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The Cryosphere Discussions

Interactive comment on "Case study of spatial and temporal variability of snow cover, grain size, albedo and radiative forcing in the Sierra Nevada and Rocky Mountain snowpack derived from imaging spectroscopy" *by* F. C. Seidel et al.

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This paper presents a really interesting data set of snow properties (optical grain size, broadband albedo and radiative forcing due to impurities) retrieved from hyperspectral airborne data over two mountainous areas. The areas and the retrieval methods are first described. The authors then present the results in term of spatial and temporal variations of the above mentioned snow properties. Note that the retrieval method has been described and evaluated in a previous paper (Painter et al., 2013).

This study is well written and fits well with The Cryosphere scope. The data set pro-

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vided by the authors is quite unique. The study demonstrates the benefits of using high resolution airborne optical data to study in detail temporal and spatial variations of snow properties. It offers a new insight for the study of snow properties variability avoiding the limitations of point measurements. I think however that several questions should be addressed before it can be published.

Main Comments

1/ My first main comment focused on the grain size retrieval accuracy in presence of liquid water. It is stated section 3.3 that the range of wavelengths used in the grain size retrieval is 1.17 to 1.27 μm allowing to reduce the "bias (induced) by liquid water" with reference to Painter et al., 2013. In Painter et al., 2013, it is on the contrary stated that the retrieval is done using 1.03 to 1.06 μm wavelengths (section 4.3) and that the "technique could be less sensitive to biases due to liquid water and water vapor". It is also stated that this assumption is not based on field measurements. Are the range of wavelengths used similar in this study and in Painter et al., 2013 or not ? In my mind, the assumption concerning the limited impact of liquid water on the retrieval should be discussed and demonstrated in more depth.

For example, considering figure 1 in Gallet et al., 2014a or Green et al., 2002, there are some differences between the ice and water refractive indices in the considered range of wavelengths. This can induce some errors on the grain size retrieval and should probably be included in the discussion. The algorithms developed in Green et al., 2002 can also probably be used to investigate in more detail the effect of liquid water of the grain size retrieval and also to identify on the AVIRIS data snow with liquid water. I think this point is really crucial to infer the uncertainty of grain size retrieval and to strengthen the discussion on the grain size spatial and temporal variations presented in this study.

Gallet, J.-C., Domine, F., and Dumont, M.: Measuring the specific surface area of wet snow using 1310 nm reflectance, The Cryosphere, 8, 1139-1148, doi:10.5194/tc-8-1139-2014, 2014a.

Green, R. O., Dozier, J., Roberts, D., Painter, T. (2002). Spectral snow-reflectance models for grain-size and liquid-water fraction in melting snow for the solar-reflected spectrum. Annals of Glaciology, 34(1), 71-73.

2/ The second main comment focuses on the grain size/elevation inverse relationship in case of large impurity load discussed in section 5. I think this is a really interesting finding and it would result in a negative feedback. It also has to be linked to other recent studies showing that light-absorbing impurity can reduce the density of melting snow (Meinander et al., 2014) or studying the effect of soot on anisotropy factor (Peltoniemi et al., 2015) However, the discussion should be strengthen to be more convincing. The first thing is that the mean decrease of grain size is roughly 50 μm (figures 7 and 9) which is close to the accuracy of the grain size retrieval method (the one given in Painter et al., 2013). Consequently, I think before discussing the possible physical causes of the grain size/elevation inverse relationship, the authors should probably discuss the significance of the grain size decrease relatively to differences sources of errors. There are several sources of errors that might have to be taken into consideration e.g. : a/ grain size retrieval accuracy in presence of liquid water (see my previous comment) b/ the fact that as stated by the authors the surface roughness is high. Consequently the HDRF derived from spherical model are probably more anisotropic that the natural surface inducing a larger error on the grain size for the rough surface than for flat one. c/ Peltoniemi et al., 2015 (see full reference below) also demonstrated that under large impurity load, the impurity sank in the snow and largely modify the HDRF . . . this also leads to an error in the grain size retrieval. d/ Finally, as discussed in Skiles PhD thesis (e.g. chapter 3, figure 1), it is possible that for really high impurity content, the snow reflectance is more dust-like than snow-like in the IR (and then higher in the NIR not due to snow grain size but to impurity particles). This effect seems to be overestimated by SNICAR (compared to field measurements) but it can still affect the grain size retrieval and results artificially smaller grain size.

Lastly, the processes leading to a decrease of snow grain size could probably further discussed : the presence of a large content of impurity largely modifies (and shortens) the light penetration depth so that the energy is absorbed closer to the surface. The temperature profile and the heat and vapour transfer are consequently modified leading to modified metamorphism. Note that the formation of sublimation crystals has also been discussed in Antarctica (Gallet et al., 2014b, see full reference below).

