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

J. Abermann et al.

christophe.kinnard@ceaza.cl

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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) 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 shape, convex U-shape, concave shape, cosine shape 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 4.1 and Fig. 5 in revised version).
   (b) illustrate the interaction between material albedo and penitent geometry and their effects on shortwave radiation budget (explained in results Section 4.2 and Fig. 6 in revised version).
   (c) 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).
   (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 additionally in discussion Section 5.2 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 or area-averaged albedos in the energy balance models (Corripio and Purves, 2005, Pellicciotti et al., 2008, Winkler et al., 2009). However, the albedo measured over a*

TCD

7, C2273–C2286, 2013

Interactive Comment

penitent surface may be quite different from the effective or area-averaged albedo depending on the location 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 effective albedo depending on the position of the sun and sensor with respect to the surface topography, the height of the sensor above the surface, and the shape, size, and orientation of the surface topography. This stresses the need for a comprehensive understanding of 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.

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 the representativeness of the apparent albedo measured over a penitent surface and how it can vary with height 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 effective albedo and apparent albedo measured by sensor placed at different heights above a penitent surface, and iii) to use the uncertainty due to the use of apparent albedo to compare albedo data from AWS measurements to satellite albedo data. Within this framework, a radiative transfer model is used to simulate the incoming/outgoing radiation within a penitent trough 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*

TCD
7, C2273–C2286, 2013

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 new Fig. 7 is introduced (partly replacing original Fig. 4) that shows 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. Additionally a Fig. 8 has been added to explain the differences between

TCD

7, C2273–C2286, 2013

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.

(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 9 (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) Effective albedo of a penitent (Section 5.1), 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.

   (b) Apparent albedo vs. effective albedo (Section 5.2), where we discuss the accuracy of apparent albedo measurements to represent effective albedo and how this varies in function of the penitent geometry. Within this context we highlight the shortcomings of using sensors with a cosine response to measure radiation/albedo over a surface that has i) large heterogeneity in incoming/outgoing radiation ii) large variation in topography resulting in large viewing obstructions. Additionally, we discuss the effect of non-uniform material albedo's on the obtained results.

TCD

7, C2273–C2286, 2013

(c) Apparent albedo vs. remote sensing albedo (Section 5.3). 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)

(d) Implications for interpretation of albedo measurements (Section 5.4), 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 responsability. 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 Referee 2

General comments The paper presents analyses of ground- and satellite-based albedo measurements over a penitent-covered glacier. The subject is very relevant because of the practical difficulty in carrying out ground-based measurements over those surfaces, the difficulty in assessing error estimates for both ground- and satellite-based albedo retrievals over glaciers, and the large impact of surface albedo on the mass budget of glaciers, which are undergoing substantial reduction in many areas of the world. The paper addresses the measurement uncertainties related to the vertical displacement of the sensor above the surface of the glacier, and the temporal evolution *of the glacier albedo during two summer seasons. Both are very relevant scientific questions. However, the first part of the paper related to the vertical profiles of albedo suffers from serious misinterpretation and improper methodology, thus almost only the second part of the data analysis, related to the albedo time series, is acceptable for publication. I therefore recommend a major revision of the paper, which should properly account for all the criticism listed below. Moreover, a through language check should be made to improve the fluency and eliminate the grammatical errors.*

R2.1: We thank the reviewer for his detailed review which raises valid concerns. We agree that the original manuscript could lead to misinterpretation as we only discussed the measured apparent albedo which can differ from the effective albedo depending on the position of the sun and sensor with respect to the surface topography, the height of the sensor above the surface, and the shape, size, and orientation of the surface topography. To address this issue we have included the intra-surface radiation (ISRT) model which provides a framework to interpret and discuss the representativeness of the measurements, and how apparent and effective albedo can differ significantly (See general comments).

Main problems 1) The first criticism concerns the attempt to measure the albedo inside the penitent troughs. The utilized method is inadequate, as only the reflected radiation is measured below the tip of the penitents. To infer the effective albedo there, which would also give a measure of the solar radiation absorbed inside the troughs, the downward radiation should be measured at the same time and at the same vertical level as the upward looking sensor that measures the reflected flux. The authors define the albedo inside the penitent troughs as the ratio between the reflected radiation measured inside the trough and the downward radiation measured above the penitents, but this definition is physically inconsistent, as the amount of solar radiation reaching the interior of the troughs is much less than the downward radiation above tip of the penitents.

R2.2: This is a key point both in the review by reviewer 2 and by M. Dumont (R1.2).

