

## Performance of snow density measurement systems in snow stratigraphies

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### ABSTRACT

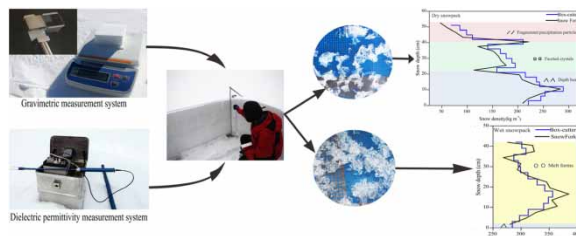
Gravimetric and dielectric permittivity measurement systems (DMS) are applied to measure snow density, but few studies have addressed differences between the two measurement systems under complex snowpack conditions. A field experiment was conducted to measure the snow density using the two measurement systems in stratigraphical layers of different densities, liquid water content (LWC), hardness, and shear strength, and the performance of the two measurement systems was analyzed and compared. The results showed that the snow density from the DMS tended to underestimate by 9% in the dry snowpack and overestimate by 3% in the wet snowpack, expressed as the percentage of the mean density from the gravimetric measurement system (GMS). Compared with the GMS, the DMS has relatively low precision and accuracy in the dry snowpack and similar precision and accuracy in the wet snowpack. The accuracy and precision of the two measurement systems increased with the increase of hardness and shear strength of snow in the dry snowpack, but the accuracy and precision measured of the DMSs increased with the decrease of hardness and shear strength of snow in wet snowpack. The results will help field operators to choose a more reasonable measurement system based on snowpack characteristics to get reliable density data and optimize field measurements.

**Key words:** dielectric permittivity measuring systems, gravimetric measuring systems, precision and accuracy, snow density, snow stratigraphies

### HIGHLIGHTS

- The performances of the gravimetric measuring system and the dielectric permittivity measuring system at different snow stratigraphies have been compared.
- The precision and accuracy of the snow density measurement systems are found to be sensitive to the shear strength and hardness of snow.
- The snow density measurement systems show relatively low precision and accuracy in low-density snow.

### GRAPHICAL ABSTRACT



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## INTRODUCTION

Snow cover is a critical component linking the global climate system and the Earth's surface system and provides water resources to large populations worldwide (Sturm *et al.* 2002; Barnett *et al.* 2005; Huning & AghaKouchak 2018; Skiles *et al.* 2018). The density is one of the fundamental and important snow properties, which varies over time (Carroll 1977; Conger & McClung 2009; Michele *et al.* 2012). It plays a key role in shaping a wide range of snow properties and physical processes (Bormann *et al.* 2013). Snow mechanical parameters are determined and estimated based on their density (Jamieson & Johnston 2001; Abe *et al.* 2006; Wang & Baker 2013; Hannula *et al.* 2016). The permeability photochemistry, and thermal conductivity are linked to density and depend on vertical density variations (Sturm *et al.* 1997; Calonne *et al.* 2011, 2012). The snow density is also an indispensable input parameter for snow dynamic models such as SNOWPACK (Lehning *et al.* 2002) and CROCUS (Brun *et al.* 1989). The snow density has many applications in hydrological cycle studies (e.g. Sturm *et al.* 2010), ecosystem studies (Rixen *et al.* 2008), climatology studies (Okuyama *et al.* 2003), and avalanche forecasts (Schweizer & Jamieson 2001). Thus, it is important to precisely measure the standardized snow density. However, different studies with similar aims often used different measurement systems to obtain snow density, and snow density data from different measurement systems in the same snowpack were significantly different (Hawley *et al.* 2008; Conger & McClung 2009; Bormann *et al.* 2013; Proksch *et al.* 2015). It is difficult to integrate snow density data from different studies with different measurement systems into global databases due to a lack of quality control and assimilation of snow density from different measurement systems (Bormann *et al.* 2013).

Snow density has been measured in the field and laboratories using various measurement systems. These measurement systems include gravimetric measurement system (GMS), dielectric permittivity measurement system (DMS), the neutron-scattering probe (NSP), micro-computed tomography (MCT), and diffuse near-infrared transmission (Hawley *et al.* 2008; Conger & McClung 2009; Gergely *et al.* 2010; Proksch *et al.* 2015). In the field, snow density is normally measured by technical staff, and measurements are made at flat study plots (Schweizer & Jamieson 2001; Conger & McClung 2009; Proksch *et al.* 2015). Taking the cost of measuring equipment, the technical simplicity, and the efficiency of observation into consideration, GMS and DMS are often applied to measure snow density in the field (Wilhelms 2005; Hawley *et al.* 2008; Conger & McClung 2009; Kinar & Pomeroy 2015). GMS consists of two parts: high precision electronic balance and different style cutters with a given volume. To determine snow density, a core sample of snow is extracted from the snow profile using a snow sampler. The density of the sampled snow is determined by a weighted snow mass divided by the cutter's volume with a unit of  $\text{kg}/\text{m}^3$ . DMS is based on the principle of measuring the response characteristics (travel time, reflection, and attenuation) of an electromagnetic signal through the snow (Frolov & Macheret 1999). The ratio of water, air, and ice in snow determines the dielectric permittivity of snow (Tiuri *et al.* 1984; Schneebeli *et al.* 1998). The snow density is determined using the electrical properties of ice, water, and air measured by DMS (Tiuri *et al.* 1984; Kovacs *et al.* 1995). Carroll (1977) reported that there was no significant difference among 200  $\text{cm}^3$ , and 100  $\text{cm}^3$  box-type cutters and 500  $\text{cm}^3$  tube-type cutters for snow density measurement, and those inexperienced operators tended to overestimate the densities compared with more experienced workers. Hawley *et al.* (2008) evaluated the accuracy of GMS, DMS, and NSP. DMS underestimated snow densities in lower-density snow but agreed with the GMS for higher-density snow. Conger & McClung (2009) compared snow density measurement using box-, wedge-, and cylinder-type density cutters and reported that the variation of snow density is about 3–12% among the three cutter types. Proksch *et al.* (2015) compared the measurement results from GMS and MCT and found snow densities measured by two measurement systems agreed by 9%. Leppänen *et al.* (2015) reported that the snow density from DMS was lower than that from GMS. Recently, López-Moreno *et al.* (2020) reported that notable differences were observed among the different GMS and suggested that it is necessary to understand the natural variability of snow characteristics and the instrumental, and observer-induced error before snow density measurement. Although the previous studies evaluated and compared the accuracy of different measurement systems in the same snowpack condition and analyzed the influence of measuring instrument and personnel errors on measurement accuracy, the accuracy of different systems under different snowpack conditions was explicitly not evaluated and compared.

