedo and surface air temperature as well as the extent of snow cover via what they call the ice-snow-albedo feedback. The work is based on the use of a SNICAR-ADv4 radiative transfer model (which explicitly represents the optical properties of snow and ice, taking into account several species of light-absorbing constituents) implemented in the CoLM surface model. It also takes advantage of MODIS products combined with data quality-indices to provide more reliable physical properties of bare ice that are used as inputs to SNICAR-ADv4. The simulation results are compared with those from an earlier version of SNICAR (SNICAR-AD), which uses constant ice albedo values. Comparison of the results from the two SNICAR versions allows to assess the importance of changes in ice properties (i.e. bare ice metamorphism) on the albedo and the surface climate.

The method does not appear to be novel as it is similar to that proposed by Wicker-Clarke et al. (2024), albeit with the Energy Exascale Earth System Model (E3ESM) rather than CoLM. A similar study has also been conducted by Antwerpen et al. (2022). You mention that you added quality-information regarding MODIS products. However, both Wicker-Clarke et al. (2024) and Antwerpen et al. (2022) excluded some pixels from the analysis and filtered data. Wouldn't this be a way of adding quality information? However, I acknowledge that the evolution of Greenland is a growing matter of concern with increasing mass losses now dominated by changes in surface mass balance (SMB). SMB is strongly dependent on surface albedo which is expected to decrease in response to surface meting and increase in the extent of darken areas. It is therefore of primary importance to investigate the response of a variety of models to surface processes including bare ice metamorphism. This is why, I recommend the publication of this paper after major (and minor) comments (see below) have been addressed.

Responses: We greatly appreciate your thorough evaluation and constructive feedback on our study. They are very helpful for improving our manuscript. We carefully revised the manuscript according to these comments. Our point-by-point responses are detailed below.

Major comments

1/ First of all, I found that the methodology is not sufficiently explained. This is detrimental for the overall understanding of the paper. I had to read the paper several times. I had to read Section 2 several times to understand the whole procedure. In my opinion, part of the problem is that the description of the method closely resembles that described in Wicker-Clarke et al (2024) but with the removal of a certain amount of information that would have been necessary for a full understanding of the method. More details should also be given about the different models used in this study. A number of things are not very clear:

i/ Which variables are simulated by CoLM and and for this study? It seems to me that this is not clearly stated anywhere. Is it albedo, but I thought that the albedo was calculated by SNICAR?

Responses: Thanks for your questions. In this study, we analyzed output variables from three sets of CoLM simulations: (1) those using SNICAR-AD with fixed bare ice albedo (0.6 for visible and 0.4 for near-infrared), (2) those using SNICAR-ADv4 with annually-varying bare ice properties and (3) those using SNICAR-ADv4 with fixed bare ice properties (2000 values). The simulations output two variable groups: (a) surface albedo (visible, near-infrared, and shortwave under direct radiation) and bare ice fraction for albedo evaluation; (b) 2-m temperature, snow cover fraction and snow water equivalent to quantify the effect from the bare ice metamorphism. These clarifications have been incorporated into Section 2.4 (Model Simulations) of the revised manuscript.

All of the aforementioned variables are output by the CoLM (Figs. 5-9 of the original manuscript), while the variables such as band 2, visible and near-infrared albedo from standalone SNICAR-AD (Figs. 2 and 3 of the original manuscript) are solely used for generating lookup tables and obtaining MODIS-informed bare ice physical properties of the GrIS.

ii/ Why is the BATS scheme mentioned (at the same level as SNICAR) whereas you never refer to in the rest of the paper? Mentioning the BATS scheme adds to the confusion.

Responses: Thanks for your question. The reference to the BATS scheme was inadvertently included in our initial draft but does not contribute to the current analysis of our study. We have now removed all mentions of BATS throughout the manuscript to eliminate any potential confusion and maintain focus on the CoLM SNICAR-AD/SNICAR-ADv4.

My recommendation is therefore to clearly explain the functionalities of each of the models used in this study: SNICAR-AD, SNICAR-ADv4 and CoLM. In fact, in the current version of the paper, I have the feeling that the information is diluted in various places or that it arrives too late. To make things clearer, a scheme similar to that of Figure 10 could be incorporated in Section 2 (obviously without the panel illustrating the ice-snow-albedo feedback).

Responses: We sincerely appreciate this valuable suggestion. To clarify, we have thoroughly restructured Section 2 to provide concise, focused descriptions of SNICAR-AD, SNICAR-ADv4, and CoLM functionalities. Detailed revisions are presented in Section 2 (beginning on page 5 of this file). We relocated the model schematic (originally Fig. 10) to Section 2 as the new Fig. 1, now excluding the ice-snow-albedo feedback components. These modifications allow readers to immediately understand how CoLM SNICAR-AD and SNICAR-ADv4 simulate snow and ice albedo without consulting later sections.

This would also offer the opportunity to briefly present the physical processes associated with the evolution of the snowpack, such as compaction and refreezing, among others (see for example Flanner and Zender, 2005). This aspect is important because it is involved in the ice-snow-albedo feedback highlighted in the present paper.

Responses: Thank you for the valuable suggestion. The physical processes associated with the evolution of the snowpack, such as compaction and refreezing, are indeed important components of the ice-snow-albedo feedback. These processes were covered in the second-to-last paragraph of Section 4 Conclusions and Discussion (the font color was marked in red), as shown below:

Our findings also highlight the role of the bare ice-albedo feedback linked to changes in ice surface properties, as shown in Fig. 11. A marked reduction in snow cover occurred due to lowered albedo in the ablation zone, exposing more bare ice and further reducing regional albedo, especially in northern GrIS. This agrees with previous findings that increased bare ice exposure has intensified the snow-albedo feedback in this region, with its strength rising by 51% from 2001 to 2017 (Ryan et al., 2019). The physical processes governing snowpack evolution play a crucial role in modulating surface albedo and associated feedbacks, particularly in the ablation zone of the GrIS, where snow loss accelerates bare ice exposure and amplifies radiative forcing. More specifically, new snow quickly loses reflectivity through grain growth and vapor diffusion, with subsequent changes driven by temperature gradients and compaction (Flanner and Zender, 2006). Meltwater accelerates these processes through melt-refreeze cycles (Brun 1989), creating a self-reinforcing system where both ice exposure and snow aging enhance surface darkening. While biological and hydrological factors such as algal growth play a secondary role in ice darkening (Ryan et al., 2019), our results demonstrate that changes in bare ice properties, particularly a downward trend in specific surface area at a rate of -0.007 yr^{-1}, exert significant control over meltwater production. We collectively term these processes of the variation in the bare ice albedo associated with snow melting the bare ice-snow-albedo feedback (Fig. 11). As rising temperatures may further reduce ice albedo, this feedback could substantially increase Greenland's contribution to sea level rise through enhanced melting (Ryan et al., 2019), highlighting the need for improved process understanding in climate projections.

References:

Flanner, M. G., and Zender, C. S. Linking snowpack microphysics and albedo evolution, J. Geophys. Res., 111(D12), https://doi.org/10.1029/2005JD006834, 2006.

Brun, E.: Investigation of wet-snow metamorphism in respect of liquid-water content, Ann. Glaciol., 13, 22–26, https://doi.org/10.3189/S0260305500007635, 1989.

Ryan, J. C., Smith, L. C., van As, D., Cooley, S. W., Cooper, M. G., Pitcher, L. H., and Hubbard, A.: Greenland Ice Sheet surface melt amplified by snowline migration and bare ice exposure, Sci. Adv., 5(3), eaav3738, https://doi.org/10.1126/sciadv.aav3738, 2019.

In the introduction, you also mention that the vertical profile of snow grain size as well as snow thickness are considered as input variables of the SNICAR model. If so, where do these input data come from? On the other hand, it seems to me that the snowpack model should be able to simulate these variables itself. They should therefore be considered as output variables. Can you clarify or comment please?

Responses: We sincerely appreciate your insightful comments. You are absolutely correct that these variables are simulated within CoLM's snowpack physics routines. To clarify their dual roles: (i) they are prognostic variables calculated by the snowpack model at each timestep, while (ii) functionally serving as inputs to the embedded SNICAR radiative transfer subroutine for snow albedo computations. This integrated architecture ensures physical consistency between snow evolution and albedo calculations.

Overall, I suggest to reorganize Section 2 (while addressing the above comments) as follows: Section 2.1: Snow and ice albedo schemes / Section 2.2: Data / Section 2.3: Method / Section 2.4: CoLM simulation

Responses: We sincerely appreciate your insightful suggestions for improving the manuscript's organization. Following your recommendation, we have completely restructured Section 2 as follows:

2 Models, Data, and Methods

2.1 Snow and Ice Albedo Scheme

This study utilizes two distinct implementations of the SNICAR model within the CoLM for snow and ice albedo simulations: (i) the baseline SNICAR-AD version (Dang et al., 2019) and (ii) the enhanced SNICAR-ADv4 version (Whicker-Clarke et al., 2024). Both versions adopt identical snow albedo algorithms but exhibit distinct ice albedo treatments. Specifically, as shown in Figs. R1a and b, the SNICAR-ADv4 accounts for radiative transfer through the ice column, while the SNICAR-AD prescribes ice albedo as constant values: 0.6 for visible (VIS: 0.3–0.7 μm) and 0.4 for near-infrared (NIR: 0.7–5.0 μm) bands. The snow albedo scheme of SNICAR-AD/SNICAR-ADv4 in the CoLM computes snow albedo for the multi-layer (up to 5 layers) snowpack with the two stream radiative transfer scheme of the delta-Eddington approximation and adding-doubling technique, accounting for the effects of snow properties (e.g., size and shape) and LAC contamination on snow albedo.

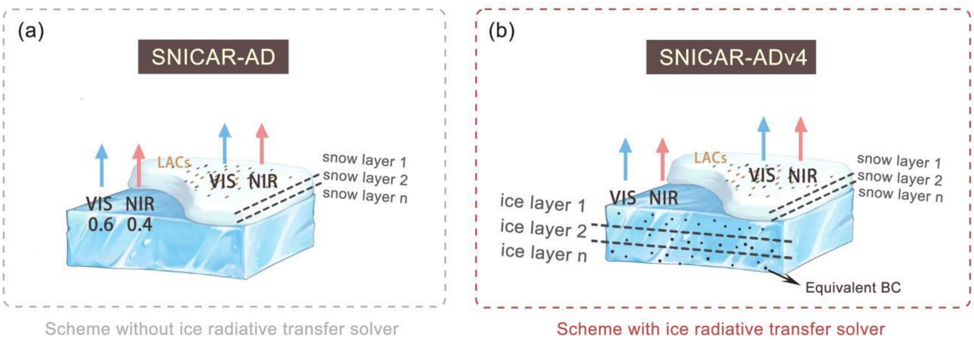

Figure R1. Schematic representation of the snow and land ice column in CoLM SNICAR-AD and SNICAR-ADv4.

