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Uncertainty analysis for evaluating the accuracy of snow depth measurements

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Abstract

A methodology for quantifying the accuracy of snow depth measurement are demonstrated in this study by using the equation of error propagation for the same type sensors and by compariong autimatic measurement with manual observation. Snow depth was measured at the Centre for Atmospheric Research Experiments (CARE) site of the Environment Canada (EC) during the 2013–2014 winter experiment. The snow depth measurement system at the CARE site was comprised of three bases. Three ultrasonic and one laser snow depth sensors and twelve snow stakes were placed on each base. Data from snow depth sensors are quality-controlled by range check and step test to eliminate erroneous data such as outliers and discontinuities.

In comparison with manual observations, bias errors were calculated to show the spatial distribution of snow depth by considering snow depth measured from four snow stakes located on the easternmost side of the site as reference. The bias error of snow stakes on the west side of the site was largest. The uncertainty of all pairs of stakes and the average uncertainty for each base were 1.81 and 1.52 cm, respectively. The bias error and normalized bias removed root mean square error (NBRRMSE) for each snow depth sensor were calculated to quantify the systematic error and random error in comparison of snow depth sensors with manual observations that share the same snow depth target. The snow depth sensors on base 12A (11A) measured snow depth larger (less) than manual observation up to 10.8 cm (5.21 cm), and the NBRRMSEs ranged from 5.10 to 16.5 %. Finally, the instrumental uncertainties of each snow depth sensor were calculated by comparing three sensors of the same type installed at the different bases. The instrumental uncertainties ranged from 0.62 to 3.08 cm.

1 Introduction

Solid precipitation has a significant effect on human life, as it can lead to issues such as flight delays and slippery roads, harm to crops, and building collapses (Rasmussen

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et al., 2003). The impact of these issues can be mitigated with more accurate weather forecasts and representative engineering standards, the development of which require accurate solid precipitation and snow on the ground measurements. In addition, precipitation and snow on the ground measurements are important for various meteorological and hydrological applications, such as climate change, remote sensing calibration, and water supply forecasts (e.g. Michelson, 2004; Rasmussen et al., 2012; Theriault et al., 2012). However, accurate measurement of solid precipitation is difficult due to wind-induced loss and the spatial and temporal variability of snow shape, size, and density (Roebber et al., 2003; Nitu, 2013). The measurement of snow on the ground is also prone to numerous errors due to snow redistribution, blowing snow, and compaction (Ryal et al., 2008). Thus, there is a requirement for the accuracy of solid precipitation and snow on the ground measurements to be evaluated systematically. This study focuses on the measurement of snow depth, which is the total vertical height of snow on the ground within the observation period.

Graduated rulers or snow stakes are used to measure snow depth by trained human observers; these manual measurements are considered to be the reference for snow depth measurements. However, manual snow depth measurements have significant limitations such as consistency, continuity, spatial and temporal resolution, and time and manpower consumption (Ryan and Doesken, 2007). Meanwhile, snow depth sensors based on various operating principles have been developed as a result of the automation of meteorological observation systems (Nitu et al., 2012). Automatic snow depth sensors can help to overcome the limitations of manual snow depth measurements, but they also have limitations (Ryal et al., 2008; Fischer, 2008; Haij, 2011). Ultrasonic snow depth sensors are currently the most frequently used, due to their ease of use and low power consumption. Two aspects of the operation of these sensors need to be properly managed: first, the temperature dependency of ultrasonic pulses; and second, the risk of interference within the field of view, since ultrasonic pulses have the shape of a cone, for example a cone of 22° for the Campbell Scientific SR50 sensor (Ryan and Doesken, 2008). Laser snow depth sensors have sufficient sensitivity

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to measure a few millimeters of snow, but have issues with the representativeness of snow depth measurements, given the small sample area (Haji, 2011).

The required resolution and uncertainty for snow on the ground measurements are suggested by the World Meteorological Organization (WMO). The snow depth should be reported with 0.1 cm resolution and the uncertainty should fall within 1 cm for ≤ 20 cm and 5 % for > 20 cm (WMO, 2008). Thus, the performance of snow depth sensors needs to be evaluated using field observations. Ryan and Doesken (2008) compared ultrasonic snow depth sensor with manual snow depth measurements at seven sites in the United States. The mean absolute error and root-mean square error normalized by average snow depth ranged from 0.75–6.36 cm and 2–170 %, respectively. Random error also exists in snow depth measurements, but is not well quantified. Thus, uncertainty analysis of random errors should be performed to evaluate the accuracy of snow depth measurements.

In 2010, the WMO initiated the Solid Precipitation InterComparison Experiment (SPICE). The main objective of SPICE is to define the (automatic) operational reference system and to evaluate the performance of various automatic snow depth and snowfall measurement instruments (WMO/CIMO, 2011, 2012a, 2012b, 2013). The Centre for Atmospheric Research Experiments (CARE) in Egbert, Ontario, Canada, is one of the lead SPICE sites and hosts one of the SPICE experiments for snow on ground. On this site, several models of snow depth sensors (ultrasonic, laser) are tested against manual reference measurements, as part of an Environment Canada (EC) study project, as well as a contribution to SPICE.

The main purpose of this study is to document methodology for analyzing the uncertainty of snow depth measurements from automatic snow depth sensors. This procedure is demonstrated using data collected at the CARE site during the 2013–2014 winter season. The quality control (QC) procedures applied to the data sets used are similar to those established for the first level of QC in SPICE, and constitute the baseline for any advanced QC that may be required. SPICE will investigate and report on more advanced QC techniques, tailored to specific sensors. In Sect. 2, the methodol-

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ogy for the quantification of uncertainty in snow depth measurements is proposed. The procedures for snow depth measurements are described in Sect. 3. The manual and automatic snow depth data are shown in Sect. 4, along with suggested QC procedures for automatic snow depth measurements. The uncertainties in manual and automatic snow depth measurements are detailed in Sect. 5. Section 6 summarizes the results and provides conclusions.

2 Quantification of uncertainty

The uncertainty analysis is performed using two approaches: statistical measures and the propagation of error. The standard quantities for measuring the accuracy are defined under statistical measures. In the propagation of error, the uncertainty of individual instruments is calculated from the difference of two measurements of the same type. These approaches are explained in further detail below.

2.1 Statistical measures

Standard statistical measures are used to quantify the uncertainty of snow depth measurements. The Bias Error (BE), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Bias Removed Root Mean Square Error (BRRMSE) are defined as follows:

$$\mathrm{BE} = \frac{1}{N}\sum(y-x) \quad (1)$$

$$\mathrm{MAE} = \frac{1}{N}\sum|y-x| \quad (2)$$

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum(y-x)^2\right]^{0.5} \quad (3)$$

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$$\text{BRRMSE} = \left[\frac{1}{N}\sum (y - x - \text{BE})^2\right]^{0.5} \quad (4)$$

where x and y are snow depths from pairs of manual measurements, manual and automatic measurements sharing the same snow target, or two instruments of the same type at different targets, and N is the number of data points for a given pair. The NBE, NMAE, NRMSE, and NBRRMSE are the normalized forms in which BE, MAE, RMSE, and BRRMSE are divided by the average of x.

