Review: Gallet et al. - Measuring the specific surface area of wet snow using 1310 nm reflectance

This study investigates the effect of liquid water on the measured reflectance and derived specific surface area (SSA) of snow samples using the DUFISSS instrument, which has been previously introduced for SSA measurements of dry snow. This is a relevant research topic despite the small effect of liquid water on the obtained SSA results.
However, the small influence of liquid water on snow SSA measurements and the use of DUFISSS for wet snow for the first time (as I understand) should demand a careful assessment of the uncertainties associated with the presented SSA measurements of wet snow, which is not included in the current manuscript. The lack of a quantitative uncertainty analysis is the main point that should still be addressed before publication (see below for some details).

We wish to thank reviewer#1 for his/her comments. Answers are inserted in blue below.

General comments

- Uncertainty analysis:

A comparison of two alternative measurement methods is no substitute for an uncertainty analysis (in this manuscript: SSA measurements of wet snow are compared to SSA measurements of the same refrozen snow samples). An uncertainty analysis is based on the uncertainties associated with the input quantities of the applied measurement protocol and the propagation of these uncertainties through the measurement process to yield the combined uncertainty of the final determined quantity. While a full formal uncertainty analysis, e.g. according to the GUM (JCGM 100:2008 "Guide to the expression of uncertainty in measurement"), is probably far beyond the scope of the presented study, I would strongly suggest to present at least reasonable estimates of the uncertainties affecting the SSA measurement of wet snow with the DUFISSS instrument.

Specifically, what are the major uncertainties (quantified e.g. as relative uncertainties in percent) of the uncertainties associated with the assumptions that 'freezing does not lead to any detectable change in structure' (p. 5259 l. 7) and that 'the LWC is not perfectly uniform' (p. 5259 l. 22), with the density and liquid-water-content measurements (p. 5260 l.1, this may possibly be the most important contribution), with the measurement protocol (p.5260 l.5 to end; p. 5263 l.5 'fairly homogeneous snow'), with the 'approximation that wet snow consists of disconnected ice spheres' (p. 5264 l.16), with the 'slight modifications to the code relative to Gallet et al. (2009)' (p.5265 l.26)? Some of these listed effects have already been addressed briefly in the manuscript, but not in a very clear and organized manner. The various uncertainties should be combined in one chapter, and the major uncertainties should be quantified. And how do the major uncertainties affect the final SSA values across a wide range of snow types (i.e. quantify the impact of the input uncertainties on SSA measurements of wet snow for different snow liquid water content, SSA and density)?

We agree that uncertainty analysis is important and needs to be treated adequately. However, most similar papers do not include a specific chapter on uncertainty evaluation. This is of course mandatory in subjects such as the establishment of standards, where a very high accuracy is critical. Here, we measure SSA based on a method whose claimed and published uncertainty is 10%, and in fact we only bring minor adjustments to the method, so that we will only produce second order additional uncertainties. While we will do our best to improve the uncertainty evaluation in the revised version, we do not feel that major additions to this aspect will increase the interest of our paper to most readers. Moreover, we believe that most of the reviewer's concerns are due to a lack of clarity on our part on some aspects, and on the use of non-optimal vocabulary. These will be corrected in the revised version.
A possible confusion is that most of our discussion stresses the apparent value of the SSA of wet snow, SSA_{app} while in fact this variable is not the objective of our paper, which is actually SSA_{wet}, obtained from eq.8. Another confusion is probably due to our use of the word "error" instead of "correction" on page 5265, lines11-13. Our uncertainty on SSA_{app} is essentially the same as that on any other SSA measurement, i.e. 10%. An additional error is due to the determination of SSA_{wet}, and we do admit that we were not clear enough on that aspect, and we will improve this in the revised version. The central point is the uncertainty caused by the use of eq.8 if we do not know the liquid water content (LWC). First, please note that as shown in Figure 6, not knowing the LWC produces no uncertainty on SSA_{app}. Figure 7 shows that not knowing the

LWC does produce an uncertainty on SSA_{wet}, and we discuss this in the conclusion. This is the main additional source of uncertainty in the determination of the SSA of wet snow, relative to that of dry snow. We will strengthen this aspect of the discussion and possibly modify Table 1 to quantify the uncertainty as a function of SSA. Adequate reference to Figure 7 will also help explain uncertainties on SSA_{wet}.
Regarding the effect of refreezing, we admit that there is a potential additional uncertainty here, but this is most likely second order and very difficult to evaluate. We will nevertheless discuss this in more depth and use published scanning electron microscope images to support our hypothesis that modifications, if any, are minor.