For snow albedo simulation, the SNICAR-AD/SNIACR-ADv4 embedded in CoLM uses the physical properties of the snowpack and albedo of the top layer of the underlying ground to determine the column albedo (Flanner and Zender, 2006). The input variables consist of direct and diffuse radiation, the surface downward solar spectrum, the solar zenith angle (for direct radiation), the ground albedo beneath the snowpack, vertical profiles of snow grain size, snow layer thickness and density, aerosol concentrations of each snow layer, as well as the optical properties of both snow and aerosols. Meanwhile, parameterizations for snow grain shapes (sphere, spheroid, hexagonal plate, and Koch snowflake) and LACs-snow mixing states (BC/dust externally or internally mixed with snow grains) are included to improve the simulations of snow surface energy and water balances (Hao et al., 2023).

For ice albedo modeling, the advent of the SNICAR-ADv4 enables us to explore the regional climatic response induced by changes in ice albedo using the ice microphysical properties derived from satellite products. As proposed by Whicker-Clarke et al. (2024), the radiation transfer process within the ice layer can be calculated in the land surface model, which requires input variables such as ice density, air bubble effective radii within the ice, equivalent BC concentrations, and downward solar spectra. The need for air bubble parameters arises from the representation of ice layers as collections of independently scattering air bubbles within a solid ice medium in SNICAR-ADv4, while snow layers are treated as independently scattering ice crystals in an air medium (Picard et al., 2016; Whicker-Clarke et al., 2022).

1.1 Data

MODIS MCD12C1, MOD09CMG, and MOD10C1 products with consistent 0.05° spatial resolution were utilized for GrIS bare ice monitoring during the summer melt seasons of 2000-2020. The MCD12C1 Version 6.1 annual land cover type product (Friedl et al., 2010) provided initial cryospheric classification by excluding grids not categorized as snow or ice. The MOD09CMG (Vermote 2021) band 2 reflectance (0.841–0.876 μm) was employed for bare ice-snow discrimination, where pixels with reflectance values below 0.6 were classified as bare ice. Comparative spectral analysis of MODIS imagery by Shimada et al. (2016) revealed markedly greater surface reflectance in snow-covered pixels relative to bare ice across all spectral bands, with maximal contrast observed at 0.86 μm. The robustness of this threshold was confirmed by Antwerpen et al. (2022) through comparison with Landsat 8 OLI

(Operational Land Imager), with a relative error of 0.16%. The MOD10C1 product was further used to exclude pixels with cloud obstruction percentage exceeding 90% or snow cover fraction above 90% (Antwerpen et al., 2022; Whicker-Clarke et al., 2024). The derived bare ice extent was filtered by excluding pixels above the mean equilibrium line altitude of 1679 m a.s.l., defined as the 95th percentile of ablation zone elevations. This conservative threshold minimizes sporadic high-elevation detections while maintaining robust estimation of the mean equilibrium line altitude (Antwerpen et al., 2022).

The MODIS MCD43C3 product (Schaaf et al., 2002) is used to retrieve bare ice physical properties by using standalone SNICAR-ADv4 and evaluate CoLM-simulated albedo over the GrIS bare ice regions. This daily product provides spectral (MODIS bands 1 to 7) and broadband (VIS 0.3–0.7 μm, NIR 0.7–5.0 μm and shortwave 0.3–5.0 μm) black-sky albedo (BSA) and white-sky albedo (WSA) at local solar noon, derived from 16 days of Aqua-Terra merged surface albedo dataset based on the bidirectional reflectance distribution function (BRDF) algorithm (Schaaf and Wang, 2021). Among the GLASS-AVHRR and C3S-v2 albedo products, MCD43C3 stands out as the most reliable for monitoring snow albedo, exhibiting the lowest bias and RMSE over snow and consistent performance across diverse snow cover conditions (Urraca et al., 2022). In the GrIS, MCD43A3 was found to outperform the GLASS albedo product and even the reconstructed albedo based on the MOD10A1, for the sites located in the GrIS ablation zone (Ye et al., 2023).

Considering the little difference between BSA and WSA for a typical summer day, using BSA is considered acceptable for analyzing the GrIS during the summer (Alexander et al., 2014; Stroeve et al., 2005). The extracted variables in this study from MODIS MCD43C3 include Band 2 BSA, broadband BSA (visible, near-infrared and shortwave), along with local noon solar zenith angles (SZAs) and albedo quality index. The MCD43C3 albedo quality index helps identify regions with cloud cover contamination, detrimental atmospheric conditions, or insufficient observational data. Figure R2a shows the daily variation of the regionally weighted average SZA over Greenland during May-September. The period with SZA>70° occurs primarily in September. For the relationship between the SZAs of MCD43C3 and their spatiotemporally corresponding albedo quality index (Fig. R2b), it can be seen that the percentage of low-quality indices (4 and 5) rises drastically as the SZA increases at higher SZA. Therefore, we excluded albedo values identified with a low-quality index when the SZA exceeded 70° to derive more reliable satellite-retrieved bare ice physical properties.

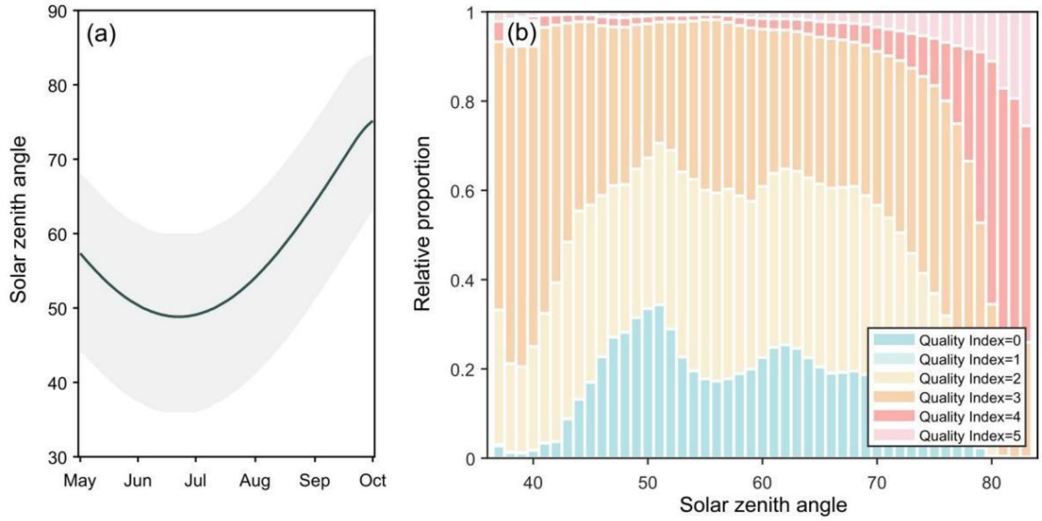

Figure R2. Regional-weighted mean SZAs of Greenland at local noon from May to September (a; solid line). Grey shaded area represents the range of SZAs over Greenland. Relative proportion of the quality index of MCD43C3 albedo dataset under different SZAs over Greenland during May to September (b; 0 for best quality and 5 for poorest quality)

1.2 Method

The method for obtaining ice physical properties (ice density, air bubble effective radius and equivalent BC) from MODIS bare ice albedo involves two main steps (Whicker-Clarke et al., 2024). First, as detailed in Section 2.2, bare ice spatiotemporal distribution was determined through the integrated use of MODIS products, employing MCD12C1 to exclude non-cryospheric pixels, MOD09CMG to distinguish bare ice from snow cover, and MOD10C1 to apply snow and cloud masking. Second, the bare ice physical properties (ice density and air bubble effective radius) are retrieved using MCD43A3 band 2 BSA and its corresponding SZA to match the closest physical properties within the precomputed lookup table by standalone SNICAR-ADv4 model. Notably, this step derives only ice density and air bubble effective radius, whereas equivalent black carbon (BC) concentration requires additional processing steps described later in this section. After obtaining all bare ice physical properties (ice density, air bubble effective radius, and equivalent BC concentration), we upscaled the data from a spatial resolution of 0.05°×0.05° to 0.5°×0.5°.

The lookup table was generated using the standalone SNICAR-ADv4 radiative transfer model by testing a range of parameter combinations within physically constrained ranges, including ice density (650-916 kg·m^{-3}) and air bubble radii (100-1500 μm), as well as the SZAs spanning 35° to 75° to represent typical local noon conditions across the GrIS grid cells. Ice with densities above 650 kg·m^{-3} is conventionally classified as cryospheric media, consistent with in situ measurements (Whicker-Clarke et al., 2022). However, because the density-bubble radius relationship for GrIS bare ice remains poorly constrained, we apply a linear density-radius relationship as a first-order approximation for calculating the specific surface area (SSA), where densities of 650 kg·m^{-3} and 916 kg·m^{-3} corresponding to bubble radii of 50 μm and 1500 μm, respectively (Fig. R3a). This parameterization awaits future observational validation. For each parameter combination, the band 2 albedo, specific surface area (SSA) and the volume fraction of air (V_{air}) were then output by the standalone SNICAR-ADv4. The SSA is a measure of the total surface area of ice-air interfaces relative to the ice mass. The relationship between the SSA (α, units: m^2·kg^{-1}) and ice density and air bubble effective radius is given by Eq.1, where ρ_{blk} is layer bulk ice density used to calculate the volume fraction of air (Eq.2).

$$\alpha = \frac{3V_{air}}{\rho_{blk}R_{eff}} \qquad \text{(Eq. 1)}$$

$$V_{air} = \frac{\rho_{ice}-\rho_{blk}}{\rho_{ice}} \qquad \text{(Eq. 2)}$$

Figure 3b shows the band 2 albedo from the SNICAR-ADv4 lookup table as a function of SSA. This functional degeneracy indicates that the radiative transfer modeling depends primarily on the SSA rather than the specific ice density/bubble size combination. Consequently, the retrieval algorithm selects the (density, radius) combination that most closely reproduces the observed Band 2 albedo. Since MCD43C3 provides the band 2 albedo and SZA for each bare ice grid cell, the corresponding bare ice physical properties can be inferred from the lookup table. It is important to note, however, the resulting bare ice property maps (Figs. 3c-f) represent just one plausible solution among several combinations that could yield similar SSA and albedo values.

