Measuring the specific surface area of wet snow using 1310 nm reflectance

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Abstract. The specific surface area (SSA) of snow can be used as an objective measurement of grain size and is therefore a central variable to describe snow physical properties such as albedo. Snow SSA can now be easily measured in the field using optical methods based on infrared reflectance. However, existing optical methods have only been validated for dry snow. Here we test the possibility to use the DUFISSS instrument, based on the measurement of the 1310 nm reflectance of snow with an integrating sphere, to measure the SSA of wet snow. We perform cold room experiments where we measure the SSA of a wet snow sample, freeze it and measure it again, to quantify the difference in reflectance between frozen and wet snow. We study snow samples in the SSA range 12–37 m² kg⁻¹ and in the mass liquid water content (LWC) range 5–32 %. We conclude that the SSA of wet snow can be obtained from the measurement of its 1310 nm reflectance using three simple steps. In most cases, the SSA thus obtained is less than 10 % different from the value that would have been obtained if the sample had been considered dry, so that the three simple steps constitute a minor correction. We also run two optical models to interpret the results, but no model reproduces correctly the water–ice distribution in wet snow, so that their predictions of wet snow reflectance are imperfect. The correction on the determination of wet snow SSA using the DUFISSS instrument gives an overall uncertainty better than 11 %, even if the LWC is unknown. If SSA is expressed as a surface to volume ratio (e.g., in mm⁻¹), the uncertainty is then 13 % because of additional uncertainties in the determination of the volume of ice and water when the LWC is unknown.

1 Introduction

Snow is a porous medium made of air, ice, small amounts of impurities and occasionally liquid water. It is one of the most, or perhaps even the most reflective surface on earth so that its albedo is a key parameter to determine the planetary energy budget (Hall, 2004; Lemke et al., 2007). The albedo of snow is determined mostly by its impurity content and grain size, but the liquid water content (LWC) also plays a role (Warren, 1982). In the visible range of the solar spectrum, the albedo of dry snow is little dependent on the snow grain size and is mostly controlled by the impurity content. In the infrared, snow grain size controls the albedo of dry snow (Warren, 1982). The effect of water on snow albedo depends on its location. When present in small amounts, water is located only at grain boundaries (Colbeck, 1973; Ketcham and Hobbs, 1969) and a slight decrease in albedo is observed (Wiscombe and Warren, 1980). For a high water fraction, water entirely coats the snow grains so that large water–ice clusters are formed resulting in a larger decrease in albedo (Colbeck, 1973).

Even if the contrast between water and ice refractive indices is small, maxima and minima for water are shifted towards shorter wavelengths, as shown in Fig. 1 (Segelstein, 1981; Warren and Brandt, 2008; Kou et al., 1993) so that a
SSA quantifies the ice–air interface per unit mass. For wet snow, the optical radius of ice spheres having the same SSA as the snow. This radius varies from one study to another (Aoki et al., 2000). More recent studies have used the surface/volume ratio, i.e., the ratio of SSA to their volume, \(M\), with measured values ranging from 1.9 to 223 m\(^2\) kg\(^{-1}\) for dry snow (Domine et al., 2007, 2011).

In field studies, when wet snow is encountered, air temperature is often above 0°C so that the sample cannot be refrozen on site. All current snow SSA measurement techniques have been developed and validated for dry snow. Many techniques, such as CH\(_4\) adsorption (Domine et al., 2007) or X-ray tomography (Flin et al., 2004), cannot be used because they require that the snow be frozen. Optical methods, on the other hand, are potentially appropriate. Such methods have been used to measure the SSA of dry snow (Arnold et al., 2011; Gallet et al., 2009; Matzl and Schneebeli, 2006; Montpetit et al., 2012; Painter et al., 2007; Picard et al., 2009), but none has been tested for wet snow. Here we used the DUFISS instrument (Gallet et al., 2009) to measure the 1310 nm reflectance of wet snow. Briefly, Gallet et al. (2009) used an integrating sphere to measure the reflectance of a snow sample at 1310 or 1550 nm and determined its SSA with a calibration curve obtained by the simultaneous measurement of reflectance and SSA using CH\(_4\) adsorption. The shorter wavelength was used for SSA lower than 60 m\(^2\) kg\(^{-1}\) while the longer one was used for higher snow SSA. The estimated accuracy of this instrument is 10% and allows a fast measure of SSA in the field for every type of dry snow.

