Attribution of Greenland's ablating ice surfaces on ice sheet albedo using unmanned aerial systems

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Summary:
The authors investigate the influence of difference surface types on Greenland ice sheet (GrIS) albedo within a region of exposed ice in the lower accumulation zone. They use an unmanned aerial system (UAS), which includes a set of pyranometers, a digital camera and other instruments. Measurements are taken across a transect spanning 25 km in the lower west coast ablation area of the GrIS for three days during the summer of 2014. Pyranometer measurements are compared with coincident measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS). Fractional coverage of different surface types and their relative albedo is estimated using digital photographs. It is found that spatial variations in albedo at the ~500 m MODIS scale ("mesoscale") is primarily associated with spatial variations in the fractional area covered by distributed impurities. Streams, lakes, cryoconite holes are found to have a strong local impact, but do not contribute to this large scale variability. The authors suggest that future surface mass balance models for the GrIS should take into account the evolution of different surface types and account for their dynamic impact on surface albedo.

General Comments:
This study is an important contribution to our understanding of albedo in snow-free areas of the Greenland Ice Sheet ablation area. The work is highly important for improving simulations of surface mass balance in the area. The study is well thought-out, well organized and well written. It should be published after relatively minor revisions discussed below. A few general points:

(1) I think there needs to be a bit more discussion about the spatial scales of the processes and observations involved. While distributed impurities appear drive variations in albedo at the "mesoscale", variations in albedo at finer scales may be more sensitive to liquid water or cryoconite holes. At coarser scales, perhaps snow vs. ice coverage is more important. The authors should clarify that the results are valid at the "mesoscale", which is at the fine end of the spatial scale used by climate models and therefore important for that application.
(2) The conclusion that melting is a consequence rather than a cause of spatial variations in albedo is not really supported by the observations of this study, and overlooks the feedbacks linking melt to surface albedo change. See specific comments.
(3) Some additional details should be provided about differences between the measurements being compared, such as the spatial extent of different overlapping measurements, and the spectral range of different sensors. See specific comments.

Specific Comments:

1. **P. 1, Line 2:** Suggest changing "importance of distinct surface types on albedo" to "importance of distinct surface types on variations in albedo"
2. **P. 1, Line 18:** Change "ice melt (van den Broeke…" to "ice melt in ice-covered regions (van den Broeke…" to be a bit more clear.
3. **P. 2, Line 34:** What kinds of errors are introduced by variations in the height of the UAS as it flies? How these errors contribute to errors in the pyranometer and digital image albedo measurements?
4. **P. 3, Section 2.2:** Can the authors comment on the spatial extent of the area being measured by the pyranometers? While the pyranometers measure radiation over the entire hemisphere, there must be a radius within which surface albedo has a stronger impact on the measurements. This is important for comparison with MODIS because the 500 m MODIS pixel may not completely overlap with the area being "seen" by the pyranometers. This source of differences should also be discussed and mentioned as a source of error in the comparison.
   What does the 1 Hz sampling rate translate into in terms of the "spatial resolution" of the albedo measurements?
5. **P. 4, Line 11:** Please define and explain EXIF data.
6. **P. 4, Line 14:** Were the white reference measurements acquired by the UAS by taking a photograph of a reference target on the ground, or were the measurements taken on the ground using another sensor while the UAS was flying? Or was the reference target somehow flying on the UAS? Please clarify.
7. **P. 4, Lines 18-20:** This statement also needs clarification. Were the ground measurements taken at specific sites where coincident photographs were available, or were the photo-derived albedo of surface materials visible in the photographs compared against ground measurements of similar materials in other locations? How many photographs and measurements were used in this analysis?
8. **P. 4, Line 21:** Suggest changing "two products" to "the α_{camera} and surface albedo measurements" for clarity.
9. **P. 4, Lines 23-25:** The uncertainty results from the difference between the wavelength ranges of the two sensors; they represent albedo taken over different ranges. There is no defined wavelength range for albedo, although the 280 to 4000 nm range covers most of the radiation that comes from the sun. A "true" albedo would have an infinite wavelength range, but in practice a range must be defined. I suggest noting that the CM3 pyranometer covers a wider wavelength range, which covers the majority of the solar spectrum, and that the estimated uncertainty results from the shorter wavelength range of the CMOS sensor.
10. **P. 4, Lines 25-27:** 35% is quite a large percentage of the solar radiation. I would exclude mention of this as the important point is whether a shorter wavelength range can be used to estimate albedo over a longer wavelength range. Also the error from Corripio et al. (2004) is specific to that study. Corripio et al. (2004) estimate errors of 4-5% associated with a camera that does not capture NIR radiation using a radiative transfer model for snow, accounting for variability in NIR reflectance associated with different snow types. The error will be different for different materials. For the measurements of this particular study, the spectrum for ice, impurities, and water will be fairly uniform across all