Then natural snowpack develops from a series of winter snowfall and contains many layers with different characteristics (Sturm *et al.* 2002; Kärkäs *et al.* 2005). Having undergone different meteorological conditions, the structure in each snow layer evolves differently from adjoining layers in terms of density, hardness, wetness among others. The snowpack is made up of many snow layers with different hardness and density, and snow stratigraphy is constantly changing during a snow cover period. This is especially true in the thick snowpack, where stratification boundaries of the snowpack are obvious,

and the characteristics of adjacent snow layers are significantly different (Harper & Bradford 2003). The change of snow stratigraphy with different physical properties may influence the accuracy and precision of the used density measurement system. Different measurement systems have different performances in the same snow stratigraphy. The selection of proper measurement systems will help to obtain more reliable data and optimize field measurements under different dry and wet conditions with various snow stratigraphies. Although the existing literature provides an overview of the merits and drawbacks of different measurement systems, tangible guidance on how to make decisions based on measurement system selection in various snow stratigraphies for users is also not fully provided.

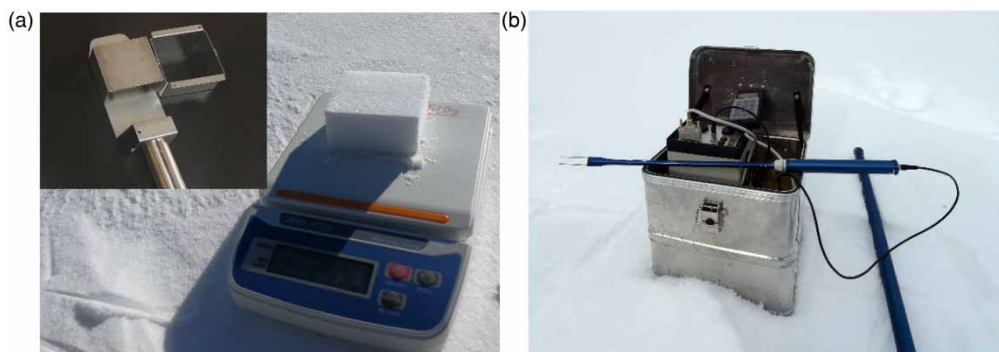
To better understand the performance of different measurement systems under the dry and wet conditions with various snow stratigraphies, snow-pit measurements were carried out at the Tianshan Station for Snow cover and Avalanche Research (TSSAR) in the winter season of 2017/2018. GMS and DMS were applied to measure snow density in various snow stratigraphies with significant differences in hardness, density, and wetness. The objectives of this study are to assess whether the same measurement system had similar accuracy and precision in different snow stratigraphies, and whether the two measurement systems provided similar results in the same snow stratigraphy. Precision and accuracy, as well as merits and drawbacks of two measurement systems in terms of applicability (time and labor needed), were discussed, and recommendations in terms of practicality for field measurement were given. The result will help field operators to choose a more effective and reasonable measurement system based on snowpack characteristics in the field.

## DATA AND METHODS

### Measurement systems of snow density

This study used GMS and DMS to measure the snow density in TSSAR during the winter season of 2017/2018. GMS with the 100 cm<sup>3</sup> box-cutter with 6 cm × 5.5 cm × 3 cm was used in this study (Figure 1(a)) based on a design originated from the Institute of Low Temperature Science, Japan. The box sampler is a rectangular frame open at both ends. It has a handle on one end. The digital electronic weighing scale (from <http://snowmetrics.com/shop/prosnow-kit-i/>) is plastic, portable, and waterproof, and measures up to 1,000 g at a 0.1 g resolution with an accuracy of ±0.01 g, under an operating environment of −25 °C to +40 °C. The researchers used a snow shovel to dig a snow pit from the snow surface to ground level and used a snow saw to obtain a profile of snowpack in the observation field. The weighing scale was then placed on a flat surface and zeroed. The cutter was pushed horizontally into the target layer being measured to collect the sample, and all snow was cleaned from the outside of the sampler. The snow sample was extracted and put in a plastic bag, and then the sample was put on the weighing scale and weight data recorded.