To extend the validation of the method to wet snow, experiments were performed in a cold room. We used DUFISS to measure the 1310 nm reflectance of wet snow of known density and liquid water content. We then let the wet snow sample refreeze and measured its reflectance again, so that the reflectances of the same snow sample, wet and frozen, could be compared. Radiative transfer calculations using the DISORT model (Stamnes et al., 1988) were also used in order to compare our cold room data set with theoretical calculations.

2 Experimental protocol

The idea of our cold room experiments was to prepare a homogeneous wet snow sample. We then measured its density and LWC and took a sample whose reflectance was measured at 1310 nm with DUFISS placed in a cold room at −2.2°C. The sample was then allowed to refreeze without any disturbance to its structure so that the reflectance of the very same sample could be measured again once refrozen. During freezing, several processes could take place that may result in structural changes that could affect SSA. These include (1) metamorphism and the related SSA decrease and (2) structural changes caused by the crystallization of water. Regarding (1), using the Crocus model (Brun et al., 1992), we calculated that the time to refreeze the first cm of our snow sample is of the order of 15 to 20 min, under the conditions in our cold room. Within this timescale, we calculate using Eq. (13) of Taillandier et al. (2007) that snow with an initial SSA of
40 m^2 kg^-1 would decrease to 39 m^2 kg^-1 after an hour. For lower SSAs and lower durations, the SSA decrease would be even less and therefore hardly detectable. Regarding (2), the work of Brzoska et al. (1998) showed that snow subjected to flash freezing, a process much more prone to produce structural changes than the slow freezing used here, did not lead to any detectable structural change. Furthermore, scanning electron micrographs by Erbe et al. (2003) (their Fig. 9) and Wergin et al. (1995) (their Fig. 17) show that refreezing of melted snow did not produce any detectable structural changes, as what was observed was just the solidification of the liquid water, without the formation of any other structure that could perturb SSA. Based on these considerations, we conclude that frozen snow most likely has a structure and a SSA comparable to that of the parent wet sample, except for effects due to volume expansion.

The snow used was taken from large plastic boxes filled with snow from the mountains around Grenoble and stored at −20°C. Snow from two distinct snowfalls was used: one about a week old and the other from the previous season. To make uniform samples, batches of about 500 g of snow were mixed in a dough kneader placed in a cold room at −2.2°C. Several such batches were placed inside a large plastic box and were further mixed with a shovel. The resulting sample was then transferred into a Plexiglas box 15 cm × 25 cm in horizontal section and 25 cm in height.

To obtain a wet snow sample, we used the method detailed by Brun (1989). Briefly, the Plexiglas box was placed between two conductor plates within an insulated box, and between these plates a current of 4000 V at 20 kHz was applied. The instrument was also located in the cold room at −2.2°C. At 20 kHz frequency, the energy absorption by snow is such that homogeneous heating is produced, so that a uniform LWC content can be obtained. Of course, the LWC is not perfectly uniform because of conductive losses at the edges. Furthermore, percolation can take place if the LWC exceeds the percolation threshold (Coleou and Lesaffre, 1998). However, the results showed that possible moderate variations in LWC within the box are not critical.

Six snow samples were heated for durations between 23 and 90 minutes. The Plexiglas box was then taken out of the heater and placed on a bench in the cold room at 2.2°C. Snow density was then measured using a 100 cm^3 LWC within the box are not critical. Furthermore, percolation can take place if the LWC exceeds the percolation threshold (Coleou and Lesaffre, 1998). How-
**Table 1.** Density, liquid water content (LWC), reflectance at 1310 nm (R), and specific surface area (SSA m$^{-2}$ kg$^{-1}$) of the samples studied, wet at 0 °C and frozen. SSAs for wet samples are apparent values as defined in the text.

