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Interactive comment on "Albedo over snow and ice penitents" *by* J. Abermann et al.

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General response

First, we would like to thank both reviewers for their careful evaluation of our work as they have raised many valid concerns. We address each of these suggestions and questions (*in cyan italic*) in this response document with reference to Section in the revised version in red and *cited text in the revised version in magenta italic*. Moreover, if the reviewers accept our responses, we will provide a complete revised version that will include all proposed changes.

Major changes

As a summary, the proposed major changes include:

1. Separation of the measurements in below tip measurements (expressed as nor-

malized outgoing radiation) and above tip measurements (expressed as apparent albedo). This change will address both M. Dumont's and reviewer 2's major concerns on the measurement of albedo inside the penitents troughs.

2. Inclusion of a two dimensional (2D) intra-surface radiative transfer ISRT model (explained in the added Section 3.3 in the revised version and discussed in Section 5.1) to simulate the measurements of outgoing radiation (within penitent trough) and albedo (above penitent tip). The ISRT model is initialized based on the measured experiment conditions (size parameters H and W) and run for different penitent surface shapes (triangular shaped, convex shaped, concave shaped, cosine shaped penitents Fig. 4 in revised version). The results of the ISRT model runs for the different penitent geometries (size/shape) allow to:
   (a) understand the variability in incoming radiation (Sin) and outgoing radiation (Sout) within the penitent troughs (explained in results section Section 4.1 and Fig. 5 in revised version).
   (b) compare the outgoing radiation within the penitent trough as measured by the sensor with modeled outgoing radiation that would be measured by the sensor for the different penitent geometries. This comparison shows the effect of i) the surface geometry and ii) the position of the sensor on the measured outgoing radiation (explained in results Section 4.2 and Fig. 6 in revised version).
   (c) illustrate the interaction between material albedo and penitent geometry and their effects on shortwave radiation budget (explained in results section Section 4.3 and shown in Table. 4 in revised version).
   (d) compare the measured apparent albedo with the modeled apparent albedo based on the ISRT model over a homogeneous penitent field (explained in results Section 4.3 and Fig. 7 in revised version. This comparison illustrates the representativeness of the measured apparent albedo over a homogeneous penitent field.

(e) compare the apparent albedo as measured by a sensor with the effective albedo of a penitent surface (i.e., SW energy leaving the penitent field /SW energy entering the penitent field); (explained in results Section 4.3 and Fig. 7 in revised version). This comparison allows quantifying the differences between apparent and effective albedo over a penitent surface before using albedo data for validation of remote sensing imagery, interpretation of automated weather station (AWS) radiation data or incorporation in energy balance models

Consequently, the results of the ISRT model runs provide a framework to interpret and discuss the representativeness of the measurements, and how apparent and effective albedo can differ significantly. Both topics were major concerns of reviewer 2.

Adaptions in revised version

The following adaptations to the revised version can be expected based on the proposed changes:

1. The introduction of the paper has been adapted to incorporate major concerns raised by reviewer 2 (R2.2 and R2.3) based on which we introduced the ISRT model to compare the apparent albedo measured by the sensor with the true or effective albedo: *Although the use of radiative transfer models (Cathles et al., 2011, in press; Fortuniak, 2007; Pfeffer and Bretherton, 1987) allows quantifying the effect of penitent surface topography on effective albedo, their use in energy balance models remains limited (e.g., Corripio and Purves, 2005) as the penitent topography often remains unknown. Instead albedo measurements derived from shortwave radiation sensors or remote sensing data are used as effective albedos in the energy balance models (Corripio and Purves, 2005, Pellicciotti et al., 2008, Winkler et al., 2009). However, the albedo measured over a penitent surface may be quite different from the effective albedo depending on the position*

and footprint of the sensor, since penitent surfaces are heterogeneous in their incoming/outgoing radiation (Corripio and Purves, 2005). In this context, Pirazzini (2004) discusses the apparent albedo (i.e., the albedo measured under particular geometric conditions) and how it can differ from the 'true' or effective albedo depending on the position of the sun/sensor with respect to the surface, and the shape, size, and orientation of the surface topography. This stresses the need for a comprehensive understanding of the differences between material albedo, apparent albedo and effective albedo over a penitent surface. This understanding is specifically important when using albedo data for validation of remote sensing imagery, interpretation of automated weather station (AWS) radiation data or incorporation in energy balance models.