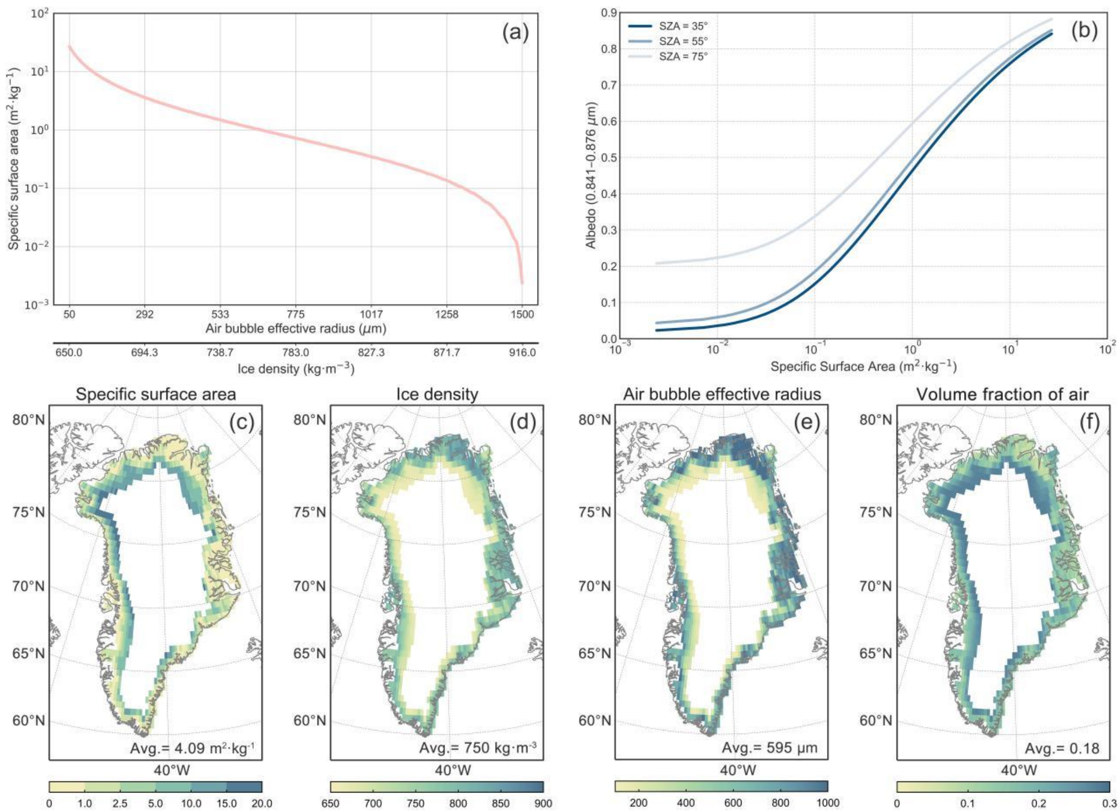

Figure R3. The relationship between ice specific surface area (SSA; $m^2 \cdot kg^{-1}$), air bubble effective radius (μm) and ice density ($kg \cdot m^{-3}$) under a linear density-radius relationship (a first-order approximation) assumed in this study (a). MCD43C3 band 2 (0.841-0.876 μm) albedo as a function of SSA and solar zenith angle (b). Spatial distribution of JJA (c) specific surface area ($m^2 \cdot kg^{-1}$), (d) ice density ($kg \cdot m^{-3}$), (e) air bubble effective radius (μm) and (f) volume fraction of air in the period of 2000-2020.

After acquisition of the daily ice density and air bubble effective radius of the GrIS (Figs. R3d and 2e), we again employed the standalone SNICAR-ADv4 model to simulate the NIR and visible albedo for each bare ice grid cell of the GrIS. Using an iterative optimization approach, we derived the equivalent BC concentration by adjusting the BC input parameter in the standalone SNICAR-ADv4 until its simulated visible albedo matched the MODIS MCD43C3 observations. This inversion method relies on the strong influence of LACs on visible albedo and their negligible impact on NIR albedo over bare ice (Schneider et al., 2019). As seen in Figs. R4a-c, there is minimal difference in the albedo in the NIR band, with a slight underestimation of 0.029 by the standalone SNICAR-ADv4. In contrast, the SNICAR-ADv4 significantly overestimated the visible albedo by up to 0.293 when using these bare ice properties, as it did not account for the LACs (Figs. R3d-f). We incrementally adjusted the input BC concentration in the standalone SNICAR model to match the visible albedo values from MCD43C3 data at each GrIS bare ice grid cell (Figs. R4h and i). This process yielded the daily equivalent BC concentrations shown in Fig. R4g. Based on the MODIS data and the standalone SNICAR-ADv4 lookup table, the daily 0.5-deg ice density, air bubble effective radius and equivalent BC data were then processed into monthly timescale as input for CoLM. Besides, it is worth mentioning that not all bare ice grid cells are informed by the bare ice physical properties data in each summer month. These grid cells are filled with the climatological mean values of bare ice physical properties when retrievals fail due to clouds or poor data quality.

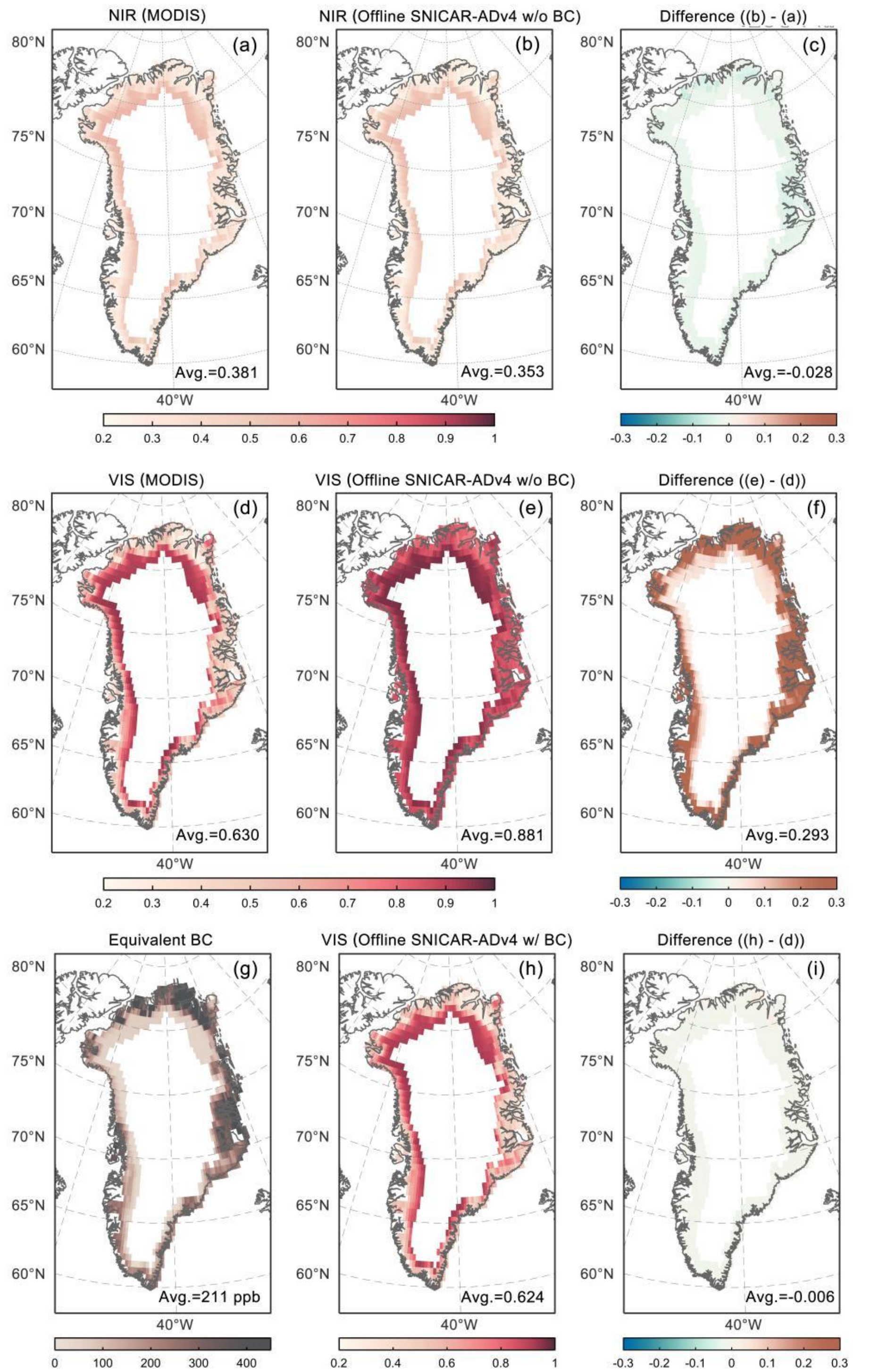

Figure R4. The spatial distributions of MODIS bare ice albedo and standalone SNICAR-ADv4 bare ice albedo excluding LACs in (a, b) near-infrared and (c, d) visible bands for the JJA from 2000 to 2020, along with (c, f) their differences. The spatial distributions of (g) equivalent black carbon, (h) the standalone SNICAR-ADv4 bare ice visible albedo with equivalent black carbon (ppb), and (i) its difference from the MODIS bare ice visible albedo.

We use the standalone SNICAR-ADv4 and briefly examine aforementioned factors influencing spectral albedo of ice with direct light conditions, including the SZA, ice density, air bubble effective radius (R_{eff}), and equivalent BC. As shown in Fig. R5a, total internal reflection occurs at wavelengths around 3μm for SZA greater than 55°, and the wavelength range for total internal reflection expands with the increases in SZAs. This phenomenon occurs for pure and smooth ice surfaces but is not representative of naturally occurring ice, which typically has impurities and rough surfaces. For the dependency of albedo on ice density, air bubble effective radius, the spectra show that the albedo declines as the ice density and air bubble radius increases since air bubbles within ice are responsible for the scattering light and smaller bubbles scatter light more efficiently in the visible and near-infrared parts of the spectrum (Figs. R5b-c). Furthermore, BC impacts ice albedo rather uniformly across the visible spectrum and has almost no impact at $\lambda > 1.0$ μm.