<table>
<thead>
<tr>
<th>Snow sample name</th>
<th>Heating time, min</th>
<th>Density Wet snow kg m$^{-3}$</th>
<th>LWC, mass %</th>
<th>$R$ wet snow</th>
<th>$R$ frozen snow</th>
<th>SSA$_{app}$ wet snow</th>
<th>SSA frozen snow</th>
<th>$R$ frozen – SSA$_{app}$ wet</th>
<th>SSA frozen – SSA$_{app}$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>cen_1</td>
<td>45</td>
<td>182</td>
<td>9.6</td>
<td>0.4411</td>
<td>0.4437</td>
<td>35.5</td>
<td>35.6</td>
<td>0.0030</td>
<td>0.10</td>
</tr>
<tr>
<td>cen_2</td>
<td>45</td>
<td>182</td>
<td>9.6</td>
<td>0.4321</td>
<td>0.4326</td>
<td>33.4</td>
<td>33.5</td>
<td>0.0005</td>
<td>0.10</td>
</tr>
<tr>
<td>cen_3</td>
<td>86</td>
<td>283</td>
<td>31.0</td>
<td>0.3215</td>
<td>0.3215</td>
<td>18.4</td>
<td>18.4</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>cen_4</td>
<td>86</td>
<td>283</td>
<td>31.0</td>
<td>0.2435</td>
<td>0.2509</td>
<td>12.1</td>
<td>12.6</td>
<td>0.0074</td>
<td>0.50</td>
</tr>
<tr>
<td>cen_5</td>
<td>23</td>
<td>208</td>
<td>5.0</td>
<td>0.4399</td>
<td>0.4439</td>
<td>34.9</td>
<td>35.6</td>
<td>0.0040</td>
<td>0.70</td>
</tr>
<tr>
<td>cen_6</td>
<td>23</td>
<td>208</td>
<td>5.0</td>
<td>0.4503</td>
<td>0.4541</td>
<td>36.9</td>
<td>37.7</td>
<td>0.0038</td>
<td>0.80</td>
</tr>
<tr>
<td>cen_7</td>
<td>90</td>
<td>296</td>
<td>32.1</td>
<td>0.2936</td>
<td>0.3014</td>
<td>15.9</td>
<td>16.5</td>
<td>0.0078</td>
<td>0.60</td>
</tr>
<tr>
<td>cen_8</td>
<td>90</td>
<td>296</td>
<td>32.1</td>
<td>0.4321</td>
<td>0.4570</td>
<td>33.4</td>
<td>38.2</td>
<td>0.0249</td>
<td>4.80</td>
</tr>
<tr>
<td>cen_9</td>
<td>43</td>
<td>153</td>
<td>7.2</td>
<td>0.4301</td>
<td>0.4298</td>
<td>33.0</td>
<td>33.0</td>
<td>−0.0003</td>
<td>0.00</td>
</tr>
<tr>
<td>cen_10</td>
<td>43</td>
<td>153</td>
<td>7.2</td>
<td>0.4480</td>
<td>0.4512</td>
<td>36.4</td>
<td>37.1</td>
<td>0.0032</td>
<td>0.70</td>
</tr>
<tr>
<td>cen_11</td>
<td>60</td>
<td>260</td>
<td>21.6</td>
<td>0.3082</td>
<td>0.3155</td>
<td>17.1</td>
<td>17.8</td>
<td>0.0073</td>
<td>0.70</td>
</tr>
<tr>
<td>cen_12</td>
<td>60</td>
<td>260</td>
<td>21.6</td>
<td>0.3180</td>
<td>0.3275</td>
<td>18.0</td>
<td>19.0</td>
<td>0.0090</td>
<td>1.00</td>
</tr>
</tbody>
</table>

For simplicity, we will use the term reflectance as equivalent to albedo, even though the proper term for our calculations and measurements is directional–hemispherical reflectance (Schaepman-Strub et al., 2006). To illustrate model performance and consistency, Fig. 2 presents the reflectance calculated with both codes for pure ice and pure water spheres for a SSA of 30 m$^{2}$ kg$^{-1}$. All calculations have been done under direct illumination with a zero zenith angle and for an optically semi-infinite layer. As expected, the minima and maxima are shifted towards shorter wavelengths for water. Both codes show similar results for each medium with an average difference over the 800–1400 nm range lower than 0.3 % and 1.0 % for ice and water respectively.