2. Simultaneously the aim of the paper has been reformulated to clarify the objectives (R1.2) and integrate the comparison between apparent and effective albedo over a penitent surface: *This paper aims to address the current need for a more thorough understanding of effects of penitents on surface albedo and how it can vary depending on the position of the sensor and size/shape of the penitents. More specifically, the objectives are i) to assess the effect of penitent size and shape on the outgoing radiation and effective albedo, ii) to quantify the difference between material albedo, apparent albedo and effective albedo measured by a sensor placed at different heights above a penitent surface, and iii) to use the uncertainty related to the use of apparent albedo data to compare albedo data from AWS measurements and satellite observations. Within this framework, a radiative transfer model is used to simulate the incoming/outgoing radiation within a penitent trough and the apparent and effective albedo above a penitent surface. The simulated radiation and effective albedo data derived from the radiative transfer model are subsequently compared to radiation and apparent albedo measurements over a real penitent surface with varying geometrical/sun conditions. Moreover, the uncertainty due to apparent albedo is put into context*

by presenting albedo time-series for two markedly differing ablation seasons and comparing them with satellite-derived albedo.

3. The data and methods section has been reorganized to include the ISRT model description (Section 3.3). Within this framework a new Fig. 4 will be introduced that illustrates the different penitent geometries (size/shape) that have been included during the ISRT modeling.

4. The results section has been adapted to:

   (a) illustrate the variability in incoming/outgoing radiation within a penitent trough (Section 4.1). Within this context, a new Fig. 5 is introduced that shows the variability in incoming radiation (Sin) and outgoing radiation (Sout) over the modeled penitent surfaces demonstrating the effect of the penitent geometries in combination with multiple reflections and shading.

   (b) present i) the measured apparent outgoing radiation below the penitent tips and ii) modeled apparent outgoing radiation for the ISRT model experiments (Section 4.2). A new Fig. 6 is introduced (partly replacing original Fig. 4) that shows i) the measured outgoing radiation with a penitent trough and ii) the ISRT model output that simulates the measured outgoing radiation for different penitent geometries.

   (c) demonstrate the observed changes in measured and modeled apparent albedo above the penitent tips in function of sensor height (Section 4.3). Moreover, the difference between apparent and effective albedo in function of sensor location and penitent geometry is presented. In this context, a two new figures are introduced (partly replacing original Fig. 4) that show (Fig. 7) in function of the sensor height above the penitent tips: i) the changes in modeled/measured apparent albedo and ii) the changes in effective albedo, and (Fig. 8 the sampling bias due to the use of individual measurements) Additionally a Fig. 9 has been added to explain the differences between

apparent and effective albedo based on different viewing conditions (of the sensor) over a surface that has i) large heterogeneity in incoming/outgoing radiation ii) large variation in topography resulting in large viewing obstructions. Also Fig. 10 has been added to illustrate the diurnal evolution in apparent albedo, effective albedo and sampling bias.

   (d) a confidence interval on the temporal evolution of AWS albedo data has been introduced based on the uncertainty in albedo data due to differences in apparent and effective albedo (Section 4.4 and added to Fig 11 (i.e., original Fig. 5)). This confidence interval allows putting the comparison between AWS and satellite albedo into context.

5. The discussion section has been reorganized. Firstly, the discussion on changes in effective albedo with height in function of anomalies of a distribution with unknown mean and variance (former lines 3832:16-3835:5) has been removed. Secondly, discussion subsections have been added to clarify the different subjects of discussion (as raised by M. Dumont's comment R1.3). These include sections on:

   (a) ISRT model (Section 5.1), where we discuss the advantages and limitations of using the ISRT model.

   (b) Effective albedo of a penitent (Section 5.2), where we discuss the effect of penitent geometry (size and shape) on the effective albedo and relate our results to the work of Warren et al. (1998), Pfeffer and Bretherton (1987) and Cathles et al. (2011). Moreover, we discuss the effect of sun position and shading on the effective albedo.

   (c) Apparent albedo vs. effective albedo (Section 5.3), where we discuss the accuracy of apparent albedo measurements to represent effective albedo. Within this context we highlight the shortcomings of using sensors at specific locations when large viewing obstructions are expected.

(d) Apparent albedo vs. remote sensing albedo (Section 5.4). In this section we discuss the comparison the albedo derived from Landsat and MODIS with the apparent albedo in the framework of previous studies (L3835:6 - L3836:12 in the original submission)

(e) Implications for interpretation of albedo measurements (Section 5.5), where we put our obtained differences between apparent and effective albedo into context and discuss the possible constraints/solutions when using albedo measurements for validation of remote sensing imagery, interpretation of automated weather station (AWS) radiation data or incorporation in energy balance models.

