J4.13 AN ALGORITHM TO DERIVE SNOWFALL FROM SNOW DEPTH OBSERVATIONS

Alexandre Fischer* and Yves Durocher
Environment Canada, Downsview, Ontario, Canada

1. INTRODUCTION

The socio-economic value of accurate quantitative precipitation forecasts have been well documented in the 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).

Traditionally, measurements of SF have been done by humans using a snow ruler course or instrumentation aid such as a snow board. Over the last few years, however, both the United States and Canada have begun to replace human observers at airports with Automated Surface Observation Systems. Because of this, 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).

The primary approach undertaken by Environment Canada (EC) to automate SF reports has been the use of Ultrasonic Snow Depth Sensors (USDS). Using USDS has the potential advantage over Satellite and Radar techniques of deriving SF in that these instruments are relatively inexpensive to purchase (Goodison et al. 1984), and the measurements they record are in-situ. One of the drawbacks of using USDS is that the sound pulses they emit may be modified by high wind and low density snowfall (Brazenec and Doesken 2005). These occurrences in the SR50 time series may have to be identified and filtered out before any further data manipulation can occur.

The USDS chosen by EC is the Campbell Scientific Sonic Ranging Sensor (SR50; CSD 2003). 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 “Snow on Ground” (SOG) measurement. The change in SOG levels over time gives, in theory, a SF measurement.

2. OBJECTIVE

The objective of this study is to propose and evaluate an algorithm which will produce an automated SF value that is as accurate as possible. Currently at EC’s Surface Reference Climate Stations (RCS) and Surface Weather Stations (SWX), official SF measurements taken by contract observers are reported in one hour, six hour or twenty-four hour time intervals. At locations with no contract observers, EC does employ a crude algorithm using the SR50. A single SR50 takes the time differential of snow depth observations over any time interval desired. Obviously using this method can lead to major errors. Some of the reasons why will be discussed in this study.

The snowfall algorithm described in this paper will use three SR50’s and a Geonor Total Precipitation Gauge. The three SR50’s will be used to construct a “consensus” SF measurement, while the Geonor will be used as a verification to ensure that changes in SOG level are most likely due, or primarily due to SF. Extensive work has been done on minimizing the systematic errors generated the Geonor (Campbell et al. 2005). This gives greater confidence in using an instrument which measures the liquid water equivalent of SF.

The reason for using two different types of sensors is that both the SR50 and Geonor were not developed to measure SF (i.e.; SOG and accumulating precipitation measurements, respectively). SF, which will be derived from SR50

---

* *Corresponding author address*: Alexandre Fischer, Environment Canada, 4905 Dufferin Street, Downsview, Ontario, Canada, M3H 5T4; e-mail: alexandre.fischer@ec.gc.ca.

SOG measurements, will obviously have a higher degree of uncertainty than SOG measurements.

The use of multiple SR50 instruments acts as a filter identifying anomalous readings. SOG 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. Additionally, Neumann et al. (2004) have shown that there is a relationship between the landscape and SOG readings. All these factors taken together can generate "false" SF reports; as well as result in either the underestimating or overestimating of actual SF (if one uses a single USDS sensor to measure SF).

The authors of this paper strongly recognize the triple configuration precipitation algorithm developed by NOAA's National Climatic Data Center for the Geonor Weighing Precipitation Gauge (Baker et al. 2005). The SF algorithm which will be presented in this paper is an adaptation of this algorithm. The SF value presented in this paper will be compared to the "measured 24 hour SF totals" (MSF) owing to the fact the manual observations of SF were measured at this time frequency.

3. TEST DATA SETS

In a joint research effort with two other groups from EC, raw data was collected from six SR50's and a Geonor at Edmonton International Airport, Alberta, Canada (CYEG) during the winter of 2004-05. These instruments were placed away from the airport in an open field, so the measurements they take are representative of the local area. Climatologically, Edmonton tends to experience very cold temperatures throughout the winter. This is conducive for the production of ice-crystals; which can lead to very light, long-lived precipitation events.

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 to calculate the statistics which will be documented later in this paper. The first period runs from 00 UTC Dec 23, 2004 to 00 UTC Jan 05, 2005. The second period runs from 00 UTC Jan 20, 2005 to 00 UTC March 28, 2005.

