Improving the quality of in-situ measurement of solid precipitation in Canada

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Abstract

The number of human observations at Surface Weather and Reference Climate Stations in Canada has decreased significantly since 1990's and are being replaced by automated stations. A number of initiatives have been taken to improve the representativeness of precipitation related measurements, solid precipitation in particular, at automated stations.

One initiative has been the development and implementation of a complex algorithm to allow the derivation of snowfall observations from snow depth measurements using multiple snow depth sensors and other in-situ observations. The algorithm has been tested with good results. Additional work is being done to estimate the effects of snow drift, as well as snow pack compaction and snow pack creep. The presentation will focus on the results of reporting snowfall amount using the developed algorithm.

Introduction

The socio-economic value of accurate quantitative precipitation forecasts have been well documented in the scientific literature (Fritsch et al. 1998). During the winter accurate measurements of snowfall (SF) are critical to many activities such as avalanche forecasting (Ferguson et al. 1990), and snow removal operations triggered by exceeding specified snow-depth thresholds (Gray and Male 1981). SF measurements are also very important for meteorological, climatological and hydrological applications.

As the number of human SF observations using the manual Nipher Snow Gauge in Canada has decreased, official measurements of SF at many locations have stopped altogether. This has had the effect, amongst others, of interrupting many long-term climate records (McKee et al. 2000).

Environment Canada (EC) operates about 900 weather observing stations across the country, the majority of which are automated. These stations serve different purposes such as weather forecast, aviation and climatology, and they can be broadly classified into two networks: Surface Weather Station (SWX) network and Reference Climate Station (RCS) network. Two maps showing the distribution of the SWX and RCS stations are provided in Figures 1 and 2.

