Revision of EGUSPHERE-2024-2583 - RC3

We thank the reviewer for a positive and encouraging feedback, which helped us clarify the opportunities and challenges associated with scaling-up our method. We address the different comments below, with our answers highlighted in purple.

Major comments

Major comment 1 – A short description in the methods of biosnicar/SNICAR would be useful. This should include the optical schemes used and any error associate with the model.

Reply: To address this comment as well as the general comment 1 from reviewer 1, we have changed section 2.1.1 to better describe 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 [. . .]"

Major comment 2 – This work is very exciting for potential use in larger scale hyperspectral measurements. The conclusions could use some discussion of any potential issues or challenges of scaling the model up to regional or gloabal scale, especially with the mention of satellite use. For example, dust optical properties can vary by region. Would this impact use of the model?

Reply: Thank you for the positive feedback! We have included the following paragraph at the end of the conclusion to discuss the challenges that we could identify, as well as our efforts to promote the usability of the method:
"To facilitate future usage and development of the method, the full code running the model and the inversion was made available into an open-source python package. Ongoing developments currently focus on making the inversion algorithm resolution-agnostic and hence adaptable to several remote sensing products, as well as adding the possibility to prescribe sensor-specific spectral responses. The application of the method to new areas using remotely sensed imagery will present additional challenges to consider, such as (i) the variability in mineral dust optical properties that may require new mineral mixtures in the model, (ii) the presence of shallow snowpacks of which signature could be confounded with that of black carbon (Warren et al., 2019), or (ii) the variability in spectral resolution between sensors, where lower resolution imagery may require stronger constrains on the inverse problem."

Minor comments

Minor comment 1, line 27: "..allow to study the impacts of LAPs..." is a bit difficult to read, consider rewording.

Reply: We have rephrased as "By contrast, inverse modelling approaches consider the impact of LAPs in snow directly from their measured apparent optical properties instead of prescribing all the above parameters, circumventing some of the uncertainty associated with forward modelling experiments."

Minor comment 2: In the RTM model setup, two snow layers are used, with the lower layer being a semi-infinite layer. Dust and black carbon tend to be deposited in layers throughout the season, often together. The assumption of the near semi-infinite lower layer can introduce some error during the melt season as these buried LAP layers get close to the surface.

Reply: We agree with the reviewer (and reviewer 2) that this configuration is a simplification of the complex distribution of LAPs in the snowpack. In the context of this study however, we aimed at quantifying the impact of LAPs, which is not affected by the depth at which the LAPs are considered because the model will simply adapt the retrieved concentration to match the apparent properties of the LAPs to yield the impact on the BBA. For forward runs, the concentration of LAPs must however be understood as a "2cm-equivalent", which we clarified in the text: "A 2 cm depth was chosen for the upper layer as this depth was used to quantify algal cells in recent field studies [Engstrom et al., 2022, Healy and Khan, 2023], hence the LAP concentrations represent 2cm-equivalents".

Minor comment 3: The title of Section 2.3 should be updated to say daily radiative forcing instead of instantaneous based on the methods described. Instantaneous radiative forcing would multiply the BBA reduction by the incoming solar radiation at the time of the measurement.

Reply: We had omitted the description of the incoming solar radiation at the time of the measurement in the methods, hence we have corrected the title to "radiative forcing" and added a description of the instantaneous radiative forcing in addition to the daily radiative forcing:
"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]."

Minor comment 4: The methods in Section 2.3 could use some more information. When calculating reduction in BBA from a LAP, is a spectrum with the same grain size and other LAP concentrations being used.

Reply: We have clarified this point in the methods:
"The BBA reduction associated with a given LAP was calculated by differencing the BBA of the retrieved solution with the BBA calculated with the exact same conditions (grain size, SZA, LWC...) except the concentration of the given LAP, which was set to 0."

Minor comment 5: The results mention both daily average and instantaneous radiative forcing. If both are being used, the calculation of instantaneous radiative forcing should be covered in Section 2.3.

Reply: We have added the description of the calculation of instantaneous radiative forcing in Section 2.3 as explained in the minor comment 3.

References

C. B. Engstrom, S. N. Williamson, J. A. Gamon, and L. M. Quarmby. Seasonal development and radiative forcing of red snow algal blooms on two glaciers in british columbia, canada, summer 2020. *Remote Sensing of Environment*, 280:113164, 2022.

M. G. Flanner, J. B. Arnheim, J. M. Cook, C. Dang, C. He, X. Huang, D. Singh, S. M. Skiles, C. A. Whicker, and C. S. Zender. Snicar-adv3: a community tool for modeling spectral snow albedo. *Geoscientific Model Development*, 14(12):7673–7704, 2021.

S. M. Healy and A. L. Khan. Albedo change from snow algae blooms can contribute substantially to snow melt in the north cascades, usa. *Communications Earth & Environment*, 4(1):142, 2023.

N. Pirk, K. Aalstad, Y. A. Yilmaz, A. Vatne, A. L. Popp, P. Horvath, A. Bryn, A. V. Vollsnes, S. Westermann, T. K. Berntsen, F. Stordal, and L. M. Tallaksen. Snow–vegetation–atmosphere interactions in alpine tundra. *Biogeosciences*, 20(11):2031–2047, June 2023. ISSN 1726-4189. doi: 10.5194/bg-20-2031-2023. URL `http://dx.doi.org/10.5194/bg-20-2031-2023`.

C. A. Whicker, M. G. Flanner, C. Dang, C. S. Zender, J. M. Cook, and A. S. Gardner. Snicar-adv4: a physically based radiative transfer model to represent the spectral albedo of glacier ice. *The Cryosphere*, 16(4):1197–1220, 2022.