6. The major conclusions of the paper have been adapted to integrate the changes described above.

7. Finally we would like to ask the editor to agree on a change in first authorship of the re-submitted article which is in accordance with each of the authors. This is due to major additional work that has very much shifted responsibility. The newly proposed order is: S. Lhermitte, J. Abermann and C. Kinnard.

Sincerely yours, J. Abermann, C. Kinnard, and S. Lhermitte

Response to Reviewer Comment of M. Dumont

Main comments 1) The first comment is about the definition of the albedo. If I understood correctly, you measured the outgoing radiation from different heights above the ground and you divide it by the incoming radiation measured above a flat surface nearby. I completely agree that while doing that you will get the albedo as soon as the downward sensor is above the tip of the penitent but it is not true when the sensor is below the tip since in this case, the incoming radiation would also be modified. Consequently, it seems to me that you are not studying the evolution of albedo below the tip of the penitent but only the evolution of the outgoing radiation. I think this point deserves clarification in the paper.

R1.1: This is a key point both in the review by M. Dumont and by reviewer 2 (R2.2). Although we had raised this problem in the initial submission (p3831 L17-21), we resolve this issue by separating the results into two sections: a) below tip measurements between the penitent tip and the trough bottom (expressed as normalized outgoing radiation) in Section 4.2 and b) above tip measurements (expressed as apparent albedo) in Section 4.3. To do so, we replaced Fig. 4, which showed the albedo measurements, with Figures 6-7, which show the measured normalized outgoing radiation below the tip (Fig. 6) and the measured effective albedo above the tip (Fig.7) for all experiments.

2) The second main comment is about the objectives of the paper. I think they should be more clearly stated in the introduction, abstract and conclusion. In the abstract, you are for example writing than the albedo is lower than the albedo of a smooth surface. You have some data to quantify this difference. I think this point is important in a mass balance perspective and should be more thoroughly developed in the paper. I think that the important questions raised by this paper are : what is the albedo of penitent ? How does it vary with the penitent and sun geometries ? At which height should be placed an pyranometer to measure an effective albedo ? What are the implications of penitent on glacier surface albedo ? Are satellite sensors capable of monitoring the albedo of such fields ?

R1.2: We agree that the key points could be formulated clearer. After adapting the introduction due to raised concerns of reviewer 2, the aim of the paper has been reformulated to clarify the objectives and integrate the ISRT experiments. These aims and objectives are also rephrased in the abstract, discussion and conclusion sections to clarify the main story of the paper. Moreover, as you suggest, we have also quantified the reduction in effective albedo in comparison with a flat surface based on the ISRT model (Section 4.3 and Section 5.2)

3) The last comment is on the discussion. There is a lot of interesting things there but you need to help the reader in following it. You are treating a lot of different points. I think that you have to carefully put only one subject per paragraph (see for example last paragraph of page 3834). Maybe using title for each subsection would also be useful.

R1.3: We agree that the discussion could be organized more clearly. Within the revised version we have reorganized the discussion in subsections to clarify the different subjects of discussion for the reader. These include sections on the ISRT model (Section 5.1), Effective albedo of a penitent (Section 5.2), apparent albedo vs. effective albedo (Section 5.3), apparent albedo vs. remote sensing albedo (Section 5.4), and implications for interpretation of albedo measurements (Section 5.5),

Specific comments Page 3825, second paragraph . There have been a lot of other studies on the evolution of albedo as a function of surface roughness such as : Leroux and Fily, 1998, Hudson and arren, 2007, Zhuravlela and Kokhanovky, 2011. Perhaps, some of these studies might be useful for the paper discussion.

R1.4: We thank M. Dumont for the suggestion of these interesting papers. We have included their results/conclusion in the introduction and discussion of the revised article.

Section 3.1. In my opinion the albedo of penitents should also change with the sun azimuth if they are tilted ? Are the penitent in your cases completely vertical or are they tilted ? Did you investigate this effect ?

R1.5: An interesting point. The penitents showed little or no tilt during the experiments (see Fig. 2 in original submission), which now is also clearly formulated in the revised version: *Each experiment showed elongated penitents with a east-west orientation of the ridges and troughs but with little or no tilt.*. Due to the little or no tilt of the penitents we did not investigate this effect in the paper.

Page 3828 line 10-15. Could you please quantify the correction ?

