Comparison of digital and manual methods of snow particle size estimation

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ABSTRACT

Maintaining long time series of observations of the Cryosphere is a key issue in climate research. Long observational time series involve problems due to change in methodology or observers. In order to extend time series and introduce new methods, careful comparisons must be made to ensure homogeneity in the observational data. We have compared an established method for snow grain-size observations used by the Abisko Scientific Research Station (ASRS) in northern Sweden, based on visual interpretation, with a newly developed method for Digital Snow Particle Properties (DSPP) analysis. Transition from subjective visual method into digital reproducible analysis creates less subjective and more comparable results. The ASRS method generates size classifications excluding quantitative analysis size ranges. By determining the sizes of the classified snow using the DSPP method, actual size ranges for classified snow can be established. By performing a digital analysis of the reference samples and the snow samples classified, we can compare the ASRS classification system to existing official classification systems. The results indicate underestimation of the visual particle size in comparison to the reference samples. Our results show how to quantify the historical data set, which enables us to perform quantitative analysis on the historical data set.

Key words | Abisko Scientific Research Station (ASRS), classification, methods, particle size, snow

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INTRODUCTION

Long time series of environmental observations play a vital role in all assessments of effects of climate change (e.g. ACIA 2005; Lemke *et al*. 2007). A particular problem that may appear in long time series concerns changes in measurement systems or other methodological or operator-induced errors that cause inhomogeneities in the data. Much effort must therefore be spent on homogenization of data series before they can be used in wider analysis (Alexandersson & Moberg 1997). Another issue concerns changes in methodology by introducing more robust digital methods in place of, in some cases, more subjective methods (Gay *et al*. 2002). Abisko Scientific Research Station (ASRS) in northern Sweden has been monitoring the winter snow pack on a bi-weekly basis since 1961 using manual sampling and visual observation of snow pack-related parameters, yielding a series of 483 observations (until spring 2010). Within these measurements are observations of particle size based on comparisons to a fixed reference material.

Comparison of observations of snow particle size from different observers at ASRS shows that the observations of snow grain size are consistent. The ASRS method to classify the snow grain size therefore seems to be yielding consistent results, but is still subjective as individual observers interpret the same observational system. By translating the observed parameters into values, these data can be used for modelling purposes and be compared with other datasets. We apply a digital method for snow grain-size analysis that allows a rapid and objective determination of a large number of samples. In this paper, we apply the

doi: 10.2166/nh.2012.078

method to snow samples and the size reference objects used at ASRS to evaluate the actual sizes of the objects and determine the method for continued operation in snow grain-size monitoring.

Snow grain-size and the shape of grains are important parameters when monitoring the snow pack via spaceborne instrumentation. Snow grain-size and shape affect the scattering of electromagnetic waves used for remotely sensing a snow pack (Nolin & Dozier 1993). Methods for adjusting remotely sensed data for such effects also rely on grain-size data as basic information although, in such analysis, grain shape is typically assumed spherical (Nolin & Dozier 1993).

A large number of satellite-mounted sensors with varying functions enable complex analysis and investigation of the snow pack, most recently the CryoSat (Drinkwater 2003). In addition, increased frequency of flight passes and downloads increase the accessibility of datasets. One observation platform of particular interest to snow-related investigations is Synthetic Aperture Radar (SAR). The propagation path of a radar wave is affected by several aspects of the snow pack, its grain-size, the density of the snow and occurrences of ice layers within the snow pack (Ulaby & Dobson 1989). In addition, the surface roughness and the incidence angle of the radar beam also affect the backscattered energy. In a granular medium, backscatter depends on the grain-size of the medium and on the wavelength of the radar wave. It is therefore important to know the snow grain-size distribution when attempting to evaluate SAR backscatter images of a snow cover (Nolin & Dozier 2000) as well as for density modelling of the snow pack, essential for altimetry corrections (Brenner *et al.* 2007).

In addition to the remote sensing aspect of snow-cover monitoring, snow grain-size is also an important parameter for grain-growth models (Gravner & Griffeath 2008), snow pack evolution models (Lehning *et al.* 2002) and snow pack water equivalent, important input information for hydrological power plants (Larsen *et al.* 2005). Common to all these models is that they have so far relied on relatively simple information. In most radar backscatter models, for example, the snow grains are assumed to be spherical (Nolin & Dozier 2000). Other models rely on averages of size and shape of grains rather than their full size distributions. Furthermore, due to the time-consuming manual analysis of snow grain-size samples, size distributions within each sample are rarely captured.

We have introduced a Digital Snow Particle Property (DSPP) method for analyzing snow samples, yielding extensive information on grain-size and shape as well as size distribution. This method has the advantage of automatic classification of several geometric properties of snow grains and hence does not rely on manual and (possibly subjective) determinations. We use the term ‘particle size’ for the DSPP method results since grain-size, by definition, refers to crystal size and it is not possible to automatically distinguish between single and multiple crystal particles with the DSPP method.

