Revision of EGUSPHERE-2024-2583 - RC1

We thank Niklas Bohn for a thorough and encouraging feedback on our manuscript, which improved the clarity and justification of the presented work. We address the different comments below, with our answers highlighted in purple.

General comments

General comment 1 – A short introduction to BioSNICAR/SNICAR would be good. What are its basic concepts? Which input options exist? What's the output quantity? Which radiative transfer approach is used (two-stream vs. multi-stream)? In particular, Section 2.1.1 would better go as an introduction to the utilized radiative transfer model, i.e., BioSNICAR, with changing the section title accordingly. You could still keep the description of input and output data, but expand a bit more on the underlying physics of SNICAR.

Reply: We have incorporated this suggestion and updated section 2.1.1 with a new title "Radiative transfer model simulations" and a general description of BioSNICAR:
"The RTM BioSNICAR simulates the bi-hemispherical albedo of snow and ice surfaces by solving the two-stream radiative transfer equations. The model considers the snowpack as homogeneous and plane parallel, and an infinite number of layers with varying snow grain size and shape, density and light absorbing particle concentrations can be prescribed. Several types of incident irradiance can be selected in the model, notably varying with the solar zenith angle. The capabilities and physical equations of the model are similar to the latest SNICAR version, and are detailed in Flanner et al. [2021] and Whicker et al. [2022]. Here, the RTM was parametrised with [. . .]"

General comment 2 – You represent snow as a granular medium with spherical grains. However, many controversies exist in the literature about how to model the shape of snow grains. I usually apply the 'collection of spheres' approach from Grenfell and Warren (1999) myself, but a brief discussion about potential impacts of assuming the spherical representation, and possible alternatives would be good.

Reply: We agree that a discussion on this assumption was needed, and we added new sentences in the section 2.1.1 to justify our approach and mention alternatives:
"Snow grains were represented by spheres as per the original formulation of the SNICAR model [Flanner et al., 2021, Wiscombe and Warren, 1980]. Recent work showed that light penetration in snow is better represented using irregularly shaped grains [e.g. Robledano et al., 2023], notably yielding more accurate retrievals of snow specific surface area (SSA), but here we chose to use spherical grains mainly because 1) one objective of this study was to incorporate liquid water in snow using the validated framework of Donahue et al. [2022], which is based on spherical grains, and 2) the main focus of the study was the retrieval of light absorbing particles rather than snow physical properties, hence spherical-equivalent snow SSA were deemed appropriate. Future developments of the emulator may consider more realistic physical representations of snow such as a collection of hexagonal plates [Whicker et al., 2022], irregularly shaped grains [Picard and Libois, 2024], or a random mixture of ice and air phases characterized by their mean chords [Malinka, 2023]."

General comment 3 – There are different sets of dust optical properties available in SNICAR, depending on their source and/or sampling region. Please provide more detail about which exact dataset you used and why.

Reply: We have used the optical properties generated by Skiles et al. [2017] with the size range 10-50 μm because large dust particles are often found in snowpacks [Flanner et al., 2021, Skiles et al., 2017]. This has been clarified in the methods:
"For the light absorbing particles, the optical properties of black carbon (BC) and dust were directly available in the model. For BC, we used the uncoated BC optical properties from Flanner et al. [2012] and for the dust we used the optical properties of the dust mixture from Skiles et al. [2017] in the size bin 10-50 μm, which are representative of measurements from dust in snowpacks [Flanner et al., 2021, Skiles et al., 2017]."

General comment 4 – It would be good to have a paragraph in the introduction highlighting the potential of hyperspectral/multispectral sensors for remote sensing of LAP in snow.

Reply: We agree that mentioning the relevance of remote sensors was missing from the introduction so we added the sentence copied below, however we decided not to include a full paragraph so as to not deviate from the focus of the study, which does not include any analysis of remotely sensed data.
"[In addition, inverse methods offer a remote-only approach to detecting and quantifying LAPs in hard-to-access areas and/or over spatial scales that are too large to cover on foot]. They are hence particularly relevant in the context of ongoing (e.g. PRISMA, EnMAP) and emerging (e.g., SBG) satellite missions providing remotely sensed reflectance imagery at high spectral resolution."

Specific comments

Specific comment 1, lines 25 - 26 – Can you provide any references to studies that did these forward modeling experiments?

Reply: We are unfortunately not aware of forward modeling experiments that quantified uncertainties related to the high number of free parameters in RTMs. However, several modeling studies including for example Flanner et al. [2021] or He [2022], referenced in the sentence above, have demonstrated the large difference in the simulated BBA for e.g. varying snow grain shape, snow algae pigmentation or cell size, highlighting the potential errors arising from fixing these parameters arbitrarily.

Specific comment 2, line 37 – Bohn et al. (2021) do not actually use Gaussian processes, but simply optimal estimation that acts on the assumption that state parameters and their errors show a Gaussian distribution.