DMS has widely been used in many studies (Tiuri *et al.* 1984; Harper & Bradford 2003; Sugiyama *et al.* 2010). The Snow Fork, as a representative of DMS, has been applied to measure snow density in this study (Figure 1(b)). The Snow Fork is designed to operate in extreme conditions with lower temperatures as low as −25 °C (Toikka 2009). As a portable instrument, the Snow Fork consists of an electronics box, a sensor, a keyboard, and rechargeable batteries. It probes samples of snow within a cylindrical volume of about 2 × 7.5 cm and operates between 500 and 1,000 MHz. The sensor of the Snow Fork



**Figure 1** | Snow density measurement systems used in the study: (a) GMS (the 100 cm<sup>3</sup> box-cutter and the weighing scale) and (b) DMS (the Snow Fork).

is a steel fork used as a microwave resonator. Resonant frequency, attenuation, and 3-dB bandwidth are measured by the Snow Fork, and the results are used to accurately calculate snow density ( $\rho$ ) and LWC. The details of the instrument operation can be found at <https://toikkaoy.com/>.

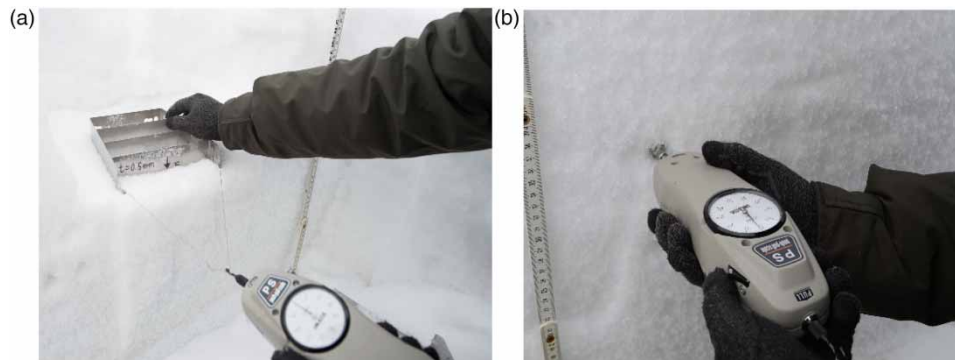
### Stratigraphy and mechanical properties of snow

The snowpack is made up of many snow layers with different physical properties. A stratigraphic layer is a certain stratum with similar properties (size of the grains, microstructure, shear strength, and hardness) in the snowpack according to Fierz *et al.* (2009). An overview of the methods which were used to measure these snow properties is described as follows.

The snow depth was the measurement of the vertical length of snow from ground to snow surface. The ground was taken as a reference datum and recorded as 0 cm, and the vertical length from the ground to the snow surface was recorded as the snow depth. Snow rulers were used to measure snow depth. We also used a brush to gently remove snow from the profiles and then examined the snow crystal diameter with the aid of a snow crystal screen which has two grids of 1 and 2 mm under an 8 $\times$  or a 10 $\times$  magnifier.

Snow has characteristics of easy compression and deformation (Sturm & Holmgren 1998). Its samples are compressed and sheared by the cutter and fork in the process of sampling, which can cause the densification of snow samples. This may result in density from measurement being overestimated or underestimated. It is difficult to quantify the deformation degree and compressibility of snow in the field, so we used shear strength and hardness as an indicators (Pielmeier & Schneebeli 2003). Shear strength is one of the fundamental mechanical properties of snow, which is the strength of snow against yield (Mellor 1974; Nakamura *et al.* 2010). The shear strength of snow is determined by the microstructure and reflects the bond strength between the snow particles. The shear frame system is usually used to measure the shear strength of snow (Mellor 1974; Nakamura *et al.* 2010). The measurement system consists of two parts: a shear frame with an area of 0.025 m<sup>2</sup>, and the attached force gauges with a full load capacity of 100 N (Figure 2(a)) (Jamieson & Johnston 2001; Abe *et al.* 2006; Jamieson *et al.* 2007). Overlying snow was removed, leaving about 40 mm of undisturbed snow above the measured snow layer. The shear frame was inserted onto the target snow layer and manually pulled smoothly and quickly to ensure fracturing of the target snow layer. The shear strength is obtained by dividing the force gauges data by the effective shear area. In this study, the shear strength of the measured layer was estimated by the shear strength from 12 shear measurements (Jamieson & Johnston 2001; Abe *et al.* 2006; Jamieson *et al.* 2007; Nakamura *et al.* 2010).

Snow hardness indicates an ability of resistance to penetration or the pressure required for the penetration of snow (Pielmeier & Schneebeli 2003). Snow compressibility and the degree of snow deformation decrease with the increase of the hardness (Kaur & Satyawali 2017). Snow hardness was measured with the push-pull gauge with a full load capacity of 100 N at observation sites (Figure 2(b)). The attachment of the push-pull gauge was penetrated horizontally into the snow profile at a uniform speed. When the snow was completely covered with the attachment, the dial readings were recorded. The snow hardness value PR<sub>15</sub> is the recorded data divided by the area of the attachment, and the unit of PR<sub>15</sub> is Kpa. In this study, the hardness of the measured layer was estimated by the hardness from 12 hardness measurements (Takeuchi *et al.* 1998).



**Figure 2** | The measurements of snow mechanical properties: (a) snow shear strength measurement and (b) snow hardness measurement.

### Field experiment design

To investigate the performance of two measurement systems in different snow stratigraphies, snow density data measured on different snow stratigraphical profiles by two measurement systems were collected. Data for analysis were collected in the observation field of the TSSAR. Established in 1967, the TSSAR (43°16'N, 84°24'E) with an elevation of 1,776 m above sea level is located in the upstream branch of the Künes River basin in the mid-mountain zone of the Tianshan Mountains. The geomorphological setting and the climate of TSSAR were previously described by others in published literature (Lu *et al.* 2016; Hao *et al.* 2018).