The purpose of this study is to compare different methods for grain-size analysis. The *International Classification for Seasonal Snow on the Ground* (Fierz *et al.* 2009), largely based on Colbeck *et al.* (1990), provides guidelines for snow sampling and analysis and provides a reference for our study. The snow grain-size analysis is based on visual interpretation of six suggested size classes: very fine (<0.2 mm), fine (0.2–0.5 mm), medium (0.5–1.0 mm), coarse (1.0–2.0 mm), very coarse (2.0–5.0 mm) and extreme (>5.0 mm) (Fierz *et al.* 2009). Their definition of grain-size is the largest extension (axis) of the grain. The ASRS monitoring system, however, uses a different system.

The ASRS grain-size (referred to as such because it is not known if it can correctly identify grains) observations are carried out by the station personnel, and the snow grain observations are based on size comparisons with common household objects. The observations are divided into six classes corresponding to the reference objects: flour (F), semolina (S), rice (R), peas (P) and nuts (N) as well as flakes, which is a separate class referring to crystal objects such as ice needles or parts of dendrites, etc. Peas are interpreted as yellow peas, nuts as hazelnuts and the size of rice as the length of the rounded rice grain (personal communication with the ASRS observers). The point of these choices for reference objects is that they constitute well-known household types known to the observers. Such a choice of reference objects is clearly not related to Fierz *et al.* (2009); there is therefore a need to establish more quantitative methods for grain-size determination to couple the ASRS observations to established standards. In addition, the ASRS observers have inadvertently added intermediate size classes by marking two adjacent classes when uncertain of the snow grain-size classification.

The ASRS method is simple to perform but has a clear disadvantage in that it is not comparable to other classification systems. To investigate this problem, we have applied the DSPP method to field snow samples that are classified by the ASRS system. The DSPP method has also been applied to the reference materials used by the ASRS for their monitoring measurements. The aim is an objective quantitative measure for the ASRS snow grain-size dataset which, for example, can be used in further quantitative analysis of the historical ASRS snow grain-size dataset. The digital method has the advantage of requiring a minimum of understanding of snow classification while providing a much more detailed dataset of the sampled snow, including grain-size distributions rather than simple classification systems. It is also better to apply established classification systems such as that of Fierz *et al.* (2009).

STUDY SITES

The ASRS (68°21′ N, 18°49′ E) is located in northern Sweden (Figure 1). Weather observations have been made at ASRS since 1913 (Kohler *et al.* 2006; Callaghan *et al.* 2010). The climate is characterized by a low annual precipitation (310 mm during the period 1913–2000) due to a strong rain shadow effect from the Scandinavian mountain range, and had a mean annual temperature of −0.7 °C during the period 1913–2000. ASRS performs an extensive monitoring program (Callaghan *et al.* 2010) which includes snow pack observations. Snow depth measurements are made daily during the winter season and observations of snow pack properties are made twice a month (normally around the 1st and 15th day of the month). The snow pack observations include depth, layering, snow layer hardness, grain-size, grain compactness and snow layer dryness. Grain solidity is a parameter measured by ASRS which is not part of the typical classification scheme such as that compiled by Colbeck *et al.* (1990). Information on the underlying ground is also documented as frozen or non-frozen, and the basic vegetation is recorded.

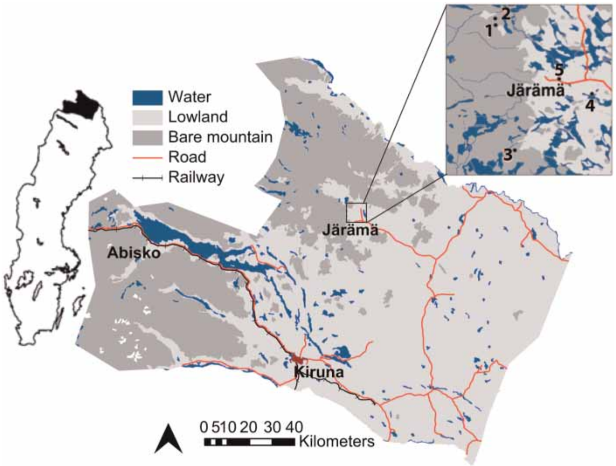

Figure 1 | Map of Kiruna Municipality in Sweden, the two field sites Abisko and Järämä highlighted. The close-up shows the location of the field campaign in Järämä. Numbers 1–3 indicate locations at which snow observations were made in grid samples and 4–5 are transects (©Lantmateriet Gävle 2010; approval no. I 2010/0027-0060).