wavelengths, and therefore the errors will actually be less than those estimated by Corripio et al. (2004). However, I think the authors should address and if possible, quantify this source of error more carefully, perhaps by examining the spectra of the different surface materials.

11. **P. 5, Line 4:** Was manual digitization only applied on a subset of the images? How many? Please clarify.
12. **P. 5, Line 21:** Please specify the wavelength range for the MOD10A1 product (300 to 3000 nm).
13. **P. 5, Line 24:** How is a "segment" determined? From Fig. 3 it seems that α_{pyra} is somehow averaged onto the 500 m MODIS grid, but this is not discussed. Clarify here, and perhaps also add details in Section 3.1.
14. **P. 6, Line 3:** Why not include α_{camera} in this plot? Since you are reconstructing the surface types from the camera measurements, showing that α_{camera} compares well to α_{pyra} and α_{MODIS} would help support the conclusions.
15. **P. 6, Line 5:** There was no detectable bias between α_{MODIS} and what other measurement? Do the authors mean to say that α_{MODIS} did not change detectably over the three-day period?
16. **P. 6, Line 9:** Figure 6 is discussed in section 3.2 but Figs. 4 and 5 are not mentioned until the discussion section. I suggest adding another paragraph here that qualitatively discusses Figures 4 and 5, introducing the different surface types. Figures 4 and 5 could also be moved to follow Fig. 6, but it may be useful to introduce the different surface types before discussing their fractional area and impact on albedo.
17. **P. 6, Line 24:** It seems appropriate to also cite Fig. 6 here, since it includes the fractional surface types.
18. **P. 6, Line 22:** Can a figure be added that shows the results of PCA analysis?
19. **P. 7, Lines 15-16:** Please explain in more detail how the RGB signatures are similar. Are the authors referring to the inset plots in Figs. 4 a, b and c and 5 a, b, and c? These insets should be discussed somewhere in the text. Also, since the authors do not have biological samples from these areas, it should be noted that this is not conclusive evidence that the RGB signatures are associated with algae.
20. **P. 7, Lines 24-25:** Other possibilities for the change in extent of the dark region should be noted, such as the consolidation of impurities due to increased melting.
21. **P. 7, Line 32 – P. 8 Line 2:** The statement seems to contradict itself in implying that increased fractional area of streams are not found in the dark region, yet there is a preponderance of meltwater there. Also, while meltwater may not directly drive spatial variability in albedo, melting is involved in the exposure, consolidation, and transport of impurities. One cannot conclude from the evidence presented that meltwater does not play an important role in the observed spatial variations in albedo. I suggest changing the last part of this sentence to note that the dark area cannot be explained as a direct consequence of spatial variations in fractional area covered by meltwater, and that the spatial variability at the MODIS scale is driven primarily by impurity concentrations, but noting that meltwater may play a role in the consolidation of impurities here.