TCD
7, C2273–C2286, 2013

Although we had raised this problem in the initial submission (p3831 L17-21), we will discuss it more in-depth in the revised version. Moreover, 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. Moreover, 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. Fig. 5 also shows the issue raised by reviewer 2 that the amount of solar radiation reaching the interior of the troughs is much less than the downward radiation above tip of the penitents. In this context, Fig. 5 also shows that this decrease in radiation reaching the surface depends on the geometry of the surface.

The whole discussion related to these measurements inside the troughs is unphysical, as it is based on the idea that the shaded areas inside the troughs have a lower albedo than the areas exposed to direct sunshine. This is wrong, and in fact the opposite is true, the snow/ice albedo is higher when illuminated with diffuse radiation, which is richer in the wavelengths for which snow has higher albedo.

R2.3: We agree that the spectral characteristics of direct/diffuse radiation and snow/ice albedo have an effect on the multiple reflections in each spectral wavelength. This could also be seen, when we replot Fig 5 with a higher material albedo (0.9) for smaller wavelengths and lower material albedo (0.2) for larger wavelengths. From the comparison of both these figures it is obvious that the material albedo has a large effect on the Sout. Firstly, it strongly changes the total Sout. Secondly, it affects the multiple reflections as high material albedo values results in more multiple reflections compared to low material albedo values. In the revised version, we discuss this effect of different

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Interactive Discussion
Discussion Paper

(spectral) material albedo in the results Section 4.1, but we do not show them to limit the amount of figures. We, however, do not discuss the spectral shift in radiation due to different spectral albedos as we believe it is outside the scope of the paper and would require repeating the experiments with different spectral albedos, which would extend the paper enormously.

It follows, thus, that a general misunderstanding characterizes the author's interpretation of the measurements: the effective albedo of a penitent field is lower than that of a glacier with flat surface not because of the presence of shadows inside the troughs, as suggested by the authors, but because the intense multiple reflection inside the troughs cause more radiation to be absorbed by the penitent vertical walls, and because the effective solar zenith angle over a rough surface is lower than over a flat surface (the authors are invited to read and refer to Warren et al. (1998), Effect of surface roughness on bidirectional reflectance of Antarctic snow, J. Geophys. Res., 103, 25789-25807).

R2.4: We agree and have clarified this point again in the introduction: *Warren et al. (1998) reviewed the effect of surface roughness over sastrugis and mention two causes for albedo reduction. Firstly, sastrugis lower the averaged incidence angle, which reduces the albedo (Warren, 1982) ... Secondly, multiple reflections between the walls cause light-trapping in the trough*. Additionally, we have included a discussion section on the effective albedo of a penitent (Section 5.1), where we discuss the effect of penitent geometry (size and shape) on the effective albedo and how multiple reflections play an important role here.

2) A second serious problem is the misinterpretation of the measurements above the tip of the penitents. In the author's opinion, the albedo measured at the level of the tip is the effective albedo of the penitent trough (p. 3833, line 6). In reality, what is measured there is the effect of shadows and tilted walls on the radiation received by the sensor, and it cannot be regarded as the albedo of anything, neither the walls nor the trough. It is rather an "apparent" albedo (see Pirazzini (2004), which is referred to in

TCD

7, C2273–C2286, 2013

Interactive Comment

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Interactive Discussion

Discussion Paper

the paper). The real albedo of a single trough or penitent simply cannot be measured with hemispherical pyranometers.

R2.4: We agree that the original manuscript could lead to misinterpretation as we only discussed the measured apparent albedo. To address this issue we have included the intra-surface radiation (ISRT) model which provide a framework to interpret and discuss the representativeness of the measurements, and how apparent and effective albedo can differ significantly (See general comments). Moreover, we clearly distinguish in the revised manuscript between:

1. material albedo: the albedo of the surface material, which relates to the albedo of the surface in flat conditions when we assume no dependence on solar conditions.
2. apparent albedo: the albedo measured by a sensor under particular geometric conditions. In the framework of the paper it is a sensor with cosine response.
3. effective albedo: one minus the ratio of energy that is absorbed in the trough to the energy entering the trough. The effective albedo relates to the true albedo of a penitent field when we make abstraction of the surface topography.

