Application of snow specific surface area measurement using an optical method based on near-infrared reflectance around 900-nm wavelength to wet snow zones in Japan

Satoru YAMAGUCHI1, Hiroki MOTOYOSHI1, Tomonori TANIKAWA2, Teruo AOKI3, Masashi NIWANO3, Yukari TAKEUCHI4 and Yasoichi ENDO5

1 Snow and Ice Research Center, National Research Institute for Earth Science and Disaster Prevention, Nagaoka 940-0821, Japan
2 Japan Aerospace Exploration Agency, Tsukuba 305-8505, Japan
3 Meteorological Research Institute, Tsukuba 305-0052, Japan
4 Tohkamachi Experimental Station, Forestry and Forest Products Research Institute, Tohkamachi 948-0013, Japan
5 International YUKIGATA Society, Tohkamachi 948-0081, Japan

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Abstract

The specific surface area (SSA) of snow can be used as an objective measurement to define the optical sphere diameter of snow; it is therefore a helpful parameter to describe the physical properties of snow, such as albedo. Recently, measurement of snow SSA in the field has become easier with the use of optical methods based on near-infrared reflectance values (Ref). However, existing optical methods have only been validated for dry snow conditions in the field. In this study, we tested the possibility of applying the optical method using light with wavelength of around 900 nm (NIR photometry) to wet snow zones in Japan by comparing the findings with snow pit observation data. Our results indicated that NIR photometry can be applied to wet snow zones before the main melt season when the liquid water content is small, but problems arose during melt season due to the appearance of darker layers with more high liquid water content. To resolve these problems, we propose three improvements to NIR photometry: using three calibration targets ranging from high Ref to low Ref in coverage; establishing an estimation formula for SSA from measured Ref, including lower Ref values; and considering how water in the snow influences Ref.

Key words: snow specific surface area, near-infrared reflectance of snow, optical grain size, wet-snow

1. Introduction

The specific surface area (SSA) of snow is defined as its surface area per unit mass or volume. Because the SSA of snow includes information relating to the grain type, grain size, and connections among grains, it is a powerful parameter for quantifying the exchange of matter and energy between the snow and the atmosphere (Domine et al., 2006). Additionally, it is also an essential parameter for modeling mass transfer (air or water) in snow cover (e.g. Colone et al., 2012). Therefore, development of accurate and simple methods to measure the SSA of snow is a major topic in snow science.

Several methods are available to measure the SSA of snow, such as the stratigraphy method (e.g. Narita, 1969, 1971), X-ray method (e.g. Coleou et al., 2001; Kerbrat et al., 2008), and gas adsorption method (Brunauer–Emmett–Teller, BET method) (e.g. Legagneux et al., 2002; Kerbrat et al., 2008). However, these methods are not suitable for field observations because they require special instruments and considerable time and labor. Recently, optical methods based on the near-infrared reflectance value (Ref) have been used to measure the SSA of snow in the field (e.g. Matzl and Schneebeli, 2006; Gallet et al., 2009; Arnaud et al., 2011; Zuanon, 2013). Although this kind of optical method is useful for field measurements, it has only been applied to dry snow, with the exception of one preliminary examination in cold room experiments (Gallet et al., 2013). Gallet et al. (2013) referred to the possibility of applying the optical method to measure the SSA of wet snow, but their examinations were limited and whether the optical method can be applied to wet snow observation in the field has yet to be determined.

Areas of snow cover in Japan are distributed from latitude 35˚N to 45˚N and have various climatic conditions. Ishizaka (1998, 2008) categorized Japanese areas of snow cover to four regions, as shown in Fig. 1(a): a depth hoar region (blue zone), a dry snow region (gray zone), an intermediate-snow region (yellow zone) and a wet snow region (red zone). The snow conditions in the first (depth hoar) and second (dry snow) regions are basically dry during the winter season, and the summed area of these two region areas comprise 46.8% as a percentage of the
total area of Japan (Ishizaka, 2008). The snow conditions in these two regions should be suitable for SSA measurements using the optical method because of their dry snow conditions. Kuchiki et al. (2013) compared SSA results obtained by the optical method and by other methods (the BET method and snow pit observations) at Kitami in Hokkaido (depth hoar region), and found the results similar. However, snow in the third (intermediate snow) and fourth (wet snow) regions is exposed to temperate climate conditions even in mid-winter, so snow in these areas develops melt forms layers containing liquid water. Although these two regions account for only 18.2% of the total area of Japan (Ishizaka, 2008), they have the heaviest snowfall. Hence, a large number of snow disasters (e.g., avalanches, landslides related to snowmelt) occur during the winter season in these regions. Therefore, methods to measure detailed snow characteristics, including SSA information, are necessary for advances in modeling snow disasters.

