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 transmissivity using X-ray microtomography and geometric optics" by Theodore Letcher et al., The Cryosphere Discuss., https://doi.org/10.5194/tc-2021-310-RC2, 2021

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 20um 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.

Response: In response to another reviewer who shared the same concern, we have decided to reframe the phase function such that grain segmentation and individual particles are no longer required, since the phase function was the only optical property that required grain segmentation. This method follows more closely to Xiong et al. 2015 and Haussener et al. 2012. Upon further reflection, we understand that this method is more consistent with the estimation of the extinction coefficient and computation of absorption within the snowpack, and as a result substantially improves our results. However, this change does require major rewrites to the methods section, and changes in our results interpretation.

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

Response: The uncertainty for a given value of the extinction coefficient is very low for set parameters. For example, repeating the calculation of it for the same sample, same wavelength, and same curve fitting technique yields a standard deviation of <0.05 if enough photons are used (>2000 seems to be sufficient for convergence). However, there is more substantive uncertainty if the parameters that influence the curve fitting are modified. For example, if the distance sampling is different, or if the initial guess that feeds into the curve fit is modified can yield differences as high as 0.3.

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 potentialunderlying causes of this.

Response: Thank you for the suggestions and relevant references. We have incorporated some discussion on these points to the manuscript. In particular, on the first point related to differences in the top 1mm of snow vs. the top 2cm. Specifically, we find that the physical and optical properties of a 1cc rendering of snow, are quite variable over short depths (e.g., 2cm of snow can have a range of optical properties depending on how the uCT renderings are subset). However, as noted above, our results are substantially improved by modifying the phase function such that it determines the scattering direction at individual dielectric boundaries, rather than "whole particle" scattering. We believe that this orientation is much more consistent with the overall framework, as it intrinsically assumes photons are traveling between scattering events, not particles.

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.

Response: As mentioned, this was done in accordance with computational expense, and this is often assumed that n_ice is constant throughout the visible and NIR at ~ 1.33 in other studies. As part of a more comprehensive discussion, we have added some comments on this, specifically related to the phase function, and include a new figure showing how the phase function varies according to wavelength.

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".

Response: Done, thank you for this suggestion.

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.

Response: Thank you for this suggestion, accordingly we have added a couple of sentences further discussing this shortcoming:

"While some work has been done incorporating diffraction into geometric optics scattering for non-spherical particles (e.g., Yang et al. 1997; Liou et al. 2011), because this framework treats snow as a two-phase medium rather than a collection of particles, accounting for diffraction isn't straightforward. Further, because the diffraction pattern is strongly forward scattering (Xiong et al. 2015), we anticipate that this simplification is appropriate here, though we acknowledge that diffraction may be more important for the longer NIR wavelengths."

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

Response: Done, thank you.

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?

Response: Yes, the curve-fit is from P_ext to L, through Beers law to get the extinction coefficient. The uncertainty is generally very small (<0.05), however by playing around with how the curve fitting is performed, it becomes a little larger, specifically by changing the sample distance (L) for calculating P_ext, and modifying how the curve fit is performed. See above response for more information.

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?

Response: This is a great question. The boundaries are represented as facets (i.e., planar). And yes, it is resolved to approximately voxel size, with limited smoothing related to the level-set function that differentiates the snow from the air along the voxel boundary.

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

Response: We have removed all methods related to particles, so this section has been rewritten in it's entirety.

Line 169: Perhaps I missed it, but how many dTheta bins are used for the calculation of p(cos(Theta))?

Response: We used 180 bins, but this is a user configurable option.

Line 176: Grammatical issue.
Response: Corrected, thank you.

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

Response: In this method, the energy absorption is computed directly from the absorption coefficient of ice and a mean distance traveled within ice between scattering events, whereas most commonly in medium models, the medium is assigned an absorption coefficient based on the complex refractive index and single-scattering albedo.

Equation 20: How many bins are used to compute the DCRF?
Response: We used 10x10 degree bins following Kaempfer et al. 2007.

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 +/- X% reflectivity) could shed light on how important this uncertainty is for interpretation of model-measurement comparison.

Response: We suspect that the uncertainty of this is rather small, we took numerous reflectance measurements of this panel throughout the data collection periods and found a majority of the uncertainty was concentrated within the water vapor and CO2 bands. In response to this comment, we have performed these runs with +- 5% uncertainty in the lower-boundary reflectance, and show negligible impacts, even at the shallowest snow.

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.

Response: These mesh samples were generated from individual micro-CT scans of approximately 2.0cm width and 10cm depth. These are subsets of that to avoid assimilating edge pixels along the circumference of the micro-CT sample. We have reiterated how the 3D samples are used to generate the optical properties for 1D samples.

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.

Response: Thank you for this suggestion, we have clarified this to read "transmittance depth" following a similar comment from another reviewer.

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

Response: Done, thank you.

References:

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