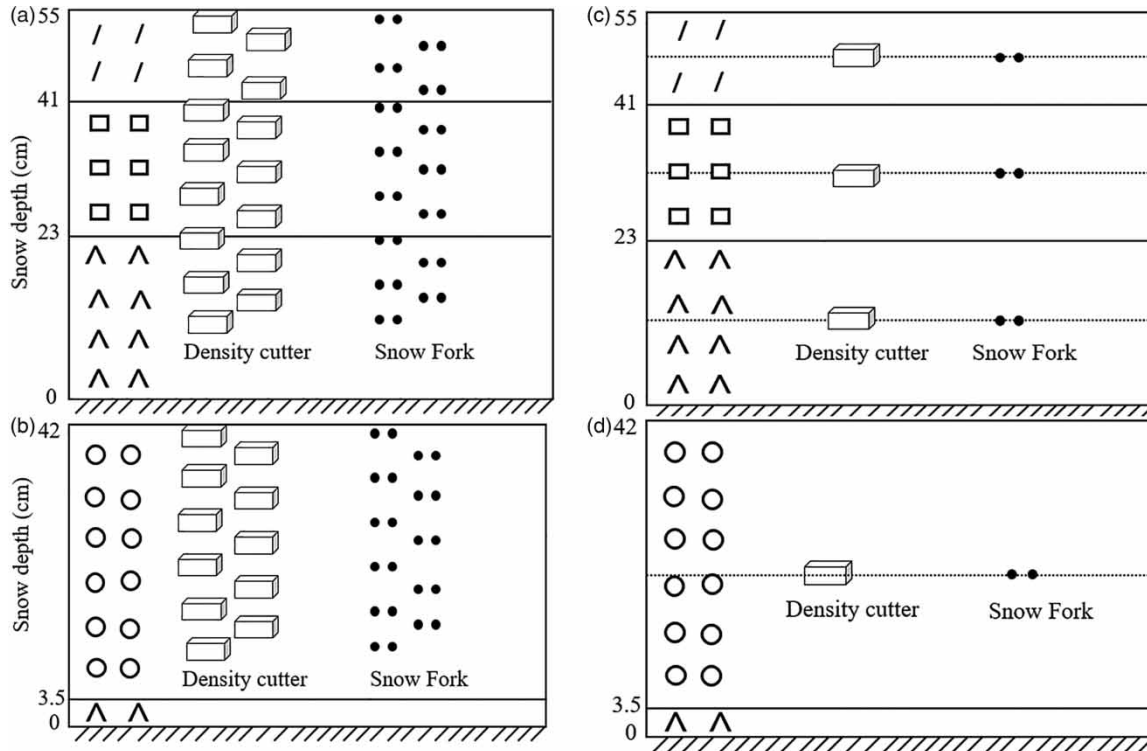
To obtain snow density data within various stratigraphies, the experiment was carried out during different periods when the snow stratigraphy was significantly different. Based on the LWC in the snow, snow was divided into two types: wet snow and dry snow. Wet snow was defined as snow with volumetric LWC greater than 3%, which was characterized by the fact that water can be recognized at 10× magnification by its meniscus between the grains (Fierz *et al.* 2009). Wet snow indicates that water will likely percolate through the snow since the transition from the pendular to the funicular regime starts at a LWC of 3% (Denoth 1980; Techel & Pielmeier 2010). If the volumetric LWC in the snow is less than 3%, the snow is defined as dry snow. The experiment was first conducted on 20–21 January 2018, which represents a period of dry snowpack conditions. The depth of the snowpack was 55 cm with the LWC ranging from 0 to 0.45% due to solar radiation reaching the surface of the snowpack. The snowpack crystals consisted of decomposing and fragmented precipitation particles (DF) with 25%, faceted crystals (FC) particles with 33%, and depth hoar (DH) particles with 42%. According to Fierz *et al.* (2009), there were more high temperature gradient metamorphism grains (snow class FC, DH) than low temperature gradient metamorphism grains (snow class DF) in the snowpack. The experiment was performed again on 10 March 2018, which represents a period of wet snowpack conditions. The depth and LWC of the snowpack were 42 cm and 3.0–6.0%, respectively, and the snowpack crystals consisted of DH with 8% and MF with 92%. Before implementing each density measurement experiment, a rectangular snow-pit was excavated in a previously undisturbed location and all measurements were made on a shaded side-wall of the snow-pit. The same experienced individuals took all samples and measurements.

### Measurements in dry and wet snowpack

To compare the performance of two measurement systems in the same snowpack, the whole dry snow layer density data were collected on 20 January 2018. The sampling was performed from the snow surface to the ground at intervals of 30 mm and snow density was measured (Figure 3(a)). The average density value of 18 snow blocks from the snow surface to the ground was calculated as the density of the whole snow layer. The middle position of cutter snow sampling corresponded to the points of the Snow Fork to compare the density from two measurement systems at the same level. After one measurement of density within a whole snow layer, the observation position moved 10 cm horizontally to the next one. The density measurement of the whole snow layer was repeated 20 times. Density data of the whole wet snow layer by two measurement systems were collected on 10 March 2018. The same experimental method for measuring the whole dry snow layer density was used to measure the whole wet snow layer density (Figure 3(c)). The average value of 14 snow blocks density from the snow surface to the ground was calculated as the density of the whole wet snow layer.