Figure 3 shows calculations at 1310 nm (wavelength used in subsequent experiments) for snow SSAs of 5 and 30 m$^{2}$ kg$^{-1}$ and LWC from 0 to 100 % per mass. At that wavelength ice and water have very close refractive indices, with water absorbing and scattering slightly more. Mie shows reflectance values decreasing with increasing LWC because water absorbs more and because here, when the LWC increases, ice is replaced by water. For the layered code, the reflectance first increases and then decreases as LWC increases. Our understanding is that a small amount of water is creating a thin layer of water around the ice particles. Scattering is then enhanced while the increase in absorption is negligible for low LWC, explaining the increase in reflectance. For higher LWCs, the water shell is thicker and absorption is not negligible anymore so that reflectance decreases. The decrease in reflectance is observed slightly before for smaller SSA because the shell of water is thicker for the same amount of water compared to higher SSA. Average differences between the two codes are of 0.9 and 2.1 % respectively for SSAs of 30 and 5 m$^{2}$ kg$^{-1}$ with maximum differences of...
5.7 % for 70 % LWC and low SSA. For reasonable values of LWC, i.e. below 40 %, the difference is no higher than 1.2 %.

However, neither Mie nor the layered codes represent correctly the location of water in the snowpack for low LWC. Ketcham and Hobbs (1969) showed that, in melting snow, water first appears as a meniscus on the ice surface where three grains join. Wet snow therefore obviously has water–ice interfaces, but the water coverage on ice is partial and of variable thickness. For higher LWC, water forms a continuous network (Colbeck, 1973) and even covers all the ice surfaces at sufficiently high LWC, so that the layered code may then be a reasonable approximation of processes, even though the thickness of the water film is never uniform. In any case, we test both codes over a wide LWC range below.

### 4 Results and discussion

The experimental results obtained are shown in Table 1, where the calculated SSAs for wet samples are apparent values. For four out of the six experiments, both samples from each experiment produced similar data, supporting our claim that our system produces fairly homogeneous snow. However, this does not seem to be valid for both samples with the highest LWC (31 and 32.1 mass %). These values certainly exceed the percolation threshold (Coleou and Lesaffre, 1998), resulting in large spatial variations and rapid changes in LWC, so that the values given are just indicative.

Figure 4 compares the reflectances of the wet and frozen samples. The differences are small. The sample cen_8 is an outlier. Figure 5 shows a similar graph for SSA and compares the SSA of the frozen sample, SSA\textsubscript{frozen}, to the apparent SSA of the wet sample, SSA\textsubscript{app}, which we retrieved using the relationship from dry snow from Gallet et al. (2009). The outlier of Fig. 4 expectedly also shows up in Fig. 5. The maximum relative difference in reflectance is 3 %, corresponding to a SSA difference of 1 m\textsuperscript{2} kg\textsuperscript{-1}, if the outlier is not considered. We also calculated the difference in SSA, SSA\textsubscript{frozen}–SSA\textsubscript{app}, and plotted these as a function of LWC in Fig. 6. The correlation between SSA differences and LWC is low with $R^2 = 0.14$ (dashed red line). If the outlier is removed, $R^2$ values drop to 0.0001 (black solid line). These results show that the difference in SSA is not correlated to the LWC in the range studied. The mean SSA difference shown in Fig. 6 between frozen and wet samples is 0.5 m\textsuperscript{2} kg\textsuperscript{-1} when the outlier is not considered.

