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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) 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*

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*

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

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.

(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

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