Our ultimate goal is establishing a method for measuring SSA in wet snow zones in Japan using the optical method, but it is difficult to interpret wet snow SSA measurements using the optical method because the SSA of dry snow involves only the surface area between ice and air, whereas the SSA of wet snow also involves the surface area between ice and water and between water and air. In this paper, we apply the optical method to wet snow zones in Japan and compare traditional grain size (Fierz et al., 2009) determined based on the snow pit research with grain size determined by SSA using the optical method. Then, we provide a preliminary discussion of the causes for the large differences between grain size measured by snow pit observation and grain size determined using the optical method. Finally, based on these results, we propose ways to improve the optical method for application to wet snow zones in Japan.

2. Optical method

Optical methods are mainly classified into two types: one using light of around 900 nm (Matzl and Schneebeli, 2006) and the other using light of around 1310 nm wavelength (Gallet et al., 2009; Arnaud et al., 2011; Zuanon, 2013). For this study, we used an optical method using around 900 nm wavelength light, and refer to this as near-infrared (NIR) photometry. Detailed descriptions of NIR photometry have been provided by Matzl and Schneebeli (2006), so we will provide only a brief description of the concept of NIR photometry and the measurement procedure. Hereafter, the dimension of SSA is defined as surface area per unit volume (mm\(^{-1}\)), following Matzl and Schneebeli (2006).

The pit wall was smoothed as much as possible, and the pit was covered with a shower curtain to supply homogeneous illumination conditions given downward solar radiation [Fig. 2(a)]. Calibration targets consisting of two spectranol standards with near-infrared reflectance values (Ref) of 55 % and 99 % were set around the observation zone [Fig. 2(b)]. More than four targets are usually set; we used eight targets. The pit wall NIR image with targets was measured using digital photography in the NIR spectrum. Analyses used NIR images in the form of JPEGs instead of raw data due to software limitation. Digital photographs were taken using a Nikon
D3S, which was improved to detect near-infrared areas with a 25-mm Zeiss 2F-IR lens and gelatin filter (X-Nite 850 nm Filter) that selected wavelengths from 840 to 940 nm. The camera was set at a position approximately 1 m from the pit wall [Fig. 2(a)]. After measurement of the NIR image of the pit wall, the measured zone was covered with a cover that simulated snow (white thermal insulating material) [Fig. 2(c)], and then its NIR image was taken under the same conditions as those used for the NIR image of the pit wall. The Ref of the calibration targets and the spatial distribution of the Ref of the simulated snow were used to correct variations in illumination in the original NIR image of the pit wall.

The following empirical relationship between the Ref and SSA (mm⁻¹), which was obtained based on measurements in dry snow, was used to determine the SSA from the measured Ref:

\[ SSA = A \exp\left(\frac{\text{Ref}}{t}\right), \quad (R^2 = 0.908), \]  

where \( A = 0.017 \pm 0.009 \text{ mm}^{-1}, \) \( t = 12.222 \pm 0.842, \) and \( R \) is a correlation coefficient (Matzl and Schneebeli, 2006).

Error increases with increasing SSA from 4% at an SSA of 5 mm⁻¹ to approximately 15% for SSA values around 25 mm⁻¹ (Matzl and Schneebeli, 2006).

### 3. Information about observation sites and snow conditions

We selected two observation sites. One was the Tohkamachi Experimental Station, the Forestry and Forest Products Research Institute (37°08′N, 138°46′E, 200 m a.s.l.), at Tohkamachi in Niigata Prefecture, Japan [A in Fig. 1(b)]; we named this site TOH. The other was the Snow and Ice Research Center, National Research Institute for Earth Science and Disaster Prevention (37°25′N, 138°43′E, 98 m a.s.l.), at Nagaoka in Niigata Prefecture, Japan [B in Fig. 1(b)]; we named this site NAG. According to the classification system set out by Ishizaka (2008), TOH is an intermediate snow region while NAG is a wet snow region. Snow pit observations [stratigraphy including grain type and traditional grain size (Fierz et al., 2009), snow temperature, density, and liquid water content using dielectric measurement (Denoth et al., 1984)] were performed during winter seasons at both sites (approximately every 10 days at TOH and every week at NAG). Detailed descriptions of those snow pit observations have been published previously by Takeuchi et al. (2009) for TOH, and by Hirashima (2012) for NAG. In addition, both sites have recorded long-term and detailed data on meteorological condition (e.g., air temperature, humidity, solar radiation, precipitation, snow depth, snow mass).