The six SR50's were spaced approximately 5.5 and 3 meters apart in the East-West and North-South directions, respectively. Three of the six sensors were then chosen to be used in the development of the algorithm based on the type of surface beneath the sensors, and on the criteria that they had the least amount of missing data. Underneath two of the SR50's (hereafter referred to as SRa and SRb) a closely mowed grass surface was used as a target. Beneath the third SR50 (hereafter referred to as SRc) white landscape rock was placed. For the SRa sensor only 5 data points were missing. The SRb and SRc sensors had both 119 missing data points. For the last two sensors, this represented approximately one missing data point each day.

The SR50 array collected data minutely, which was then filtered to retain values at zero, fifteen, thirty, and forty-five minutes of each hour. Any missing data was replaced by the value recorded fifteen minutes prior. This was done to emulate as close as possible the operational conditions and criteria that will be found at EC's RCS and SWX stations.

Because the speed of sound is dependent on the density of air (primarily as a function of temperature), the distance to target measurements have to be corrected by the following equation:

$$CDT = RDT*(T_{KELVIN}/273.15)^{0.5} , \tag{1}$$

where CDT = Corrected Distance to Target Reading in metres

RDT = Raw Distance to Target Reading in metres

T_{KELVIN} = Air Temperature in Kelvin

The Geonor Total Precipitation Gauge was sited close to the SR50 array. It had one transducer, and an Alter-Shield. The instrument took readings every five seconds of the weight of liquid water captured by the instrument (change of liquid water over time yields a "precipitation" statistic). Each measured reading was inserted into the following recursive equation (a low-pass filter):

$$F(X_i) = W*X_i + F(X_{i-1})*(1-W) , \tag{2}$$

where F is the value of the Geonor at any given X_i and is denoted by $F(X_i)$

X_i is the current output value of the Geonor

W is the weighting function which in this case is 10 percent (0.1)

Using this equation ensures that anomalous readings are filtered out, and that no missing values in the time series would be recorded.

Finally, daily 24 hour MSF at 06 UTC, and hourly aviation Metars taken by a NavCanada contract weather observer were recorded. The 24 hour MSF, which is defined as the "Truth" in this study, will be compared to the SF values outputted by the algorithm in order to validate the algorithm's "goodness".

4. DESCRIPTION OF THE SNOWFALL ALGORITHM

There are two main parameters upon which this algorithm (which from this point forward will be referred to as the Three Sensor or S3 algorithm) is dependent on. The first parameter must deal with the aforementioned problem that changes in SOG levels may not be because of SF. The second parameter sets a time limit over which changes in SOG levels beneath each SR50 sensor are compared.

Once the parameters have been defined, a detailed description of the S3 algorithm will be presented. Please refer to Appendix 1 (section 10) for the flowchart of this algorithm.

4.1 *Threshold Snowfall Parameter*

To deal with the issue that SOG levels can be caused by factors other than SF, a "snowfall threshold" (ST) value is introduced (for this study 0.5, 0.7, 0.8 and 1.0 cm, respectively). The purpose of the ST is to set a minimum value where changes in SOG must occur beneath each SR50 sensor before deciding that SF possibly occurred beneath that sensor (the precision of the SR50 is ±1.0 cm). At time step zero, SOG values for the three SR50 sensors (a, b, and c), and the measured weight of water collected by the Geonor are put into place-holder reference levels. For each subsequent time step (every 15 minutes), new SOG measurements are recorded and then subtracted from the reference levels as denoted in equation 3.

Δ (SOG for the SRa) if (3)
(SRa – SRahold) $\geq$ ST or
(SRa – SRahold) $\leq$ ST

Δ (SOG for the SRb) if
(SRb – SRbhold) $\geq$ ST or
(SRb – SRbhold) $\leq$ ST

Δ (SOG for the SRc) if
(SRc – SRchold) $\geq$ ST or
(SRc – SRchold) $\leq$ ST

When at least 2 of the 3 SR-50's meet these criteria, the following procedure is performed. If the Δ SOG levels are negative, the three SRholds and the Geonorhold are reset to the new values measured at the last time step. The process then begins again with step 3.

Otherwise if the Δ SOG levels are positive, the three SRholds and the Geonorhold are reset to the new values measured at the last time step. A check is then done to see if the Geonor has also indicated precipitation using equation 4.

(Weight of water presently in Geonor) (4)
– Geonorhold > 0.0 mm

If equation 4 is not true, then the process begins again with equation 3. Otherwise, if equation 3 is true, the algorithm will assume that SF has occurred. How the SF statistic is actually calculated will be presented is subsection 4.3.

