## Review for TC Cintron-Rodriguez et al Light absorbing particles and snow aging feedback enhances albedo reduction on the Southwest Greenland ice

## General comments

This manuscript describes a set of observational data taken in the southwest ablation zone of the GrIS and applies SNICAR to estimate the total impact LAP and snow metamorphism have on albedo. These measurements include dust and BC concentration, snow density, and snow grain size and shape. This data is useful for constraining the concentration of LAPs and snow properties in southwestern Greenland. This set of observational data is interesting and useful. This paper is generally well written and is an interesting concept. However, I think this paper needs major revisions and the methodology needs to be revisited. Overall, it is unclear to me how properties used, assumptions made with regard to grain shape and size, and the calculation of total change in albedo and impact of LAP on snow metamorphism is unclear.

My most substantial suggestions are (in no particular order)

- 1. Use the multi-layer SNICAR-ADv3 or 4 (both are available online). While properties lower in the snow pack will only minimally influence the albedo, it would be beneficial to utilize the in situ measurements with depth. It would also be nice to see the modeled output albedo for the simulations constrained by measurements, with the caveat that the true albedo is not known.
- 2. Address the influence of grain size with regard to the results presented in figure 7, the manuscript states that both grain size and grain shape change with snow metamorphism and both have implications on albedo. However, only snow grain shape is addressed with the measurements taken. It is also important to provide justification of why hexagonal grains are used to represent fresh snow and spheroid grains are used to represent aged snow.
- 3. It is unclear what the relationship between LAP and snow metamorphism is, for example, what concentration of LAP justifies a transition from hexagonal shaped grains to spheroidal grains? How much of the grain growth and shape change can we attribute to LAPs rather than environmental variables such as temperature?
- 4. Please provide a more thorough justification for the snow properties and LAP concentrations used to simulate the results presented in figure 8. These results are all theoretical as there is no justification of the snow conditions used to simulate the albedo differences.
- 5. There needs to be significant clarifications within the methods for how the change in albedo is calculated. It is unclear how the total changes and % changes in albedo are calculated, and as a result these results are not easily reproducible.
- 6. I think the introduction could include more discussion about other measurements and how the measurements described here are different and useful (the measurements were taken with depth, you measure the grain size, shape, and density of the snow).

I have other specific comments below.

Specific comments

- 1. Line 19-20: "SNICAR simulations constrained by our measurements show that LAPsnow aging feedback reduce albedo reduction 4 to 10 times more than previously thought," Please add more nuance than "more than previously thought". For example, are you comparing to a study that also used measurements and RT modeling? Then say "more than previous studies have estimated" It's also important to elaborate on how this range was calculated in your methods / results.
- 2. Line 33-34: "However, sparse measurements of LAPs from the Greenland ice sheet snow limits our understanding of the LAP and Greenland albedo reductions" it could be useful to briefly discuss past measurement campaigns and different LAP data and to move your discussion of previous measurements to the introduction and then in the results you can say your measurements compared well and explain the possible discrepancies (Bøggild et al., 2010; Wientjes et al., 2012; Wientjes and Oerlemans, 2010; Cook et al., 2020; Onuma et al., 2019).
- 3. Line 53-55: "BC and other carbonaceous aerosols could reduce projected temperature increase by 0.5°C by 2050 while preventing millions of premature air pollution-related deaths and crop losses. (Samset et al., 2014; Lee et al., 2013; UNEP & WMO, 2011)." The removal of BC?
- 4. Lines 61-64: "During transport particles may fractionate and reduce the size of the dust particles transported over long distances to less than 20 to 30 μm (van der Does et al., 2018; Ryder et al., 2013; Kok et al., 2012). Evidence suggests that Arctic dust comes from Gobi and Taklaman deserts in Asia (38%), Saharan dust in Africa (32%), and local high latitude sources (27%) (Takemura et al., 2009)." This doesn't seem very relevant. It would be more useful to provide background on relevant measurements in this region of the ice sheet.
- 5. Snow and ice algae and the exposure of bare ice/crustal surfaces have been found to be very strong albedo reducers, I think your discussion should include some mention of these other mechanisms (Chevrollier et al., 2022; Tedstone et al., 2020; Ryan et al., 2019)
- 6. Line 83-86: "While global climate models include snow radiative transfer computation, including parametrizations of snow physical characteristics (particle size, particle shape, impurity load and solar zenith), the positive feedback of LAP on snow is often unaccounted in Greenland Ice Sheet measurements (Saito et al., 2019; He et al., 2018; Yasunari et al. 2011; Gardner and Sharp 2010; Marshall and Oglesby 1994)." He and others have done significant work to improve this representation, it is likely worth mentioning their work (He, 2022; Hao et al., 2022). It is also unclear if this sentence is about the importance of this representation in model or measurements. Please adjust.
- 7. Line 93: "Snow, Ice, and Aerosol Radiative (SNICAR) model (Flanner et al., 2007)" It is unclear which version of SNICAR is used in this study. The 2007 version does not allow for various grain shapes. There are multiple newer versions of this model that have been recently released that allow for multi-layer simulations and various grain shapes (Whicker et al., 2022; Flanner et al., 2021; Dang et al., 2019). These newer versions do not utilize the Toon 1989 solving method. Please clarify in the methods.
- 8. Line 200: "We used the single-layer Snow, Ice, and Aerosol Radiation (SNICAR) model to estimate snow albedo" It would be more interesting if you used a multilayer approach