In comparisons between manual observations, the BE is calculated to investigate the spatial distribution of snow depth relative to the average snow depth measured by snow stakes at each target. The average snow depth of four stakes on the same snow depth target is considered as x in Eq. (1) for the calculation of BE in comparisons between manual observations and automatic snow depth sensors, which indicates the systematic bias of measurements from individual snow depth sensors relative to the reference. The MAE (NMAE), RMSE (NRMSE) and BRRMSE (NBRRMSE) indicate the random errors in snow depth measurements.

2.2 Error propagation

The error propagation equation is used to quantify the uncertainty of manual snow depth measurements and automatic snow depth sensors. When z is the difference between x_1 and x_2 ($z = x_1 - x_2$), the variance of z (σ_z^2) is expressed as follows:

$$\sigma_z^2 = \sigma_{x_1}^2\left(\frac{\partial z}{\partial x_1}\right)^2 + \sigma_{x_2}^2\left(\frac{\partial z}{\partial x_2}\right)^2 + 2\sigma_{x_1x_2}^2 \quad (5)$$

where x_1 and x_2 are the snow depths from pairs of two manual measurements or two instruments of the same type.

The terms $\sigma_{x_1}^2$ and $\sigma_{x_2}^2$ represent the variance or error of x_1 and x_2 and the $\sigma_{x_1x_2}^2$ term represents the covariance of x_1 and x_2. The random errors for two instruments of the

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same type, which have the same sampling volume and resolution, are nearly identical. Those for two manual measurements performed using the same procedure are also identical. Thus, the $\sigma^2_{x_1}$ and $\sigma^2_{x_2}$ terms are assumed to be identical when two manual measurements are compared and when two instruments of the same type are used. The covariance is set to be zero ($\sigma^2_{x_1 x_2} = 0$) by assuming the random errors from the two measurements are not correlated. Thus, $\sigma^2_{x_1}$ or $\sigma^2_{x_2}$ can be calculated by:

$$\sigma^2_{x_1} = \sigma^2_{x_2} = \frac{\sigma^2_z}{2} \quad (6)$$

Even though two manual measurements are performed by the same procedure, and the two instruments are the same type, bias error can still exist in each case. Therefore, the variance of z in Eq. (6) can be also written as follows:

$$\sigma^2_z = \frac{1}{n}\sum_n z^2 - \mathrm{BE}^2 \quad (7)$$

By combining Eqs. (6) and (7), the $\sigma^2_{x_1}$ or $\sigma^2_{x_2}$ terms can be expressed as follows:

$$\sigma_{x_1} = \sigma_{x_2} = \sqrt{\frac{\frac{1}{n}\sum_n z^2 - \mathrm{BE}^2}{2}} \quad (8)$$

The uncertainties in manual observations are calculated using pairs of snow stakes. The average uncertainties for all snow stakes, each base, and each snow depth target are compared. The comparison among snow depth sensors of the same type is performed to quantify the instrumental uncertainty of each snow depth sensor using the same procedure.

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3 Snow depth measurements

The CARE site (44°14′ latitude, 79°47′ longitude, 251 m elevation) has a humid continental climate. The average temperature is −8.2 °C in January and the average total snowfall is 157 cm. The mean wind speed for the period from November to April is 3.5–4.0 m s^{-1} (WMO/CIMO, 2012a). The prevailing wind direction is west to east. The site has a slight slope east to west and is well-exposed.

The layout of the snow depth measurement system at the CARE site during the 2013–2014 winter season is shown in Fig. 1. This system is configured around three bases, each with four snow depth sensors (three ultrasonic and one laser-based) pointing at three snow depth targets developed by EC. Four snow stakes, used for the manual measurements, are posted at the corners of each snow depth target, in the shape of a square. A total of 36 manual observations are performed. Snow depth targets are composed of grey plastic decking (Fig. 2a). The size of each target is 130.18 ± 0.64 cm × 129.54 ± 0.64 cm. To help perceive even a few millimeters of snow, and to better represent the ground surface around the target, the surface of each target is painted grey. Holes in each target help in draining water, and the gap between the target and ground mimics the layer of short grasses on the ground, and acts like an insulation layer.

The manual observations taken using wooden snow stakes (Fig. 2b) are considered to be the reference observations for snow depth. Gradations with 0.5 cm resolution are marked on the snow stakes. The snow stakes are perpendicular to the surface of the ground and the snow targets. The trained human observer measures snow depth once a day, starting from the southeast side of the site during non-precipitating periods. The duration and resolution of manual observation are about 20 min and 0.5 cm, respectively.

Three automatic snow depth sensors are installed on each base as in Fig. 2c. The pole on each base has the three arms. One ultrasonic snow depth sensor is installed on each arm. The laser snow depth sensors, which are installed at the top of the pole,

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point to the middle snow depth target. Care has been taken during the installation of the laser snow depth sensor to avoid pointing at the holes of the snow depth target. The output of all snow depth sensors under test is collected every 30 s. The snow stakes are located outside the field of view of each snow depth sensor.

In this experiment the following snow depth sensors are being tested, the FELIX SL300 (hereafter, FEL), SOMMER USH-8 (hereafter, SOM), CAMPBELL SR-50A (hereafter, SR50A), and JENOPTIK SHM 30 (hereafter, JEN). One each of these sensors is installed on each base. The FEL, SOM, and SR50A are ultrasonic snow depth sensors, and the JEN is a laser snow depth sensor. The general characteristics of the snow depth sensors are outlined in Table 1 (Sommer Mess-Systemtechnik, 2008; Jenoptik, 2009; Campbell Scientific Corp., 2011; Felix Technology Inc., 2014). The measurement range of FEL, SOM, SR50A, and JEN are 0.43–6.10, 0.00–8.00, 0.50–10.0, and 0.00–15.0 m, respectively. The resolution of SOM, SR50A, and JEN are 1.00, 0.25, and 1.00 mm, respectively. The JEN requires 10–30 VDC (15–24 VDC) without (with) heating.

4 Data

Snow depth data from the manual observations and automatic snow depth sensors (FEL, SOM, SR50A, and JEN) are used to demonstrate the proposed methodology for the analysis of uncertainty in snow depth measurements. The data were collected at the CARE site from 20 December 2013 to 26 March 2014.

4.1 Manual data

Figure 3 shows the time series of snow depth at each snow stake from the manual observations at each base (Fig. 3a–c), and the average snow depths from the four snow stakes at each target (Fig. 3d). The maximum snow depths recorded at bases 12A, 20, and 11A during the observation period were 40.0, 42.5, and 44.0 cm, respectively. The

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average snow depth from the four snow stakes at each target is calculated to investigate the spatial distribution of snow depth and compare with the automatic sensors at the same target. The variation in manual snow depth measurements between the four corners of a target is attributed to the uneven deposition of snow on the surface of that target (Fig. 4). The manual snow depth data are also used to analyze the uncertainty of manual snow depth measurements.