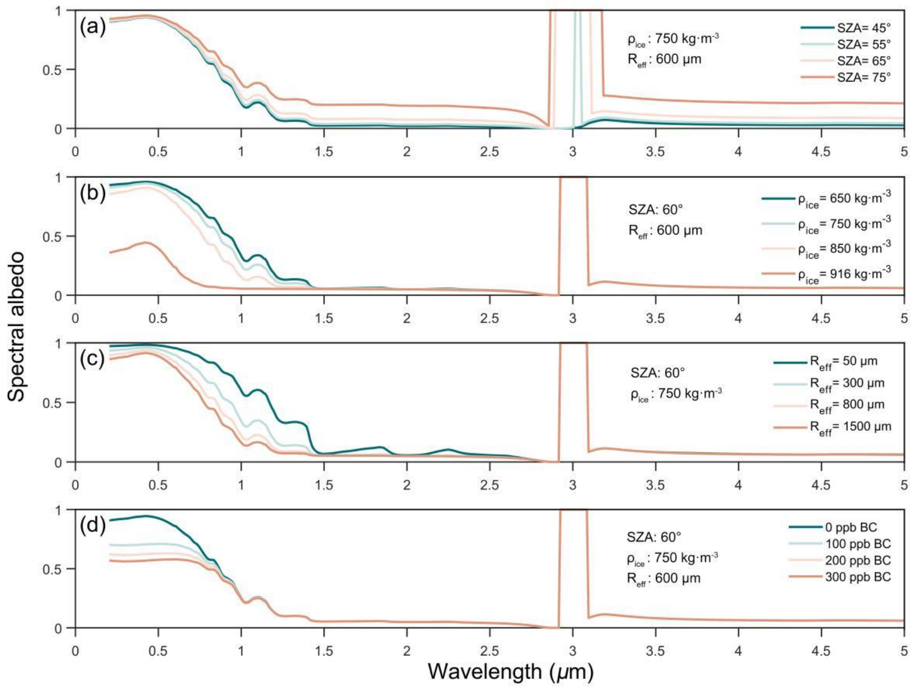

Figure R5. Spectral albedo simulated by standalone SNICAR-ADv4 under direct incident irradiance with varing (a) SZA, (b) ice density, (c) air bubble effective radius and (d) BC concentration.

1.3 Model simulation

We conduct several offline CoLM simulations with the embedded SNICAR-ADv4 and SNICAR-AD schemes on a 0.5×0.5-degree resolution driven by the atmospheric forcing from the 6-hourly European Center for Medium-Range Weather Forecast's fifth-generation atmospheric Reanalysis (ERA5) in the GrIS. Compared with other atmospheric forcings, ERA5's precipitation rates exhibit a higher correlation with measured net accumulation over the GrIS (Schneider et al., 2023). We run the model simulations for the years 1980–2020 and the summer melt season (June, July and August; JJA) during 2000-2020 is used for analysis. Aerosol concentration in the snow layer is calculated based on the prescribed monthly aerosol (BC, dust, OC) wet and dry deposition flux from the CESM2-WACCM simulations participated in CMIP6 experiments (Danabasoglu et al., 2020). The monthly bare ice properties for ice radiative transfer process are inferred from MODIS products using the standalone SNICAR-ADv4 over the bare ice region of the GrIS, covering the JJA from 2000 to 2020, as the MODIS products has been available since 2000. To prevent possible unusual model behavior when shifting bare ice albedo schemes, the bare ice properties from the summer of 2000 were used in a brief spin-up run for the variable bare ice conditions in our experimental runs from 1998 to 2000. For land ice patches informed by the ice properties, the bare ice albedo is first calculated and replaces the constant values (0.6 for VIS and 0.4 for NIR). If snow is present over the ice, the new ice albedo of underlying ice column is used as the lower boundary to calculate snow albedo. The total patch albedo is then determined by the fractional coverage of land types and snow cover.

In this study, we analyzed output variables from three sets of CoLM simulations: (1) those using SNICAR-AD with fixed bare ice albedo (0.6 for visible and 0.4 for near-infrared), (2) those using SNICAR-ADv4 with annually-varying bare ice properties and (3) those using SNICAR-ADv4 with bare ice properties held constant at year 2000 values for all years. The simulations output two variable groups: (a) surface albedo (visible, near-infrared, and shortwave under direct radiation) and bare ice fraction for albedo evaluation; (b) 2-m temperature, snow cover fraction, snow water equivalent (SWE) and surface runoff to quantify the effect from the bare ice metamorphism.

L130 (and also L154 and L203): You mention that ice albedo is 0.80 and 0.55 for VIS and NIR spectra. These values correspond more to the albedo values for fresh snow than to the albedo values for bare ice. Do SNICAR-AD-CoLM simulations actually use these values for bare ice? If so, it is not surprising that the use of SNICAR-ADv4 leads to a significant reduction in albedo. If this is the case, you should redo a SNICAR-AD-CoLM simulation with values more characteristic of those for bare ice.

Furthermore, Figure 10 shows that the ice albedo values for SNICAR-AD are 0.6 and 0.4 for VIS and NIR respectively (which seems more realistic to me). Please clarify

Responses: Thank you for your insightful comments regarding the bare ice albedo parameters. In response, we have updated all CoLM SNICAR-AD simulations with more realistic bare ice albedo values (0.60 for VIS, 0.40 for NIR), which now properly align with the original Figure 10. The revised results (Figs. R6 and R7) demonstrate that CoLM SNICAR-ADv4 still reduces the albedo overestimation compared to the CoLM SNICAR-AD, even after this parameter adjustment. All relevant sections of the manuscript and supplementary materials have been updated accordingly.

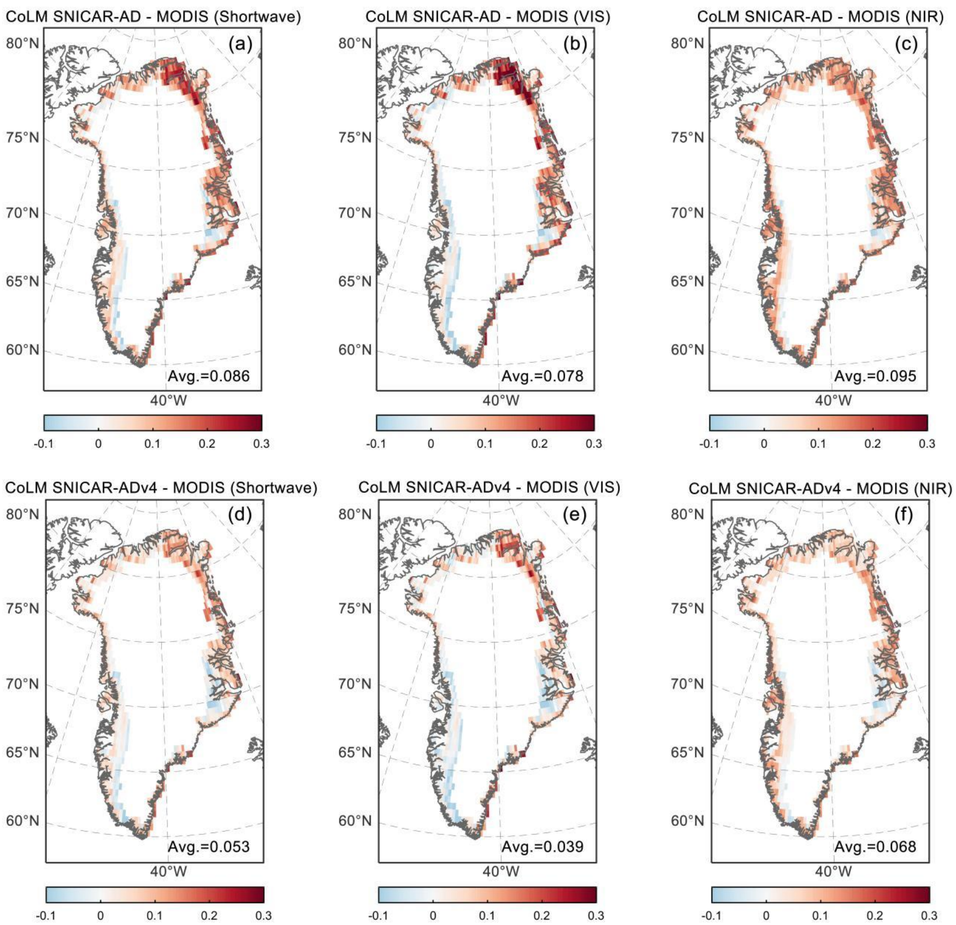

Figure R6. Spatial distribution of the difference of the 2000-2020 JJA albedo between the CoLM with different snow/ice albedo schemes (SNICAR-AD and SNICAR-ADv4) and the MCD43C3 in the (a, d) shortwave (0.3–5.0 μm), (b, e) visible (0.3–0.7 μm) and (c, f) near-infrared (0.7–5.0 μm) bands.