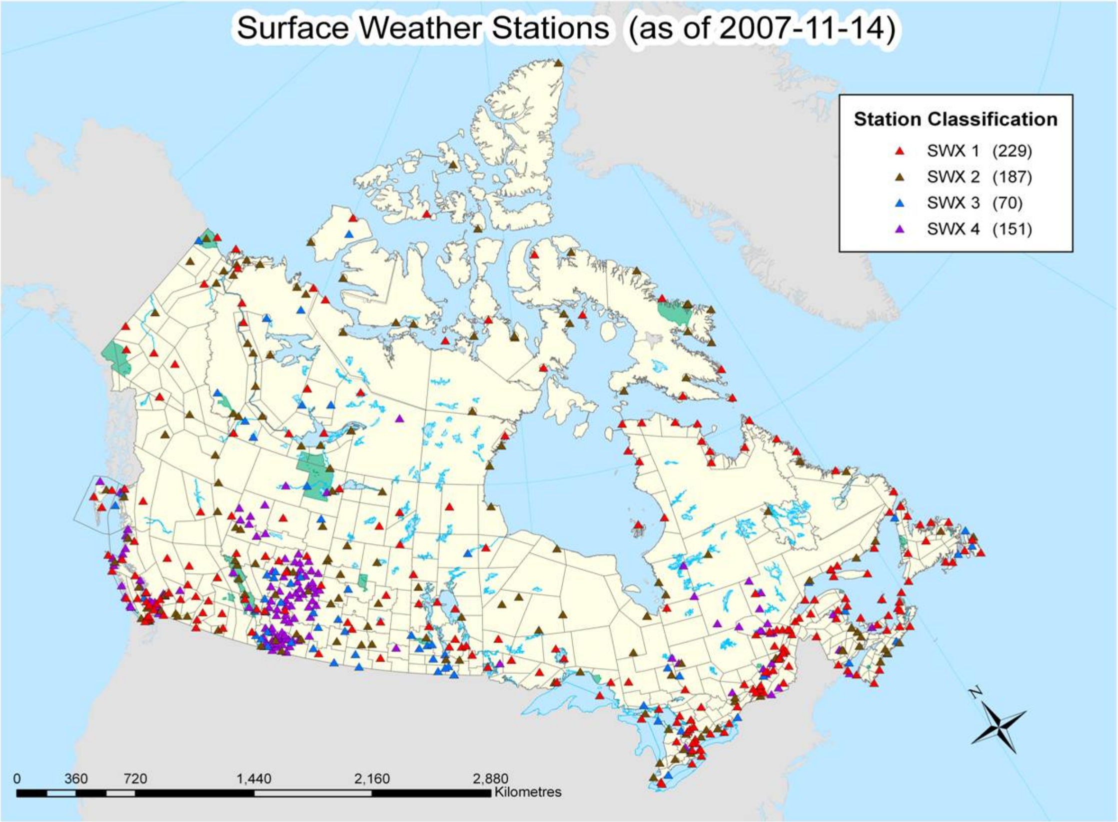

Figure 1 – Surface weather (SWX) stations.

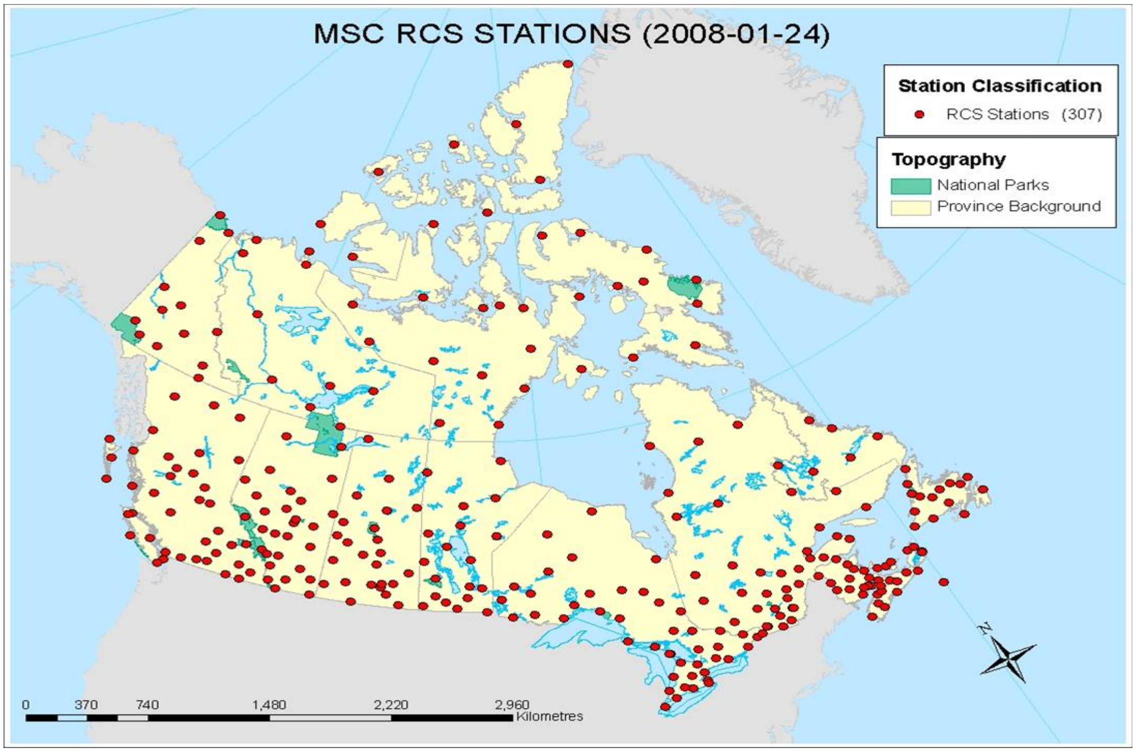

Figure 2 – Reference Climate (RCS) stations.

In a plan for upgrading the networks, it was proposed that an improved automated snowfall algorithm be included in the new configuration using Ultrasonic Snow Depth Sensors (USDS). The decision to use USDS to derive SF measurements is based on the fact that these instruments are already in use in the EC operational networks measuring snow depth (SD) and SF (a crude time differential of SD measurements is currently used operationally though the results can have large uncertainties and have false snowfall events being recorded); they are relatively inexpensive to purchase; and they have been used in the past to quality control automatic recording gauge measurements by providing additional details on the type, amount, and timing of precipitation (Goodison et al. 1988).