The optimal distance above the surface to measure the effective albedo of a rough field depends on the sources of errors (shadows, tilted walls), which are related to the geometry of the rough elements (again, see Warren et al., 1998). Below that distance, the calculated apparent albedo depends on the particular location of the sensor with respect to the nearby roughness features, on the solar azimuth angle, and it changes by moving the sensor few centimeters/decimeters apart. In conclusion, the whole discussion on the vertical profiles of albedo (including equations 1-4 and figures 6-7) is incorrect.

R2.5: Based on the results of the ISRT model experiments, we agree that significant differences between apparent and effective albedo can occur. The magnitude of these differences depends on the penitent/sun geometry and the height of the sensor above the surface. In the revised version, we extensively demonstrate and discuss this in Section 4.3. Moreover, this difference between apparent and effective albedo and the implications for interpretation of albedo measurements has become one of the major points of the revised version. Additionally, the discussion on the vertical profiles of albedo, that was in the original submission, has been removed in the revised version.

3) The study on the vertical profile of albedo had the purpose of assessing the measurement uncertainties of the albedo time series obtained from the AWS. This should be more clearly stated. Were the measured vertical albedo profiles sufficient to assess the quality of the AWS albedo? On p. 3834, lines 7-20, the authors claimed that their profiles demonstrated that the AWS measured albedo are representative of the surrounding surface. Maybe, but you have too little data to draw conclusions. On the basis of Figure 4, my impression is that the sensor should be placed three or more meters above the penitent tips to measure the effective albedo, but higher and more profiles would be needed to reach a conclusion. What was the range of distance that the AWS albedometer had from the nearby penitent tips? On the basis of the presented data, the authors could extract an averaged error for the AWS albedo measurements, but with the warning that it could be an underestimation due to the limited dataset.

R2.6: One of the underlying objectives of the paper was indeed to assess the uncertainty of the albedo time series obtained from the AWS. We have clarified this in the revised introduction *This paper aims to address the current need for a more thorough understanding of the representativeness of the apparent albedo measured over a penitent surface and how it can vary with height of the sensor and size/shape of the penitents. More specifically, the objectives are ... iii) to use the uncertainty due to the use of apparent albedo to compare albedo data from AWS measurements to satellite albedo data ... 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.* Moreover, based on the comparison between

TCD
7, C2273–C2286, 2013

apparent and effective albedo from the ISRT experiment, we believe that the individual measurements are not representative for the surrounding surface due to the uncertainties coming from the cosine response 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. In this context, 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 Fig. 8 (former Fig.5)). This confidence interval allows putting the comparison between AWS and satellite albedo into context.

Specific comments -p. 3824, line 5 of the Abstract: the expression: "the vertical dependence of albedo" is unclear. I would rather express the concept as "the dependence of the measured albedo on the vertical distance from the penitent-covered surface"

R2.7: This will be accounted for in the revision, where this concept will be addressed by "the dependence of the measured albedo depending on the position of the sensor with respect to the surface topography"

p. 3826, line 4: here a definition of "effective albedo" is given referring to previous work, but a sentence explaining that the same definition will be applied in the present work (if so) is missing.

R2.8: In the revised manuscript we clearly distinguish (in the introduction but also throughout the paper) between:

1. material albedo: the albedo of the surface material, which relates to the albedo of the surface in flat conditions when we assume no dependence on solar conditions.
2. apparent albedo: the albedo measured by a sensor under particular geometric conditions. In the framework of the paper it is a sensor with cosine response.
3. effective albedo: one minus the ratio of energy that is absorbed in the trough to

TCD
7, C2273–C2286, 2013

the energy entering the trough. The effective albedo relates to the true albedo of a penitent field when we make abstraction of the surface topography.

p. 3828, lines 26-27: the vertical profiles of albedo are calculated from the ratio of measurements taken with sensors having different spectral range. How this is accounted for in the calculation?

R2.9: This must be a misunderstanding. The vertical profiles of albedo have been calculated with the same type of Apogee-sensors (spectral range: see Tab. 2). The AWS KippZonen CNR1 has been used to compare to the Landsat-derived albedo.

p. 3841, Table 1: in the caption (and everywhere else in the paper) the ratio H/D (penitent height/penitent distance) should be replaced by D/H, as it is calculated in Table 1.

R2.10: We agree and adapted the manuscript. Moreover, we changed the tip distance to penitent width (W), which is also commonly used in literature (e.g., Warren et. al., 1998) (see also R1.16)

p. 3835, lines 7 and 12: how many digits after decimal point are really significant for the bias between AWS and satellite albedo? Definitely less than three, on the basis of the error estimation for AWS albedo

R2.11: We agree with the reviewer and stay consistent with two significant digits in the revised version.

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