The Cryosphere Discussions

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Reply on RC1

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Author comment on "SNICAR-ADv4: a physically based radiative transfer model to represent the spectral albedo of glacier ice" by Chloe A. Whicker et al., The Cryosphere Discuss., https://doi.org/10.5194/tc-2021-272-AC1, 2022

Thank you for the helpful and thorough comments. All comments are addressed below, with the original comment and the response are italicized.

Review #1 (Anonymous):

Summary and recommendations

This manuscript describes a physically based radiative transfer model (RTM) to represent the spectral albedo of glacier ice, called SNICAR-ADv4. In this RTM, air bubbles in the ice were treated as a scatterer, the layer structure was considered, and the ice and the snow overlying the ice were coupled, resulting in that the RTM of coupled atmosphere-snow-ice system was completed as SNICAR-ADv4. It can be said that we have taken a step forward to understand the spectral albedo of glacier surface. This is a very important research for the climate studies using SNICAR-ADv4. Reviewer gives a certain appreciation for reasons mentioned above. However, there are some concerns regarding the explanation and technical details of the validation method of SNICAR-ADv4, which are list below. Given this, I recommend this paper for publication after minor revisions with attention to comments.

Major comments

- Regarding the surface roughness, called "the surface scatter layer (SSL)" which consists of "Fresnel layer" plus "thin snow layer". Reviewer guesses that the SSL is to avoid a specular reflection in the flux calculations. This is a good representation but the SSL is the approximate one even in a physical-based method. There are some more realistic models proposed (e.g Stamnes et al., 2011, Sun et al., 2019). In order to confirm this representation properly, reviewer recommends to depict the solar zenith angle dependence on the spectral albedo and then explain it at high solar zenith angle.

You are correct in that the SSL is used to avoid specular reflection over ice surfaces. We see total internal reflection around 3 μm, where the refractive index of ice drops below that of air, for SZA greater than ~55 °. As requested, we've added a figure showing spectral albedo at different SZA (Figure 1 in supplement), and the revised manuscript will include the figure and a description of influence of the Fresnel layer at λ ~ 3 μm at high SZA.

- Authors described the effects of the air bubble and the SSL on the spectral albedo especially in the VIS and NIR regions. However, there is no mention about those at wavelength > 3 um. Authors should describe the spectral features in these regions as well.

Thank you for pointing out this oversight. We've added a brief explanation of the generally constant low albedo and the minimal contribution to BBA due to the limited insolation at wavelengths > 3 μm.

- In general, the glacier surface tilted so there seems to be a limitation for the application of the plane-parallel RTM. It is desirable to mention the effect of slope on the spectral albedo calculations with the scope of application of SNICAR-ADv4.

Thank you for pointing this out. In situations where the surface is slightly angled but still relatively smooth, plane-parallel approximations can be applied with an effective solar zenith angle adjusted for the slope and aspect of the surface. Other studies have analyzed the sensitivity of albedo to sloped and rough surfaces and developed methods to account for surface roughness and slope (Picard et al., 2020; Larue et al., 2020). However, these effects are out of the scope of the paper. A brief discussion on the limitations of the plane-parallel approximation has been added to the manuscript.

- Regarding the model evaluation against measured spectral albedo (Figs. 8-10),

- authors mentioned in the manuscript that for most of the comparisons, the exact conditions are unknown (L361). Thus, some of input data were determined (constrained) from the comparison between model and measurements. However, it is not clear what parameter(s) was(were) constrained in the RTM calculations. Authors should described these parameters in the manuscript to distinguish known parameters from the input data clearly.

The model input parameters that were well constrained now have an asterisk next to them in Appendix A. We've also included more detailed descriptions in each model evaluation section (3.3.1-3.3.4) that indicate which variables were well constrained and which were not.

- It seems that input parameters including the constrained ones shown in Appendix provide good agreement between model and measurement (Figs. 8-10) . However, there are no sufficient explanations in the manuscript as to how reasonable the constrained values are. Authors should give a careful explanation here.

For each model – measurement comparison we utilized all the known model parameters from observations. All tuned or "unconstrained" model input variables were carefully chosen to both achieve good agreement between the model and measurements and also to be physically realistic. For unconstrained model parameters, we apply loose physical constraints that snow and ice follow with depth. For example, density and grain size increase with depth and LAC decreases with depth. We also utilize normal ranges of snow and ice properties, such as density and grain size/specific surface area, from measurements in similar regions. A more thorough explanation of how the unconstrained variables are chosen has been added to the revised manuscript.