Fig. 3 shows daily snow height at 9:00 A.M. and daily mean air temperature at both sites during the winter of 2012/2013. The maximum snow height during the winter of 2012/2013 at TOH was 289 cm (February 25), and at NAG it was 200 cm (February 22); the average maximum snow height (for 1918-2007) at TOH is 236 cm (Takeuchi et al., 2008), and the average maximum snow depth (for 1981-2010) at NAG is 135 cm (Yamaguchi et al., 2013a). Hence, during the winter of 2012/2013, both sites experienced heavier than average snow conditions. Because the daily mean air temperature at both sites was frequently above zero, even in midwinter, snowmelt likely occurred at times, including in midwinter.

The three observations involving NIR photometry were performed on the same days as the snow pit observations: February 15 at TOH, before its maximum snow depth was reached (we considered these data to be gathered before the main melt season); February 28 at NAG, after its maximum snow depth was reached (data gathered at the beginning of the main melt season); and March 26 at TOH, which was almost the end of the winter (data gathered at the peak of the main melt season). Fig. 4 shows snow conditions obtained on each day of NIR photometry observation involving snow pit observations. Although the three observation periods occurred at the different times, all snow layers were at 0°C, and the dominant grain type was melt forms for three days. Therefore, the snow conditions on all days were regarded as wet.

The grain size (\( E \)) basically became homogeneous (\( E: 1.0-1.0 \text{ mm} \)) as the melt season progressed. The frequency of high density (\( \rho \)) and the volumetric liquid water content (LWC) increased as the melt season progressed. The data in Fig. 4(c) show the existence of layers with high LWC in the snow cover [arrows in Fig. 4(c)].
4. Comparison of NIR photometry data and snow pit observations

NIR images captured via using NIR photometry were taken in the lower part of the snow cover. The measured area was 120 cm in height from the ground and 60 cm wide, and it was enclosed by a steel frame (3-cm width) on which the calibration targets and the cover of simulated snow were installed [Fig. 2(a), (b), (c)]. The Ref at each 5-mm height increment was calculated and averaged over a 10-cm width with the same height in the central part of the zone. The data collected near the top (height of 120-110 cm) and the bottom (height of 10-0 cm) of the zone were not used to eliminate any effects of frame reflectance. Fig. 5(a), (b) and (c) show the measured Ref. This was calculated by a 5-data-point running mean (average height: 2 cm) to reduce the influence of any position-matching error between NIR photometry and snow pit observations.

The figures also provide the SSA values that were calculated based on Eq. (1) from the measured Ref. Comparing the distribution of SSA (Ref) and the stratigraphy data obtained from the snow pit observations, the fluctuations in SSA for each day generally agreed closely with the stratigraphy. In particular, large changes in SSA (Ref) appeared at the boundaries of each layer. SSA values sometimes exhibited small fluctuations even within the one layer determined by the snow pit observations. These results suggested that NIR photometry can detect small fluctuations in snow characteristics that may result from small differences in meteorological conditions (e.g., precipitation intensity or snowfall crystal type) or deposition conditions (e.g., water percolation or densification conditions). Because weak layers that may lead to surface avalanches, such as sun crusts or snow fall crystals, are sometimes too thin to be detected by the naked eye, NIR photometry may be a powerful tool for investigating such weak layers in avalanche surveys.

Usually, SSA values are not observed in snow pits but are estimated based on NIR photometry. It is not possible to directly compare this kind of estimate with snow pit observation data. In this study, we tried to evaluate NIR photometry based on comparisons of snow grain size (E) between the values estimated from NIR photometry and those measured in the snow pit observations.