Reply: Apologies for the error, we have corrected the sentence: "To our knowledge, only one study has developed an inverse method to discriminate between biotic and abiotic LAPs, using optimal estimation Bohn et al. [2021]."

Specific comment 3, line 45 – Why snow algae in particular? From my experience, modeling the effects of black carbon particles is clearly more challenging because of their minor absorptivity and weak occurrences.

Reply: The sentence line 45 mentioned the need to improve and validate the representation of LAPs in albedo models, and hence we mentioned specifically snow algae because very few studies have focused on the development and validation of albedo models for snow algal albedo effect, in comparison to black carbon. This sentence notably links to the conclusion of the abstract of the SNICAR paper by Flanner et al. [2021]: "More work is needed particularly in the representation of snow algae, including experimental verification of how different pigment expressions and algal cell concentrations affect snow albedo.". We agree that modeling the effect of BC is also challenging, but in our understanding this has less to do with the validity of the albedo model than the uncertainties on the presence of BC, and its overall low concentrations yielding subtle signatures that are difficult to reliably detect and model.

Specific comment 4, lines 59 – 61 – I don't think you need to mention all the used Python libraries here. Maybe only tensorflow and keras as those two are important for understanding the applied deep learning approach.

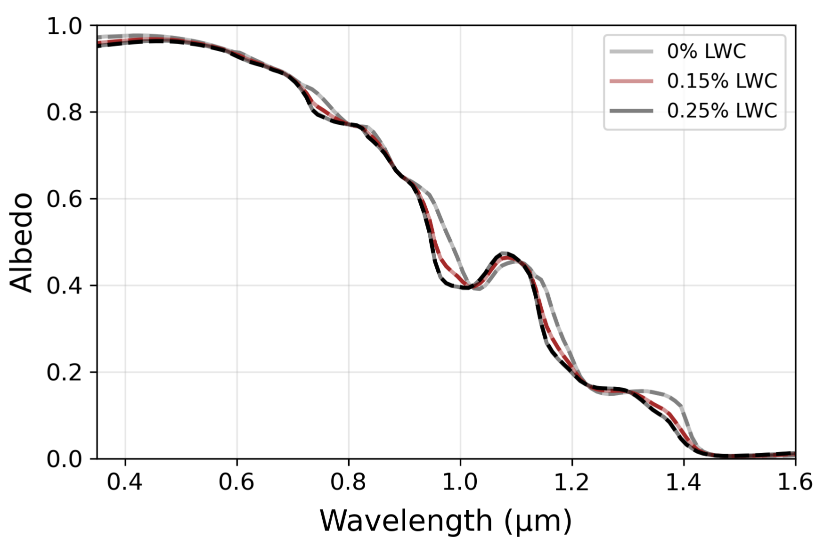
Reply: We have moved the sentence enumerating the python libraries to the acknowledgments to ease readability, but we would like to keep the sentence in the manuscript so as to acknowledge the open source developers who contributed to create the libraries used in our analysis.

Specific comment 5, line 73 – To better justify this, you could create non-linear but homogeneous grids by using Sobol sequences (`https://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.qmc.Sobol.html`).

Reply: Thank you for the suggestion, we will definitely consider using this tool for future studies!

Specific comment 6, Table 1 – Why only going up to 15%? Previous studies have shown that up to 25% could be realistic (Green et al. 2002; Bohn et al. 2021).

Reply: The training dataset included simulations with a liquid water content (LWC) only until 15% but the emulator can extrapolate beyond the training dataset and simulate the albedo with higher LWCs that accurately reproduce the original model (see figure below, the dashed lines being the emulator and the solid lines being BioSNICAR).



Specific comment 7, line 92 – Can you further substantiate this assumption?

Reply: We have added a new reference and modified the sentence to: "The optical properties are representative of algal bloom from the Greenland ice sheet where the samples were collected [Chevrollier et al., 2023], and are assumed to generalise to all red algal blooms since red snow is caused by only a few species sharing a similar pigmentation [Lutz et al., 2016]."

Specific comment 8, line 94-95 – Hyperspectral/multispectral comes out of the blue here. See general comments.

Reply: We have changed the sentence to "(2) radiometric sensors on ground, airborne or spaceborne platforms rarely detect signals above 2.5 μm".

Specific comment 9, line 123 – How fast is this inversion scheme? Could you give a few numbers?

Reply: It is difficult to give precise numbers since this highly depends on the machine, the version of tensorflow and the spectral resolution of the data, but we tried to be more precise line 190: "At present, the inversion method is fast enough to be scaled to satellite observations, with a computation time of about 50mn to invert 100km^2 of Sentinel-2 imagery at 60m resolution (tensorflow v2.16.0, CPU AMD Ryzen 7 7700X and RAM 64Gb)."

Specific comment 10, line 134 – What does 'homogeneous enough' mean? Did you have minor influences from other surface types or roughness?