A field campaign was performed during 3–5 March 2009 in Järämä Sami village (67°53′ N, 21°57′ E) located about 65 km north of Kiruna and 90 km east of Abisko (Figure 1). This field campaign was part of a larger study concerning the effects of snow on reindeer grazing and the ability to make strategic choices of herding areas based on snow quality data extracted from remotely sensed imagery. The area is mainly hilly with extensive peat plateaus and sparse vegetation; lower elevation areas are covered by mountain birch. The area is used extensively for reindeer herding.

Snow observations were made at five different locations; see Figure 1. At sites 1–3 snow observations were made in a 100 × 100 m grid (snow profile observations in the corners), and at sites 4 and 5 in a 300 m long transect (snow profile observations every 100 m). Sites 1, 2 and 3 are located in bare mountainous areas and sites 4 and 5 are located within mountain birch forest. A reindeer fence separates sites 1 and 2; reindeer access both sides but graze only at site 1 and not at site 2.

The snow profile observations from the Järämä field campaign consist of observations of grain-size, snow layer hardness, relative permittivity, snow density and snow temperature, which are made for each individual layer of the snow pack. For grain-size, the samples were classified by the ARSR method and photographed for analysis by the DSPP method. Each individual snow layer has also been classified according to its Sami snow name. Between the snow profiles, observations of snow depth were made approximately every 10 m. For sites 1, 2 and 3, snow depth observations were also made across the diagonal in the square. Only the snow particle size observations are analyzed here.

METHODS

We developed the DSPP method to efficiently analyze extensive datasets of snow grain-size from Antarctica. The field sampling is time, cost and energy efficient and uses a commercial digital camera (Canon EOS 450D) and the commercial software Definiens Developer 7.0 for object-oriented image analysis. The procedure for analysis is simple. A sample is separated from the snow pack in the field and placed on a micrometer accuracy millimetre-marked dot-grid reference plate and photographed with the digital camera. For each determination, three parallel samples were analyzed to improve statistical reliability. Each image was stored in RAW (unprocessed data form) and JPEG large/fine format (4272 × 2848 pixels). Only the JPEGs were used for analysis since the compression did not change the vital characteristics of the image file.

The DSPP method is based on segmentation and classification by object-oriented image processing. Each image is cropped to remove areas not to be included in the analysis (e.g. borders and melted snow). The image is then imported to an image processing software (here Definiens Developer 7 has been used) where the mean pixel size ($\bar{s}_P$) of the image is determined using the 1 millimetre markers on the reference plate. To determine $\bar{s}_P$, three locations (P_1, P_2, P_3) in the image have been used, at which the distance in number of pixels between the 1 mm markers (d_P) on the reference plate has been calculated in four directions (i). The mean pixel size ($\bar{s}_P$) used here is then given by:

$$\bar{s}_P = \frac{P_{\text{tot}} \times i_{\max}}{\sum_{i=1}^{4} d_{P_1}^{i} + \sum_{i=1}^{4} d_{P_2}^{i} + \sum_{i=1}^{4} d_{P3}^{i}} \qquad (1)$$

where P_{tot} is the total number of points where the numbers of pixels were counted (in this case 3 points) and $i_{\max}$ is the total numbers of pixel distances counted (4 directions times 3 points, i.e. 12).

After determining the mean pixel size relation of the image (Equation (1)), the image is segmented by the software based on shape, compactness and scale parameters (Definiens 2008). The shape and compactness segments the image and is sequentially based on the brightness, contrast and the shape of the object in the image. These parameters are held constant in the evaluation of all reference and field images. The scale parameter is however altered since it correlates to the size of the object; its value increases with larger size classes. The segmented image is classified by area, brightness and shape index. The classification parameters were computed by trial and error to optimize the number of grains classified in each image. The optimal values found for each class were then applied to all images of equivalent size classes (Table 1).

The snow grain-size samples were classified in the field by visual interpretation using the ASRS method. The same snow samples were then photographed and analyzed using the DSPP method. To be able to relate data obtained by the two methods, images of the reference material that the ASRS method is based on (flour, semolina, rice, peas and nuts) were photographed in the lab. Four samples from each class were photographed and analyzed using the DSPP method.

Table 1 | The segmentation and classification values used on the field images for each ASRS class

Parameter		**Flour**	**Semolina**	**Semolina-rice**	**Rice**	**Rice-peas**	**Peas**
Segmentation	Scale factor	40	40	60	90	120	120
	Compactness	0.8	0.8	0.8	0.8	0.8	0.8
	Shape	0.6	0.6	0.6	0.6	0.6	0.6
Classification	Area	0.035–20	0.035–20	0–20	0–20	35–60	35–60
	Brightness	116–255	116–255	100–198	100–198	93–130	93–130
	Shape index	0–2.6	0–2.6	0–1.4	0–1.4	1–1.45	1–1.45

Grain shape can also be evaluated using the DSPP method since the Definiens Developer 7 software provides automatic calculation of shape factors from basic geometric measurements (Definiens 2008). The shape factor for each snow grain is therefore defined as the ratio of length to width of the object analyzed.