### Measurements within various snow stratigraphies

To investigate the performance of the same measurement system in different snow stratigraphies and compare the performance of two measurement systems in various snow stratigraphies, the density data measured on different dry snow stratigraphical profiles by two measurement systems were collected on 21 January 2018. The shape and size of the grain and the depth of snow layers were first measured. After the stratigraphic arrangement of the snowpack was identified (Table 1), the middle position of the given snow layer was considered to be the target location for measuring snow density (Figure 3(b)–3(d)). After one measurement of density within a whole snow layer, the observation position moved 10 cm horizontally to the next one. Density measurements were made in the DF, FC, DH, and MF snow layers using both measurement systems and repeated 25 times. The shear strength and hardness of each layer were measured separately after the density measurements were completed. Similarly, density, shear strength, and hardness of the MF snow layer were measured on 10 March 2018.



**Figure 3** | Schematic diagram showing GMS (box-cutter) and DMS (Snow Fork) density measurements. (a) and (b) Density measurement of the whole snow layer from the snow surface to the ground. Intervals of the measurements in the vertical direction are 30 mm. (c) and (d) Density measurement of snow layer made up of the same type of grain. The slashes, hollow block triangular brackets, and hollow circle represent DF, FC, DH, and MF.

**Table 1** | Summary of sample layer characteristics and measurements

Snow layer	Grain shape	Layer thickness (cm)	Size of grain (mm)	LWC (%)	Data	Number of samples
1	DF	14	0.2–1	0–0.4%	21 January 2018	25
2	FC	18	1–2	0	21 January 2018	25
3	DH	23	2–4	0	21 January 2018	25
4	MF	38	1–3	3.0–4.5%	10 March 2018	25

### Data analyses

The accuracy of a measurement system is the degree of closeness of measurements of a quantity to that quantity's true value. The average density from GMS was defined as the reference true value and was derived from Equation (1). Relative error (RE) and average relative error (ARE) were used to assess the accuracy of the measurement system and formulated by Equations (2) and (3).

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

$$RE_i = \frac{x_i - \bar{x}}{\bar{x}} \times 100\% \quad (2)$$

$$ARE = \frac{\sum_{i=1}^n |RE_i|}{n} \quad (3)$$

where  $\bar{x}$  denotes the average of all samples,  $x_i$  is the density of the  $i$ th sample, and  $n$  is the total number of samples. The precision of a measurement system, related to reproducibility and repeatability, is the degree to which repeated measurements under unchanged conditions show the same results. Relative standard deviation (RSD) was used to assess the precision of each measurement system and formulated by Equation (4). The smaller RSD, the higher the precision of a measurement system.

$$\text{RSD} = \frac{1}{\bar{x}} \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{(n-1)}} \times 100\% \quad (4)$$

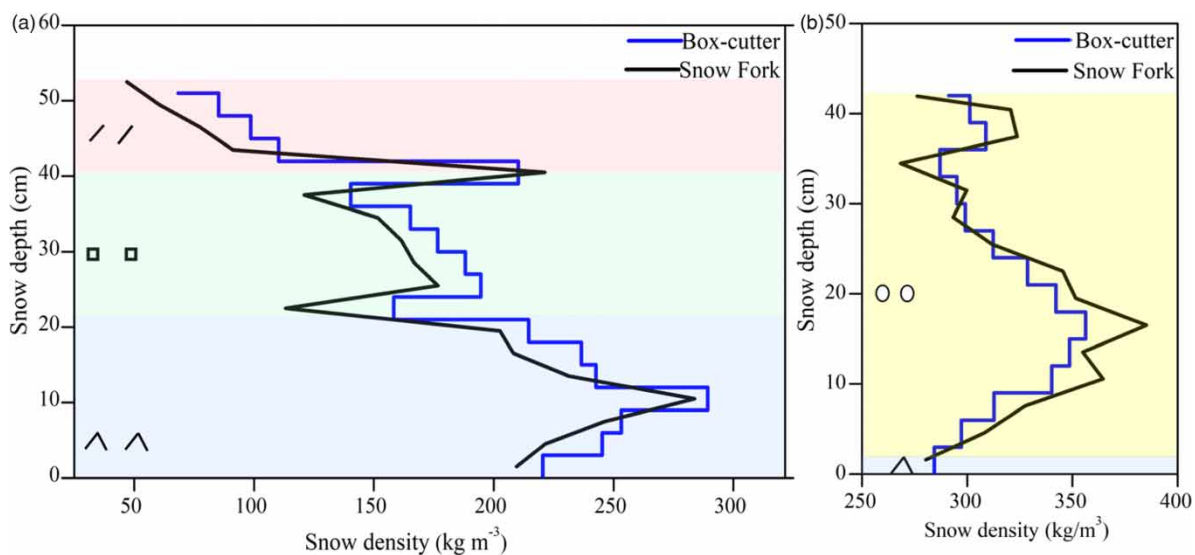
All statistical computations were implemented using the statistical software (IBM SPSS Statistics 21). RE, ARE, and RSD were calculated for accuracy and precision of two measurement systems used. Levene's test was performed to verify departures from basic assumptions of variance and normality. A one-way ANOVA was conducted to assess the overall statistical significance of differences among the measure groups ( $\alpha = 0.05$ ).

## RESULTS

### Density measurements by GMS in various snow stratigraphies

The profiles of dry snow density obtained from GMS are shown in Figure 4(a). The density of the DH layer (0–23 cm) was greater than that of DF and FC layers (23–55 cm) (Figure 4(a)). For 23–55 cm snow layers, the density of the snow layer (39–42 cm) between DF and FC layers was higher than that in other parts of the snow profile due to the existence of thin ice crust in this snow layer. The density of the newly formed DH layer (21–23 cm) was much lower than that of other parts of snow in the DH layer. The wet snow density profiles of GMS are shown in Figure 4(b). The density of snow from the 12–18 cm layer with the LWC of 5–6% was higher than that from other layers. The results of measurement error in Table 2 showed that ARE and RSD of dry snow from GMS were higher than that of wet snow, which indicated that GMS has more accuracy and precision in dry snow than that in wet snow.