In addition to the uncertainty estimates, a more detailed comparison strategy would be useful. Instead of only presenting absolute values, i.e. SSA_frozen – SSA_app_wet, in table 1, adding percent differences would make the analysis more complete.

Sure, we will add a column with percent difference.

Only then can the conclusions be drawn:

An uncertainty of x% (including the uncertainty for DUFISSS SSA measurements of dry snow presented in Gallet et al. 2009) is estimated for SSA measurements of wet snow with the presented method; the observed average of absolute percent differences between SSA of wet snow and the SSA of the corresponding refrozen snow samples is y%. The snow SSA values assuming a dry snow sample, i.e. ignoring all present liquid water, differ from the SSA values including the liquid water content by about z=10% (z is a bias, I guess, i.e. z is calculated from signed percent differences and not absolute percent differences). z is still within the estimated uncertainty of the measurement method (i.e. z < x%) due to the small effect of liquid water. Nevertheless, as a clear bias different from 0 is observed, z describes a 'real' effect or a systematic 'error' in the measurement method. If a reasonable uncertainty assessment is presented, a systematic 'error' can be excluded. Without any quantification of the uncertainty, the small effect caused by liquid water cannot be identified reliably.
Additionally, I would strongly suggest to use the expressions 'uncertainty, difference, bias, deviation' instead of 'error' throughout the manuscript. An 'error' implies knowing the exact deviation from the 'true' value of the physical quantity. This is not known, however; only measured values obtained by other measurement methods (that may be characterized by smaller uncertainties) are known. A comparison between two measured values or different series of measurements then yields differences, deviations, and possibly a bias.

Thank you for these interesting considerations. These show us that we have not been very clear in some of our explanations, as already alluded to in our response to the first point. As mentioned earlier, we will present our data differently in the revised version. Please note however that we do not believe that z is a bias. The variable z is a corrective term to obtain the true value sought from our measurement. Thus, there is not necessarily any error or uncertainty related to its use. We will make this clear in the revised version.

- Influence of SSA definition

The analysis in the manuscript is based on SSA values given by surface area per mass. SSA is commonly also referred to as surface area per volume of the snow microstructure. For all dry snow, both definitions are equivalent, only requiring the density of ice for calculating one SSA value from the other. For snow samples with different liquid water contents, however, the conversion factor is not constant across all samples and instead depends on the liquid water content of each sample, due to the density difference between liquid water and ice.
So, what is the effect of liquid water on SSA measurements when measuring SSA in terms of surface area per volume, i.e. only including the geometry of the snow microstructure and not the mass? Is it possible to give an indication for this effect based on the presented results and sum up the conclusions in a few sentences? Intuitively, I would expect the differences between SSA_app_wet values and the SSA values obtained by ignoring liquid water in the snow samples, i.e. assuming dry snow samples, to be even smaller when snow mass is not included in the SSA definition.

This is an excellent point, thank you for raising it. There has in fact been informal debate regarding the most convenient expression of SSA, mass or volume. This shows a clear advantage of using the mass formulation, as it is not affected by the presence of liquid water. We will mention that in the revised version. We will also calculate the error in the volume formulation (relative to the mass formulation) caused by not knowing the LWC.

Specific comments:

- First sentence of the Introduction:

What are small amounts? There can be more than just small amounts of impurities in snow, e.g. in black/grey snow next to roads. So, I would suggest to remove 'small amounts of'.

Snow where impurities are not in small amounts is indeed exceptional and our interest is clearly not snow on the road side. Using "small amounts" is justified and most of readers that works on snow will intuitively understand what it means and what the level of impurity is when we say "small amount".

- 2nd sentence:

Is snow always the most reflective surface on Earth? At all wavelengths of the solar spectrum? No matter how thin the snow cover is? The actual snow surface itself is not highly reflective, only multiple scattering inside the top part of the snow cover close to the surface makes snow a highly-reflective material. I suggest replacing 'the most reflective surface' with 'a highly-reflective surface material'.