4.2 Automated data

The data collection for this experiment has been configured such that the JEN, FEL, and SR50A data are reported with one millimeter resolution, while the SOM data is reported with one centimeter resolution. The time series of raw (unfiltered) snow depth data from each sensor show apparent erroneous data, such as outliers and discontinuities (Fig. 5). Some of the data from FEL, SOM, and JEN fall outside the reasonable range for a given site and observation period (Fig. 5a, b, and d). Snow depth sensor data over 1000 cm exceed the expected maximum value based on manual data for this experiment, and are considered to be outliers. Abrupt jumps or spikes (discontinuities) that are within the reasonable range of values are evident in the time series of snow depth data from SR50A (Fig. 5c). These data are excluded from data analysis through application of the QC procedures for snow depth sensor data (described in Sect. 4.3). These outliers and discontinuities could result from environment-, configuration-, or sensor-related causes. The investigation of these causes is outside the scope of this paper. The quality-controlled data are compared with manual observations on the same snow depth target and among the snow depth sensors of same type. This comparison will enable the evaluation of uncertainty for each snow depth sensor.

4.3 QC of snow depth sensor data

The following QC procedures are applied to snow depth sensor data in this study: (1) range check, (2) step test; and (3) conversion of data from 30 s temporal resolution

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into 1 min resolution. These QC procedures are similar to those considered for the first level QC of data in SPICE. The authors recognize that more advanced QC methods, taking into account the sensor specific manufacturer recommended procedures (e.g., Campbell Scientific Corp. 2011), could further improve the data used for the analysis. This is outside the scope of this paper. SPICE will investigate and report on more advanced QC techniques.

In the first QC stage, a range check is applied to remove outliers. In this study, values of 0 and 60 cm are selected as the minimum and maximum limits, respectively. The maximum snow depth threshold (60 cm) was selected based on the maximum depth measured by automatic sensors during the winter season. The second stage of the QC procedure is a step test, designed to remove discontinuities and retain only data showing realistic changes with respect to time. If the difference between consecutive data points exceeds a defined threshold, the data are flagged. Each subsequent data point is compared with the most recent preceding data point that was not flagged, so a single point or series of points exceeding the set threshold can be identified and flagged using the same procedure. In this study, the threshold value for the step test was 2 cm per 30 s. If all data are flagged during a one hour interval, a new base line is considered. The data during the two hour period before the new base line are also flagged, to draw analyst attention to scenarios in which sensor performance may have been impacted. The flagged data are excluded from data analysis. In the third QC stage, the snow depth data, which are sampled and transmitted twice per minute, are converted into 1 min data by arithmetic averaging.

The snow depth data after applying the QC procedure are shown in Fig. 6. It is evident that the outliers and discontinuities observed in Fig. 5 have been removed. Several spikes still remain in Fig. 6a, underscoring the challenge of selecting general QC thresholds for data from different sensors. The data collected from FEL (base 20) after 21 February 2014 are removed by the QC procedure, since they exceed the range check threshold. From Fig. 6, it is evident that the maximum snow depth measured by

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automatic sensors during the winter season was 58.9 cm, which is the basis for the range check threshold noted above.

It is acknowledged that the experimental configuration is such that any two identical sensors do not measure the snow deposition on the same target. Owing to the variability in snow distribution, there are differences in the depth of snow accumulated on different targets, which leads to differences in the data reported by sensors. These errors are likely well represented by the variation of manual measurements at each target. In addition, Fig. 7 shows that the snow depth sensor data show almost all zero snow depth prior to the snow accumulation (ground clear), except for FEL (11A). Thus, the uncertainty determined in this study is most likely related to the sensor response to snow signal in various conditions, and not due to sensor malfunctions.

5 Results

5.1 Uncertainty of manual observations

The BEs and uncertainties of manual snow depth measurements are calculated to analyze the spatial distribution of snow depth and uncertainty of manual snow depth measurements (Fig. 8 and Table 2). For calculation of BEs, the average snow depth of snow stakes 1 to 4 on base 12A is considered to be the reference for the purpose of this analysis. Figure 8a and Table 2 show that the BEs of base 12A (0.00, 0.86, and 3.20 cm) are the smallest, which is to be expected, given the selection of the reference for this analysis. Relative to the reference selected, the BEs of base 11A (6.46, 7.99, and 6.11 cm) are the largest. From these results, it was concluded that the snow depth is higher on base 11A (west side of the experiment area) than on base 12A (east side on the experiment area). These results characterize the spatial distribution of snow depth across the experiment area, as reported by the human observer. These results also emphasize the necessity of several manual observations within the experimental site. The uncertainties (σ_{depth}) for all pairs, on each base, and for each snow depth

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target are shown in Fig. 8b and Table 2. The total uncertainty for all pairs of stakes is 1.81 cm, for this particular configuration and measurement resolution. The uncertainty for base 12A (1.55 cm) is the largest, while that for base 11A (1.5 cm) is the smallest. When comparing each snow depth target, the uncertainty for stakes 1 to 4 on base 20 (1.58 cm) is the largest and that for stakes number 5 to 8 on base 12A (1.05 cm) is the smallest. The average uncertainties for each base (1.52 cm) are greater than that for each snow depth target (1.33 cm). The uncertainty gradually increases from target (1.33 cm) to base (1.52 cm) to all pairs of stakes on the site (1.81 cm). This is due to the temporal variation of snow depth during manual observations, which was not taken into account by the long-term BE removal. Thus, the uncertainty for manual snow depth measurements should be lower bound of the range of 1.33 to 1.81 cm.

5.2 Uncertainty of automatic observations

5.2.1 Comparison with manual observations

The snow depth measured by automatic snow depth sensors is compared with the average of the manual observations on the same snow depth target in Fig. 9. The automatic snow depth observations at the halfway point of the manual observations (that is, 10 min after starting the manual observations) are compared with the corresponding manual measurements, one data point per sensor, per day. The average snow depth from manual observation on the same snow depth target is considered to be the reference. The BE (NBE) ranged from −5.21 cm (−20.1 %) to 10.7 cm (57.8 %). The negative BE indicates underestimation of snow depth sensors relative to manual observations.

Figure 10 and Table 3 show the BEs and NBRRMSEs of each snow depth sensor. The automatic snow depth sensors on base 12A (11A) tend to measure snow depth as much as 5.02–10.8 cm (0.46–5.21 cm) larger (less) than the manual observation (Fig. 10a). The NBRRMSEs of snow depth sensors on base 12A (16.5, 12.9, 12.2, and 8.90 %) are the largest and the those of snow depth sensors on base 20 (5.10, 6.20, 7.00, and 5.70 %) are the smallest, based on the comparison among each base (Fig. 10b). The average NBRRMSEs of snow depth sensors of the same type are calculated as follows: FEL = 10.1, JEN = 9.67, SR50A = 9.03, SOM = 8.63 %. Given the spatial variability in snow depth implied by the base-to-base variability in bias and random errors outlined above, the differences in random errors among the different sensor types are not considered to be significant.