The density measured by GMS in Table 2 showed that ARE and RSD of measured density in different snow stratigraphies were significantly different ( $P < 0.05$ ). GMS showed the highest accuracy in the DH, with an RE of –5–4%, and an ARE of 2.1%. ARE of measured density in the DF layer was 3.5%, which was about two times higher than that in the DH layer. The order of RSD and ARE was as follows: DF > FC > MF > DH, which indicated the accuracy and precision of GMS to

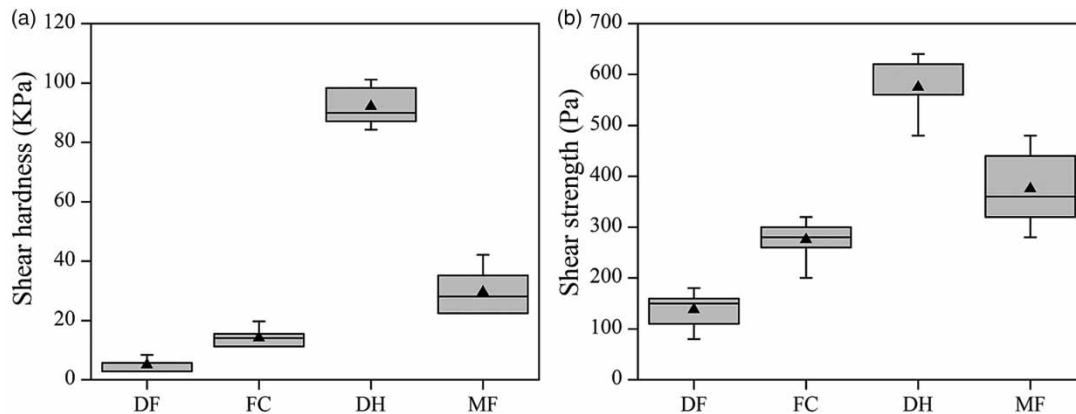


**Figure 4** | Density profile of the whole snowpack measured by GMS (box-cutter) and DMS (Snow Fork): (a) dry snow density data and (b) wet snow density data. The slashes, hollow block triangular brackets and hollow circle represent DF, FC, DH, and MF.

**Table 2** | Result summary of experimental measurement using GMS (box-cutter) in the field

Measurement system	Snow type	Layer mean density (kg/m <sup>3</sup> )	RE (%)	ARE (%)	RSD (%)
GMS	Dry snow	187.3	-5 to -6	3.4	3.3
	Wet snow	311.5	-4 to -5	2.2	2.6
	DF	93.5	-9 to -11	3.5	4.9
	FC	177.3	-7 to 7	2.9	3.4
	DH	236.8	-5 to 4	2.1	3.2
	MF	304.9	-4 to 6	2.6	3.2

RE, the range of the minimum to maximum relative error between the 25 times of sampling; ARE, average relative error; RSD, relative standard deviation.



**Figure 5** | The mechanical properties of the target snow layer: (a) the hardness of the target snow layer and (b) the shear strength of the target snow layer. Boxes represent interquartile ranges (25th to 75th percentiles), thick horizontal bars in each box denote the median (50th percentile), and a black small triangle denotes the average values.

be: DF < FC < MF < DH. Figure 5 shows the hardness and shear strength of the snow in the following order: DF < FC < MF < DH. RSD and ARE of measured density from GMS decreased with the increase of hardness and shear strength of snow layer, which indicated that the accuracy and precision of GMS increased with the increase of hardness and shear strength of snow.

### Density measurements by DMS in various snow stratigraphies

Figure 4 shows that the profiles of snow density in the same snowpack from DMS were similar to that from the GMS, but the measured snow density was significantly different ( $P < 0.05$ ). The mean density from DMS was 9 and -3% lower than that from GMS in the dry and wet snowpack, expressed as a percentage of the mean density from GMS. Table 3 shows that ARE and RSD of the measured density of wet snow from DMS were lower than that of dry snow, which indicated that DMS was more accurate and precise in wet snow than that in dry snow. Compared with GMS, DMS had relatively higher ARE and RSD in the same snowpack (Tables 2 and 3).

**Table 3** | Result summary of experimental measurements using DMS (the Snow Fork) in the field

Measurement system	Snow type	Layer mean density (kg/m <sup>3</sup> )	RE (%)	ARE (%)	RSD (%)
DMS	Dry snow	169.5	-9 to 11	5.6	6.2
	Wet snow	320.2	-7 to 8	3.6	4.4
	DF	68.7	-35 to 27	14.2	18.0
	FC	168.3	-12 to 13	4.2	5.1
	DH	224.3	-6 to 10	3.3	4.0
	MF	311.3	-9 to 7	2.6	3.6

RE, the range of minimum to the maximum relative error between the 25 times of sampling; ARE, average relative error; RSD, relative standard deviation.



ARE and RSD of density measured by DMS were significantly different ( $P < 0.05$ ) in different snow layers. For different snow layers, ARE of measured density in the DF layer was 14.2%, which was about six times higher than that in the MF layer. RSD of measured density in the DF layer was 18.0%, which was five times higher than that in the MF layer. The order of ARE and RSD of measured density was as follows: DF > FC > DH > MF (Table 3). RSD and ARE of measured density from GMS decreased with the increase of hardness and shear strength of dry snow, which indicated that the accuracy and precision of GMS increased with the increase of hardness and shear strength of dry snow. The accuracy and precision of GMS in the MF layer with relatively low hardness, high density, and LWC were better than that in the DH layer with relatively high hardness, low density, and LWC, which were contrary to the results from GMS. Compared with the density from GMS, the density from DMS was relatively low in DF, FC, and DH layers (Tables 2 and 3). In contrast, the density in the MF layer from DMS was higher than that from GMS. The snow density from GMS and DMS showed the largest difference in the DF layer and the smallest difference in the MF layer. Compared with GMS, DMS had relatively low accuracy and precision in all four snow layers.

