RE: Referee # 2 comments on Light absorbing particles and snow aging feedback enhances albedo reduction on the Southwest Greenland ice sheet

Dear Referee and Editor,

The authors would like to thank the referee for the time and effort in reviewing and providing comments to our manuscript.

Below we include point-by-point response. For the comments the are related to technical text suggestions they will be included in the manuscript unless noted below. The reviewer comments are shown in cursive and purple highlight. Our response is in regular font.

Response to Referee 2

General Comments

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.
We will clarify that we used SNICSR-ADv3 and that the simulations were constained by field measurements. As properties low in snowpack do not significantly influence albedo we did not included them here.

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.
We will revise the manuscript to further explain the selection of snow grain shapes (hexagonal and spheroid grains to represent fresh and aged snow, respectively) is rooted in the fact that the most basic and known variety of fresh snow is the simple prism, displaying hexagonal symmetry. However, as it ages snow grains become more rounded and hence we chose spheroid grains. Although we dont try to estimate the influence of grain size, given that we our field measurements only have optical grain size during measurement, we can include some context to the reader better understand the influence of grain growth with regard to the results presented in figure 7 and connect it to our sensitivity study presented in Figure 8.

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?
We will clarify that this the aim of this study is not to quantify the grain growth due to environmental variables such as temperatures vs LAP. Instead, the goal of this study is to study LAP influence over the naturally occurring snow metamorphism process. Our findings show that considering LAP in snow metamorphism process enhances impact on albedo reductions.

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.
We will clarify that the Figure 8 values are theoretical, and that the purpose is to provide a sensitivity test of the properties to a range of concentrations under differing snow properties. We will rewrite the manuscript and explain

that we selected the range of observed snow properties in previous campaigns and literature (i.e reff as little as 50 to and as large as 550) and theoretical snow densities for various stages of snow metamorphism. (Muskett, 2012)

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.
We will revise the manuscript to clarify our method to calculate % changes in albedo, i.e. the albedo reduction was calculated as the difference of broadband albedo values between clean snow and snow containing impurities (BC+dust) as a fraction of the two combined.We will reinforce this when the results are presented.

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).
As suggested, we have added discussions about this in the revised manuscript.

Specific comments:

Line 19-20: "SNICAR simulations constrained by our measurements show that LAP-snow 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.
As suggested, we will add more context here.

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).
As suggested, we will make sure to include these references

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?
As suggested, we will clarify this sentence to explain that it is the removal of BC that could result in these beneficial impacts.

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.
We agree with the reviewer and will remove this part from the manuscript and provide additional measurements in this region where available.

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)
As suggested, we will write about the suggested other mechanisms in the discussion

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.
As suggested, we will incorporate the work by He, 2022 and Hao el al. 2022 and rewrite so that it is clear that this text is about modelling.

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.
We will revised the manuscript to clarify that SNICSR-ADv3 was used in this study

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
Althought a multilayer approach and understanding the snow measurements with depth is an interesting question, we choose to focus on single layer applications in the study. We will add text in the discussion to propose using a mulitlayer methods as an extension of this study.

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 ± 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
We will clarify in the manuscript that we ran simulations with many values between each range and that model results are reported as average. We will also correct the value to 146.7.
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.
We will be keeping Figure 5 and 6 separate to avoid cluttering the image with too much information but will work on Figure 6 to look similar to Figure 5.

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.
As requested, we will provide a better explanation in the figure caption.

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.

Regarding Table 2, we agree that using the same grain size for all simulations (both SA and non-SA) may not fully capture the influence of snow metamorphism. We acknowledge that this is a limitation of our study and will include a note in the manuscript to this effect. To this effect we performed the sensitivity study (which is presented in Figure 8) to evaluate the impact of different grain sizes and LAP content in albedo reductions. We will make this more clear in our final manuscript. Regarding the use of dust and surface BC in the simulations, we only used surface BC because it tends to agglomerate in the surface due to its hydroscopicity. On the other hand, dust can be eluted by percolation, so we used the average dust concentration to accurately represent the water year period. We will clarify this in the manuscript. We apologize for the error in reporting the effective radius in SNICAR. We will correct this to 147, which is what SNICAR automatically converts 146.7 to. We will also include all SNICAR parameters in the manuscript so that our results can be easily recreated. Specifically, we will add a SA and non-SA column with all model input parameters presented in Table 2 and 4 so that the our snow aging treatment and difference between the simulations is clear. We will also create a table for the SNICAR parameters used in Figure 8 simulations.