In general, the NBE (BE) ranges from −20.1 (−5.21 cm) to 57.8 % (10.7 cm) and the random error ranges from 5.1 (1.00 cm) to 16.5 % (2.93 cm). Thus, the BE is more significant than the random error for the snow depth sensors used in this study. It is not certain why the bias is so large; this question may require further thorough investigation.

5.2.2 Comparison among automatic snow depth sensors

The snow depth measured by two snow depth sensors of the same type on different bases is compared to quantify the instrumental uncertainty of individual snow depth sensors (Fig. 11). The data quality during a snow event could be poor for ultrasonic sensors, since it is a known limitation of these sensors that the sound waves are returned by the falling snow before reaching the target. This may have an impact on the calculated uncertainty. A significant bias is shown in the comparison, and should be eliminated to quantify instrumental uncertainty. In addition, bimodal distributions are observed for a few sensor pairs (SOM on base 20 vs. 12A and 11A vs. 12A; SR50A on base 20 vs. 12A, JEN on base 20 vs. 12A). The physical reasons are not known for this peculiar characteristic.

The BEs and instrumental uncertainties of each snow depth sensor are shown in Fig. 12. The snow depth sensors on base 12A are considered to be the reference for the calculation of BE (diamonds in Fig. 12a), similar to the approach used for the assessment of manual observations. The circles in Fig. 12a represent the spatial distribution of snow depth measured by the automatic sensors. To calculate these values, the BEs in Figs. 8a and 10a are added and the snow depths from sensors on base 12A are

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used as the reference. The BEs of snow depth sensors on base 20 and 11A are negative. This could result from the spatial distribution of snow depth, and/or the systematic bias of snow depth sensors. The snow depths measured at bases 12A and 20 are lower than that measured at base 11A, based on the result from comparison of manual observations (Fig. 8a). Meanwhile, the snow depth sensors on bases 12A and 20 (11A) overestimate (underestimate) snow depth relative to the manual observations (Fig. 10a). Thus, the BEs of bases 20 and 11A are negative, as snow depths measured by the snow depth sensors on base 12A are larger than those measured by snow depth sensors on bases 20 and 11A.

When comparing each base, the instrumental uncertainties of each snow depth sensor on base 12A (2.08–3.08 cm) are the largest (Fig. 12b). The instrumental uncertainty of FEL (11A) (0.62 cm) is the smallest in the comparison among each snow depth sensor type. The average instrumental uncertainties of snow depth sensors of the same type are calculated as follows: SOM = 2.17, JEN = 1.86, SR50A = 1.84, FEL = 1.55 cm. The instrumental uncertainty of SOM is largest, and this could be due to the fact that the SOM reported the data in one centimeter resolution. These differences in instrumental uncertainties of snow depth sensors are significant, given the variations in snow depth across the site.

6 Summary and conclusion

This paper introduced a methodology for assessing the global uncertainty of instruments measuring snow depth using statistical measures and error propagation analysis. The standard statistics such as BE (NBE), MAE (NMAE), RMSE (NRMSE), and BRRMSE (NBRRMSE) are calculated in statistical measures. The BEs of manual snow depth measurements indicate the spatial distribution of snow depth on the CARE site. In addition, those computed in the comparison between manual and automatic snow depth measurements provide information about the systematic bias of each snow depth sensor. For error propagation analysis, the matrix is created from measurement pairs

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among three sensors of same type. The uncertainties of manual and automatic snow depth measurements are calculated from the constructed matrix. This methodology is demonstrated with its application on the snow depth data collected at the CARE site from 20 December 2013 to 26 March 2014, to both manual and automatic sensor measurements.

The manual snow depth measurements are performed once a day, while the automatic measurements are output every 30 s. Over the course of the study period, the reported snow depth varied by location and method of measurement, likely being influenced by the configuration of the experimental site. The values of maximum snow depth recorded by manual observations are lower than those reported by automatic snow depth sensors. The snow depth is larger on base 11A (west) than 12A (east) at the CARE site when we select the average snow depth of stakes 1–4 on base 12A as the reference. The uncertainties of manual observations for all pairs, on each base, and for each snow target were 1.81, 1.53, and 1.33 cm, respectively. The BEs of snow depth sensors on base 12A (11A) ranged from 5.02–10.0 cm (−5.31–0.46 cm) in comparison with manual observation sharing the same snow target. The average instrumental uncertainty was SOM = 2.17, JEN = 1.86, SR50A = 1.84, FEL = 1.55 cm.

As illustrated by the results of this study, the uncertainty of measurements can vary among similar instruments collocated on the same site. The variability of results obtained through this study may indicate that other additional factors could influence the uncertainty of measurement of any sensor. The identification and treatment of the influence of other factors could further improve the uncertainty of measurement, and should be further investigated as part of SPICE. Two categories of factors are recognized to influence the uncertainty of measurements that would require further investigation. The first is related to the site and sensor configuration, while the second is specific to a sensors ability to detect and measure snow on the ground.

On the topic of site and sensor configuration, at the CARE site, although the similar instruments are located in close proximity, they do not measure snowfall and snow on the ground on the same sample area. The differences in the uncertainty of mea-

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surements for similar sensors would include the differences in the accumulation due to topography, wind influence, etc. Additionally, the accuracy of measurement of the initial distance between the sensing element and the ground is critical, as is the ability to maintain this distance throughout operations. This is best illustrated by the uncertainty of measurement calculated for periods of time with no snow on the ground, before and after the snow season. The stability of the configuration would influence the ability to derive accurate snow depth measurements.

The second category of factors is related to how the sensor data is sampled and treated. All snow depth sensors tested at the CARE site have their own internal data processing algorithms and report data based on their own internal processing of multiple raw samples. These sensors also output signal quality indicators, reflective of the interpretation of the returned raw signals, as processed by the internal sensor algorithms. Some manufacturers provide recommendations on the approaches for data filtering.

The QC methodology reported in this paper has not taken into account the specific approaches recommended by manufacturers, focusing on testing generic approaches. Additional analysis of uncertainty of measurement and error propagation using more advanced data quality controlled will be included in the SPICE work.

The proposed methodology for assessing the uncertainty of measurement of automatic sensors is an effective tool to quantify and compare the ability to measure of various sensors, and SPICE will further investigate its use at various time scales and in different conditions, to develop recommendations on how to characterize the quality of measurements of automatic measurements, in general.

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Table 1. General characteristics of snow depth sensors. The L, φ, W, and H represent length, diameter, width, and height.