## DISCUSSION

### Performance of GMS and error analysis

The results of the field experiment showed that ARE of dry snow density from GMS was 3.4% (Table 2), which was similar to the findings by Conger & McClung (2009), i.e., the GMS with 100 cm<sup>3</sup> box-cutter has an error of  $\pm 4\%$ . The accuracy and precision of GMS in different snow stratigraphies of the dry snow showed as follows: DF < FC < DH (Table 2). ARE of measured density in the DF layer was lower than that of other layers and whole dry snowpack. GMS had relatively low accuracy in the lower-density snow layers, which was in agreement with earlier findings where the accuracy of GMS with 100 cm<sup>3</sup> box-cutter in high-density snowpack was higher than that in the low-density snowpack (Conger & McClung 2009). Carroll (1977) and Proksch *et al.* (2015) also reported that GMS had relatively low accuracy and tended to overestimate density for lower-density snow.

The degree of compression and deformation of the snow sample are affected by the force and velocity of the thrust of the box-cutter into the snow. The force and speed of propulsion cannot be constant in each measurement in the field. Therefore, the hardness and shear strength of snow affect the performance of GMS. Experimental observations found that the accuracy and precision of GMS increase with the increase of hardness and shear strength of snow. The DF layer was located at the top of the whole snow layer (Figure 3) and had low temperature gradient metamorphism grains (Fierz *et al.* 2009) with low density, hardness, and shear strength (Table 1). Low hardness and shear strength caused high susceptibility to compressive deformation and shear failure from an external force. The degree of compressive deformation and shear failure varied greatly with each measurement for the DF layer due to low shear strength and hardness, so that measured density values showed high disparity and dispersion. Thus, the lowest accuracy and precision of GMS was found in the DF layer with the lowest density. A similar conclusion was drawn by Hawley *et al.* (2008) who reported that unconsolidated snow near the snow surface affects the accuracy measurement of GMS. The DH layer was located at the bottom of the whole snow layer, and its hardness and shear strength were the largest (Table 1). High hardness and shear strength of the DH layer caused low compressibility with low variation, resulting in measured density values with relatively low disparity and dispersion.

### Performance of DMS and error analysis

The accuracy and precision of DMS in low-density snow (snow class DF) were lower than that in high-density snow (snow class FC, DH, and MF) (Table 3). In terms of the accuracy of DMS, a similar result was shown by Hawley *et al.* (2008) who found RE up to 20% in the lower-density sections and 10–13% in the higher-density sections for DMS. DMS was extremely unstable in low-density snow. There are several other interesting facts worth discussing based on the findings of the field experiment. Hawley *et al.* (2008) pointed out that low-density snow had a bigger air gap between the grains resulting in unstable capacitance readings. Sugiyama *et al.* (2010) reported that the structure of snow affected the stability of dielectric signals and the permittivity of unconsolidated snow was smaller than that of compacted snow. However, they did not consider how the damage of the resonator to the snow structure would affect the accuracy and precision of DMS. The snow sampling was not compressed in DMS measurement, but the snow structure was damaged when the resonator was inserted horizontally into the snow profile. The destruction resistance capability of snow affected the accuracy and precision of DMS. The disparity and dispersion of the measured value increased with the increasing degree of damage to the snow structure from the resonator. Because low-density snow (snow class DF) had relatively low destruction resistance capability due to low shear

strength and hardness (Figure 5), DMS showed relatively low accuracy and precision in low-density snow. In contrast, although the shear strength and hardness of the MF layer were lower than that of the DH layer, the accuracy and precision of the measurement system in the MF layer were slightly higher than that in the DH layer. The air gap between the grains in the MF layer is smaller than that in the DH layer due to the existence of liquid water filling in the gap between the grains in the MF layer, which results in a relatively low variation of dielectric signals of DMS in the MF layer when the resonator was inserted into the snow. Relatively stable dielectric signals cause the accuracy and precision of DMS in the MF layer to be slightly higher than that in the DH layer. In addition to shear strength and hardness of snow, temperature and sand-dust in snowpack also affect the dielectric permittivity of snow (Fujita *et al.* 1992; Dong *et al.* 2012). There were significant differences in temperature and sand-dust between snow layers. However, we did not take the effect of temperature and sand-dust on the accuracy and precision of DMS into consideration because of the lack of conditions for measuring temperature and sand-dust within the snowpack in the study. Understanding the effects of these factors on density measurement would be worthwhile in future research projects.