The E for NIR photometry was taken to be the value of the optical sphere diameter (d opt), which was calculated from the SSA (Grenfell and Warren, 1999) as:

$$d_{opt} = \frac{6}{SSA}.$$ (2)

Several researchers (e.g., Grenfell and Warren, 1999; Mitchell, 2002; Langlois et al., 2010) have pointed out the difference between d opt and traditional grain size measured in snow pit observation, which was defined by Fierz et al. (2009). To compare the optical properties of snow and measured E in the field, Aoki et al. (2007) proposed three definitions of E in field observations: d 1, the length of the major axis of crystals or dendrites; d 2, the branch width of dendrites or the width of a narrower portion of broken crystals; and d 3, the thickness of plate-like crystals. Aoki et al. (2007) also reported that d 2 generally corresponds to d opt. We did not measure d 1, d 2 and d 3 in this study, but the dominant grain types in the data from the three pits were melt forms and rounded grain (Fig. 5), which can be considered almost spherical shapes. Thus, we regarded the snow grain size measured by the pit observation in this study (d pit) to have the same value as d 2. Because our definition of d opt...
leaves room for various interpretations, we are not overly concerned here with the difference between $d_{opt}$ and $d_{pit}$; our focus is the relationship between the snow condition and the occurrence of order-scale difference between $d_{opt}$ and $d_{pit}$.

The $d_{opt}$ and $d_{pit}$ values before the main melt season [Fig. 5(a)] exhibited the same fluctuation trends, and the values of $d_{opt}$ and $d_{pit}$ agreed closely. The $d_{opt}$ and $d_{pit}$ values at the beginning of the main melt season [Fig. 5(b)] agreed closely showed in the upper part of the measured zone, but large differences ($d_{opt} > d_{pit}$) appeared in several lower parts of the measured zone. The $d_{opt}$ values at the peak of the main melt season [Fig. 5(c)] were frequently larger than those of $d_{pit}$. In particular, $d_{opt}$ values in the middle part of the measured zone were more than 10 times greater than $d_{pit}$ values. Areas with large differences between $d_{opt}$ and $d_{pit}$ corresponded to areas with lower Ref, and the frequency of lower Ref increased as the melt season progressed.

Based on these results, we concluded that the results of NIR photometry were reasonable before the main melt season, but became problematic as the melt season progressed and lower Ref layers appeared. Therefore, we need to investigate the reasons for these problems in NIR photometry involving lower Ref data before it applied to wet snow zones in Japan.

5. Causes for discrepancies between NIR photometry data and snow pit observations

5.1 Technical limitations of NIR photometry

In the algorithm for NIR photometry, the Ref of snow was calibrated from its pixel intensity by considering a linear relationship between the intensity of the 99% calibration target and that of the 55% calibration target. This relationship was also used to calibrate the Ref of snow with lower intensity than that of the 55% calibration target. However, the information included in JPEGs, which we used in this study, is usually limited compared with the information included in raw data, so there is no evidence that the Ref of snow with values smaller than 55% was correctly calibrated this way.

To investigate the effect of the estimated relationship, we performed cold room experiments. Using snow samples with darker Ref values resulting from high volumetric liquid water content, we performed NIR photometry with three calibration targets (99%, 55%, and 10%) [Fig. 6(a)]. In the experiments, we calibrated the Ref of snow using two different methods. One was the same as NIR photometry, i.e., the linear relationship between the intensity of the 99% and 55% targets was used to calibrate the Ref of snow even if the snow was darker than the 55% calibration target. We named the Ref calibrated using this method Cal_2. The second method used all three calibration targets. In its algorithm, the Ref of snow brighter than the 55% calibration target was calibrated using the linear relationship between the intensities of the 55% and 10% targets. We named the Ref calibrated using this method Cal_3. The Cal_3 values appear to be more accurate than Cal_2 values for snow darker than 55%. Fig. 6(b) shows the results of the comparison between Cal_2 and Cal_3 for snow with
Ref darker than 55%. Cal_2 and Cal_3 differed minimally around 55% Ref but differed more substantially at lower Ref values. Moreover, Cal_2 became negative when the accurate Ref (the value of Cal_3) became less than 25%. Thus, for Ref less than 55% (see Fig. 5, which was estimated using the original NIR photometry), it should have yielded a smaller value as the correct value. Hence, the SSA calculated from Eq. (1) should have been smaller than the value given. According to Eq. (2), a smaller SSA value leads to a larger d_{opt} values. Based on this result, if JPEGs are used for analyses instead of raw data, we propose using three calibration targets covering high Ref to low Ref instead of the original NIR photometry with two targets when SSA measurements are performed in wet snow zones in Japan.