The images of the reference materials were photographed in a laboratory and are referred to as reference images. All classes in the ASRS classification (nuts, peas, rice, semolina, flour and flakes) were photographed except flakes; the latter do not strictly constitute a size class but are a class for fragments of snow crystals such as dendrite parts of a snowflake. Samples were arranged to clearly display the object edges and not clusters of objects. All classes were analyzed for length, defined as longest axis in a bounding box (Definiens 2008); this is similar to Colbeck *et al.*'s (1990) 'greatest extension'. Length is simple to evaluate for circular objects but introduces a complication for rice through its elongated shape. The problem lies in comparing a snow crystal of random shape with an elongated object, and raises the question as to what axis in the oval rice grain is used in the comparison. The ASRS instructions are not clear as to what axis to use, introducing a large uncertainty in this class. The size presented in this study is referred to as the longest axis of rounded rice.

The field samples were classified visually by the ASRS method and then measured for size by the DSPP method. The calculated sizes for each class in the actual snow samples are presented in Table 2. Here all classes are represented except nuts, as no grains of such extreme size were identified in the field. As separating two classes in the field by using the ASRS classification was sometimes complicated, we introduced two intermediate classes between semolina and rice (SR) and rice and peas (RP).

Table 2 lists the number of images taken of each class in the field samples, explaining the representativity of each class in the field campaign. The images are separated into three different classes based on quality good, OK and poor. Only images of good quality are used in this analysis; the field images used are only based on quality and class so the depth or placement of the samples are of no importance here. This shows that the most common classes in the field campaign are semolina, semolina-rice, rice and peas. The quality is better in the smaller classes (semolina and semolina-rice) and poorer in rice and peas. This implies that snow grain photography returns best results in middle-sized classes, according to the UNESCO standard system.

All analyzed images result in a particle size distribution. The data are well described by a Weibull distribution, which takes the form:

$$f(E+m) = \frac{c}{A}\left(\frac{E}{A}\right)^{(c-1)} \exp\left[\left(-\frac{E}{A}\right)^{c}\right] w \qquad (2)$$

where E is particle size, A is a scale factor, c is a form factor, m an offset value and w the width of the bins. The Weibull coefficients are determined by using the cumulative distribution of the snow particle size. The Weibull distribution

Table 2 | Reference object mean size and standard deviation (determined by DSPP); field snow grain mean size and standard deviation (classified by ASRS and size determined by DSPP); and representativity of the different ASRS classes in the field samples and image quality

Category	Reference Mean (mm)	St. dev. (%)	Field Mean (mm)	St. dev. (%)	Representativity Image quality Good	OK	Poor	Total
Flakes	–	–	1.05	53.3	6	7	2	15
Flour (F)	0.23	52.2	1.57	37.6	10	7	1	18
Semolina (S)	0.82	18.3	1.48	39.2	49	10	1	60
Semolina/rice (SR)	–	–	2.87	23	26	2	1	29
Rice (R)	4.99	10	4.43	25.1	24	17	1	42
Rice/peas (RP)	–	–	3.61	41	4	2	0	6
Peas (P)	8.26	9.2	6.68	23	8	2	19	29
Nuts (N)	16.1	13.3	–	–	–	–	–	–

is often used for data with a distinct lower limit, a high number of smaller objects and a tail of larger objects (Haan 1977). Weibull distributions are used in extreme event analysis and are commonly used to describe the wind speed and streamflow distributions. By taking twice the logarithm of the distribution and plotting it against the logarithm of the snow particle size, a linear relation is obtained. The slope of the curve gives the shape factor c and the scale factor A is the exponential of minus the ratio of the offset and the slope of the curve.

RESULTS

Figure 2 shows examples of the original images and the classification results for both the reference materials and the field samples. Figure 2 contains only classes that are comparable between the reference and field samples: flour (F), semolina (S), rice (R) and peas (P). These images show the difference between the reference images and field samples. The reference samples contain fewer objects that are well separated and of very uniform size. In contrast, the field samples contain objects that are complex in shape, with poorer contrast and clustering of the grains.

Figure 3 depicts the size distributions of the formal snow particle size classification from: (a) Fierz *et al*. (2009); (b) the distribution of grain sizes in the reference material; (c) the size distribution of the field samples; and (d) the suggested size classes to be used for converting the ASRS snow grain-size classification to sizes given in millimetres. The results in Figure 3(b) and (c) (reference and field data, respectively) were obtained by DSPP; note that new intermediate classes have been introduced in the analysis of field data. Each class is represented by the statistical representation of data from four sample images.