We will then propose a simple modification of the algorithm used for dry snow to measure the SSA of wet snow in the field. What we measure is the reflectance of wet snow, $R\textsubscript{wet}$, from which we deduced an apparent SSA, SSA\textsubscript{app}, from the relationships $f$ of Gallet et al. (2009):

$$SSA\textsubscript{app} = f(R\textsubscript{wet}).$$
From Fig. 6, we have determined experimentally that

$$\text{SSA}_{\text{app}} = \text{SSA}_{\text{frozen}} - 0.5 \text{ m}^2 \text{ kg}^{-1}. \quad (3)$$

If we now assume that, upon freezing, no structural changes take place except those due to the volume expansion, we then have the actual SSA of the wet snow that verifies

$$\text{SSA}_{\text{wet}} = \psi \text{SSA}_{\text{frozen}}, \quad (4)$$

where $\psi$ is a non intuitive factor that depends on the geometry of the snow and on the distribution of the water in the snow sample. Combining the above 3 equations, we obtain

$$\text{SSA}_{\text{wet}} = (f(R_{\text{wet}}) + 0.5) \psi. \quad (5)$$

The general form of $\psi$ can be expressed as a function of the various interfaces in wet and frozen snow. We call $S_{a/i}$ and $S_{a/w}$ the area of the air–ice and air–water interfaces in wet snow and $S_{a/i}$ the area of the interface between the air and the refrozen water in the frozen snow. Equation (4) then becomes

$$\text{SSA}_{\text{wet}} = \text{SSA}_{\text{frozen}} \frac{S_{a/i} + S_{a/w}}{S_{a/i} + S_{a/f}}. \quad (6)$$

Because of the expansion upon freezing, $S_{a/w} < S_{a/f}$ and $\psi$ is therefore always less than 1 considering there are no other structural changes. If we make the approximation that wet snow consists of disconnected ice spheres surrounded by a homogenous water layer whose thickness is determined by the LWC, the ice in the wet snow is not in contact with the air so that we then have

$$\text{SSA}_{\text{wet}} = \text{SSA}_{\text{frozen}} \frac{S_{a/w}}{S_{a/f}}. \quad (7)$$

Also using Eqs. (4) and (5), we calculate that in this case we have

$$\text{SSA}_{\text{wet}} =$$

$$\left(f(R_{\text{wet}}) + 0.5\right) \left[1 - \text{LWC} \left(1 - \rho_{\text{ice}} / \rho_{\text{water}}\right)\right]^{2/3},$$

with the derivation detailed in Appendix A. This expression is only an approximation based on a structural simplification, and we attempt to evaluate it in the subsequent modelling part. Assuming for the moment that this approximation is acceptable, we propose that to measure the SSA of wet snow with DUFISSS, we just need to measure its 1310 nm reflectance, obtain an apparent value from the relationships of Gallet et al. (2009), add 0.5 m$^2$ kg$^{-1}$ to that value, and then multiply by the factor $\psi$, which can be calculated with the coated sphere structural approximation (Eq. 8). We note that in general both these additive and multiplicative corrections are small and in opposite directions, so that in most cases corrections are minimal. This is illustrated in Fig. 7.

$\psi$ has a small effect and is between 0.9994 and 0.9778 respectively for LWC of 1 and 40 % per mass so that omitting $\psi$ results in an uncertainty of < 2.2 %. The total correction is large only for very small SSAs, because the addition of 0.5 m$^2$ kg$^{-1}$ is not negligible in front of a low SSA value. For SSA ≥ 5 m$^2$ kg$^{-1}$, the total correction is < 10 %, and for SSA ≥ 10 m$^2$ kg$^{-1}$, the total correction is < 5 %. The data used to generate Fig. 7 show that not knowing the LWC results in uncertainties always less than 3 %, for LWC < 0.40 and based on our disconnected coated spheres structural approximation. This deduction is in line with our experimental observation of Fig. 6 that LWC has a very limited impact on the correction.

In practice, omitting these corrections often results in deviations much smaller than the instrumental uncertainty, estimated at 10 % for dry snow (Gallet et al., 2009). The uncertainty in determining SSA of wet snow can be estimated from Eq. (8). Relative to the determination of the SSA of dry snow, extra uncertainties are due to the addition of (i) the 0.5 m$^2$ kg$^{-1}$ factor and (ii) the use of the $\psi$ factor. To these, we must add (iii) uncertainties caused by our structural model approximation, used to derive Eq. (8). Given the strength of the 0.5 m$^2$ kg$^{-1}$ factor, uncertainty (i) is certainly negligible. Given the small impact of $\psi$, the resulting uncertainty can only be small, and in any case we estimate that (ii) causes an uncertainty < 1 %. The uncertainty caused by our structural model approximation is difficult to evaluate accurately. However, given that this model predicts a small effect of LWC on the correction while data indicate no effect, it is likely that the model introduces an uncertainty.