	FEL	SOM	SR50A	JEN
Range of measurement (m)	0.43–6.10	0.00–8.00	0.50–10.0	0.00-15.0
Power requirements (VDC)	8–24	5–10	9–18	10–30
Maximum current (mA)	80	200	250	–
Operating temperature (°C)	−40–85	−35–60	−45–50	−40–50
Dimensions (cm)	L: 21.0	L: 35.0	L: 10.1	L: 30.3 W: 13.0
	φ: 13.0	φ: 11.0	φ: 7.60	H: 23.4
Weight (kg)	0.86	2.00	1.42	2.50
Resolution (mm)	–	1.00	0.25	1.00

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Table 2. BEs and uncertainties (σ_{depth}) of manual snow depth measurements for all pairs, each base, and each snow depth target.

		BE	Uncertainty
All pairs		–	1.81
Base	12A	–	1.55
	20	–	1.52
	11A	–	1.50
Snow depth target	12A 1–4	0.00	1.56
	12A 5–8	0.91	1.05
	12A 9–12	3.31	1.15
	20 1–4	1.96	1.58
	20 5–8	1.97	1.34
	20 9–12	3.80	1.28
	11A 1–4	6.62	1.47
	11A 5–8	8.18	1.40
	11A 9–12	6.28	1.18

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Table 3. BEs and NBRRMSEs of each snow depth sensor in comparison between manual observation and snow depth sensors.

Base	Snow depth sensor	BE	NBRRMSE
12A	FEL	9.72	16.5
	SR50A	10.8	12.9
	JEN	9.52	12.2
	SOM	5.02	8.90
20	SR50A	2.30	5.10
	SOM	2.25	6.20
	JEN	2.34	7.00
	FEL	3.07	5.70
11A	SOM	−4.87	10.8
	FEL	−4.08	8.20
	JEN	−5.21	9.80
	SR50A	−0.46	9.10

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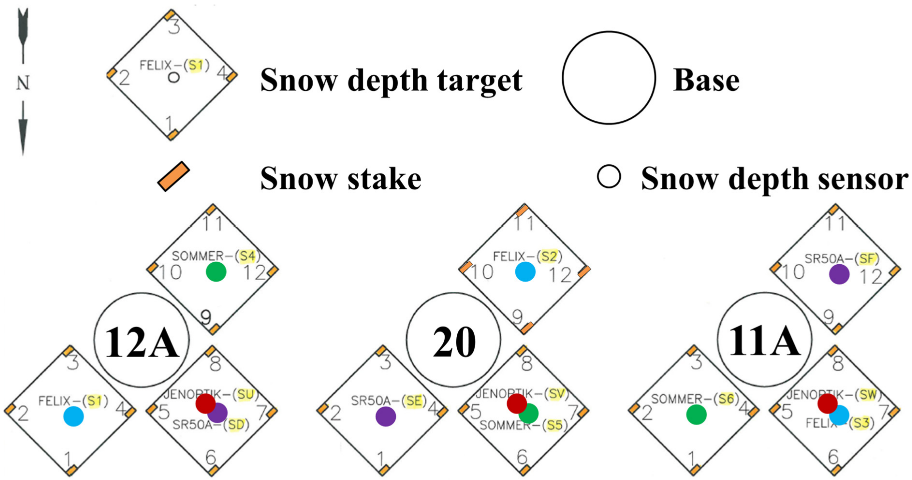

Figure 1. Layout of snow depth measurement system at the CARE site during the 2013–2014 winter season. The large circles (squares) represent bases (snow depth targets). The orange rectangles and small circles indicate snow stakes and snow depth sensors, respectively (courtesy: Environment Canada).

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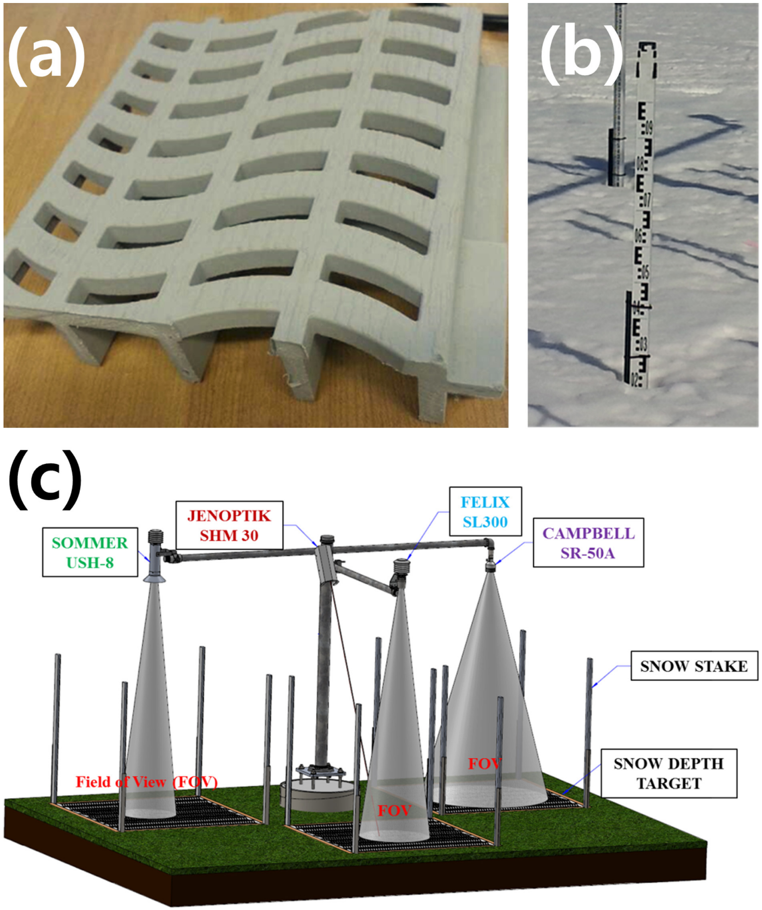

Figure 2. Snow depth measurement system. **(a)** Grey plastic decking comprising snow depth target, **(b)** wooden snow stake, and **(c)** installation of snow depth sensors for base 11A (courtesy: Environment Canada).