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?

We agree that using the term "observed" might not be appropriate and we will change it to ensure is clear albedo reductions are simulated. The clarifications for Table 2 explained in the previous comment might help clarify to the reader the nature of this observations. Regarding the relative magnitudes of the albedo reductions, it is not uncommon to find higher albedo reductions by the BC component than the combined component because given the non-linearity relationship, as light penetration increases with LAP concentration (Dang et al., 2017).

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 550um grain size is much larger than the 146.2 um grain size estimate.

We will revised the paper and explain that we selected Warren's snow grain radius because these measurements were done in the Summer, which is our target season. In the revised paper, we will better explain that we use the bottom layer concentration because it is representative of summer 2016 conditions. The grain size observed in the bottom layer of our study may not be representative of the time when this layer (2016) was on the surface, as it could have been impacted by compaction and post-depositional processes. Therefore we used Warren 550um grain size as it is representative of summer melting snow conditions and the impact LAP can have in that season.

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.

We will adjust the legend and better explain that the simulations includes BC and dust, and that the concentrations used for only-dust simulations are in parenthesis.

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)?
We will revise to clarify that we were using both concentrations in one simulation. We are using ug/g (micrograms/gram)

332-334: "a)reff 50μm,60kgm-3 (fresh snow); b) 110 μm, 150 kg m-3 (slightly aged); c) 200 μm, 250 kg m-3 (settled snow); d) 350 μm, 375 kg m-3 (wind packed snow); e) 550 μm, 600 kg m-3 (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.
As suggested, we will revise the manuscript to include citations and explain that all values for Figure 8 were selected to provide a sensitivity study and these are theoretical values not obtained from literature.

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.
As suggested, we will clarify this sentence as it should read his simulations are computed as the albedo of pure snow (hexagonal shape) minus the albedo of LAP-containing snow (spheroid shape)

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.
We will rewrite this sentence and provide quantitative results and range. This sentence was specifically referring to Figure 8e but we agree it could be improved for clarification.

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?
Indeed this sentence is poorly worded. We will revise to clarify that we are comparing fresh snow with out LAPs with aged snow with LAP.

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.
We will revise the text to clarify that our albedo estiamtes are made with a model, while previous studies are based observations. We will also add the citations. We will also clarify that the the albedo reductions referred to here are estimated with model simulations using measured snow properties.

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.

We will revise the text to clarify that a section of NIR is included in figure 7 (i.e. 700 - 1000 nm). We will also add text to explained that grain shape strongly influence NIR and cannot alone explain the difference in the VIS region.

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

As requested, we will clarify this sentence.

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)?

We disagree with the reviewer. The aim of this study is not to quantify the influence of LAP on grain shape, but show that LAPs influence grows as snow ages. As can be seen in figure 7, snow aging by itself cant explain the albedo reduction over the VIS region. We will work on the discussion section to make this argument more clear.

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?

We will reword this part to explained that it is relevant to mention the sky conditions because it is a parameter of the SNICAR albedo simulations.

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".

We agree this model does not fully capture snow metamorphism. The reasoning behind our choice is that we don't have an accurate way to determine the size of fresh snow without impurities or estimate the grain growth rate. The inclusion of snow grain size growth would very likely result in even greater albedo reductions, thus, we wanted to avoid non-observation estimations that could lead to overestimations given that snow grain size plays such a significant role on snow albedo. We will make sure that this limitation and its impact on the interpretation of results is much clearer to the reader on the discussion.

Lines 434-436: "These albedo reductions are 4 to 10 times larger than previous studies with 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.

We will revised the manucript and explain in more detail how the calculations were done

All other minor technical and editorial suggestions will be corrected in the revised manuscript.