using SNICAR-ADv3 or SNICAR-ADv4 and utilized your snow measurements with depth

- 9. Line 216: "These values of reff are used in the SNICAR model to bracket the likely range of actual reff." There was no use of a range of reff in the results? If you were going to use  $146.2 \pm 28.8$  as a range you would need to run 3 simulations, one for reff of 146.2-28.8, one for 146.2, and one for 146.2+28.8. This is also different from the values reported in table 2.
- 10. Figure 5 is great, it could be interesting to try and overlay [dust/BC] so we can see all the snow properties in one figure, or at least improve the dust/BC figure to look similar to figure 5.
- 11. Figure 7 caption: Please find a way to more clearly represent what delta albedo you are showing. It is unclear which figures include changing snow grain shape and which only include the influence of LAPs. For example use a more descriptive ledged like "spheroid grains w/ LAPs hexagonal plate w/ LAPs". The last line of the caption makes it seem like the same grain size and shape was used for all simulations "All spectral albedo changes represent the difference between the LAP impacted snow and the clean snow simulated with the model using the same snow properties." It is also unclear which snow properties are used in 7d, please refer to the corresponding table.
- 12. Table 2: The same grain size was used for all (both SA and non-SA) simulations? If that is the case, these simulations don't capture the full influence of snow metamorphism. Why is the average dust concentration used but only the surface BC used in the simulation? Also the effective radius 146.7 is not an option within SNICAR please adjust. Please also include all SNICAR parameters so these results can be recreated. For example, make a SA and non-SA column with all model input parameters (including the varying LAPs) so these simulations can easily be recreated and the differences between the simulations are clear. Please also apply this technique to the SNICAR parameters used for the figure 8 simulations.
- 13. Line 300-303: "We observe that snow aging related BC, dust, and LAP combined albedo reductions are 2.6±0.5, 1.18±0.06, and 1.18±0.04, respectively, times greater than those related to non-SA simulations." These albedo reductions are simulated, not observed. It is also not clear which simulations these reductions are based on. Why is the BC only reduction larger than that of the LAP combined albedo reduction?
- 14. Line 320: "Using previous studies' summer measured snow grain size of 550 μm (Warren, personal correspondence) and the LAP concentrations in the depth hoar layer, detailed in Table 4, we parameterize the SNICAR model to estimate the spectral albedo reductions for summer 2016 (Figure 7d) " Table 4, The density values in table 4 are not representative of the summer 2016 values as the snowpack has been compacted by melting, refreezing, and fresh snowfall. While the density doesn't influence the albedo of snow in SNICAR, it is likely worth mentioning that this density is greater than that of the 2017 snow density and making sure the reader understands that this will not have an impact on the delta albedo calculations. Please explain why using the snow grain radius from Warren is better than following the method used for the 2016 grain size, the 550 μm grain size is much larger than the 146.2 um grain size estimate.
- 15. Line 336: "f) Broadband albedo reductions for snow with LAP at reff of 50,110,200,350,and550μm." This simulation only includes BC, correct? Please adjust the legend accordingly.