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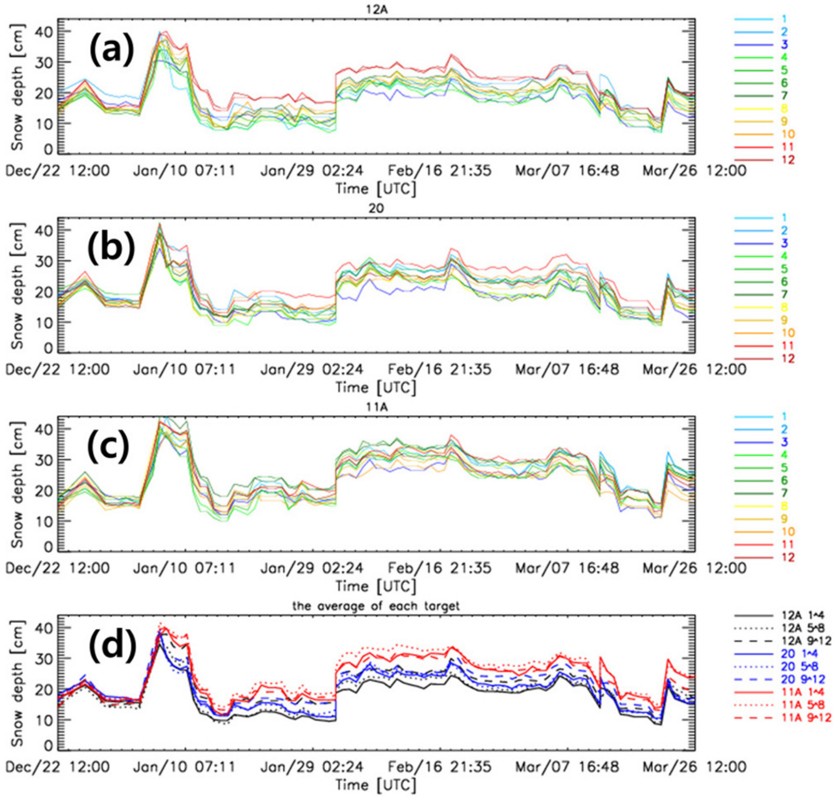

Figure 3. Time series of snow depth from snow stakes on base **(a)** 12A, **(b)** 20, and **(c)** 11A from manual observations over the period from 22 December 2013 to 26 March 2014. The line colors indicate individual snow stakes. **(d)** Average snow depth of four snow stakes on same snow depth target. The line color indicates each base. The solid, dotted, and dashed lines represent average snow depth of stake numbers 1–4, 5–8 and 9–12 on the same snow depth target.

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Figure 4. Photograph of the uneven snow deposition on the surface of snow depth targets.

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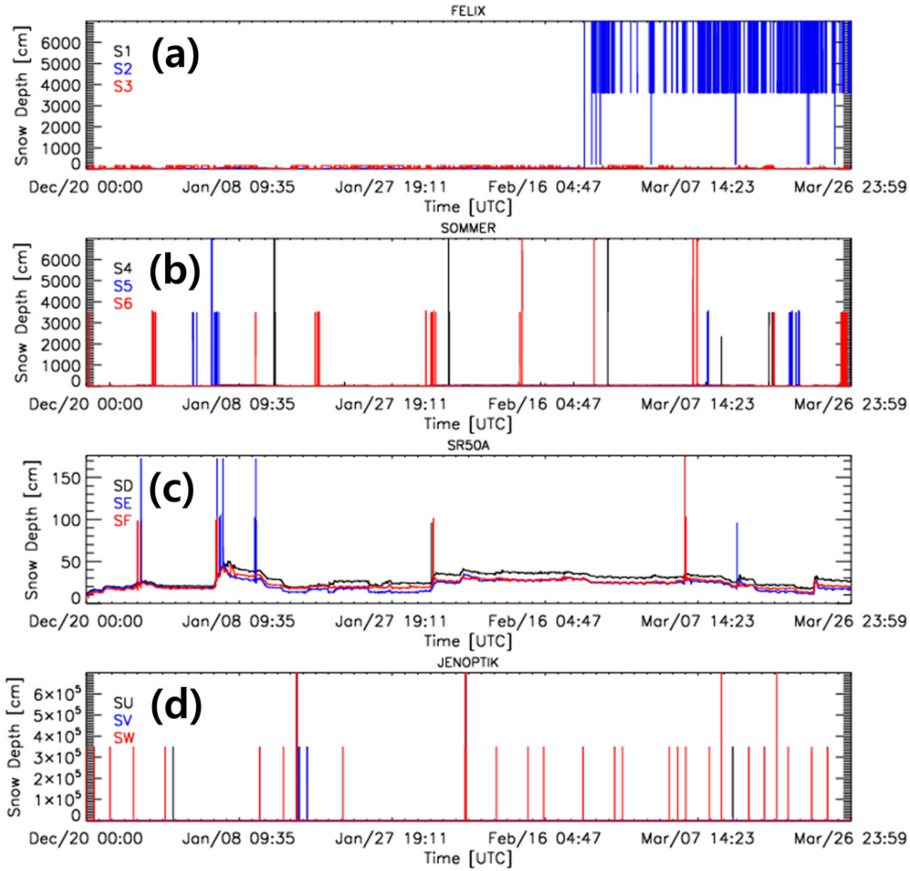

Figure 5. Time series of snow depth from **(a)** FEL, **(b)** SOM, **(c)** SR50A, and **(d)** JEN for the period from 20 December 2013 to 26 March 2014. The black color indicates sensors on base 12A. The blue color indicates sensors on base 20. Finally, the red color indicates sensors on base 11A.

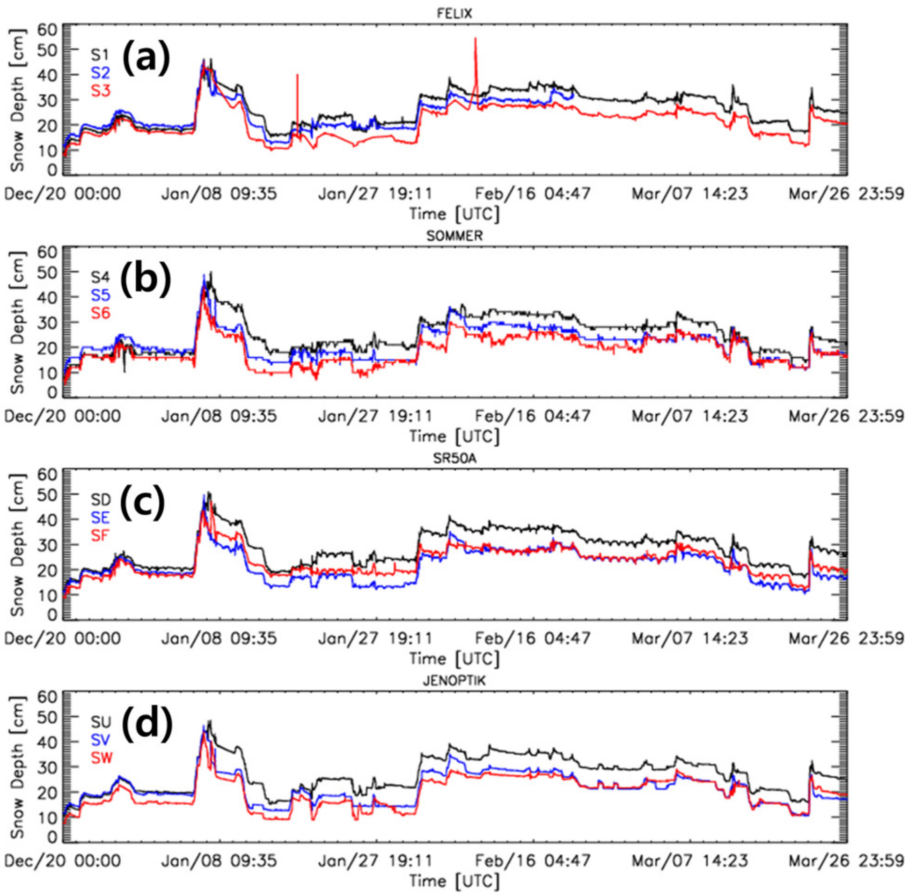

Figure 6. Same as in Fig. 5 except for data after applying the QC procedure described in Sect. 4.3.