Fig. 7 shows the dependence of SSA on Ref used in the original NIR photometry, along with the Ref range used to determine it (red area: 70-98%). We also plotted the results using a multiple-scattering radiative transfer model developed by Aoki et al. (1999; 2000). In this model, we assumed a homogeneous one-layer snow model consisting of an independently scattering sphere with a constant size distribution for the diameter d. We considered the optical condition in the simulation to be the same condition as the camera system used in this study, based on the filter used (http://www.maxmax.com/aXNiteTreeFilterComparison.htm). Mie theory, a conventional light-scattering theory, was used to calculate the single-scattering parameters of snow grains. These single-scattering parameters were then used to constrain the radiative transfer model to calculate the nadir reflectance Ref. The model parameters for snow depth and density were set at 5 cm depth and 500 kg m^{-3}, respectively.

The illumination condition employed in this calculation was diffuse light adjusted according to the procedure reported by Matzl and Schneebeli (2006). We did not consider the effect of the wall of the snow container in the calculation. SSA was calculated using Eq. (2) with d, and then the relationship between Ref and SSA was obtained.

The results of NIR photometry were in close agreement with the model results for Ref in the red area, and the SSA values calculated from NIR photometry were generally smaller than those in the model when Ref was smaller than that in the red area. Moreover, differences between the model and NIR photometry increased as Ref decreased. One reason for this difference between NIR photometry and the model results under lower Ref is probably that Eq. (1) was used to calculate the SSA outside of its application range (70-98%). Although we cannot assess which results were correct because of the lack of measurement data for SSA with dark Ref, the values of SSA calculated by NIR photometry may have been underestimated in the lower Ref area. If this was the case, the values of d_{opt} would have been overestimated.

5.2 Effects of reducing the technical limitations of NIR photometry

The regression equation to change Cal_2 to Cal_3 based on Fig. 6 is:
The relationship between Ref values up to 70% and SSA (mm⁻¹), which was obtained based on the simulation results in Fig. 7, is:

\[ SSA = A_s \exp \left( \frac{\text{Ref}}{t_s} \right), \quad (\text{Ref} \leq 70\%) (R^2=0.996) \] (4)

where \( A_s = 0.13 \), and \( t_s = 18.83 \). Comparing Eq. (1) and Eq. (4), \( t_s \) is almost the same value as \( t \) (12.22), whereas \( A_s \) is approximately 10 times larger than \( A \) (0.017). Using Eqs. (3) and (4), we found that our proposed improvements yielded NIR photometry results that were close to measured values. We calculated SSA and \( d_{opt} \) under two conditions to investigate each effect. The first was improvement using only Eq. (3). In this case, SSA was calculated using Eq. (1) based on Ref revised according to Eq. (3). We named this improvement IMP_1. The second improvement used Eqs. (3) and (4). In this case, SSA was calculated using Eq. (4) from Ref revised according to Eq. (3). We named this improvement IMP_2.

Fig. 8 shows the results of these improvements. In the figure, the red lines represent the original results (the same values shown in Fig. 5), the green lines represent the results of IMP_1, and the blue lines present the results of IMP_2. The results of IMP_1, shown in Fig. 8(a), indicate that all Ref values were higher than 55%, whereas the lower Ref values shown in Fig. 8(b) and 8(c) were improved; the values are now higher, based on Eq. (3). Although these improvements appeared in the SSA and \( d_{opt} \) values of IMP_1 in Fig. 8(b) and (c), the improvements in SSA and \( d_{opt} \) were limited, indicating that this improvement was not effective. However, most cases of overestimated \( d_{opt} \) values were resolved in IMP_2 [e.g., in the middle part of the results shown in Fig. 8(b) and the upper and lower parts of the results shown in Fig. 8(c)]. From these results, we can conclude that our two proposed improvements are effective for application of NIR photometry to wet snow zones in Japan. The improvement to our SSA estimation formula for lower Ref values was essential. Thus, we need to examine the relationship between SSA and Ref values for darker snow. Based on these data, we will be able to greatly improve the estimation formula of the SSA from Ref in NIR photometry.

5.3 Influence of the presence of water in snow

Although our proposed improvements were effective, \( d_{opt} \) was still overestimated in some layers in the results of IMP_2, such as the lower part of the results in Fig. 8(b) and the middle part of the results in Fig. 8(c). These areas corresponded to layers with darker Ref. To investigate the characteristics of these layers, we focused on the distribution of volumetric liquid water content (LWC) and wet density (\( \rho \)) (Fig. 8). The distributions of the darker Ref layers basically coincided with high-LWC layers, although the darker Ref layer sometimes appeared at slightly lower or higher positions the high LWC. This was probably due to the mismatch in height arrangement between the snow pit observations and the NIR photometry analysis. Based on these results, we can conclude that layers with darker Ref resulted from high LWC.