Sure, vegetation is more reflective than coarse grain snow in the SWIR but on a broadband basis, which is the variable of interest for Earth energy budget calculations, snow is the most reflective surface on Earth. To avoid any lengthy discussion, we will write "snow is one of the most, and perhaps even the most, reflective surface on Earth."

- p. 5258 l.5:

The presented values may be true for the cited articles, but the statement implies that all measured snow SSA values fall within this range. Other studies have included snow with lower SSA, both machine made snow and natural snow. For example, Matzl and Schneebeli 2006, Gergely et al. 2010: First experiments to determine snow density from near-infrared reflectance, Cold Regions Science and Technoogy 64, 81-86; Gergely et al. 2013: Simulation and Validation of the InfraSnow: An instrument to measure snow optically equivalent grain size, IEEE Transactions on Geoscience and Remote Sensing.
In fact, some of the low SSA values have been observed specifically for refrozen spring snow, i.e. snow which is sometimes characterized by a substantial liquid water content due to repeated melting and freezing. The lack of such low-SSA samples with SSA < 12 m2 kg-1 in the presented manuscript also supports the requirement for a thorough uncertainty analysis: only a reasonable uncertainty analysis allows transferring or extrapolating the presented results and conclusions to other measurement conditions and thus to snow samples with low SSA.

Thanks for spotting this. The actual range in Domine et al. (2007) starts at 1.9 $m^2 kg^{-1}$, not at 7. To our knowledge, this is the lowest value measured, and we will correct that. Regarding the uncertainty analysis, we are fully aware that the SSA range in the current study is limited. We do mention that, for example in the conclusion, and do address the issue in the simulations.

- Conclusions: The conclusion that the range of validity for the findings can also be extended to snow types that are characterized by low SSA values and that have not been investigated in this study, like coarse spring snow, can only be reached after an appropriate analysis is included to quantify the uncertainties associated with DUFISSS SSA measurements of wet snow (see comments above).

Yes, we agree, this has been discussed.

- Table 1: Also present relative differences for SSA (and maybe remove the reflectance-difference column). SSA is the main analyzed quantity and deserves a detailed analysis.

Table 1 will be modified.

Technical corrections:
- p. 5260 l. 15: Remove ‘careful’ and ‘most likely’. Instead, quantify/estimate the uncertainty (see comments on uncertainty analysis above)
- p.5260 l.20: Remove ‘certainly’
- p.5263 l. 3: Remove ‘only’

The whole vocabulary will be reconsidered as far as it seems necessary.

- l.11: Is there a reason why cen_8 might yield such a different result, is it special in some way (instrument malfunction, more time between sample preparation and measurement, …)?

We do not know. We just observe that it is an outlier and remove it. This is common in experimental studies.

- l.14, l.26: Which relation was used? As this is a major step in the presented analysis, a short explanation of the used relation should also be presented in this article, even though the relation was already introduced in Gallet et al. 2009.

This is the relationship shown in Figure 5 of Gallet et al. (2009). It was obtained by simulation using DISORT. We will mention that.

- l.16: Remove ‘at the most’ and insert ‘maximum’ in front of ‘relative difference’
- p.5264 l.6: Replace ‘complex’ with one of the following expressions to avoid ambiguity with ‘complex’ as in ‘complex numbers’: complicated, non-trivial, involved

- Eq (8): I could not understand how this equation was derived exactly, especially where the exponent ‘2/3’ stems from. Was this obtained using only the equations listed in the manuscript or also using other sources (if the latter is the case, please cite)?

We will add an appendix that details the different steps.

- p.5265 l.3: Remove ‘of course’
- l.4: Remove ‘Assuming … acceptable,’
- p.5266 l.7: Remove ‘actually’
- l.10, 12: Replace forms of ‘comfort’ with corresponding forms of ‘confirm’
- l.27: Remove ‘Admittedly,’
- Fig.1 could be removed. The differences/similarities at 1309 nm can be specified in the text.
- Fig. 4 could be removed to streamline the article, i.e. to focus on the SSA analysis and not include that many details on reflectance.

We will do our best to write a concise version, while clarifying the uncertainty discussion. For online journals, space is not much of an issue, while readability and clarity are. We believe that both Figures 1 and 4 improve readability and clarity.