To explore this uncertainty in more detail, we estimated as a first step the effect of the LWC on the SSA using the Mie and layered codes. We ran both models using the geometry of our DUFISSS instrument as we did earlier (Gallet et al., 2009). This means that the snow is subjected to mostly direct lighting as well as to diffuse light due to the laser diode beam being reflected in the integrating sphere and
re-illuminating the sample. We first calculated the reflectance of snow that should be measured by DUFISSS for samples having the properties of our experimental snow. Calculations were performed for dry and for wet snow with the LWCs determined experimentally. Both Mie and layered codes were used. The calculated reflectances were then converted into snow SSA using polynomial fits (Gallet et al., 2009). Slight modifications to the code had to be made, compared to Gallet et al. (2009) because of constraints in the layered code, as detailed in Appendix B. These calculations yield the apparent SSA of wet snow, as determined in our experiments. Similarly to Fig. 6, we can plot the difference between the SSA of the frozen sample and the apparent SSA of the wet sample. This was done in Fig. 8, where data obtained using both models were plotted together with the experimental data. The outlier identified previously has been omitted. Figure 8 shows that the dry–wet differences are not the same for both codes and for the experimental data. This is expected since neither code reproduces the configuration of the actual sample, with respect to liquid water distribution. However, it is interesting to note that both codes show little correlation between the SSA difference and LWC, with correlation coefficients of only 0.007 and 0.06. This comforts our experimental result that the SSA difference does not depend on LWC and indicates that the difference depends mostly on the location of water. As water is simulated in Mie as single disconnected droplets and in the layered code as shells of water surrounding ice particles, both models simulate the two extreme cases where water could be located in a wet snow sample. In the Mie code, none of the ice surface is covered by water while all the ice is covered by water in the layered code. In natural samples, part or all of the ice is covered by water (Ketcham and Hobbs, 1969; Colbeck, 1973), depending on LWC. Figure 8 shows that the 0.5 m² kg⁻¹ experimental difference is in between the values calculated by the models and both modelled SSA differences show a very weak (and in opposite direction) dependence to LWC so that neither of these codes can be discriminated. Since the physical representation of water by the layered code is much closer to reality as water is expected to cover all or most of the ice surfaces particularly for high LWC (Colbeck, 1973), we feel that the coated structural approximation used to derive Eq. (8) is adequate but not ideal to represent water in a wet snowpack, comforting its partial validity.

To estimate the uncertainty introduced by the use of the coated sphere approximation to derive Eq. (8), we investigated the differences between the experimental frozen SSA and the calculated wet SSA as in a way slightly different from that presented in Fig. 8. Here, we used the measured LWC and wet reflectances to calculate the SSA of the wet snow samples using both models. We also used Eq. 8 introduced above. These three data sets (Mie, layered code and Eq. 8) yielding values of the SSA of wet snow are compared to the frozen SSA measured experimentally. The average differences between the experimental frozen SSA and the new calculated wet SSA are 1.9%, 1.3% and 2.9%, for the Mie code, the layered code and the use of Eq. (8), respectively. The highest difference between the experimental frozen SSA and the calculated wet SSA is obtained using Eq. 8, with a value 1% and 1.6% higher than the Mie and the layered code, respectively. Thus, the uncertainty introduced by the use of the coated sphere approximation to derive Eq. (8) is estimated to be no higher than 2%.