Each class in Figure 3 also gives the number of objects analyzed within each class. The results show that more objects are analyzed in the smaller size classes than in the

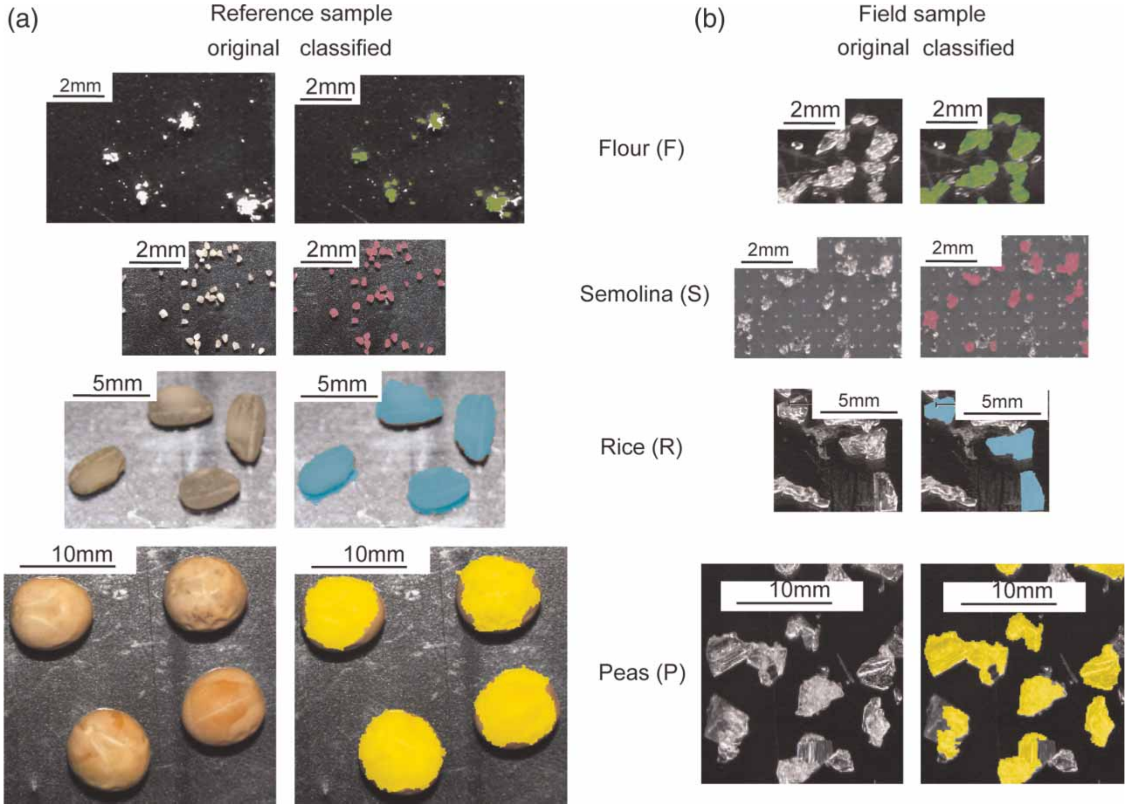

Figure 2 | ASRS reference object samples in four comparable classes: (a) flour, semolina, rice and peas (original images to the left and DSPP-classified objects to the right); and (b) snow classified by the ASRS method in the four classes flour, semolina, rice and peas (originals to the left and the DSPP-classified objects to the right). Note that the pictures have been scaled to be directly comparable within each size class.