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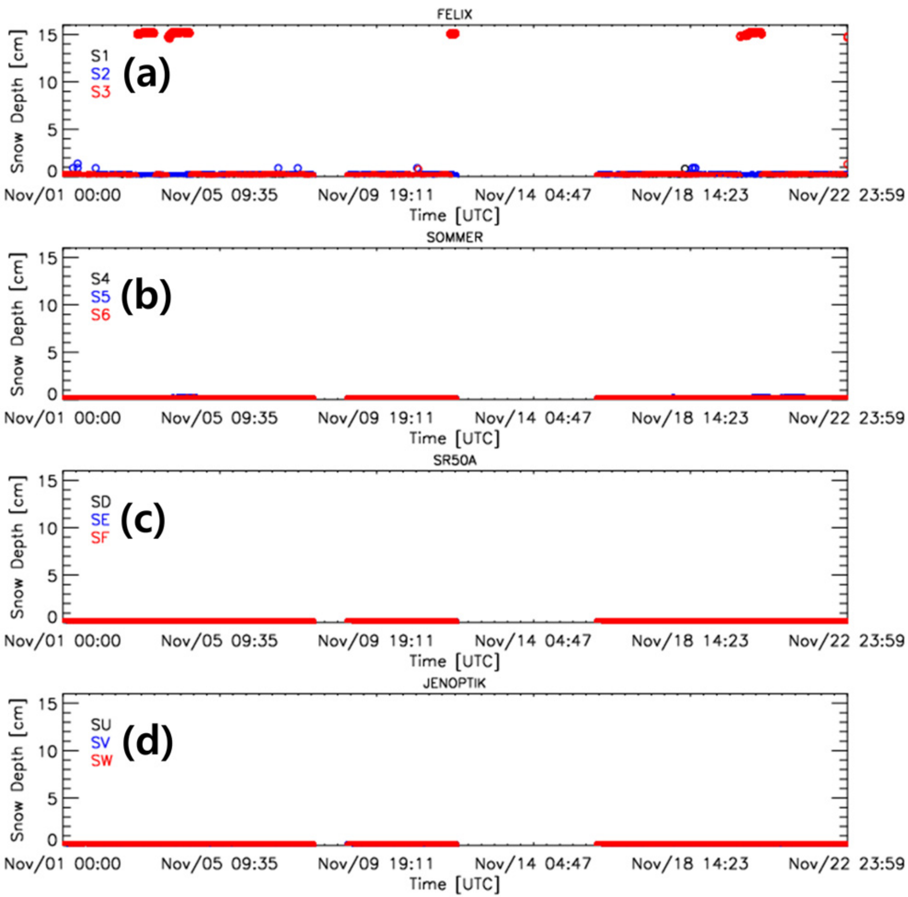

Figure 7. Same as in Fig. 6 except for the events prior to snow accumulation. Snow was mostly not seen on the ground on 08 November 2013 and from 12 November 2013 to 15 November 2013.

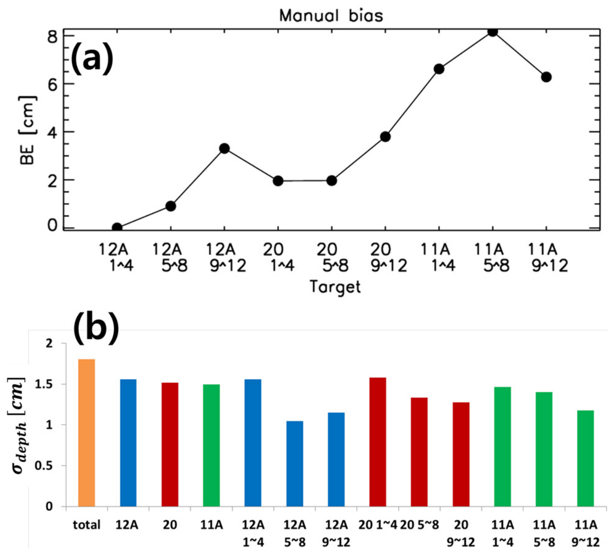

Figure 8. (a) BEs and **(b)** uncertainties of manual snow depth measurements. The BEs are calculated for each snow depth target. The orange bar represents the σ_{depth} for all pairs. The 2nd–4th (5th–13th) columns indicate the σ_{depth} for each base (snow depth target). The color of bars indicates the same base; the blue, red, and green bars represent σ_{depth} for bases 12A, 20, and 11A.

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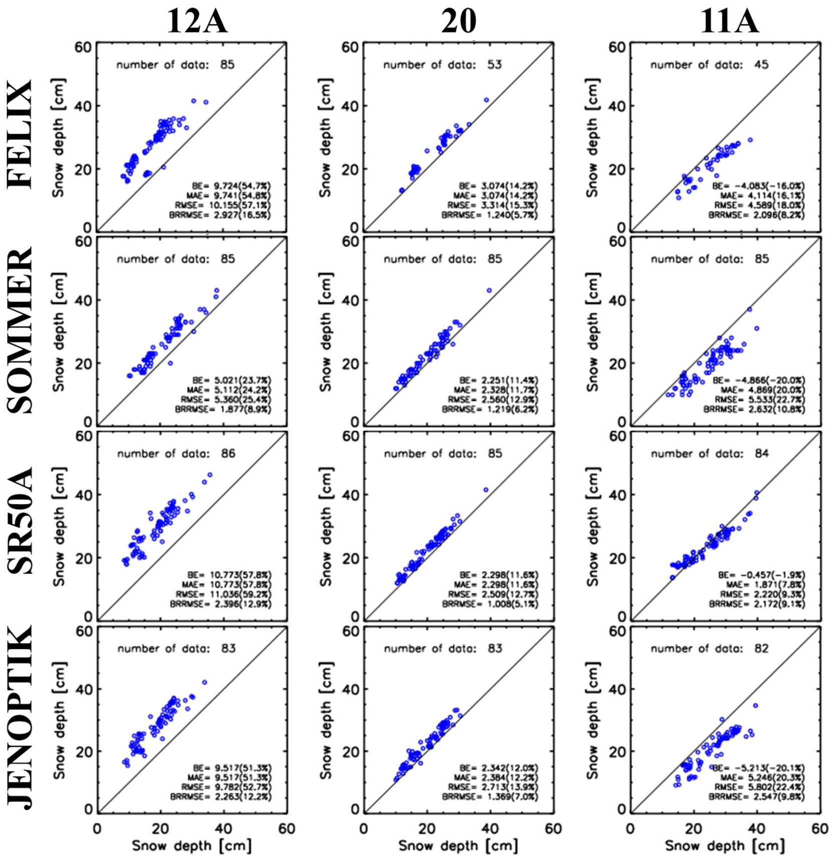

Figure 9. Scatter plots of snow depth measured by automatic snow depth sensors (*y* axis) and average snow depth of manual observation (*x* axis) on bases 12A (left), 20 (middle), and 11A (right): FELIX (first column), SOMMER (second column), SR50A (third column), and JENOPTIK (fourth column). The values in brackets indicate the NBE, NMAE, NRMSE, and NBRRMSE.