This algorithm is also run with the permutation of not using the verification check done by the Geonor in equation 4. This will reveal the importance of using the Geonor to verify that the Δ SOG levels is primarily due to precipitation.

4.2 *Time Limit Parameter*

The second parameter that the S3 algorithm is dependent on is related to how long one holds the SOG place-holders if SF has not occurred. In theory, one can keep going forward in time subtracting every 15 minutes the new SOG measurements from the place-holders until this subtraction becomes a value greater than/less than or equal to the ST value. The problem with doing this is that it increases the uncertainty to the reasons why the Δ SOG values have occurred. Besides the aforementioned possibilities in previous sections, the Δ SOG levels could be due to a series of very-light snowfall events (thus the SF statistic produced by this algorithm would not be representative of a single, continuous SF event).

Before the algorithm computes the values denoted in equation 3, the current time is subtracted from the time of the SOG placeholders (i.e.; the Time count). If this value exceeds 6 hours (i.e.; a difference of 6 hours and 15 minutes), all the SOG and Geonor placeholder values are advanced 15 minutes to the measurements recorded 6 hours earlier.

To summarize, the minimum amount of time that new SF could be indicated by the S3 algorithm is 15 minutes (i.e.; one time step). The maximum amount of time allowed between the current SOG reading for each sensor and its' associated reference level place-holders is 6 hours (i.e.; 24 time steps).

4.3 *The Calculation Procedure*

The procedure described in this subsection assumes that all three equations met the criteria in equation 3. In the cases where only two of the three sensors met these criteria, the procedure that will be described below is only applied to the relevant SR50 sensors. Since this is a subset of the overall procedure, all of these possible permutations will not be described in this paper.

Once the conditions set subsections 4.1 and 4.2 have been met, a question has to be asked about which Δ SOG value is the most representative of the actual SF. To answer this question a "difference in the Δ SOG" (DSG) statistic is introduced. In this statistic all the Δ SOG's are subtracted from each other, and then seen if they are less than a maximum threshold value. The equations are calculated as follows:

$$\text{DSGab} = \text{ABS}\,(\Delta\,(\text{SOG for the SRa}) - \Delta\,(\text{SOG for the SRb})) \leq 1.5\text{ cm} \qquad (5)$$

$$\text{DSGac} = \text{ABS}\,(\Delta\,(\text{SOG for the SRa}) - \Delta\,(\text{SOG for the SRc})) \leq 1.5\text{ cm}$$

$$\text{DSGbc} = \text{ABS}\,(\Delta\,(\text{SOG for the SRb}) - \Delta\,(\text{SOG for the SRc})) \leq 1.5\text{ cm}$$

The left-hand side (LHS) of equation 5 checks how far apart the Δ SOG values are for two SR50's. If the DSG numbers are not small, this means that one cannot be certain that other meteorological conditions, such as drifting snow, influenced the observed Δ SOG values.

By introducing a maximum threshold value (1.5 cm on the right-hand side (RHS) of equation 5) for which the equations in equation 5 must meet, one introduces a check to ensure that the Δ SOG levels were primarily due to SF. The value of 1.5 cm was chosen because the precision of an observation taken by the SR50 is ±1.0 cm. Subtracting two SR50 observations from each other results in a number with an error value slightly greater than ±1.4 cm (this number was rounded up to 1.5). A DSG number greater than the absolute value of 1.5 cm means that the two Δ SOG levels are statistically different from each other. In contrast, a DSG number less than this value means that the SF answers produced by the two SR50 sensors are statistically similar to each other.

There are four possible outcomes of equation 5 which are as follows:

<u>Outcome # 1</u>

DSGab, DSGac and DSGbc are all ≤ 1.5 cm. In this case all three sensors give a possible SF answer. Therefore all three Δ SOG values averaged.

$$\text{SF} = \text{Average of } (\text{SRa} - \text{SRahold}),\ (\text{SRb} - \text{SRbhold}), \text{ and } (\text{SRc} - \text{SRchold})$$

<u>Outcome # 2</u>

Two of three DSG's are ≤ 1.5cm (take DSGab and DSGac as an example). In this case the Δ SOG that occurred beneath the SRa sensor is within 1.5 cm of both the SRb and SRc sensors. However the Δ SOG that occurred beneath the SRb and SRc are different by more than 1.5 cm. Therefore in this case only the SRa instrument is used to calculate SF.