22. **P. 8, Lines 22:** Suggest changing "will drive" to "will play an important role". Other factors such as further expansion of the dark region or more frequent exposure of bare ice will probably also play important roles as well.
23. **P. 9, Line 23:** Perhaps to be clear, note that a decrease in concentrated cryoconite is observed in the region with the lowest α_{MODIS} values.
24. **P. 9, Line 33:** Figure 4F does not exist. Please remove the reference or add a figure.
25. **P. 10, Lines 5-8:** Do you have any justification for this assumption? How do you know that the "distributed impurities" that are observed are not characterized by many small cryoconite holes?
26. **P. 10, Line 20:** It is not just the reconstructed albedo, but the combination of calculated albedos for individual components and measurement of their respective contribution to the reconstructed albedo that provides important information for improving models.
27. **P. 11, Line 6:** Since you have primarily looked into spatial variations, I suggest changing "primary control on α_{MODIS}" to "primary control on spatial variations in α_{MODIS}".
28. **P. 11, Lines 7-8:** The signal is dominated by the distributed impurities not just because of their extensive coverage, but also because of the large spatial variation in their fractional area on the "mesoscale".
29. **P. 11, Line 10:** Although as you note, the resolution of your measurements is not fine enough to capture ~25% of cryoconite holes.
30. **P. 11, Line 15:** Again, I don't think your results have proven that meltwater is a consequence rather than a cause of darkening. They do help support the fact that meltwater is not a *direct* cause of spatial variations in albedo in the area. Please revise.
31. **P. 11, Line 23:** The evidence for this is not really discussed in the paper. I think your main piece of evidence is the apparent increase in the fractional contribution of cryoconite in areas of higher albedo. Perhaps mention this here and earlier when discussing cryoconite.
32. **Table 2:** Change "each albedo product" in the caption to "α_{MODIS} vs. α_{pyra}". Could $\alpha_{reconstructed}$ be included here as well? I think it would lend support to your conclusions about the usefulness of reconstructing, or deconstructing, albedo for improving climate models. (Table 3 does support that argument to some extent.)
33. **Figure 3:** I would suggest including $\alpha_{reconstructed}$ here as well as in Fig. 6. However, if you chose to only include these two sets of measurements, perhaps it would make more sense to include the r^2 and RMSD values on this figure instead of presenting them in Table 2. The fact that the transect is showing west on the left and east on the right should be mentioned in the caption or illustrated.
34. **Figure 4:** The small insets for Figs. 4a, b, and c do not have axis labels or a legend and are not mentioned in the caption. They are not mentioned specifically in the text either, although I think they show the RGB signatures of these images. Please mention in the text and include these details in the figure. Also revise "located in Fig. 1" in the caption to "shown in Fig. 1."
35. **Figure 5:** Again, please explain the small insets in Figs. 5 a, b, and c. Change "Highly crevassed area" to "Digital image of highly crevassed area". Also

explain that (B) and (C) are digital images. Explain that (B') is a DEM. Explain that (C') is a close-up showing albedo and (C'') is a closeup showing classified surface types.

36. **Figure 6:** Suggest showing $\alpha_{reconstructed}$ here as well.

Technical Corrections:

1. **Title: "**Attribution" does not seem to be the correct word here. Perhaps it should be changed to "influence" or "impact".
2. **Author list:** Why not simply include all authors in the authors list?
3. **P. 1, Line 8:** Change "The highest correlation with…" to "The property that exhibited the highest correlation with mesoscale albedo"
4. **P. 2, Line 12:** Change "generate" to "generated".
5. **P. 2, Line 15:** Change "Lovénbreen ," to "Lovénbreen,"
6. **P. 3, Line 6:** Change "were subsequently" to "was subsequently"
7. **P. 3, Line 13:** Change "SP-110 incorporate" to "SP-110 incorporates"
8. **P. 3, Line 14:** Change "and benefit" to "and benefits"
9. **P. 5, Line 24:** Change "have an RSMD" to "has an RMSD"
10. **P. 6, Line 14:** Change "fractional area" to "fractional areas", and change "(R^2 0.94)" to "($R^2 = 0.94$)".
11. **P. 6, Line 25:** Change "albedo patterns of albedo" to "albedo patterns".
12. **P. 7, Line 5:** Change "80% the dark" to "80% of the dark"
13. **P. 8, Line 4:** Change "is associated with" to "has"
14. **P. 10, Line 23:** Define MAR.
15. **P. 11, Line 24:** Change "(α_{camera} 0.27)" to "($\alpha_{camera} = 0.27$)"
16. **P. 11, Line 9:** Change "regions" to "region's"
17. **P. 11, Line 11:** Change "regions" to "region's"
18. **P. 11, Line 13:** Change "α_{camera} between" to "α_{camera} ranges between"