SF is defined as the accumulation of new snow over a specified period of time and can be estimated from changes in the observed total depth of snow on the ground (Ryan et al. 2008). As stated in the chapter 6 introduction of the seventh edition of the WMO Guide to Meteorological Instruments and Methods of Observation (WMO 2008), "the general problem of representativeness is particularly acute in the measurement of precipitation. Precipitation measurements are particularly sensitive to exposure, wind and topography..."

To address these concerns, Test and Evaluation (T&E) in EC has been assessing whether the usage of multiple USDS could improve upon snowfall measurability and representativeness. This study gives a summary of our efforts to quantify improvements in reporting SF amounts using this approach.

Overview of the S3-1 Snowfall Derivation Algorithm

The S3-1 stands for 3 USDS (Campbell Scientific SR50's) and one Total Precipitation Gauge (TPG) algorithm (primarily the Geonor is used). What differentiates the S3-1 algorithm from other traditional approaches of automated SF measurements is the ability of this approach to measure freshly fallen snow over very short "time" scales (which should be very useful for operational forecasting). The operating principle of the S3-1 algorithm is that 3 SR50's (Campbell Scientific Document; CSD 2008) are used to find correlations of positive changes in SD between concurrent SD time series. These concurrent measurements are combined to construct a "consensus" SF measurement; while the TPG is used as a verification to ensure that changes observed in the SD levels by the SR50's occurred during a period of precipitation.

The use of multiple SR50 instruments also acts as an inherent filter identifying anomalous readings and echo returns of poor quality. SD measurements can be influenced by conditions such as melting, settling, drifting and blowing snow. These may only occur beneath one sensor, or occur at different rates beneath different sensors. All these factors taken together can generate "false" SF reports and result in either the underestimating or overestimating of actual SF if only one SR50 is used.

The SR50 consists of a transmitter/receiver which emits/receives a 50 kHz ultrasonic pulse. The time it takes for the pulse to return to the receiver (after reflecting off a targeted surface) divided by two gives the distance to the target in metres. The more snow there is on the ground beneath the sensor, the less time it takes for the sound to return the receiver. Subtracting this number from a fixed reference point creates a SD measurement. The change in SD levels over time should give, in theory, a SF measurement.

At Time Step zero, defined as the reference point, the SD values for the three SR50 sensors (denoted hereafter as a, b, and c), and the measured weight of water collected by the TPG are put into place-holder reference levels. For each subsequent Time Step (15 minutes was used in this case study), new SD measurements are recorded and then subtracted from the reference levels. To help remove some of the small-scale SD measurement uncertainties, an empirically defined "Minimum Increase in Snow Depth Threshold" (MISDT) value is introduced (1.0 cm was found to be the threshold chosen, though 0.5, 0.7, 0.8, 1.2, and 2.0 cm were also investigated). The purpose of the MISDT is to set a minimum SD threshold value where changes in SD over time beneath an SR50 sensor must exceed before considering the possibility that SF occurred beneath that SR50 sensor. A SF value is produced if at least two of the three SR50 sensors indicated a change in SD ≥ MISDT, and if the TPG recorded at least 0.2 mm of liquid equivalent precipitation.

Another permutation of the algorithm which is explored is to run the algorithm without the TPG verification check. This should determine if some false precipitation events can be eliminated using another measurement which is related to the occurrence of SF.

Please refer to Fischer and Durocher (2006) for a more complete description of the algorithm.