$$\text{SF} = (\text{SRa} - \text{SRahold})$$

<u>Outcome # 3</u>

Only one of the three DSG's has a value ≤ 1.5 cm (in this example take DSGab). In this case the Δ SOG that occurred beneath the SRa and SRb sensors are within 1.5 cm of each other. The Δ SOG that occurred beneath the SRc sensor is different by than 1.5 cm to both the SRa and SRb sensors. Therefore only the Δ SOG values for the SRa and SRb sensors are averaged in this case.

$$\text{SF} = \text{Average of } (\text{SRa} - \text{SRahold}), \text{ and } (\text{SRb} - \text{SRbhold})$$

<u>Outcome # 4</u>

In this case all three DSG's have values > 1.5 cm. This means that underneath all three sensors, large Δ SOG values occurred that were not within 1.5 cm of each other. Situations like this are most likely to occur when heavy SF, such as lake-effect, occurs. Therefore, another test is needed to calculate a SF statistic. To deal with this possible scenario, a normalization parameter (NP) is introduced, as is calculated as follows:

$$\text{NPab} = (\text{DSGab}) / (\Delta\,(\text{SOG for the SRa}) + \Delta\,(\text{SOG for the SRb})) \leq 0.1 \qquad (6)$$

$$NPac = (DSGac) / (\Delta \text{ (SOG for the SRa)} + \Delta \text{ (SOG for the SRc)}) \leq 0.1$$

$$NPbc = (DSGbc) / (\Delta \text{ (SOG for the SRb)} + \Delta \text{ (SOG for the SRc)}) \leq 0.1$$

In equation 6, the LHS represents the "difference of SF" (DSG) in the numerator divided by the "total magnitude of snowfall" in the denominator. The RHS of equation 6 checks to see if the LHS is ≤ to 10 percent (denoted by 0.1) of the total magnitude of SF which occurred underneath both sensors.

The procedure then continues exactly as before (this time using equation 6) when the four possible outcomes of equation 5 were considered. If this time Outcome # 4 is reached, a SF value of zero cm is given. Once a SF statistic has been produced, the procedure begins again with subsections 4.1 and 4.2.

Although the statistics presented in this paper will be for 24 hour SF totals, the S3 algorithm was developed to automatically output an answer every 6 hours (i.e., at 00, 06, 12, and 18 UTC).

5. CASE STUDIES

5.1 *Overview Of The Figures*

When examining the SR50 and Geonor curves displayed in Figs. 1 and 2, 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 SOG 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 Weather Indicator (WxInd) curve is a function which takes the values of either zero or one. At each time step where no weather is occurring (i.e.; clear skies), the function is given a value of zero. Otherwise, if precipitation is occurring (i.e.; SF, freezing rain, etc) then the function is given a value of one.

The measured snowfall (MSF) curve is outputted each day at 06 UTC. Its value is set to zero at every other time step. This function represents the 24 hour MSF totals taken by the NavCanada contract observer at Edmonton International Airport.

The rest of the curves represent various permutations of the S3 algorithm. For example, the notation of using the Geonor with a 1.0 cm ST is 1.0S3GY. In comparison, the notation of not using the Geonor with a 0.8 cm ST is 0.8S3GN. The S3 curves are step functions where each step takes the value of the SF statistic. Segments of the curves where the slope is zero represent no SF observed. Obviously there will be a delay between the actual start of a SF event and the S3 algorithm outputting a SF statistic.