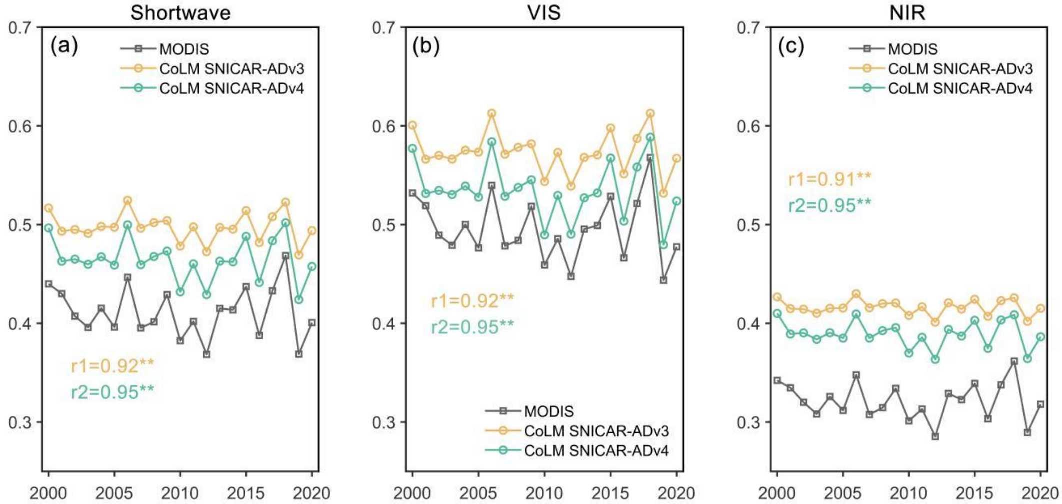

Figure R7. Time series of the 2000-2020 JJA CoLM SNICAR-AD and SNICAR-ADv4 albedo versus the MCD43C3 albedo over bare ice region, in the (a) shortwave (0.3–5.0 μm), (b) visible (0.3–0.7 μm) and (c) near-infrared (0.7–5.0 μm) bands. Double asterisks indicates significance at the 99% confidence level.

2/ My second comment is related to the effect of bare ice metamorphism on the surface ai temperature (+ 0.071°C) and on the reduction of ~1% of the snow cover. This does not seem very significant. To be more convincing, I recommend to provide additional diagnostics. As SNICAR (AD and Adv4) includes a snow scheme, I guess that all the elements are available for computing the surface mass balance and the runoff coming. This should help better quantify the actual impact of a more realistic calculation of the ice albedo.

Responses: Thank you for this insightful comment. We fully agree that further diagnostics would help clarify the physical implications of albedo changes and appreciate your suggestion regarding surface mass balance (SMB) and runoff. In response, we first revised the manuscript wording to more accurately reflect the spatial variability of the 2-m air temperature and snow cover changes, replacing terms like “pronounced” with “significant” where appropriate.

In addition, given the limitations of the current model, SMB and glacier runoff cannot be explicitly computed. The CoLM framework incorporates a thermodynamic glacier scheme that assumes fixed ice thickness and mass. Within this scheme, meltwater generated (if it occurs) from glacial ice is assumed to be fully retained in the ice column and does not contribute to runoff. This assumption precludes the SMB calculation and affects runoff interpretation. To better quantify the hydrological implications within these constraints, we conducted a diagnostic analysis of snow water equivalent (SWE), which integrates processes such as snow accumulation, retention of meltwater, and sublimation. The results indicate an average SWE reduction of 1.345 mm due to the bare ice metamorphism represented by annually varying ice properties, consistent with the decrease in snow cover. To further highlight the regional variability and covariation of key variables, we introduce a new panel (Fig. R8e) that presents the statistical distributions of differences in 2-m air temperature, snow cover, and SWE using combined boxplots, jittered points, and half-violin plots. These distributions reveal that certain regions are strongly affected by the reduced albedo. Together, these coordinated changes highlight a pronounced bare ice-snow-albedo feedback, in which darkening of the bare ice surface leads to amplified warming and accelerated snow cover depletion.

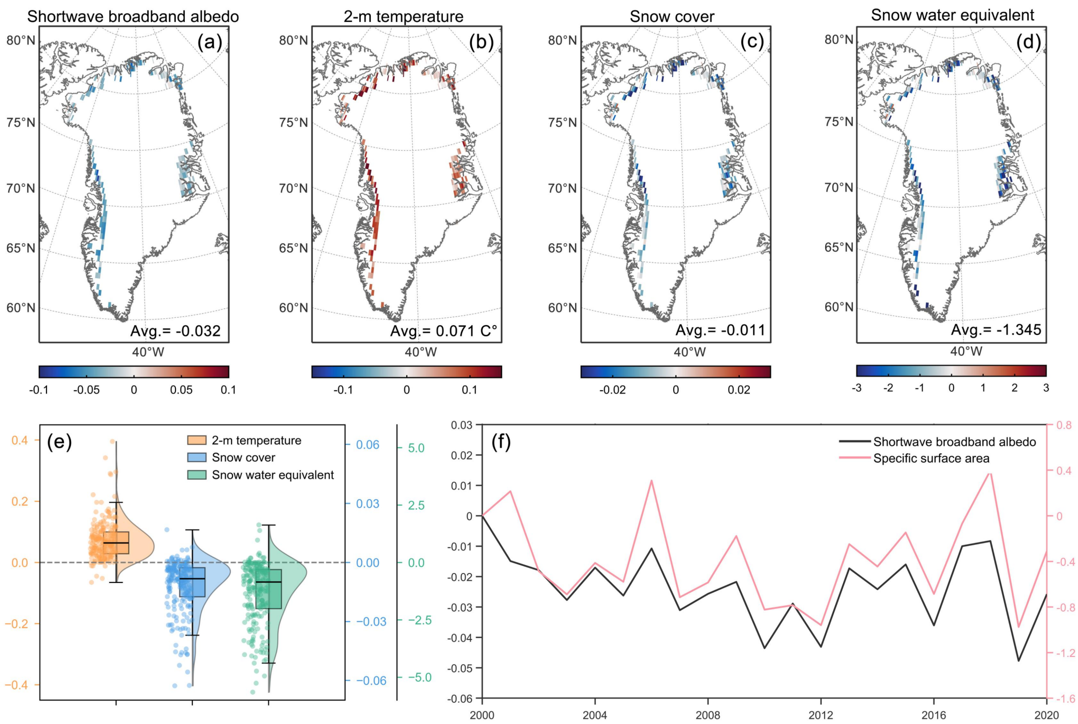

Figure R8. Spatial differences between simulations using annually varying bare ice properties and those using fixed year-2000 values during JJA (June–August) from 2000 to 2020: (a) surface albedo, (b) 2-m air temperature (°C), (c) snow cover fraction, and (d) snow water equivalent. (e) Statistical distributions of differences in 2-m air temperature, snow cover, and snow water equivalent, shown using combined boxplots, left-side jittered points, and right-side half-violin plots. (f) Time series of differences in specific surface area ($m^2 \cdot kg^{-1}$) and simulated shortwave broadband albedo between the two experiments.

Although the runoff analysis is precluded by model limitations, we examined the diagnostic output of surface runoff and found a counterintuitive reduction in runoff in most regions under the low albedo scenario. This is driven by: (i) retention of glacial meltwater in the ice layer, (ii) earlier snow depletion shortening the runoff season, and (iii) enhanced sublimation dominating local mass loss. Due to the structural limitations of the CoLM glacier scheme, we chose not to pursue detailed runoff analysis further.

We have revised Section 3.3 to incorporate these findings, and updated Section 4 to clarify the limitations associated with the glacier hydrology scheme. These updates emphasize the need for future work to couple the CoLM with a dynamic ice sheet model, which would allow more accurate SMB and ice-melt runoff simulations and thus provide a more complete picture of the GrIS mass loss response to albedo changes.

3/ The Discussion section lacks a detailed comparison with the results of Antwerpen et al. (2022) and Wicker-Clarke etal. (2024).

Responses: Thank you for your suggestion to strengthen the discussion by integrating a detailed comparison with Antwerpen et al. (2022) and Wicker-Clarke et al. (2024). In response, we have expanded our Section 4 (“Conclusions and Discussion”) to include a detailed analysis of how our results relate to the findings of Antwerpen et al. (2022) and Wicker-Clarke et al. (2024). The additional content, now forming a new paragraph, has been inserted following the first paragraph of Section 4, as shown below:

Our results are consistent with, and extend, recent progress in modeling bare ice albedo modeling over the GrIS. Antwerpen et al. (2022) demonstrated that the regional MAR model overestimated bare ice albedo by 22.8% below 70°N, leading to significant underestimation of meltwater production. Similarly, Wicker-Clarke et al. (2024) found that the global ELM-E3SM model overestimated shortwave broadband albedo by ~5% due to the use of fixed albedo parameters, and showed that incorporating more realistic bare ice albedo reduced the surface mass balance by approximately 145 Gt between 2000 and 2021. Although both studies focus on the GrIS, they differ in model structure and spatial resolution: MAR is a high-resolution regional climate model, while ELM-E3SM is part of a coarser-resolution global Earth system model. Despite these differences, both studies highlight a persistent bias—systematic overestimation of bare ice albedo. The convergence of evidence from diverse modeling frameworks underscores the need to improve bare ice representation in land surface models. Building on these insights, our study examines the role of bare ice metamorphism, particularly changes in specific surface area, in driving progressive surface darkening. By isolating the feedback between evolving ice properties and surface energy balance, we propose a physically mechanism for the observed albedo decline. Our sensitivity analysis underscores how bare ice metamorphism can influence surface energy balance and the importance of incorporating such processes in future model developments.

References:

Antwerpen, R., Tedesco, M., Fettweis, X., Alexander, P.,and vandeBerg, W. J.: Assessing bare-ice albedo simulated byMAR overthe Greenland icesheet(2000–2021) andimplications formeltwater production estimates, The Cryosphere, 16(10), 4185–4199, https://doi.org/10. 5194/tc-16-4185-2022, 2022.

Whicker-Clarke, A., Antwerpen, R., Flanner, M. G., Schneider, A., Tedesco, M., and Zender, C. S.: The effect of physically based ice radiative processes on Greenland ice sheet albedo and surface mass balance in E3SM, J. Geophys. Res.-Atmos., 129, e2023JD040241, https://doi.org/10.1029/ 2023JD040241, 2024.

Other comments:

Section 1:

1. L63-65 The sentence is too long. Please, split in two parts.
2. L63: extend → extent

Responses: Thanks for your suggestions. The revised sentence is as follows: "Fluctuations in the snowline dictate the relative extent of dark bare ice versus brighter snow (Ryan et al., 2019). These directly influence GrIS surface melt through the exposure of bare ice (Antwerpen et al., 2022) and the processes that darken bare ice itself (Chevrollier et al., 2023)."

3. L64: Surface melt is also associated with a reduction of snowpack thickness and is not only due to bare ice exposure. However, I agree with the fact that surface melting over bare ice surfaces contributes to GrIS mass loss. This should be better explained.

Responses: We sincerely appreciate your insightful comment. You highlighted that GrIS surface melt involves not only the bare ice exposure but also the reduction of snowpack thickness. In the paragraph in question, our focus was on how surface albedo influences melt processes. Compared with snowpack thinning accompanied by snow grain metamorphism and growth, the transition from snow to bare ice causes a more substantial reduction in albedo.