Reply: In this context, homogeneous enough meant that the surfaces "seen" by the different fibers in the FieldSpec were similar enough so as to not produce a discontinuity. This issue is described in Painter [2011]: "The optic cable of the ASD (Analytical Spectral Devices, Inc.) Field Spec spectroradiometer has an anisotropic distribution of the wavelength-dependent fibers that creates a sampling scenario in which different areas of the surface are observed with different parts of the spectrum. Without a randomizing filter, this often results in stepwise differences between the ASD FieldSpec VNIR (Si), SWIR1 (InGaAs) and SWIR2 (InGaAs) spectrometers that have wavelength ranges of 350–1000 nm, 1001–1800 nm and 1801–2500 nm, respectively." We have added the reference to Painter [2011] in the sentence to clarify the meaning of the sentence.

Specific comment 11, line 145 – Calculated radiative forcing is not instantaneous when you use 24h daily averaged shortwave incoming radiation. To get the instantaneous radiative forcing, you would need to multiply the BBA reduction by the incoming radiation at the exact time of the measurement.

Reply: Indeed, we had omitted to describe the instantaneous radiative forcing in the section 2.3 and corrected accordingly:
"The daily and instantaneous radiative forcings (W m^{-2}) were calculated by multiplying the BBA reduction with respectively the 24h daily averaged and instantaneous shortwave incoming radiation, as measured with a four-component radiometer (CNR4, Kipp and Zonen, The Netherlands) at the local weather station [Pirk et al., 2023]."

Specific comment 12, line 195 – You need to clarify a bit better if you applied the ARFs to the HCRF spectra before doing the inversions. I guess you did not, but it's not fully clear from the text.

Reply: We have clarified this sentence to indicate that the inverted quantities correspond to the direct measurements: "The inversion algorithm successfully reproduced the ground HCRF spectra measured on snowfields in Southern Norway [..]".

Specific comment 13, line 208-210 – So why not using a multi-stream RTM such as DISORT to account for reflectance anisotropy?

Reply: The reason we chose the two-stream model BioSNICAR in this study was because 1) it already has several features of interest built-in and 2) to the best of our understanding the anisotropy of the surface highly depends on its properties and it is unclear how well the BRDF of a collection of spheres as prescribed in DISORT can represent the BRDF of densely packed, wet and contaminated snow, which is why we used empirical coefficients instead to discuss the effect of anisotropy. On the other hand, an important aim of this study was to provide a framework replicable with any RTM, and we agree that using a model that may be more advanced than BioSNICAR/SNICAR would be a significant upgrade.

Specific comment 14, Figure 2 – I don't see the values of the retrieved grain radius in these figures.

Reply: We originally decided to omit the grain size values in the figures to ease readability and reduce the size of the legend since it was not the focus of the study, but we have now changed the legend to add the grain size.

Specific comment 15, line 239 – You need to clarify in the methods section how you calculated the IRF.

Reply: This was addressed in specific comment 11.

Specific comment 16, line 253 – Again, please clarify at the beginning, which type of dust OPs you're applying in this study. See general comments.

Reply: We have clarified this in the methods as per our answer in the general comment 3.

Specific comment 17, line 256 – The expression light absorbing particles darkening snow surfaces sounds odd, please try to revise.

Reply: We have revised as "Light absorbing particles have varying apparent optical properties, challenging the quantification of their albedo reducing effect using forward modeling and making inverse methods relevant for their detection."

Specific comment 18, Figure A1 – : Again, the grain size values are missing in this plot.

Reply: We originally decided to omit the grain size values in the figures to ease readability and reduce the size of the legend since it was not the focus of the study, but we have now changed the legend to add the grain size.

Technical corrections

Line 1: Several different types of light absorbing particles (LAPs) darken snow surfaces, ...

Reply: Corrected.

Line 49: BioSNICAR

Reply: Corrected.

Line 56: BioSNICAR

Reply: Corrected.

Table 1: The caption should be located above the table.

Reply: Corrected.

Line 93: spectral albedo

Reply: Corrected.

Line 134: an hour prior **to** the measurements . . .

Reply: Corrected.

Line 140: Since the measurements are not equivalent to . . .

Reply: Corrected.

Line 148: the spectral albedo output by the . . .

Reply: Corrected.

Line 171: The emulator is therefore a practical . . .

Reply: Corrected.

Figure 1, caption: . . . to the (b) highest and (c) lower mean . . .

Reply: Corrected.

Table 2: Again, I think the caption goes above the table.

Reply: Corrected.

Line 216: if the spectral diffuse and direct partitioning . . .

Reply: Corrected.

Figure 2, caption: . . . is approximately 45x45 cm, centered on . . .

Reply: Corrected.

Line 252: . . . could be integrated in the . . .

Reply: Corrected.

Line 259:. . . emulating a radiative transfer model, and an . . .

Reply: Corrected.

Figure A1, caption: . . . is approximately 45x45 cm, centered on . . .

Reply: Corrected.

Figure A2, caption: The retrievals of LAP concentrations are compared to the retrievals when applying ARFs from . . .

Reply: Corrected.

References

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