Heavy Snowfall Case Study at St. John's International Airport (CYYT)

- *Data Collection Procedure*

Data was collected from three SR50's and a Geonor at St. John's International Airport, Newfoundland, Canada (CYYT) from 06 UTC 01 February 2006 to 06 UTC 2 February 2006. The SR50's were attached onto posts approximately 2 metres high off the ground. The posts were connected onto a trestle oriented in the northeast-southwest direction. The first SR50 sensor (hereafter referred to SR50a), faced northwest and was placed 7 metres to the northeast of the other two sensors. The remaining two of SR50's (hereafter referred to as SR50b and SR50c, respectively) were oriented 180 degrees apart from each other at the southwest end of the trestle, and faced southeast and northwest respectively. The concrete posts on which the trestle was mounted also comprised somewhat this experiment, because snow could occasionally pile up near the posts.

The SR50's were configured to detect three target echoes and send serial ASCII messages with distances and quality numbers. Sensors were polled once a minute and output data was recorded in daily files with a time stamp. Any missing return signals or data of low quality were replaced by the value recorded by that SR50 one minute earlier.

- *Description of the Functions in Figure 3*

When examining the SR50 and Geonor functions displayed in Fig. 3, one needs to look at their derivatives and not instantaneous values. The starting points for the three SR50 curves were arbitrarily set (the Geonor curve was set to zero) for easier visual examination. A positive derivative (either Δ SD values underneath each SR50 sensor over time; or Δ in measured weight of water captured by the Geonor over time) indicates periods were SF might have occurred. The S3-1 algorithm run uses a 1.0 cm MISDT value.

The Weather Indicator (WxInd) curve is a function which takes the values of either zero or three. At each time step where no weather is occurring (i.e.; clear skies indicated by the NAVCAN contract observer), the function is given a value of zero. Otherwise, if SF is observed by the NAVCAN observer, then the function is given a value of three.

The measured snowfall (MSF) function represents the 24 hour MSF total taken by the NAVCAN contract observer at 06 UTC.