5.2 *06 UTC 23 December 2004 To 06 UTC 24 December 2004*

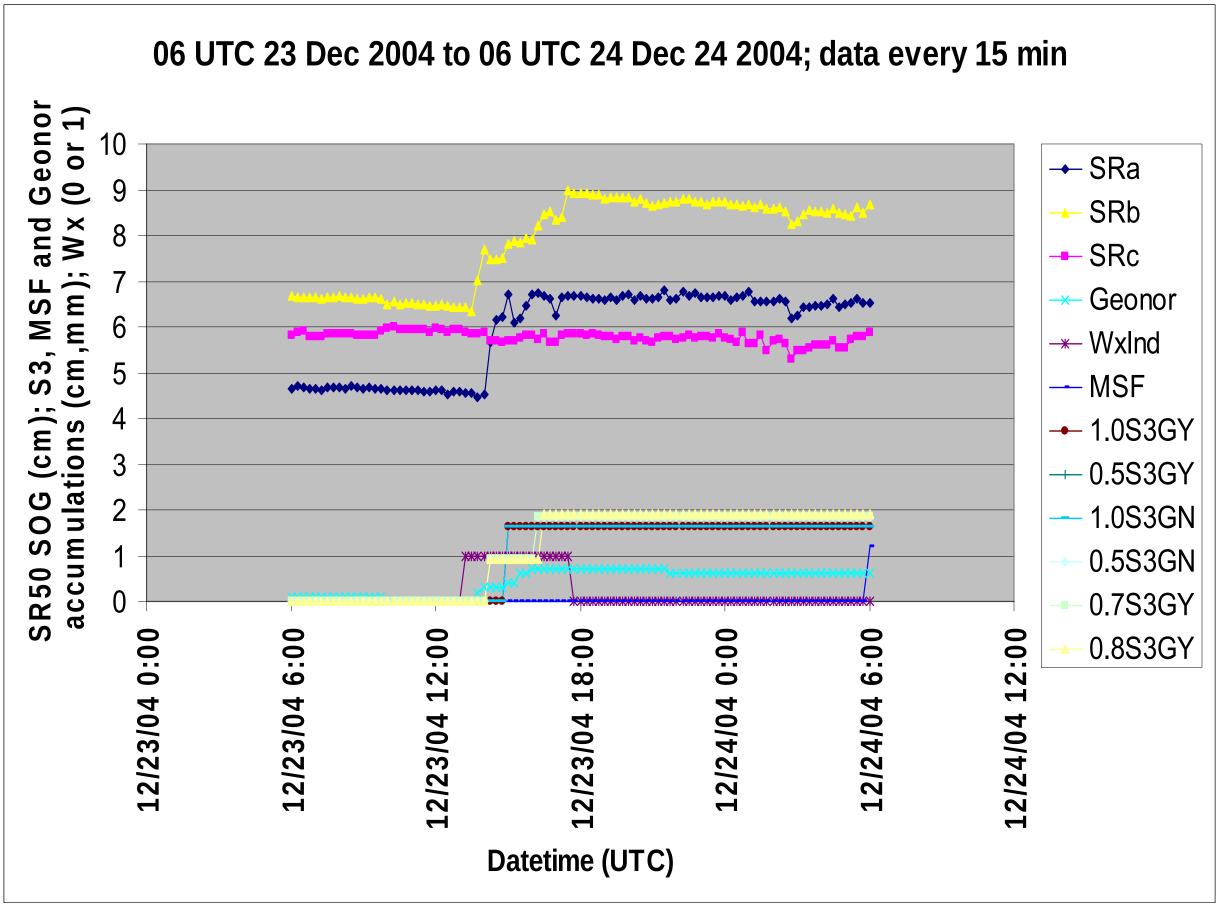


Figure 1. SR50 SOG measurements, accumulative Geonor and S3 algorithm functions, Aviation Metar Weather Indicator (WxInd; zero = no snow or one = snow), and daily 06 UTC 24 hour measured snowfall (MSF) at Edmonton International Airport (CYEG), Alberta, Canada for 23 December 2004.

For the first case study (Fig. 1), conditions were mainly clear except for a brief period of SF and freezing drizzle which occurred for approximately 4 hours early in the morning (note that there is a 7 hour difference between local and universal time). The winds for the most part were light ranging from 5 km/h to 10 km/h. The temperatures started at -23° C at 06 UTC Dec. 23rd and rose to 4° C at 06 UTC Dec. 24th (they were between -14° C and -9° C when the precipitation occurred). These facts strongly confirm that the changing SOG values observed by the SR50 sensors were due to precipitation.

All of the S3 algorithms performed very well on this date yielding SF values between 1.6 cm and 1.8 cm as compared to a MSF of 1.2 cm by the climate observer. All outputted SF statistics only while precipitation was falling. The two 1.0 ST algorithm curves are identical. In contrast, the 0.5, 0.7, and 0.8 algorithm curves are in a different subgroup (all these curves are nearly identical).

It is important to note that only the SRa and SRb sensors placed over mowed grass indicated that SF fell. The SRc placed over white landscape rock showed no evidence of SF. This shows the importance of using three SR50 sensors to produce a “consensus” SF statistic (one SR-50 may miss SF).