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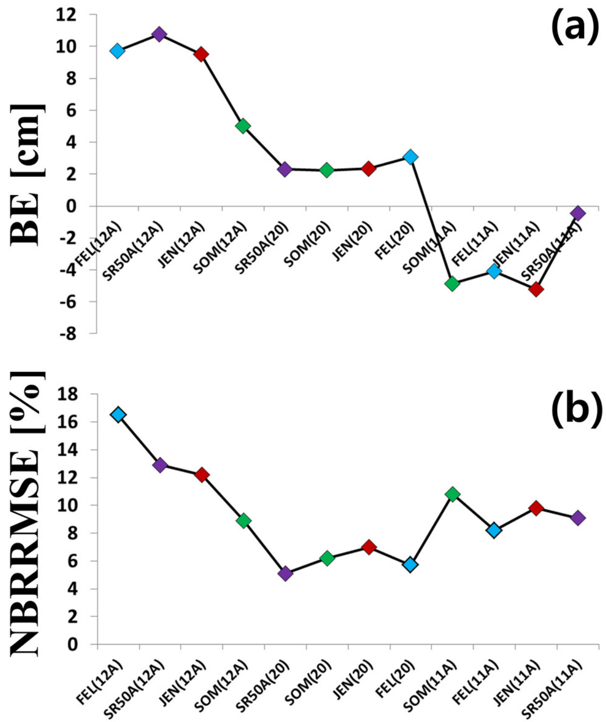

Figure 10. (a) BEs and **(b)** NBRRMSEs of each snow depth sensor. The blue, purple, red, and green diamonds represent FEL, SR50A, JEN, and SOM.

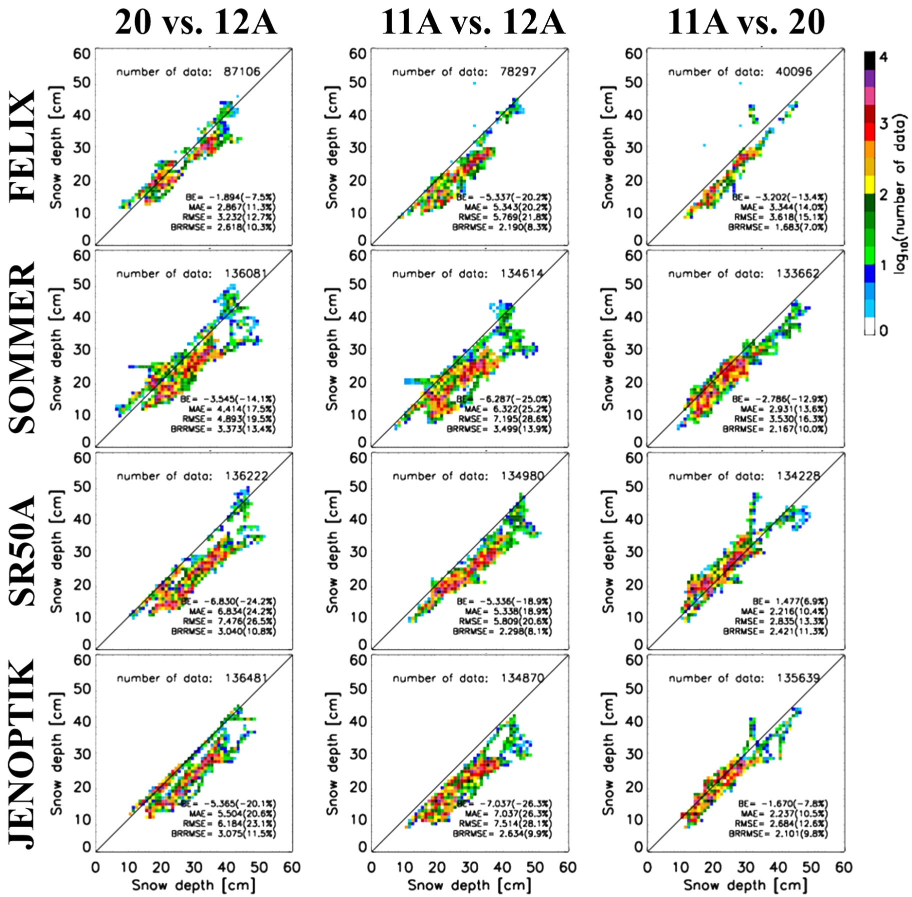

Figure 11. Scatter plots of snow depth measured by two snow depth sensors of the same type on bases 20 vs. 12A (left), 11A vs. 12A (middle), and 11A vs. 20 (right): FELIX (first column), SOMMER (second column), SR50A (third column), JENOPTIK (fourth column). The values in brackets indicate the NBE, NMAE, NRMSE, and NBRRMSE.

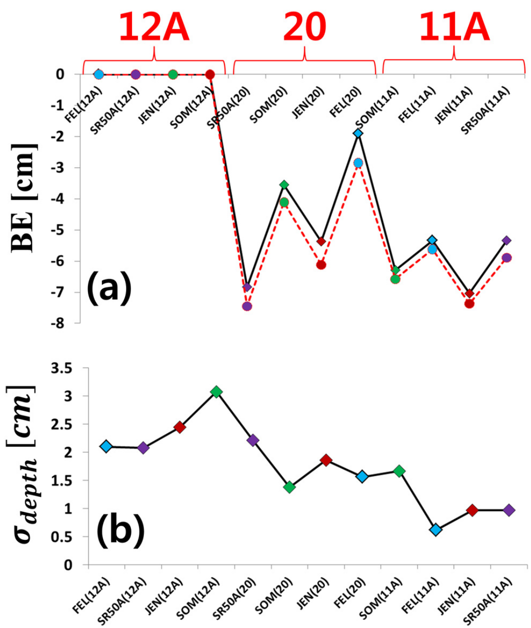

Figure 12. (a) BEs of each snow depth sensor. The diamonds (circles) are calculated by considering the snow depth sensors on base 12A as reference (the BEs in Figs. 8a and 10a are added and snow depth from snow depth sensor on base 12A are then used as reference). **(b)** σ_{depth} of each snow depth sensor. The blue, purple, red, and green diamonds indicate FEL, SR50A, JEN, and SOM.

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