- In addition, spectral albedos were seemed to be calculated under fixed conditions as follows: the mid-latitude winter profile in the atmospheric profile (even in Greenland ice sheet), the solar zenith angle of 50 degree (for all cases) and the hexagonal plate as snow grain shape (even in large grain size). Reviewer knows that similar spectral albedos can be achieved using different model parameters (L322). But, I think these conditions do not suit the validation of the SNICAR-ADv4 even though authors showed good agreement between model and measurement. At least the latter two parameters should be determined (constrained) from the measurement values to calculate the spectral albedo properly.

Thank you for pointing out this oversight. The SZA used in the model – measurement comparisons has been changed to be the SZA at solar noon for each measurement date and location. Because the measurements used do not include information about the shape of the snow grains, non-spherical grains are used in the modeling because spheres produce unrealistically large scattering asymmetry parameters. In this work, we default to the hexagonal plate shape as it has an intermediate asymmetry parameter between that of spheres and Koch snowflake shaped grains (Flanner et al., 2021; He et al., 2017).

Specific comments

L152: How did you marge two refractive indices in this analysis? You need explanations more in details.

The merged ice refractive index is that described by Flanner et al., (2021). It utilizes the imaginary index of refraction from 0.2 – 0.6μm as reported by Picard et al. (2016) and the real and imaginary index of refraction reported by Warren and Brandt (2008) elsewhere in the spectrum. For more clarity, we've removed "merged", referenced the description in Flanner et al. (2021), and included a brief explanation.

L154: Definition of thin snow layer overlying ice is not clear. How thin is it? For example, give the optical thickness of thin snow layer.

In this context, the model's ability to represent a thin snow layer, of any arbitrary thickness, overlying ice is being described. That has been made more clear in the revised text. Thank you for pointing this out. The impact of varying scattering layer depths and optical properties is described in more depth in section 3.1 surrounding the discussion of figure 5.

L203: I don't know how this number oln(1.5) is valid for the size distribution of air bubble. Please give a valid explanation.

We've added the Carras and Macklin, (1975) citation which discusses previous studies finding that the size distribution of air bubbles within hailstones is lognormal. We also now reference the Dadic et al., (2013) ice bubble measurements, which show skewed bubble size distributions. Dadic et al., (2013) figure 10 shows that surface firn and ice favors smaller air bubbles (radius < 0.4 mm) and deep ice favors larger air bubbles (radius > 0.7 mm). While we are not aware of measurements supporting a geometric standard deviation of 1.5, the value assumed for the lognormal width is not particularly important. This is because the optical properties of air bubble distributions with identical specific surface area (or effective radius) are nearly identical, and we use effective radius as the descriptive variable for bubble size. The distribution just needs to be sufficiently large enough to average over Mie resonance features, and 1.5 is indeed large enough to achieve this. A brief explanation of the use of a lognormal size distribution with a standard deviation of 1.5 has been added to the revied manuscript.

L313: "SNICAR-ADv4 simulates a wide … of snow and ice". It seems that this sentence has been taken out of context.

We've adjusted the wording of this sentence to better relate it to the previous sentence.

Figure 1: I can't see the shading range of spectral albedo especially for NIR regions because y-axis is so shrunk compared to x-axis. I recommend to replot (reshape) all

figures (a-f) such as Fig. 3 or Fig. 6 for example.

Thank you for pointing this out. We have reshaped the figures so they have a closer 1-1 x-y ratio.

Figures 8, 9 and 10: I recommend to replot (reshape) all figures to see the spectral features clearly such as Fig. 3 or Fig. 6 for example. In addition, please show the difference between model and measurements in order to see how differences there are .

Thank you for pointing this out. The figures have been reformatted so they have a closer 1-1 x-y ratio. We have also added the difference between the measurements and model albedo to each comparison plot. The difference is the modeled albedo value minus the measurement value interpolated to the higher resolution model λ scale. Negative values indicate the model is underestimating the albedo and positive values indicate the model is overestimating the albedo. Figure 2 in the supplement is an example of the model - measurement comparison reformatted with the difference plot included.

Please also note the supplement to this comment:
https://tc.copernicus.org/preprints/tc-2021-272/tc-2021-272-AC1-supplement.pdf