- 16. Line 331-332: "Upper boundary (dotted lines) correspond to modelled albedo reduction assuming BC(dust)coated and lower boundary values correspond BC (dust) uncoated" this seems like you're getting the same albedo reduction for BC and dust? As you're using one line to represent different concentrations of both. Are you using both BC and dust in one simulation? I think your units for dust concentration are incorrect on the figure. Are you using milligram/gram (mg/g) or microgram/gram (ug/g)?
- 17. 332-334: "a)reff 50µm,60kgm<sup>-3</sup> (fresh snow); b) 110 µm, 150 kg m<sup>-3</sup> (slightly aged); c) 200 µm, 250 kg m<sup>-3</sup> (settled snow); d) 350 µm, 375 kg m<sup>-3</sup> (wind packed snow); e) 550 µm, 600 kg m<sup>-3</sup> (melting snow)." There is no justification for why these specific snow properties are chosen for aged/settled/wind packed/melted snow. Please include citations and discussion for why these snow properties were chosen for each snow state. Please also justify the concentrations of dust and BC you are using. In your measurements, I see a max dust concentration of ~3ug/g and a max BC concentration of ~2ng/g, but in your figure 8 simulations you are using up to 200ug/g (I am assuming mg/g on the figure is a typo) of dust and 1500 ng/g of BC. The use of such high LAP concentration inflates the difference in albedo and these concentrations seem unjustified based on the measurements presented here and your comparison to previous measurements.
- 18. Line 334:335: "This simulations are computed as the albedo of pure snow (hexagonal shape) minus the difference of the albedo of pure snow (spheroid shape) the albedo of LAP- containing snow (spheroid shape)." It is unclear what differences are being represented here, it might be more clear if you also show the SNICAR output albedo with sufficient legends to be more clear about which albedos you are differencing and/or write out an equation. It sounds like you are differencing three albedo simulations, which does not seem correct.
- 19. Line 340: "LAPs have double the impact on albedo reductions compared to fresh snow (Figure 8)." Please include quantitative results and range, this seems like it is only true for very large LAP concentrations? If so, this result is contingent on the justification of both snow properties and LAP concentrations used in figure 8.
- 20. Line 345: "Thus, compared with fresh snow, BC concentration of 0.5 ug  $g^{-1}$ , and dust concentration of 1.0 ug  $g^{-1}$  causes an additional net albedo reduction of 0.01 0.15 depending on the impurity content in melting snow under summer conditions." Why does this depend on impurity content? Isn't this result for a simulation with BC concentration of 0.5 ug  $g^{-1}$ , and dust concentration of 1.0 ug  $g^{-1}$ ? Are you comparing fresh snow with LAP to aged snow with LAP?
- 21. Line 398-399: "While our measured LAP concentrations were relatively low, we find larger albedo reduction than previous studies." Do you have citations for these previous studies? I'm not sure this is fair to say because no in situ albedo measurements were taken. It is important to note alongside this discussion of the impact on albedo that the uncertainty associated with this albedo is unknown because no in situ albedo measurements were taken. Also, are theses albedo reductions based on theoretical snow properties and LAP concentrations (ie not measured values in figure 8)? If so that major caveat needs to also be mentioned.
- 22. Line 403: "while the isolated snow grain shape change (without LAP) influences mostly the albedo at the shorter wavelengths (Figure 7d)" What wavelengths and by how much? Changes to grain shape and size have the strongest impact in the NIR, so seems

counterintuitive to not include this region of the spectra in your analysis. Figure 7d does not show the impact of changing snow grain shape.