- *Case Study Overview*

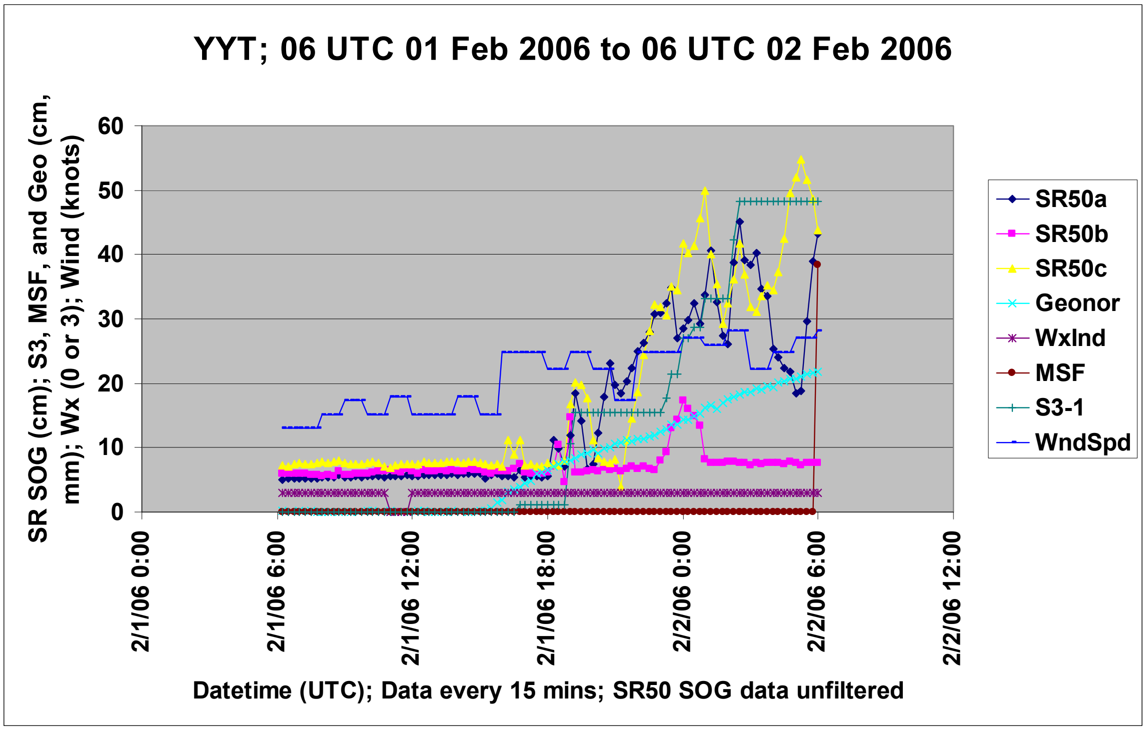

Figure 3 - SR50 SD (indicated on figure as Snow on Ground; SOG) and 10 metre Wind Speed (knots), accumulative Geonor and S3-1 (1.0cm MISDT) algorithm functions, Aviation Metar Weather Indicator (WxInd; zero = no snow or three = snow), and daily 06 UTC 24 hour measured snowfall (MSF) at St. John's International Airport (CYYT), Newfoundland, Canada for 1 February 2006.

Snow and blowing snow affected the test site throughout the day of 1 February 2006 resulting in a heavy snowfall event (note the 21.8 mm captured by the Geonor and the official MSF value of 38.4 cm). Temperatures remained below freezing starting at -4° C and rising to -0.6° C near the end of the day.

All three SR50 SD curves shown in this figure were strongly affected by drifting/blowing snow and movement of the underlying snow pack. This was due to the fact that very strong easterly winds, which slowly backed to the northeast by the end of the day, affected the test site.

There are two interesting results to take away from this figure. First, see how the SR50 time series (especially the SR50a and SR50c sensors) rise and fall much more significantly that the SR50b sensor. This shows how sensor orientation can profoundly influence the ability of an USDS to be able to detect a SF event. Second, note how little the SD values change for the SR50b sensor over the entire day. This example shows the advantage of using multiple USDS to derive a SF value from changes in SD levels in the snow pack (a value of approximately 48.5 cm was derived from the S3-1 algorithm), and also how difficult it is to extract a SF value from changes in the snow pack surface.

Algorithm Validation Results at CARE (Egbert, ON) over the Winter Season 2007-08

The results in this sub-section are from our test site at the Centre for Atmospheric Research Experiments (CARE; Egbert, Ontario, Canada), and are the first from our validation phase of the S3-1 snowfall derivation model. Owing to either missing observations or bad data from the sensors at the test site, data from two time periods were isolated and then combined. The first period runs from 06 UTC Nov 01, 2007 to 06 UTC Nov 12, 2007. The second period runs from 06 UTC Nov 16, 2007 to 06 UTC March 09, 2008. The sensors were oriented in three directions. One sensor (denoted as SR50a) was oriented towards true north while the SR50b and SR50c sensors were oriented towards the west and east, respectively.

The SR50's were configured each minute to transmit a single ultrasound and send serial ASCII messages with distances and quality numbers. Any missing return signals or data of low quality were replaced by the value recorded by that SR50 one minute earlier. The data was then filtered to retain values for the last 4 minutes of each quarter hour (each quarter hour ended at zero, fifteen, thirty, and forty-five minutes, respectively). The four minutes of each quarter hour were then checked between each other to see how many of the SD values were within 2.5 cm of each other. All the target ultrasounds which met these criteria where then were averaged to produce an averaged quarter-hour SD value.

S3-1 Algorithm	**$\sum \frac{\lvert MSF-S3-1 \rvert}{\text{Days (N)}}$**	**% Diff bet. S3-1 and MSF FOR ALL N**	**Days (N)**
1.0S3-1 TPGY	**0.88**	**39.19**	**125**
1.0S3-1 TPGN	**1.02**	**18.78**	**125**
0.5S3-1 TPGY	**0.83**	**33.98**	**125**
0.8S3-1 TPGY	**0.89**	**32.88**	**125**
1.2S3-1 TPGY	**0.97**	**38.45**	**125**
2.0S3-1 TPGY	**1.03**	**47.26**	**125**
SR50a only	**2.49**	**99.61**	**125**
SR50b only	**2.02**	**65.47**	**125**
SR50c only	**1.01**	**6.14**	**125**