4. L66: was → is

Responses: Thank you for your comment. We have revised "was" to "is".

5. L73: in → over

Responses: Thank you for your comment. We have revised "in" to "over".

6. L130 (and also L154 and L203): You mention that ice albedo is 0.80 and 0.55 for VIS and NIR spectra. These values correspond more to the albedo values for fresh snow than to the albedo values for bare ice.

Responses: Thank you for pointing this out. This issue was also addressed in the major comments, and we have already provided a detailed response there. In short, we have re-run the CoLM SNICAR-AD simulations using more realistic bare ice albedo values (0.60 for VIS, 0.40 for NIR), consistent with Figure 10. The updated results (Figs. R6 and R7) confirm that SNICAR-ADv4 still improves albedo estimation. All relevant sections have been revised accordingly.

7. L136: in ablation season à during the ablation season

Responses: Revised as suggested (in ablation season → during the ablation season)

8. L145: properties

Responses: Sorry for this mistake. We have fixed it.

Section 2:

1. L151: features enhancements à "includes improvements in the representation of…" sounds better?

Responses: Thank you for this helpful suggestion. We agree that "includes improvements in the representation of..." more clearly conveys the methodological advancements. We have revised the text accordingly: "The CoLM version 2024 (CoLM 2024) used in this study is based on the CoLM 2014 and includes improvements in the representation of surface energy, hydrology, biogeochemical cycles, and anthropogenic disturbance processes."

2. L152: What are the improvements in the anthropogenic disturbances processes? Which kind of processes are you referring to?

Responses: Thank you for pointing this out. The anthropogenic disturbance improvements in CoLM 2024 include: (i) a new reservoir module (Cama-Flood-based) enhancing regulated river flow simulation, (ii) the GPAM1 crop model simulating major crops' climate responses, and (iii) the Li fire scheme replacing GlobFIRM to better capture human-influenced wildfires (Li et al., 2019). These represent part of the anthropogenic disturbance updates in the CoLM 2024, and additional improvements are documented in the CoLM technical manual (http://172.16.102.100/colm/).

References:

Li, F., M. Val Martin, M. O. Andreae, et al. (2019), Historical (1700-2012) global multi-model estimates of the fire emissions from the Fire Modeling Intercomparison Project (FireMIP), Atmospheric Chemistry and Physics, 19(19), 12,545 - 12,567, doi:10.5194/acp-19-12545-2019.

3. L155: Please remove "is"

Responses: Sorry for this mistake. We have fixed it.

4. L177: “include snow non sphericity” à include non-spherical snow grains? Maybe, you should precise (here or in Section 2.4) that you only consider spherical grains (i.e. the SSA formulation in Eq. 1 is only valuable for spherical grains).

Responses: We sincerely apologize for any confusion caused by our initial description. To clarify, the parameterization of snow grain shapes (such as spheres, spheroids, hexagonal plates, and Koch snowflakes) is applied exclusively in the snow albedo scheme and does not apply to ice albedo simulations. For the ice layer, optical properties are derived from air bubbles within the ice media and its absorptivity (Whicker-Clarke et al., 2022). In the revised manuscript, we have reorganized the description of the snow and ice albedo schemes for better clarity.

References:

Whicker-Clarke, A., Flanner, M. G., Dang, C., Zender, C. S., Cook, J. M., and Gardner, A. S.: SNICAR-ADv4: A physically based radiative transfer model to represent the spectral albedo of glacier ice, The Cryosphere, 16(4), 1197–1220, https://doi.org/10.5194/tc-16-1197-2022, 2022.

5. L182: Accounting for ice layers in SNICAR (AD and/or ADv4) comes too late

Responses: Thank you for your valuable comment. We have reorganized Section 2.1 (Snow and Ice Albedo Scheme) to introduce the description of ice layers earlier in the section, as shown in the revised Section 2.1 (beginning on page 5 of this file).

6. L188: land-only CoLM simulations? In your results section, you do not mention any land-only CoLM simulations but SNICAR-AD-CoLM simulations or SNICAR-ADv4-CoLM simulations. I guess that in this study, you do not consider ESM simulations, but the formulation “land-only CoLM simulation”seems to be a bit confusing as you consider the snow/ice albedo schemes embedded in CoLM. Please clarify.

Responses: We appreciate your attention to this detail. In this study, we conducted offline CoLM simulations driven by atmospheric forcing data, with the embedded SNICAR-AD/SNICAR-ADv4. The term "land-only" was intended to emphasize that these simulations exclude ocean or sea-ice dynamics, but we recognize that this phrasing could be misleading. Therefore, we have replaced “land-only CoLM simulations” with “offline CoLM simulations” to avoid confusion. Additionally, the phrase "offline SNICAR-ADv4" has been revised to "standalone SNICAR-ADv4" when referring to the radiative transfer model independently from CoLM.

7. L209: grids → grid cells

Responses: Thank you for your comment. We have revised "grids" to "grid cells".

8. L231: Start a new sentence after "September"

Responses: We have revised the sentence as suggested by splitting it into two statements: "Figure 2a shows the daily variation of the regionally weighted average SZA over Greenland during May–September. The period with SZA>70° occurs primarily in September." [In the revised manuscript, the original Fig. 1 has been renumbered as Fig. 2 due to the insertion of technical schematics comparing SNICAR-AD and SNICAR-ADv4 (now Fig. 1).]

9. L235: I guess that the quality index is provided in the MODIS database? Maybe, you could add a sentence like "the quality helps to identify regions with cloud cover contamination, detrimental atmospheric conditions or insufficient observation" ? Or something equivalent…

Responses: Thank you for your helpful suggestion. We have added clarification in the revised Section 2.2 regarding the source and purpose of the MODIS quality index: "The MCD43C3 albedo quality index helps identify regions with cloud cover contamination, detrimental atmospheric conditions, or insufficient observational data." The quality index from MCD43C3 is used in our study for two purposes: to retrieve bare ice physical properties and to evaluate the albedo simulations from CoLM.

10. L247: "and SZA" → What do you mean?

Responses: Thank you for raising this important clarification regarding the use of SZA in our retrieval method. To address this point, we have revised the manuscript to explicitly state that the SZA is an essential component provided by the MCD43C3 dataset, working in conjunction with the MCD43C3 band 2 BSA to retrieve bare ice physical properties. Specifically, for each bare ice grid cell, our method utilizes both the MCD43C3 band2 BSA and its corresponding SZA to match the closest physical properties within the precomputed lookup table by the standalone SNICAR-ADv4 model.

11. L248: fist → first

Responses: Apologies for the typo. We have corrected it.

12. L248: Is the cloud mask determined with the use of the quality index?

Responses: Thank you for your question regarding the cloud masking procedure. In our study, the cloud mask was generated using the cloud obscuration percentage from the MOD10A1 product, rather than the quality index from MCD43C3. Specifically, we applied a threshold where any grid cell with a cloud obscuration percentage exceeding 90% was excluded from our analysis. This approach ensures consistent cloud filtering across all MODIS data processing. We have clarified this distinction in the revised manuscript to avoid any confusion between the albedo quality control (using the MCD43C3 quality index) and the cloud masking procedure (based on MOD10A1's cloud obscuration percentage data).

13. L253: Use the same wavelength units everywhere: nm or µm.

Responses: Thanks for your suggestion. We have carefully reviewed the entire manuscript and standardized all wavelength measurements to use micrometers (µm) as the consistent unit throughout.

14. L253: Do you mean that for reflectance values below 0.6, pixels are considered to be bare ice? This does not sound very clear for me. How has this threshold been defined ?

Responses: Thanks for your questions. The threshold of reflectance below 0.6 in MOD09CMG band 2 (0.841–0.876 µm) to identify bare ice is based on prior studies by Shimada et al. (2016) and Antwerpen et al. (2022). Shimada et al. (2016) conducted a spectral analysis of MODIS imagery, which showed a clear difference in surface reflectance between snow-covered and bare ice pixels, with the greatest contrast observed at 0.86 µm (Fig. R9). Antwerpen et al. (2022) further validated this threshold through comparisons with Landsat 8 OLI, reporting a relative error of only 0.16%, confirming its robustness.

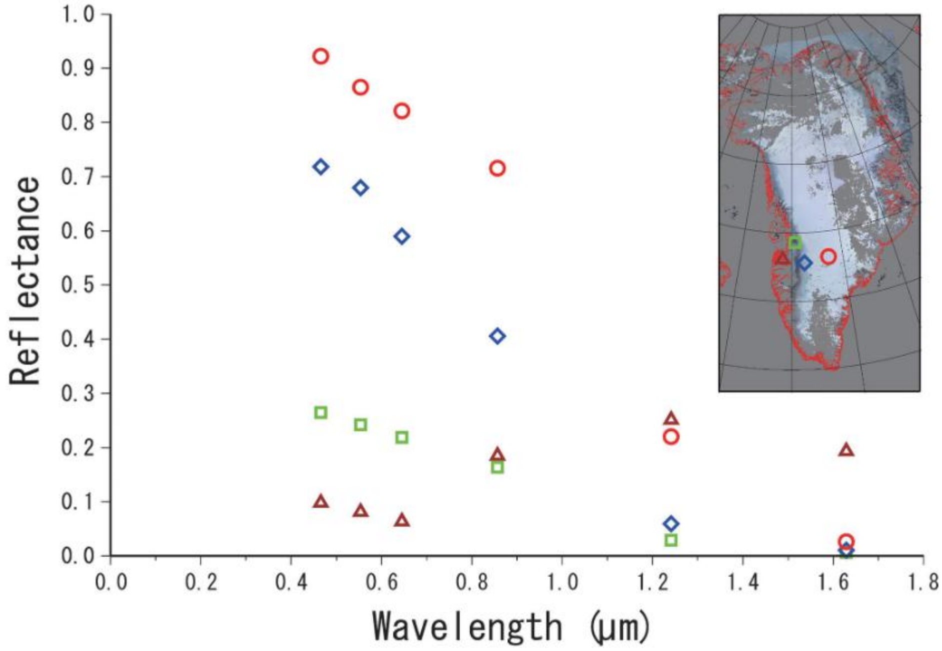

Figure R9 Spectral reflectance of snow (68∘56′33″N, 42∘27′16″W, red circle), bare ice (68∘05′10″N, 48∘01′23″W, blue diamond), dark ice (69∘32′25″N, 50∘26′56″W, green square), and bare soil (68∘23′02″N, 53∘48′13″W, brown triangle) and RGB color composite image band 1, 4, and 3 taken on 12 July 2012 derived from MODIS (Shimada et al., 2016).