Meinander, O., Kontu, A., Virkkula, A., Arola, A., Backman, L., Dagsson-Waldhauserová, P., Järvinen, O., Manninen, T., Svensson, J., de Leeuw, G., and Leppäranta, M.: Brief communication: Light-absorbing impurities can reduce the density of melting snow, The Cryosphere, 8, 991-995, doi:10.5194/tc-8-991-2014, 2014.

Peltoniemi, J. I., Gritsevich, M., Hakala, T., Dagsson-Waldhauserová, P., Arnalds, Ó., Anttila, K., Hannula, H.-R., Kivekäs, N., Lihavainen, H., Meinander, O., Svensson, J., Virkkula, A., and de Leeuw, G.: Soot on Snow experiment: bidirectional reflectance factor measurements of contaminated snow, The Cryosphere, 9, 2323-2337, doi:10.5194/tc-9-2323-2015, 2015.

Gallet, J.-C., Domine, F., Savarino, J., Dumont, M., and Brun, E.: The growth of sublimation crystals and surface hoar on the Antarctic plateau, The Cryosphere, 8, 1205-1215, doi:10.5194/tc-8-1205-2014, 2014b.

3/ The third main comment focuses on the way the data are presented in Figures 8 and 9 with respect and elevation. I think the figures really nicely described the variations of the snow parameters with respect to topographic parameters. However, especially at the end of the season, when the snowpack remains mainly on shaded slopes this way to present the data could induce a bias in the interpretation. In other words, I mean that it is, for example, not straightforward from Figure 9, 3rd row that the inverse grain/size elevation relation ship is not a bias due to uneven distribution of snow cover with elevation and aspect. Consequently, my suggestion would be to plot the value of mean grain size (colour) as a function of aspect (x-axis) and elevation (y-axis) with a representation of the RMSE or the number of points in each topographic class (transparency or size of the dots).

4/ The last main comment focuses on the uncertainties analysis provided in the paper. Though I perfectly agree that uncertainty analysis is not the main aim of the paper, I think that a deeper analysis of the errors could help to strengthen the conclusions of the paper as I explained in the previous comments. The authors refers to the uncertainties of the retrieval method provided in Painter et al., 2013 as being 25um for grain size, 0.0001 (there must be a typo there) for snow albedo and 4 Wm2 for radiative forcing. In Painter et al. 2013, the uncertainties given for albedo is 0.001-0.004 (based on two measurements only…), 2.1 +-5.1 Wm2 for radiative forcing, and the uncertainty of the grain size retrieval is an assumption. In Painter et al., 2013, only one date was available for AVIRIS data but with all the dates used in the study, I am wondering if the uncertainty data could used more broadband albedo measurements to strengthen the uncertainty analysis. Section 4.5. presents really interesting results regarding the comparison of two images acquired only one day apart from each other but it would worth a more detailed analysis. Are the given values mean values ? What are the spreads of the difference ? In my mind, the uncertainty analysis should be more careful, describing which values are assumed, what is the significance of the different values (how many measurements are used to derive the uncertainty)…

Specific Comments

Page 2, line 13 : Maybe the authors can be a bit more explicit why the SSA /optical grain radius relationship is not a strict equality.

Section 3.3 . The modeled HDRF must account for the diffuse to total incoming irradiance ratio. Therefore it could worth explaining how this ratio is calculated. For this section, please see also my main comment 1/.

Page 7, Equation 7 : If c is meant to account for imperfect terrain corrections, c probably also have a second order dependency to wavelength. This could be maybe detailed in the paper.

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Page 7, line 13 : *This assumption becomes more valid with grain growth associated with evolving metamorphism and rounding of the snow crystals*. Rounded forms do not necessarily means perfect spheres, and spheroids optical properties might significantly differ from spheres optical properties (e.g. Libois et al., 2013, full ref below, fig1). The differences between spheres and spheroids optical properties might even be larger that the ones between spheres and other snow crystals optical properties. Consequently, in my mind, this sentence should be either removed or further justified.

Libois, Q., Picard, G., France, J. L., Arnaud, L., Dumont, M., Carmagnola, C. M., and King, M. D.: Influence of grain shape on light penetration in snow, The Cryosphere, 7, 1803-1818, doi:10.5194/tc-7-1803-2013, 2013.

Page 8, lines 9-13 : The mean broadband albedo varies not only with the snow properties but also with the illumination geometry and consequently the date and time of acquisition. This should probably be discussed while presenting the results of Figure 7.

Section 4.3. Same comment as above. Snow albedo depends not only on the snow properties but also on the illumination conditions. This has, in my mind, to be taken into account in the discussion regarding the spatial variations of albedo.

Minor Comments

Page 2, line 16 : Changes is surface roughness also cause changes in snow albedo

Page 4, line 22 : “retrieved columnar water vapor”, maybe the authors could explain how, and from which data and add a reference.

Page 8, line 18 : Surface snow grain size can also be affected by wind effects.

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