Since all the uncertainties envisaged are independent, the overall uncertainty is the square root of the sum of the squares of each error (10% for DUFISSS, 1% due to the ψ factor, 2% for the coated sphere approximation), so that the overall uncertainty is 10.2% for realistic values of LWC and for snow SSAs in the range 1–40 m² kg⁻¹. If the LWC is unknown, an extra 3% uncertainty, independent of the others.
has to be added, leading to a total 10.7% uncertainty. The upper SSA limit of 40 m$^2$ kg$^{-1}$ corresponds to our experiments and calculations, but there is no reason why the uncertainty would be higher for higher SSAs. Moreover, wet snow is unlikely to have high SSA values (Domine et al., 2007). The lower limit of 1 m$^2$ kg$^{-1}$ corresponds to our calculations. Lower values must be rare, as the lowest value measured so far is 1.9 m$^2$ kg$^{-1}$ (Domine et al., 2007). We therefore estimate that the overall uncertainty of SSA measurement of wet snow using DUFISSSS is at the most 11%, if the LWC is not known.

Finally, SSA can also be defined as the surface area per unit volume of ice or water, rather than per unit mass of snow (Fierz et al., 2009). It is then conveniently expressed in mm$^{-1}$. This volumetric definition can be correlated to the mass definition presented in this work when snow is dry using the ice density $\rho_{\text{ice}}$:

$$\text{SSA}_{\text{vol}} = \text{SSA}_{\text{mass}} \times \rho_{\text{ice}},$$  \hspace{1cm} (9)

with SSA$_{\text{vol}}$ and SSA$_{\text{mass}}$ the volumetric and the mass definition, respectively. When snow is wet, we need to take into account the LWC-dependent density of the medium as it is made up of water and ice. Considering reasonable LWC values, the density of the medium will vary between 0.917 and 0.9502 for 0 and 40% LWC per mass, respectively. If the LWC is not known, this will introduce an extra 4% uncertainty in the estimation of SSA$_{\text{vol}}$. This is not independent of the 3% uncertainty associated with not knowing the LWC mentioned above, so that in the case of the volume definition, the uncertainty resulting from not knowing the LWC is 7%, bringing the overall uncertainty to 13%, slightly higher than if the mass definition were used.

5 Conclusion

Gallet et al. (2009) showed that the DUFISSSS instrument could measure reliably the SSA of every type of dry snow tested and in the field. Here, we show that DUFISSSS can also measure the SSA of wet snow with an uncertainty of 11%. Experimental data and modeling work have shown that the effect of the presence of water on snow reflectance at 1310 nm is weak and depends very little on snow SSA and LWC. Furthermore, in most cases, deriving the SSA of wet snow assuming that its reflectance–SSA relationship is similar to that of dry snow leads to small errors. For an accurate determination of the SSA of wet snow, however, we recommend to correct the SSA value determined using the experimental dry fit of Gallet et al. (2009) by adding 0.5 m$^2$ kg$^{-1}$ and multiplying the value obtained by a factor close to 1, detailed in Eq. (8). Since the correction depends little on the LWC, not knowing the LWC is not critical and assuming a LWC of 10% (i.e., a corrective factor $\psi = 0.994$) will result in errors < 2%. Our experimental SSA ranged from 16 to 38 m$^2$ kg$^{-1}$ with LWC from 5 to 32%. Admittedly, one weakness of this study is that it did not measure snow with very low SSAs. However, given the linear character of Figs. 4 and 5, we feel that the resulting error caused by extrapolating our conclusion to low SSAs is most likely very small, and in any case smaller than the intrinsic measurement error of the IR reflectance method used, which is 10% (Gallet et al., 2009).

Appendix A

This appendix details calculations to obtain Eq. (8), based on the structural approximation that wet snow consists of disconnected ice spheres with a shell of water. We need to express the factor $\psi$, i.e., the ratio $\frac{s_{\text{w}}}{s_{\text{i}}}$ = $(\frac{a_{\text{w}}}{r_{\text{i}}})^2$, with $r_{\text{w}}$ the radius of the shell of water of $r_{\text{i}}$ the radius of the core of ice, subscript w is for water, i for ice, a for air and f for the refrozen water.