References:

Shimada, R., Takeuchi, N., and Aoki, T.: Inter-annual and geographical variations in the extent of bare ice and dark ice on the Greenland ice sheet derived from MODIS satellite images, Front Earth Sci., 4, 43, https://doi.org/10.3389/feart.2016.00043, 2016.

Antwerpen, R., Tedesco, M., Fettweis, X., Alexander, P.,and vandeBerg, W. J.: Assessing bare-ice albedo simulated byMAR overthe Greenland icesheet(2000–2021) andimplications formeltwater production estimates, The Cryosphere, 16(10), 4185–4199, https://doi.org/10. 5194/tc-16-4185-2022, 2022.

15. L257-258: Explain why pixels with elevations exceeding the mean equilibrium line altitude are excluded (I guess that above a certain elevation, snow is not completely melted and therefore there is no exposed bare ice? But this could be specified).

Responses: Thanks for your request for clarification. The majority of bare ice exposures are confined to the ablation zone of the ice sheet. Following Antwerpen et al. (2022), the mean equilibrium line altitude at 1679 m a.s.l. is defined as the 95th percentile of the elevation values in the ablation zone. Taking the 95th percentile of the long-term average values supports the omission of sporadically high ablation cell detections and provides a conservative estimate of the equilibrium line altitude. The rationale behind excluding pixels above this elevation is that, in these regions, snow typically does not fully melt, and thus, bare ice is not exposed.

References:

Antwerpen, R., Tedesco, M., Fettweis, X., Alexander, P.,and vandeBerg, W. J.: Assessing bare-ice albedo simulated byMAR overthe Greenland icesheet(2000–2021) andimplications formeltwater production estimates, The Cryosphere, 16(10), 4185–4199, https://doi.org/10. 5194/tc-16-4185-2022, 2022.

16. L267: “ running offline SNICAR-ADv4 simulations ” → running offline the SNICAR-ADv4 model

Responses: Thank you for your comment. We have revised "running offline SNICAR-ADv4 simulations" to "running the standalone SNICAR-ADv4 model".

17. L267-272: This sentence is too long and is not very clear. Please better explain why do you need to adjust the input parameters. On which basis? Split the sentence in 2 or 3 parts.

Responses: Thank you for your suggestion. The input parameter adjustments serve two key purposes: First, to ensure Band 2 BSA of the lookup table range fully encompasses observed values, which requires systematically varying ice density and bubble radius in the standalone SNICAR-ADv4. Second, to establish physically meaningful parameter bounds: (1) The 650-916 kg/m³ density range reflects the transition from consolidated glacial ice (validated by measurements) to pure ice; (2) The 35°-75° SZA range covers typical GrIS local noon conditions; and (3) While SSA and albedo have a one-to-one correspondence, multiple (density, radius) combinations can yield equivalent SSA values. We therefore implement a linear density-radius relationship (50 μm at 650 kg/m³ to 1500 μm at 916 kg/m³) as a first-order approximation to resolve this degeneracy.

The revised sentence is as follows:

"The lookup table was generated using the standalone SNICAR-ADv4 radiative transfer model by testing a range of parameter combinations within physically constrained ranges, including ice density (650-916 kg·m^{-3}) and air bubble radii (100-1500 μm), as well as the SZAs spanning 35° to 75° to represent typical local noon conditions across the GrIS grid cells. Ice with densities above 650 kg·m^{-3} is conventionally classified as cryospheric media, consistent with in situ measurements (Whicker-Clarke et al., 2022). However, because the density-bubble radius relationship for GrIS bare ice remains poorly constrained, we apply a linear density-radius relationship as a first-order approximation for calculating the specific surface area (SSA), where densities of 650 kg·m^{-3} and 916 kg·m^{-3} corresponding to bubble radii of 50 μm and 1500 μm, respectively."

18. L274: ari→ air

Responses: Thank you for pointing this out. The typo has been corrected.

19. L279-280 the non-unicity of the relationship between SSA, ice density and air bubble radius should be justified/explained. It seems to me that, to the first order, pixels with larger SSA values correspond to pixels of lower density, larger Vair and smaller Reff. This defines the unicity of the relationship(?) But, maybe I missed something. In any case, this should be clarified.

Responses: We sincerely appreciate your insightful comment regarding the relationship between SSA, ice density, and bubble radius. You are absolutely right in identifying the fundamental relationship defined by the equation $\alpha = 3V_{air}/(\rho_{bulk}R_{eff})$, where $V_{air} = (\rho_{ice}-\rho_{bulk})/\rho_{ice}]$. This implies that, in most cases, larger SSA values are indeed associated with lower ice densities, higher air volume fractions, and smaller bubble radii. However, the apparent non-unicity arises because different combinations of ρ_{bulk} and R_{eff} can yield similar SSA values. For instance, a decrease in bubble radius can compensate for an increase in density, resulting in an SSA value that matches that of another, physically distinct configuration. Although the underlying equation defines a unique mathematical relationship, it does not uniquely determine the individual contributing parameters from the SSA alone without additional constraints.

We have added this clarification to Section 2.3 of the revised manuscript to prevent confusion and to explain the rationale behind our implementation of a linear density-radius relationship as a simplifying assumption.

20. L294-297: Too long sentence. Please, split in two parts.

Responses: Thank you for your suggestion. The revised sentence is as follows: "We incrementally adjusted the input BC concentration in the standalone SNICAR model to match the visible albedo values from MCD43C3 data at each GrIS bare ice grid cell (Figs. 4h and i). This process yielded the daily equivalent BC concentrations shown in Fig. 4g." [In the revised manuscript, the original Fig. 3 has been renumbered as Fig. 4 due to the insertion of technical schematics comparing SNICAR-AD and SNICAR-ADv4 (now Fig. 1)]

21. L296: Figure → Figures

Responses: Thank you for pointing this out. According to the journal's figure guidelines, the abbreviation "Fig." should be used when it appears in running text and should be followed by a number unless it comes at the beginning of a sentence, e.g.: "The results are depicted in Fig. 5. Figure 9 reveals that...". So we have standardized all figure references throughout the manuscript as follows: Singular references now use the abbreviated form 'Fig.' (e.g., Fig. 1a), while multiple figure references employ 'Figs.' (e.g., Figs. 1a and b).

22. L301-302 : Is it due to poor-quality data?

Responses: Thanks for your question. It is indeed due to the data quality limitations, such as cloud cover or insufficient observation data. We have revised the text to clarify: "These grid cells are filled with the climatological mean values of bare ice physical properties when retrievals fail due to clouds or poor data quality."

23. LL318: within ice → within the ice

Responses: Thank you for your comment. We have revised "within ice" to " within the ice".

24. L318-321: Could you explain the link between Reff and the scattering/reflection efficiency?

Responses: Thank you for your question. The link between effective bubble radius (Reff) and scattering efficiency is demonstrated in Fig. R10 from Whicker-Clarke et al. (2022), where smaller air bubbles (lower R_{eff}) produce higher albedo across visible and near-IR wavelengths due to enhanced Mie scattering. This relationship is most pronounced in low-density ice (650–850 kg·m^{-3}), as shown by the wide shaded areas in panels b–f, where bubble radius strongly modulates albedo. In higher-density ice, the effect of R_{eff} on albedo becomes less pronounced, as scattering efficiency is less sensitive to bubble size in these cases.

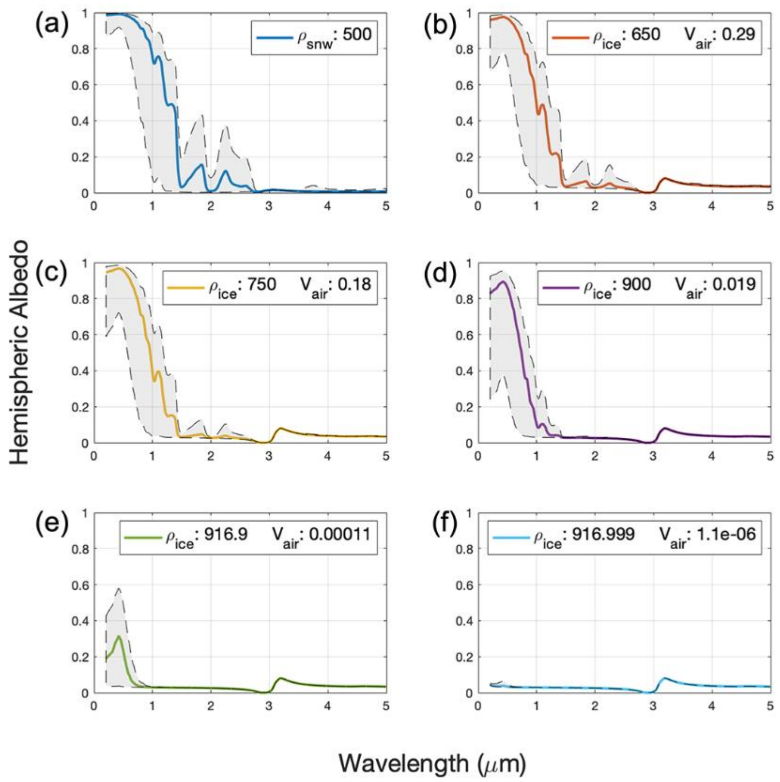

Figure R10. (a–f) Spectral albedo as a function of wavelength, snow or ice density, and the ice volume fraction of air. Shading indicates the full range of clean snow or ice albedo as a function of snow grain or air bubble radius, and the spectral albedo for an ice grain/air bubble with an effective radius of 180 µm is indicated by the colored line. Panel (a) is a snow layer; all the other panels are ice layers. The radius ranges from 30 µm (the highest albedo curves) to 20000 µm (the lowest albedo curve; Whicker-Clarke et al. 2022).

References:

Whicker-Clarke, A., Flanner, M. G., Dang, C., Zender, C. S., Cook, J. M., and Gardner, A. S.: SNICAR - ADv4: A physically based radiative transfer model to represent the spectral albedo of glacier ice, The Cryosphere, 16(4), 1197 - 1220, https://doi.org/10.5194/tc - 16 - 1197 - 2022, 2022.