### Comparison of two measurement systems

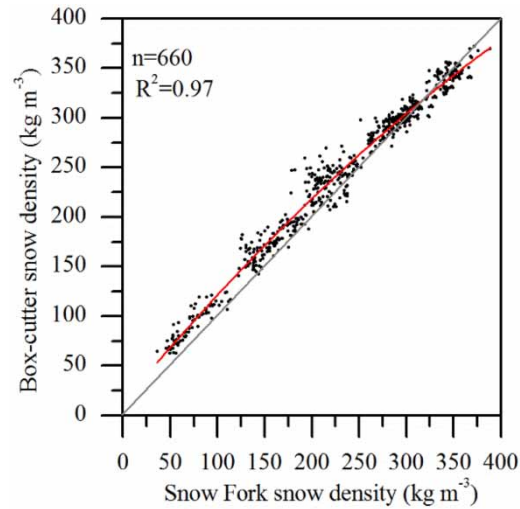
There was a significant difference in the snow density observed from the two measurement systems, and the difference varied with changes in snowpack characteristics. Taking the average density from GMS as a reference, the mean density measured by DMS was 9% lower than that by GMS in dry snow, expressed as a percentage of the mean of density from GMS, which is similar to the report by Leppänen *et al.* (2015). The density of DF, FC, and DH layers from GMS was higher than that from DMS by 26.5, 5.1, and 5.3%, respectively (Table 3). The density differences between the two measurement systems decreased with the increase in density. For the wet snowpack, the density from GMS was slightly lower than that from DMS (Tables 2 and 3). Taking the average density from GMS as a reference, the density from the DMS was higher than that from the GMS measurement system by 2% in the MF layer (Tables 2 and 3). From what has been discussed above, DMS appeared to underestimate snow density in the same dry low-density sections to GMS and slightly overestimated in the same wet high-density sections.

The accuracy and precision of GMS and DMS showed relatively lower accuracy and precision in low-density snow (snow class DF) due to the lower shear strength and hardness of lower-density snow. The accuracy and precision of GMS and DMS showed decreasing trends with increasing shear strength and hardness of snow in the dry snowpack. The accuracy and precision of GMS in the DH layer with relatively high hardness and shear strength were higher than that in the MF layer, but the accuracy and precision of DMS in the DH layer were lower than that in the MF due to the existence of liquid water in the wet snowpack. Therefore, the accuracy and precision of DMS increased with the decrease of hardness and shear strength and increase of LWC in a relatively high-density section. Compared with GMS, DMS showed relatively lower accuracy and precision in dry snow. The weight of GMS (box-cutter, flat shovel, and balance scales) was lighter than that of DMS (the Snow Fork) (Table 4). GMS was also easier for surveyors to carry in the cold environment. Although GMS may cause some errors as some of the snow escaped from the sampler or stayed in the sampler during the transfer from the sampler to weighing scales, these error sources are minimized by carefully cleaning the sampler and weighing scales during the measurements. Based on the above analysis, GMS was more suitable for field snow density measurement than DMS in dry snow. However, the vertical resolution of DMS in the millimeter range was a significant advantage on the centimeter resolution of GMS with the box-cutter (Table 4). GMS was usually insufficient to resolve the small-scale spatial fluctuations in density, so it may not meet the needs of some research. Measurement of DMS needed less time than GMS did in the cold environment. The surveyor needed an assistant to record data during GMS measurement, but DMS could automatically save data (Table 4). The most remarkable advantage of DMS over GMS is that it can measure density and obtain LWC in the snowpack at the same time in the wet snowpack. DMS may cause some errors as the damage of the resonator to the snow structure, these error

**Table 4** | Vertical resolution and weight of GMS and DMS

Measurement system	Vertical resolution (mm)	Weight (kg)	Measurement time (min)	Cost (US dollar)	Data record
GMS (Box-cutter)	30	1.3	60	20	Manual records
DMS (Snow Fork)	3	21.0	40	14,500	Automatic records

Measurement time in the field is per meter of snow depth and includes digging a snow pit.



**Figure 6** | Plots of all the data on GMS (box-cutter) vs. DMS (Snow Fork). The lines correspond to the linear regression of the two datasets.

sources are minimized by gently inserting the resonator into the snow to minimize damage to the snow structure. Different measurement systems might be used in field snow measurement due to different study conditions, such as labor needs, data requirements, and different research teams and institutions. Therefore, it was difficult to build a unified and optimized snow global database. Assimilation of the data obtained by different measurement systems provided an effective way to solve the above problem. The correlation of the density from GMS ( $\rho_G$ ) and DMS ( $\rho_D$ ) at the same snowpack was investigated using all the data obtained from this study (Figure 6). Least-squares linear regression gave the coefficients of the relationship to assimilate the data from different measurement systems.

$$\rho_G = a\rho_D^2 + b\rho_D \quad (5)$$

as  $a = -0.08 \times 10^{-2}$  and  $b = 126.13 \times 10^{-2}$  with  $R^2 = 0.97$ .

## CONCLUSIONS

This study compared snow density measured by GMS with a  $100 \text{ cm}^3$  box-cutter and DMS with Snow Fork in the TSSAR in the winter of 2017–2018. The results showed that the snow density from the two measurement systems was significantly different in the same snowpack. Taking the average density from GMS as a reference, the snow density from the DMS tended to underestimate by 9% in dry snowpack and overestimate by 3% in the wet snowpack. The accuracy and precision of the two measurement systems increased with the increase of hardness and shear strength of the snow layer in a relatively low-density section. However, the accuracy and precision of DMS increased with the decrease of hardness and shear strength and the increase in LWC in relatively high-density section. Therefore, the density in layers consisting of low temperature gradient metamorphism grains (snow class DF) was more frequently incorrectly estimated than that in layers consistent with high temperature gradient metamorphism grains (snow class FC and DH) or isothermal gradient metamorphism grains (snow class MF) in the two measurement systems. The accuracy and precision of density measurement systems are critical for experiments and observations of snow. Each system for density measurement has its advantages and limitations. The DMS showed relatively low accuracy and precision in dry snow with respect to the GMS as there was a slight difference between the densities from the dielectric permittivity measurement and GMS in the wet snowpack. Considering the accuracy and precision of the measurement system, the study results suggest snow surveyors to use GMSs during dry snow to obtain more reliable data.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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