$$V_{\text{w}} = \frac{4}{3} \pi (r_{\text{w}}^3 - r_{\text{i}}^3)$$ is the volume of water in the wet snow sample, and $V_{\text{i}} = \frac{4}{3} \pi (r_{\text{i}}^3 - r_{\text{f}}^3)$ is the volume of refrozen snow, with $r_{\text{f}}$ the radius of the refrozen shell of water. The definition of the LWC gives us

$$V_{\text{w}} = V_{\text{i}} \times \frac{\rho_{\text{i}}}{\rho_{\text{w}}} \times \frac{1 - \text{LWC}}{\text{LWC}}.$$ Using the other equation of $V_{\text{w}}$ above, we have

$$r_{\text{w}}^3 = r_{\text{i}}^3 \left[ \frac{\rho_{\text{i}}}{\rho_{\text{w}}} \left( \frac{\text{LWC}}{1 - \text{LWC}} \right) + 1 \right].$$  \hspace{1cm} (A1)

Because the mass is constant, we have $V_{\text{w}} \rho_{\text{w}} = V_{\text{i}} \rho_{\text{i}}$. Using equation of $V_{\text{w}}$ and $V_{\text{i}}$ above and Eq. (A1), we can write

$$\frac{4}{3} \pi \times \left[ r_{\text{i}}^3 \left[ \frac{\rho_{\text{i}}}{\rho_{\text{w}}} \left( \frac{\text{LWC}}{1 - \text{LWC}} \right) + 1 \right] - r_{\text{f}}^3 \right] \times \rho_{\text{w}} = \frac{4}{3} \pi (r_{\text{f}}^3 - r_{\text{i}}^3) \times \rho_{\text{f}},$$

with $\rho_{\text{f}} = \rho_{\text{i}}$, so that

$$r_{\text{f}}^3 = r_{\text{i}}^3 \left( \frac{1}{1 - \text{LWC}} \right).$$  \hspace{1cm} (A2)

Using Eqs. (A1) and (A2), $(\frac{a_{\text{w}}}{r_{\text{i}}})^2 = 1 - \text{LWC} \left( 1 - \frac{\rho_{\text{i}}}{\rho_{\text{w}}} \right)$ meaning that $(\frac{a_{\text{w}}}{r_{\text{i}}})^2 = \left( 1 - \text{LWC} \left( 1 - \frac{\rho_{\text{i}}}{\rho_{\text{w}}} \right) \right)^{\frac{2}{3}}$. Therefore,

$$\text{SSA}_{\text{w}} = \text{SSA}_{\text{f}} \frac{S_{\text{w/f}}}{S_{\text{w/f}}} = \text{SSA}_{\text{f}} \times \left( 1 - \text{LWC} \left( 1 - \frac{\rho_{\text{i}}}{\rho_{\text{w}}} \right) \right)^{\frac{2}{3}}.$$ 

$$= (f (R_{\text{wet}} + 0.5)) \times \left( 1 - \text{LWC} \left( 1 - \frac{\rho_{\text{i}}}{\rho_{\text{w}}} \right) \right)^{\frac{2}{3}}.
Appendix B

The calculations done for Fig. 8 follow the DUFISSS configuration detailed in Gallet et al. (2009). Both the Mie and layered codes used calculate the reflectance of a 25 mm thick snow sample. Direct nadir lighting is used, and diffuse lighting due to the light reflected by the sample onto the integrating sphere walls is taken into account. A collimation factor of 0.95 for the 1310 nm laser diode is used. The reflectances of both wet and frozen samples are calculated using both codes.

To obtain SSA from reflectance, a polynomial fit is used (Gallet et al., 2009). However, here the polynomial fit had to be recalculated to account for our different calculation conditions. In Gallet et al. (2009), a lognormal distribution of snow grain sizes was used. This could not be used in the layered code because that model splits the spheres that represent the snow particles in a core of ice and a shell of water. The model has a limited range of possibilities for accurate and validated results, meaning that the size and the ratio of the core and the shell are limited and cannot be out of a given range. Using a lognormal distribution generates very large and very small particles that are out of the range accessible to the layered code. To be consistent, we should have used the same distribution as in our previous publication, but that distribution should have been truncated in order to be in the range of validated particle sizes for the layered code. We therefore did not use any lognormal distribution in the layered code. Given the range of SSA values used here, the effect on calculated reflectance by the model is most likely insignificant. To allow meaningful comparisons, we did not use a lognormal distribution in the Mie code either. New polynomial fits were therefore determined for both codes, which are valid for snow grain sizes without a lognormal distribution.

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