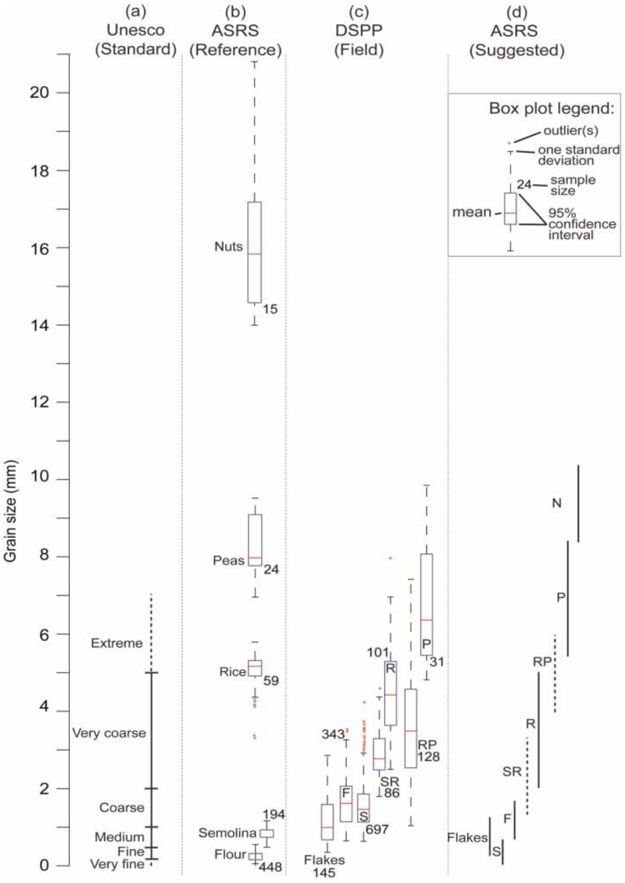

Figure 3 | The different snow particle size classification systems: (a) the UNESCO classification system by Fierz *et al*. (2009); (b) the object particle size in each class in the reference samples, size determined by the DSPP-method; (c) field samples classified by the ASRS method and size determined by the DSPP method; and (d) our suggested size classes in millimetres for the ASRS historical dataset.

larger classes. This is of course an expected result since the micrometer reference dot-grid has a limiting size of 25 cm^2 so that more objects from smaller classes can fit on the reference surface without overlap. The standard deviation is small in the smaller reference image classes (F and S); these classes also contain fewer outliers (Figure 3(b)). In the larger classes (P and N), the standard deviation is larger. When considering the relative standard deviation, however, it decreases with increasing size. In the field images (Figure 3(c)) the absolute standard deviation is generally larger than for the reference images. In the case of the field images, two new intermediate classes (SR between S and R and RP between R and P) were introduced to bridge the gaps between the original ASRS classes. This was partly in response to the ASRS investigators' routine of marking two neighbouring classes when uncertain about the classification of the snow. Among the field samples, a large number of outliers (defined as values outside one standard deviation from the mean) were present in the S class whereas in other classes the number was small. The standard deviation of the snow particle size is consequently larger in the field samples than in the reference samples.

The shape factor of the reference objects is consistently lower than for the snow crystals in the field images, which indicates that the reference objects have a more spherical shape than snow grains in the field (Table 3). The reference samples in the R class differ from the other reference samples due to the elongated shape of the rice grains. The relative standard deviation of the shape factor is also lower for the reference images than in the field images; this is of course due to the homogeneous shape of the different objects in the reference materials. The shape factor is similar in all the field classes except the P class; the number of analyzed objects in class P is however also lower ($n = 31$) than for other classes.

Table 3 | Shape statistics of classified objects in field and reference sample images. Shape factor is defined the ratio of length to width; a shape factor of 1 implies near-circular object and a shape factor of >1 implies an elliptical object

		Flour (F)		**Semolina (S)**		**Rice (R)**		**Peas (P)**	
		Reference	**Field**	**Reference**	**Field**	**Reference**	**Field**	**Reference**	**Field**
Length	Mean (mm)	0.23	1.57	0.82	1.48	4.99	4.43	8.26	6.68
	St. dev. (%)	52.0	37.9	18.0	38.9	9.9	25.1	9.3	23.0
Width	Mean (mm)	0.18	1.06	0.64	1.00	3.35	2.95	7.65	4.92
	St. dev. (%)	53.1	39.2	19.4	40.2	10.8	24.5	6.9	24.9
Shape	Mean (mm)	1.30	1.55	1.31	1.54	1.50	1.54	1.08	1.39
Factor	St. dev. (%)	22.2	36.6	19.4	29.9	10.4	25.0	6.9	23.1

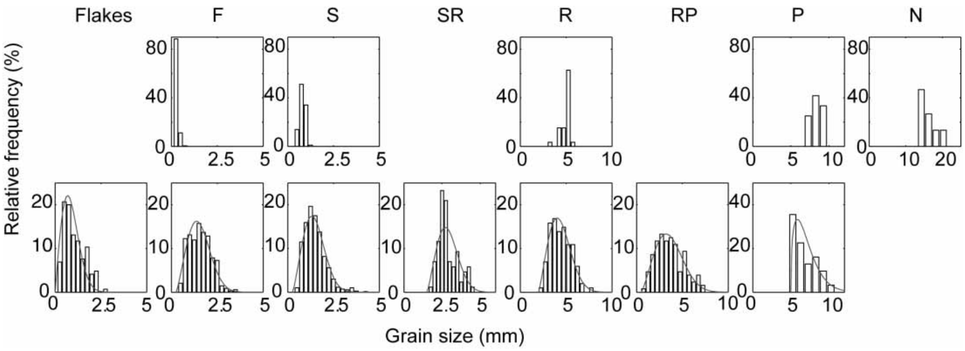

Figure 4 | The relative distribution of snow particle size in each ASRS class. Reference images in the upper histograms for the five classes photographed (flour, semolina, rice, peas and nuts). The lower histograms show the distribution of the snow particle size within the field samples, classified by the ASRS method and size determined by the DSPP method. The solid lines show the Weibull distribution (Equation (2)) fitted to the snow grain samples in each class. Note the difference in *y* scale in the field sample P class.

