

The Cryosphere Discuss., referee comment RC2
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Comment on tc-2021-310

Anonymous Referee #2

Referee comment on "A generalized photon-tracking approach to simulate spectral snow albedo and transmittance using X-ray microtomography and geometric optics" by Theodore Letcher et al., The Cryosphere Discuss.,
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This study develops and applies a Monte Carlo photon tracking model to simulate snow reflectance, using micro-CT scans of the snow as input. Because the micro-CT scans (necessarily) only apply to ~1 cubic centimeter domains, a hybrid approach is adopted to extend the optical properties of ice grains obtained from these samples to implicitly model the reflectance and transmittance of deeper, plane-parallel snowpacks. Comparisons of measured and modeled spectral albedo of snow with black targets placed at different depths was generally favorable in the visible portion of the spectrum, where the influence of the targets is strongest, indicating the simulations of bulk transmittance are likely accurate. Overall, this is a useful contribution to the literature, and the proposed approach has promise for broader application, but the issues described below should be addressed prior to publication.

General issues

Section 2, lines 90-97: The reasoning for applying these two distinct modeling approaches becomes clearer as one works through the manuscript, but I think the discussion here should be expanded to clarify the need and reasoning for these two separate approaches.

Related: One of the main attractions of explicitly applying a Monte Carlo model to 3-D snow images is that it potentially precludes the need to identify and distinguish distinct snow grains and treat them as independent scatterers. And yet, the approach applied here essentially does that, treating identified grains as independent scatterers, necessitated by the small sample size of micro-CT scans and excessive computational needs associated with tracking photons through a sufficiently large sample composed of 20µm voxels. I do think the approach developed is innovative and useful, but I would like to see a clearer discussion of (a) potential biases and limitations associated with separating ice grains and treating them as independent scatterers, and (b) potential sensitivity of modeled results

to the grain separation algorithm applied. I would think there is a fair amount of subjectivity in the identification of grain boundaries, especially in sintered snow, and I think it would be helpful to discuss the implications of this.

Line 116-119: What is the statistical uncertainty in the extinction coefficient derived with this technique?

Although the comparison between modeled and measured spectral albedo (Figure 13) is quite good in the visible, the discrepancies at wavelengths longer than 1000 nm are rather substantial. The authors speculate that this could be due to errors in the derived particle scattering phase functions, and indeed albedo in this part of the spectrum is strongly influenced by grain size and shape, so errors in the identification and rendering of individual grains could be responsible for this. Because the penetration depth of near-IR radiation in snow is very short, however, one alternative explanation is that grain morphology of the very top of the snow (e.g., top ~1mm) could be different from the mean morphology of the top 2cm, from which the sample was collected. Grenfell et al (1994) speculated that unresolved snow grain size of the top millimeter of snow could be responsible for similar discrepancies found in their study. Another potential consideration is uncertainty in the near-IR refractive indices of ice, as described by Carmagnola et al (2013) and Dumont et al. (2021). Even more serious than uncertainty in the near-IR refractive indices, however, is application of spectrally-constant refractive indices, as suggested on p.24. (Please see the next comment). Given the magnitude of the modeled albedo bias in the near-IR, I suggest expanding on the analysis and discussion of potential underlying causes of this.

Discussion on p.24 indicates that the authors assume ice optical properties independent of wavelength. I appreciate that this is done to reduce computational expense, but I believe this could lead to non-negligible biases, especially in the near-IR, and may even relate to the modeled albedo bias described above. The impact of spectral variations in ice optical properties can be seen in Mie solutions for ice spheres, which for 1000um spheres produce scattering asymmetry parameters ranging from 0.888 at 500nm to 0.915 at 1400nm, indicating differences in the scattering phase function that will lead to differences in modeled albedo. I think the importance of this issue should be probed more, potentially within the context of modeled albedo biases shown in Figure 13.

Specific issues:

Line 38: "scattering of electromagnetic energy ... determined by the different refractive indices for ice and air" - Perhaps add "and geometry of the ice-air interfaces".

Line 86: "Further, this framework ignores the wave properties of light, such as phase and diffraction" - I think it would be helpful to include a bit more discussion (i.e., 2-3 sentences) on just how important neglect of diffraction may or may not be. You could potentially draw on work from Liou et al (2011) and earlier work with co-author Yang, who

include diffraction (at some level) in their derivation of optical properties for non-spherical ice particles.

Line 99-100: Please include the units of these optical properties.

Line 118: Just to clarify, the curve is fit to P_{ext} vs. L ? As commented above, what is the statistical uncertainty in the extinction coefficient derived with this technique?

Line 136: How is the vector normal of the ice surface calculated? Perhaps the reader could be referred to section 2.5 for more info, but immediate questions that come to mind are: Are grain boundaries represented as facets (like in Figure 1), resolved only to the voxel size, or as curved surfaces? If curved, is there a resolution to the derived curve, or is it a mathematical description that gives a precise surface normal for any point of ray intersection?

Line 147-148: I assume the particle orientation is also random, but please clarify.

Line 169: Perhaps I missed it, but how many $d\theta$ bins are used for the calculation of $p(\cos(\theta))$?

Line 176: Grammatical issue.

Line 202-203: The meaning of this sentence ("... instead of...") is unclear to me. What is the distinction between these two methods?

Equation 20: How many bins are used to compute the DCRF?

Line 257: "... constant reflectance of approximately 4%..." - Is the uncertainty of this reflectance known, and if so, how important is this uncertainty? A simple model sensitivity study (e.g., with $\pm X\%$ reflectivity) could shed light on how important this uncertainty is for interpretation of model-measurement comparison.

Section 3.1: How were the mesh samples generated? Are these simply individual micro-CT scans, or were samples somehow stitched together to create the 800 mm^3 volumes? Also, it would be helpful to clarify (once again) at the beginning of this section that the 1-D model is used to simulate albedo, using optical properties generated from 3-D

simulations of individual ice particles from the scans.

Line 337: By "optical thickness", I assume you mean the thickness of snow needed to achieve 5% transmittance, but it might help to apply more precise wording.

Figure 10 caption: Please note the snow thickness assumed in these model studies.

References:

Carmagnola, C. M., Domine, F., Dumont, M., Wright, P., Strellis, B., Bergin, M., Dibb, J., Picard, G., Libois, Q., Arnaud, L., and Morin, S.: Snow spectral albedo at Summit, Greenland: measurements and numerical simulations based on physical and chemical properties of the snowpack, *The Cryosphere*, 7, 1139-1160, <https://doi.org/10.5194/tc-7-1139-2013>, 2013.

Dumont, M., Flin, F., Malinka, A., Brissaud, O., Hagenmuller, P., Lapalus, P., Lesaffre, B., Dufour, A., Calonne, N., Rolland du Roscoat, S., and Ando, E.: Experimental and model-based investigation of the links between snow bidirectional reflectance and snow microstructure, *The Cryosphere*, 15, 3921-3948, <https://doi.org/10.5194/tc-15-3921-2021>, 2021.

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Liou, K. N., Takano, Y., He, C., Yang, P., Leung, L. R., Gu, Y., and Lee, W. L.: Stochastic parameterization for light absorption by internally mixed BC/dust in snow grains for application to climate models, *J. Geophys. Res.: Atmos.*, 119, 7616-7632, <https://doi.org/10.1002/2014JD021665>, 2014.