Table 1 - Daily Average of the Absolute Value of Difference Statistics (first column) between 06 UTC daily measured snowfall (MSF; obtained from the daily average of many present weather sensors and total precipitation gauges) and various permutations of the 3 Sensor (S3-1) algorithms using different MISDT thresholds and TPG verification check (on or off). The 0.5, 0.8, 1.0, 1.2 and 2.0 cm represent the "Minimum Increase in Snow Depth Thresholds" used for each model run. The TPGY means the 0.2mm TPG Verification Check was used, while the TPGN means the 0.2mm Verification Check was not used. For the last three rows, the algorithm is run using only one SR50 sensor (each employs a 1.0 cm MISDT without using 0.2mm as the TPG Verification Check). The Percent Difference statistics (second column) are taken as the difference in the Total Measured Snowfall for the entire dataset (125 days) versus the Total Snowfall derived from the S3-1 algorithm summed over the entire dataset. The False Alarm Ratio (FAR) for the 1.0S3-1 TPGY algorithm run is 0.8%.

The statistics from Table 1 reconfirm the benefits of using 3 sensors to derive a SF value, as well as the problems of using USDS technology to measure new SF from the changing snow pack surface. First, Compare the Absolute Value of Difference column between the 1.0S3-1 TPGY and 1.0S3-1 TPGN algorithm runs, and see how that the use of the Geonor as a precipitation check can minimize the occurrence of false precipitation events. Second, compare the 1.0S3-1 TPGY algorithm run with all the runs using only one instrument (SR50a only, SR50b only, SR50c only). See how using a consensus of three sensors results in an improved derived SF value.

It is interesting to note the Absolute Value of Difference statistics produced using an MISDT of different values (0.5, 0.8, 1.0, 1.2 and 2.0 cm, respectively). They are different, and progressively become worse with increasing threshold values. This finding does suggest that the use of smaller MISDT's is better in a statistical sense. However, in an event to event analysis (case studies are not shown) no preferred MISDT value was found to systematically minimize the SF measurement errors from the underlying snow pack.

If one compares the 1.0S3-1 TPGY and 1.0S3-1 TPGN algorithm runs in the Percent Difference column, it would suggest that statistically one obtains a better answer over the entire winter season if a TPG is not used as a precipitation verification check. The reason for this discrepancy is the tendency in major SF events for the algorithm to be unable to measure new SF when the snow pack falls because of snow compaction. In some case-studies one-third to one-half of the total snowfall was lost as the snow pack began to fall under the weight of the freshly fallen "wet snow". Thus while using a TPG helps to eliminate "false precipitation events", on other days in the data set the extra precipitation gained from the "false precipitation events" in the 1.0S3-1 TPGN algorithm run helps to lower the difference between total SF observed by the human observer, and derived SF amounts derived from the algorithm.

Finally, compare the percent differences produced by the SR50a only, SR50b only, and SR50c only algorithm model runs. See how small the percent difference value for the SR50c only model run is compared to the other two. This point also re-confirms what was originally found at our St. John's test site that sensor orientation can have a profound influence on the ability to derive a snowfall value.

Conclusions

There are four definitive conclusions that can be drawn from the results of this study. First, using a triple configuration of SR50 Ultrasonic Ranging Sensors to derive daily snowfall values from changes in the snow pack levels, statistically, yields a better answer than deriving daily snowfall values using just one SR50. Second, employing the use of a Total Precipitation Gauge as a Snowfall Verification check helps to minimize false reports of snowfall. Third, better diagnosis of snow drift will be needed to further minimize snowfall measurement errors. Fourth, the orientation of the SR50 sensors (compass direction) can result in differing derived snowfall values.

This study has introduced and statistically qualified an algorithm which tries to incorporate the points identified in the previous paragraph. While this algorithm has shown promise, more work will have to be done to deal with the aforementioned problem of snow drift, as well as improve upon the measurability of very light snowfall events.

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