Figure 4 depicts the relative distribution within each snow particle size sample. The reference samples show narrow ranges with no clearly distinguishable type of distribution. In fact, some seem more normally distributed while others may exhibit skewed distribution. All distributions in field images show a similar shape, skewed towards the smaller grain sizes and longer tail towards larger sizes. This shape can be explained by a Weibull distribution (Equation (2)) and such a distribution has been fitted to each class in the field samples (Figure 4). The corresponding Weibull coefficients are listed in Table 4.

DISCUSSION

The ASRS snow pack dataset is the longest monitoring series for snow properties in Sweden but the methods used for the measurements are not adjusted to modern sampling methods. The measurements may therefore suffer from potential subjective determinations as well as the fact that the data do not adhere to any established standards. The data are therefore not directly applicable to numerical modelling projects which typically require quantitative information about the snow. Nevertheless, the series consists of an internally consistently set of measurements since the method of investigation has been the same for almost half a century. The method used in this investigation is adaptable and can be used on various types of datasets and for various purposes, for example in remote sensing validation where the DSPP method was used for correlation with MODIS, MOA and MERIS data (Ingvander *et al.* 2010). This investigation could be extended to connect additional classification systems to create a common understanding for local classification systems of snow grain-size analysis.

Table 4 | The suggested Weibull coefficients (Equation (2)) for each snow particle size class plotted in Figure 4

Weibull coefficients	*A*	*C*	*m* (mm)	*w* (mm)
Flakes	0.9680	1.9970	0.00	0.25
F	1.4480	2.2841	−0.25	0.25
S	1.3632	2.3062	−0.25	0.25
SR	1.5714	2.2505	−1.50	0.25
R	2.6880	2.1839	−2.00	0.50
RP	3.5224	2.2708	−0.50	0.50
P	2.2045	1.3671	−5.00	1.00

Our investigation uses two different methods to determine snow particle size; the DSPP method by co-observations determines the size of snow classified by the ASRS method. When studying our results, it is obvious that the ASRS data classes (Figure 3(b)) poorly adhere to the standard classification system of Fierz *et al.* (2009) (Figure 3(a)). The flour and semolina classes correspond well to the fine and medium sizes of the standard classification system. The rice class lies on the boundary between very coarse and extreme in the standard system and the peas and nuts categories are far outside the standard classification system. Only two of the five ASRS classes cover the standard classification system. There are also gaps between the ASRS classes that are larger than the 95% variability of sizes within each of the reference materials. Clearly, the ASRS system has significant drawbacks for use in applications that require a continuous classification such as that given by the standard classification system (Fierz *et al.* 2009).

The field results indicate several characteristics. First, it is obvious that snow samples are not homogeneous in terms of their size distribution. It is clear that the variability is significant. The relative standard deviation, however, decreases with increasing average size, indicating that larger particle size samples have smaller particle size variability. The distribution of each sample is furthermore strongly skewed towards smaller particle sizes and is well characterized by a Weibull distribution (Figure 4). The Weibull distribution also relates well to the physical processes of snow sublimation, where a few larger grains grow at the expense of many smaller grains (Gray & Male 1981).

The importance of establishing a distribution function is that it becomes easier to model bulk snow properties when, for example, modelling radar return in remote sensing applications (Nagler & Rott 2000). Furthermore, the grain shape affects the backscatter processes in remote sensing. In backscatter modelling, grain shape is commonly assumed to be spherical; our investigation provides information on the shape factor deviating from the spherical form where our field samples consequently shows less spherical shape than the reference samples. This is an expected result knowing the household objects being spherical and the complexity of snow grain shape (Picard *et al.* 2009). A complicating factor when comparing the smaller particle sizes is that, when analyzing the flour class in the reference dataset, the reference material tends to occur in lumps and hence artificially produce larger particle sizes. This is not critical to the DSPP method, but represents a problem with the choice of reference material for the ASRS method. Lumping is also present in the finer particle sizes of the field images (Figure 2).

The distribution of snow particle sizes in our field data (Figure 3(c)) indicates that neither the standard classification scheme nor the ASRS scheme is sufficient for describing the characteristics of seasonal snow in this area. The standard classification scheme is too focused on smaller particle sizes and the ASRS scheme suffers from gaps in particle sizes discussed above. The particle size distributions we have obtained indicate that a basic classification with five classes is not sufficient since gaps inevitably occur due to overlap between the classes.