Fig. 9 shows the relation between the imaginary part of the refractive index (I-index), which is associated with light absorption, and the wavelength for ice (Warren and Brandt, 2008) and water (Hale and Querry, 1973; Palmer and Williams, 1974; Downing and Williams, 1975). The difference in the I-index between water and ice is small at around 900 nm (line a in Fig. 9). This implies that it is difficult to eliminate the influence of water films around snow grains from the results of NIR photometry.
Therefore, the SSA of grains covered with water films obtained using NIR photometry (SSA\textsubscript{NIR}) should include the influence of the water film surface area. Moreover, the grains connected by water films should be regarded as one grain in NIR photometry, and their SSA\textsubscript{NIR} should differ from the sum of each grain surface area (SSA\textsubscript{grain}), probably such that SSA\textsubscript{NIR} < SSA\textsubscript{grain}. The difference between SSA\textsubscript{NIR} and SSA\textsubscript{grain} should become greater with increasing water film thickness and with the number of connected grains. It is therefore quite likely that the difference between \(d_{opt}\) and \(d_{pit}\) drastically increases with increasing LWC.

According to Nolin and Dozier (2000), no small volumetric liquid water content (0.03–0.05) can yield accurate snow grain size retrievals in the 950–1150 nm wavelength range. Although our wavelength (around 900 nm) was slightly smaller than this wavelength range, the improvement results shown in Fig. 8(a), in which the values of LWC at all layers were smaller than 0.05, were consistent with their results in that the data revealed close agreement between \(d_{opt}\) and \(d_{pit}\). However, Fig. 8(b) and 8(c) reveal that some areas with LWC smaller than 0.05 also exhibited large differences between \(d_{opt}\) and \(d_{pit}\). Most of these layers were highly dense. Yamaguchi \textit{et al.} (2012) reported that the pore radius (\(r_p\)) in snow becomes smaller and the concentration ratio of \(r_p\) increases with density, based on analyses of the water-retention curve feature of snow. From this perspective, the porosities in dense snow would fill with water more easily than those in light snow under the same LWC. Then, the SSA\textsubscript{NIR} of dense snow became smaller than SSA\textsubscript{grain} more easily. For this reason, differences between \(d_{opt}\) and \(d_{pit}\) in dense snow would be more strongly affected by LWC values than they would in light snow. These findings suggest that the influence of small LWC (<0.05) on the accuracy of snow grain-size retrievals cannot be neglected under dense snow conditions. Because wet snow zones in Japan correspond to areas with the heaviest snowfall, high-density layers frequently appear in the snow cover because of the large overburden pressure. Therefore, it is important not to neglect the effect of LWC on NIR photometry. Although Yamaguchi \textit{et al.} (2013b) reported preliminary results about the relationship between Ref and LWC for different grain sizes of dense snow around 900-nm wavelengths, further examination will be needed to clarify this issue before applying of NIR photometry to wet snow zones in Japan.

A theoretical approach, incorporating the radioactive transfer model to consider the relationships among several snow grains due to the existence of water in snow, will also be needed to ensure correct interpretation of wet snow SSA measured using the optical method.

### 6. Conclusions

We performed SSA measurements of snow in wet snow zones in Japan using optical methods at around 900-nm wavelengths (NIR photometry) and compared these data with snow pit observations to evaluate the possibility of applying NIR photometry in these regions. Our results indicated that the measurement results of NIR photometry were reasonable before the main melt season, but problems resulting from the appearance of darker layers due to high liquid water content occurred as the melt season progressed. To resolve these problems, we proposed three improvements. The first was using three reference targets covering high Ref to low Ref instead of the two targets used in the original NIR photometry if JPEGs are used for analyses, because JPEGs contain less information than raw data. The second was developing an estimation formula for SSA based on Ref at lower Ref zones. The third was considering how the presence of water in snow affects Ref.

One research direction that could be pursued to solve the last two points would be to compare the data between NIR photometry and other SSA measurement methods in the case of wet snow. Another direction could be developing a new optical method to measure the SSA of wet snow by linking multi-wavelengths with the difference in light absorption between ice and water. Possible wavelengths would include 950 nm (line b in Fig. 9), 1150 nm (line c in Fig. 9) and 1380 nm (line d in Fig. 9).

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