Section 3:

1. L329: Figure → Figures (same for L333, L339, L370, L374)

Responses: Thank you for your comment. We have revised 'Figure' to 'Figs.' or 'Figures' (if at the beginning of the sentence) at the noted locations. As stated in our prior response, all figure references now consistently follow the journal's style guidelines.

2. L329: demonstrate → display

Responses: Thank you for your comment. We have revised "demonstrate" to "display".

3. L341: southwest: not really convincing. Do you mean southeast?

Responses: Thank you for highlighting this concern. We have removed "southwest" from the statement, which now reads: "...higher equivalent BC concentrations occur in these areas compared to inland regions, indicating potentially more severe contamination, particularly in the southeastern and northernmost parts of the GrIS."

4. L344-346: This sounds a bit subliminal. Could you be more synthetic?

Responses: Thank you for this suggestion. We have refined the definition to more explicitly state: "The bare ice region of the GrIS in this study is defined as grid cells with exposed glacier ice (snow cover fraction <100%), where surface albedo is controlled by ice properties but also influenced by residual snow and bare soil patches."

5. L346: illustrated → illustrates

Responses: Thank you for your comment. We have revised "illustrated" to "illustrates" to ensure grammatical accuracy.

6. L348: southwestern and northeastern à Rather: everywhere in the peripheral areas of the ice sheet except in the southeastern part.

Responses: We sincerely appreciate this important correction regarding the discription of the GrIS's bare ice spatial distribution. We have revised the text to reflect that bare ice primarily occurs across the peripheral regions of the ice sheet, except for the southeastern part.

7. L346-349: Please, rephrase. I suggest the following (or something equivalent): Figure 5a shows the spatial distribution of land ice underlying the snowpack. The areas where land ice is the main type of land cover are located in the periphery of the the GrIS with the exception of the southeastern edge. Values of land ice fraction below 1 implies that the corresponding grid cells contain etc…

Responses: Thank you for this constructive suggestion. This text has been revised as follows: "Figure 6a shows the spatial distribution of land ice underlying the snowpack. The areas where land ice is the main type of land cover are located in the periphery of the the GrIS with the exception of the southeastern edge. Values of land ice fraction below 1 implies that the corresponding grid cells contain other land cover type, e.g. bare soil." [In the revised manuscript, the original Fig. 5a has been renumbered as Fig. 6a due to the insertion of technical schematics comparing SNICAR-AD and SNICAR-ADv4 (now Fig. 1).]

8. L349-350: Removing "In tandem… enabled CoLM" would make the sentence clearer

Responses: Thank you for your suggestion. We have revised the sentence by removing the indicated phrase.

9. L354: "bare ice fraction frequency": I don't understand what this means at all. Please, explain. How this frequency is determined? (same thing for Fig. 5c caption).

Responses: We appreciate the opportunity to clarify this terminology. The "bare ice fraction frequency" refers to the statistical distribution of grid cells across discrete intervals of bare ice fraction (0-10%, 10-20%, ..., 90-100%) within the bare ice zone of the GrIS. It is calculated as:

$$\text{Frequency} = \frac{N_i}{N_{total}} \times 100\%$$

where N_i is number of grid cells in bare ice fraction bin i, and N_{total} is total bare ice zone grid cells. This definition has also been clarified in the caption of Fig. 5c (now Fig. 6c in the revised manuscript).

10. L354: Figure 3d→ Figure 5c

Responses: Thank you for pointing out this mistake. It should indeed be the Figure 5c. We have corrected it. [In the revised manuscript, the original Fig. 5c has been renumbered as Fig. 6c due to the insertion of technical schematics comparing SNICAR-AD and SNICAR-ADv4 (now Fig. 1).]

11. L365: region → regions

Responses: Thank you for pointing out this mistake. We have corrected it.

12. L376-377: I would expect a single RMSE value for the whole GrIS as RSME is defined as a sum. Please explain (give the mathematical formula) how you compute the RMSE; Moreover, I am not sure I have the right idea of what you mean by "linear trend"; Linear trend of what? Please clarify in the main text and in the figure captions of the Supplement.

Responses: We appreciate the reviewer's questions regarding our RMSE calculation and trend analysis. For each grid cell over the GrIS bare ice area, we computed the RMSE between the MODIS observed albedo and model-simulated albedo (CoLM-SNICAR-AD/SNICAR-ADv4) time series (2000–2020, 21 summer values per cell). The RMSE for each cell is calculated as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\alpha_{MODIS,\,i} - \alpha_{model,\,i})^2}$$

where n=21 (years), $\alpha_{modis,i}$ and $\alpha_{modis,i}$ are the MODIS and modeled albedo values for year *i*, respectively.

The "linear trend" refers to the temporal trend in annual summer albedo for each grid cell, calculated using least-squares regression over the 2000–2020 period. Trends are expressed in units of albedo change per year (Δα/year). We will clarify this in the main text (Section 3.2): "Furthermore, comparative analysis of the spatial distributions of correlation coefficients, root mean square errors (RMSE), and linear trends (Figs. S1-S3) reveals that CoLM-SNICAR-ADv4 outperforms CoLM-SNICAR-AD across all evaluation metrics. These metrics were derived from each grid cell by comparing the 21-year summer albedo time series (2000–2020) from model simulations and MODIS observations: correlation coefficients assess temporal agreement, RMSE quantifies deviation magnitudes, and linear trends (obtained via least-squares regression) capture interannual albedo changes. The comprehensive spatial evaluation demonstrates consistent improvements in both the spatial pattern and quantitative representation." We have also updated the relevant figure captions in the Supplementary Material accordingly.

13. L384-387: Not clear. I suggest a new formulation: The decrease in the positive bias of CoLM SNICAR-ADv4 can also be clearly seen in the shortwave, visible and near-infrared albedo time series, with the area-weighted mean albedo of the GrIS bare ice regions steadily decreasing throughout the summer period from 2000 to 2020, compared with CoLM SNICAR-AD.

Responses: We sincerely appreciate your constructive suggestion to improve clarity. This sentence has been revised as you suggest.

14. L390: SNICAR-ADv4 enabled simulations à CoLM SNICAR-ADv4 simulations

Responses: Thanks for your comment. We have updated the "SNICAR-ADv4 enabled simulations" to the "CoLM SNICAR-ADv4 simulations".

15. L391 and L392: MCD43C4 à MCD43C3

Responses: Thank you for pointing out these mistakes. We have corrected them.

16. L410: from → compared to

Responses: Thanks for your comment. We have corrected it.

17. L425: has significantly reduced

Responses: Thanks for your comment. We have corrected it.

18. L440: This could be confirmed or infirmed with new diagnostics (e.g. surface mass balance and/or runoff à See Major comments)

Responses: Thanks for your suggestion. Since CoLM does not support SMB calculation, we analyzed snow water equivalent (SWE), as detailed in our earlier reply.

19. L443: northeast ablation zone: Rather northwestern and western?

Responses: Thank you for pointing out this mistake. It should indeed be the northwestern and western ablation zone. We have carefully revised this throughout the manuscript and verified all related geographical references.

20. L455: control experiment: this is the first time you use this term. Please explain what is your control experiment.

Responses: We appreciate this important clarification request. To avoid confusion, we have replaced the term "control experiment" with a more precise description in the revised text. The sentence now reads: "From Fig. 10f, the difference in BBA shows a strong positive correlation with the specific surface area, with a correlation coefficient of 0.88 (significant at the 99% confidence level), since the two simulations differ solely in their prescribed bare ice physical properties in the land surface model."

21. L456: commence → starts/begins

Responses: Thank you for your comment. We have revised "commence" to "start" in the revised manuscript.

22. L465: region → regional

Responses: Thank you for pointing out this mistake. We have corrected "region" to "regional" in the revised manuscript.

23. L468: effect → affect

Responses: Thank you for pointing out this mistake. We have corrected "effect" to "affect" in the revised manuscript.

24. L476: speciafic →specific

Responses: Thank you for pointing out this typo. We have corrected "speciafic" to "specific" in the revised manuscript.

25. L489: 2021 → 2020

Responses: Thank you for pointing out this mistake. We have corrected "2021" to "2020" in the revised manuscript.

26. L492-493: strong climate response: This sounds like an overstatement

Responses: We appreciate the your valid concern about terminology precision. The original phrasing has been revised to: "...suggesting that even a slight reduction in bare ice albedo can produce noticeable climate responses in ablation region."

27. L497: in ablation zone → in the ablation zone

Responses: Thank you for pointing out this mistake. We have corrected it.

28. L513-514: impact of the glacier calving (dynamic process) and submarine melting: Add a reference and/or develop your arguments.

Responses: Thanks for your comment. In the revised manuscript, we have refocused the discussion exclusively on sea-level linkages, as the glacier-specific connections were indeed tenuous. The text now states: "Such feedback is projected to amplify the GrIS's contribution to global sea level rise by enhancing both surface melting and runoff generation (Ryan et al., 2019). The potential acceleration of these sea-level-relevant processes underscores a critical research priority for improving future projections."

References:

Ryan, J. C., Smith, L. C., van As, D., Cooley, S. W., Cooper, M. G., Pitcher, L. H., and Hubbard, A.: Greenland Ice Sheet surface melt amplified by snowline migration and bare ice exposure, Sci. Adv., 5(3), eaav3738, https://doi.org/10.1126/sciadv.aav3738, 2019.

29. L526: coupling → coupled

Responses: Thank you for pointing out this mistake. This sentence is revised as follows: "...to investigate its effect on the GrIS's mass loss via land-atmosphere coupled models for these may produce more pronounced feedback than offline simulations."

30. The reference Wicker et al. (2024) should be changed in Wicker-Clarke et al. (2024) both in the main text and in the reference list

Responses: We sincerely appreciate this correction. The reference has been updated to "Wicker-Clarke et al. (2024)" throughout the manuscript, including both in-text citations and the reference list. We have also cross-checked all other references to ensure consistency in author naming conventions.

31. Figures: Avoid using pastel colours in some figures (e.g. Fig. 4, Fig. 5c, Fig. 6-8).

Responses: Thanks for your constructive suggestion. The color schemes in these figures have been systematically updated to employ higher-saturation, perceptually optimized palettes.