In Figure 3(c), the F and S classes overlap in size. This is largely due to lumping of grains in the smaller size class samples, and shows some of the difficulties with separation of smaller grains using the DSPP method. The SR class fills a relevant gap between the S and R classes. On the other hand, the RP class turns out to have particle sizes smaller than the R class. The reason for this seems to be that size distribution was wider for this class (Figure 4). It must be remembered that the RP class was first determined from the ASRS method; the results therefore show that using these reference sizes may fail due to the visual impression of the sample. This also indicates the strength of the DSPP method, which provides a true quantitative measure of the sample properties. The RP class has a large range that originates with the larger particle sizes in the sample. It is interesting to note that the inferred RP class in the field data largely falls between the rice and peas reference classes. This also indicates that there is significant uncertainty in what size is actually observed. Assuming the observation in this investigation is representative of the historical dataset of ASRS, a consistent underestimation of the snow particle size compared to the reference objects can be identified. The reference samples (Figure 3(b)) demonstrate the need to bridge classes in the analysis to cover the gaps between the sizes and the double size registration by the observers. However, the field samples show better coherence between the classes. Based on the classification of the field samples, we have generated a size suggestion for the classes which could be used when applying the information from the ASRS dataset in numerical modelling and comparing to other datasets (Figure 3(d)).

Based on our results we see that the ASRS classification may be of limited use because it fails to recognize large parts of the continuous spectrum of particle sizes. It is evident that the automated process gain through the DSPP method yields better data without adding much effort in the field. The benefit lies in that the snow samples can be analyzed in greater detail and that the method provides much more information about the snow particle size distribution in each sample.

By obtaining quantitative measures of snow particle size, we are able to provide ground truth validation for remote sensing. Ground truthing is necessary for correct interpretation of satellite imagery and we can therefore provide a link between local grain or particle size schemes and reference size schemes that can be used for analyzing the scattering properties of the snow. The benefits of this strategy are represented by the quantitative information on the transient particle size and distribution over an area covered by a satellite image. Furthermore, we can also address the Abisko long-term dataset and provide quantitative information for historical analysis of snow particle size. Note, however, any such analysis should be treated with caution as our comparison has involved only one field investigation and one observer for the ASRS classification system.

In addition, there is also some evidence of snow pack characteristics left for posterity through the images taken of the snow samples, allowing re-analysis at a later date if needed. However, post-processing of the data is required.

We have identified and discussed the advantages and disadvantages of using the ASRS and DSPP methods in snow particle size analysis. In the historical ARSR dataset, records are frequently found where the observers have classified samples between two neighbouring classes. We encourage this behaviour to enable more classes, especially between the classes of semolina, rice and peas. In the historical dataset, as well as in the field samples, we have identified intermediate classes. When analyzing the size of the grain using the DSPP method, the intermediate classes overlap with the existing classes. We therefore exclude them from our suggested size classification, but display the intermediate class size range with dashed lines to visualize the overlap of the classes (Figure 3(d)). The investigation validates the possibility of applying the DSPP method to the ARSR sampling procedure and also of applying quantitative values to the historical dataset.

CONCLUSION

The DSPP method has made it possible to quantify the historical ASRS so-called grain-size dataset and perform comparisons to actual field samples and established classification systems. Weaknesses in the ASRS classification system have been identified, as the classes cover a wide range and do not overlap. The analysis is subjective, relying on the observers' estimation of reference objects; recommendations on how to improve the future analysis of snow grain-size at ASRS have therefore been developed. We have also identified classes subjected to misclassification and the need for more classes overlapping in size.

Our results also show that the global standard classification system of seasonal snow may not be suitable for a region such as Abisko (and other similar areas). This is due to the limit of extreme size snow grains being 5 mm; our investigation shows a relatively large number of grains between 5 and 10 mm. In order to capture the information from large grains in the global standard classification system of seasonal snow, we suggest the implementation of an additional size class of >8 mm.

The snow grain-size distribution seems to follow a Weibull distribution. This enables us to statistically describe grain distribution instead of simply providing an average particle size for the entire snow pack. This will provide the possibility of more accurate modelling based on snow particle size, for example.

We recommend keeping the current ASRS grain-size observation method in order to maintain homogeneity within the historical dataset, but with the addition of a mean particle size to the reference object-based classification. Poor overlap of the reference classes were identified in the ASRS method and we therefore encourage the performance of parallel sampling using both methods in the future. With such data we can further refine our recommendations.

The suggested size ranges for the ASRS data have connected the ASRS data to the global system of snow grain analysis and will provide important information in future investigations on snow particle size.

ACKNOWLEDGEMENTS

We greatly acknowledge financial support from Rymdstyrelsen (81/06, 70/07:1, 70/07:2). We acknowledge the field party in Järämä 2009: Lars-Tomas Labba, Bror Labba, Hans Tømmervik and Jan-Åge Riseth. Further we acknowledge the staff at the Abisko Scientific Research Station for comments and support, and Veijo Pohjola for valuable comments on our work. We are grateful for insightful comments by Dr Charles Fierz on snow nomenclature issues. Comments from anonymous reviewers helped us to improve the manuscript.

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First received 26 August 2010; accepted in revised form 14 February 2011