R1.6: On average the slope-corrected albedo is 2% higher than the uncorrected albedo. We incorporated this in the revision by including: *The same correction as in Abermann et al. (2013) following Grenfell et al. (1994) has been applied to adjust albedo for the slightly sloping surface, however deviations from the uncorrected data are small (mean difference between corrected and uncorrected corrected 0.02) as radiation values are close to solar noon and the aspect of the surface is not very different from the North-South axis.*

Section 4.1. Please take into account main comment 1.

R1.7: We have separated the below tip measurements of outgoing radiation (Section 4.2) from the above tip measurements of apparent albedo (Section 4.3) [See also R1.1]

Discussion. Please take into account main comments 3 and 2

R1.8: We have reformulated the aim and objectives in the abstract, discussion and conclusion sections and have reorganised the discussion in subsections to clarify the different subjects of discussion for the reader (See also R1.2 and R1.3)

Page 3820, lines 19-21 and below. You are referring to albedo anomaly that induces vertical changes of measured albedo. Maybe it would be more rigorous to refer to albedo spatial heterogeneity.

R1.9: We agree that spatial heterogeneity is a better wording than anomaly. However, in the revised version this part on anomalies has been removed.

Page 3834, lines 8-10. The sentence is a bit confusing. What do you mean by between 2 and 8 m ? What happens if you are above 8 m ?

R1.10: We have removed the discussion on changes in effective albedo with height in function of anomalies of a distribution with unknown mean and variance (former lines 3832:16-3835:5). Consequently, the sentence is no longer present. Moreover, the results of the ISRT model show that, depending on the penitent geometry, it is very difficult to determine an optimal height for a shortwave sensor as the apparent albedo is strongly affected by the location of sensor with respect to the surface topography.

Page 3836, lines 15-16. The main reason for albedo vertical changes is the spatial heterogeneity of the surface not the sensor. The sentence thus looks a bit weird

R1.11: We agree that the original sentence might cause confusion. In the revised version however, we show quantitatively (using the ISRT model) that the location of the sensor with respect to the surface topography also has a strong effect on vertical changes in measured apparent albedo.

Conclusion, please take into account main comment 2.

R1.12: We have reformulated the aim and objectives in the abstract, discussion and conclusion sections.

Minor issues Page 3824, line 16 penitent without s I guess

R1.13: Indeed, we have corrected this typographical error.

Page 3825 line 1, shortwave ? (maybe not short-wave)

R1.14: Agreed and corrected throughout the manuscript.

Page 3831 and Figure 3. I think that naming Hmax penetration depth is a bit misleading but maybe I did not understood correctly. Hmax seems to be wrong in Figure 3 (see graph below). The penetration depth is something else for snow (see for example Libois et al., 2013 TCD).

R1.15: We will not refer to Hmax as penetration depth any more as it is indeed often used in snow physics and in this study it is meant in a geometrical sense.

Page 3831. The notation here are a bit difficult to follow. D is both the tip distance of the penitent and an experiment. I would also prefer the sun zenith angle to be referred as θ.

R1.16: We agree and changed the tip distance to penitent width (W), which is also commonly used in literature (e.g., Warren et. al., 1998)

Page 3833. It would help the reading to add that z=H+zp .

R1.17: We agree and adapted the manuscript to have heights above the penitent tips and depths below the penitent tips. In the discussion, the suggested changes were unnecessary as this part of the discussion has been removed.

H maxage 3835, lines 9-12. I think the sentence on Box et al. results is a bit confusing. It needs to rephrased.

R1.18: We will extend this part to: *On the other hand, less agreement between AWS and MODIS albedo than in Box et. al. (2012) is obtained. However, they focused on monthly averages over more homogenous surfaces on the Greenland ice sheet and are therefore likely less influenced by micro-scale heterogeneity than in our study.*

Page 3835, lines 15-19. I think I understand what you mean here by the anisotropic reflection factor but maybe this sentence would need to be also rephrased.

R1.19: We agree and rephrased the sentence to : *Possible explanations for the biases between Landsat-derived and AWS albedo are the spatial heterogeneity (i.e., the experiment footprint is smaller than 9x30 m) in dust and debris cover, in combination with the assumption of a flat surface when using the anisotropic reflection factor in the method of Klok et al. (2013) for converting spectral reflectance to broadband albedo. This flat surface is obviously not the case for penitents fields.*

Interactive comment on The Cryosphere Discuss., 7, 3823, 2013.