- 23. Line 404-405: "Therefore, after subtracting the clean snow grain shape change effect we can assume that all the observed absorption is due to the presence and snow metamorphism influence of LAP" This absorption is not observed, it was simulated. It is also unclear what you are trying to say here
- 24. Lines 405-407: "Contrary to the findings of Lewis et al. 2021, we found that LAP have a significant role in the albedo reduction considering their role on accelerating snow metamorphism which amplifies LAP radiation perturbation (Schneider & Flanner, 2017; Hadley & Kirchstetter 2012)." I'm not sure this is fair to say, the role LAP's play in accelerating snow metamorphism is not clear from this study. You do not calculate how the LAPs are influencing the grain shape, you simulate the impact the combined effect of LAPs and snow metamorphism have on albedo. Can you suggest the rate of metamorphism based on only LAPs (not the influence of temperature or general snow aging)?
- 25. Line 417-419: "Our results only apply for direct incident radiation given that half of our measurements were under clear-sky conditions. We note that overcast conditions in Greenland would render a slightly lower albedo perturbation than our results indicate." Why is this relevant? Wouldn't the sky conditions only be relevant for albedo measurements?
- 26. Lines 432:434: "Using our observed BC and dust concentrations values and a model that considers snow metamorphism, we found that albedo is reduced by as much as 3.0 ± 0.4% in the summer and by 1.9 ± 0.1% as an annual average in contrast to fresh snow without LAP" It seems as though in the simulations where measured dust and BC are used (figure 7) only changing snow grain shape is accounted for, there is no grain growth, so it doesn't seem accurate to say "the model considers snow metamorphism".
- 27. Lines 434-436: "These albedo reductions are 4 to 10 times larger than previous studies with 435 similar LAP concentrations and suggests that LAPs have a greater impact on surface melting through snow metamorphism than previously thought" Please explain how the 4 to 10x is calculated.

## Technical corrections

- 1. Line 79: missing period "(He et al., 2018) Furthermore"
- 2. Line 54: extra period "crop losses. (Samset et al., 2014; Lee et al., 2013; UNEP & WMO, 2011)."
- "Figure 7. SNICAR simulations of 2016-2017 southwest Greenland Ice Sheet albedo reductions with and without metamorphism" are these for 2016 or 2017? Text says measurements from 2017 "We ran the SNICAR model using the parameters listed in Table 2 for 2017 Spring albedo reductions" but the figure title says 2016-2017
- 4. "Table 4. List of site specific parameters for the summer scenario SNICAR simulations. For these simulations, SNICAR was run with the BC and dust concentrations measured in the depth hoar layer, representing previous summer concentrations." Please say the year (ie 2016) rather than "previous summer"
- 5. Lines 329-331: "Figure 8. Spectral albedo reductions due to LAP modelled using SNICAR at a solar zenith angle of 60° for different reff and snow density combinations.

Spectral albedo reductions due to LAP modelled using SNICAR at a solar zenith angle of 60° for different reff and snow density combinations" title of figure included twice

- 6. Figure 8F needs a y axis label
- 7. Please add the effective radius and snow density used for each subplot within each subplot.
- 8. Be consistent with the units of grain size, some are in mm and some are um. Please generally be consistent with unit notation.

## Relevant Citations:

Bøggild, C. E., Brandt, R. E., Brown, K. J., and Warren, S. G.: The ablation zone in northeast Greenland: ice types, albedos and impurities, Journal of Glaciology, 56, 101–113, https://doi.org/10.3189/002214310791190776, 2010.

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