A 5-point snow survey taken by a contract observer on Dec 22nd measured a mean SOG value of 10.1 cm. This last point suggests that the type of surface beneath the SRc sensor was probably not a factor as to why the SOG did not increase underneath that sensor. More definitive conclusions on this point are beyond the scope of this paper.

5.3 *06 UTC 30 December 2004 To 06 UTC 01 January 2005*

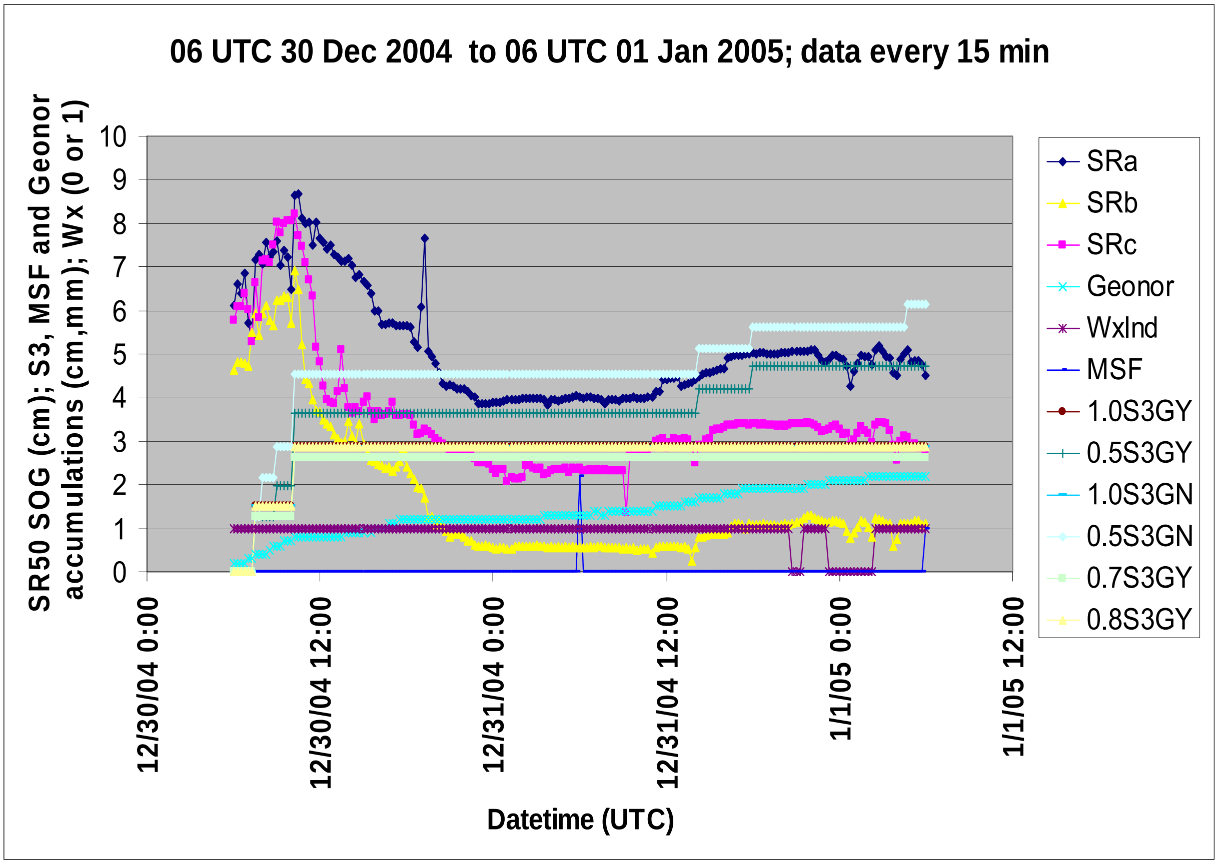


Figure 2. Same as Figure 1 for 30 and 31 December 2004.

For the second case study (Fig. 2), SF was continuous over the two days with the exception of a few brief periods early in the evening of Dec. 31st as indicated by the WxInd curve and the slowly rising Geonor curve. The winds were generally light (only a few brief periods were they increased to a maximum of 14 km/h). The temperatures remained below zero, ranging from -8 ° C to -28° C. All these conditions suggest that the periods where the SOG values fell were most likely due to settling snow, as opposed to blowing or melting snow.

From between 06 UTC and 12 UTC on Dec. 30th, a period of heavier SF occurred (note the increase of SOG levels indicated by all three SR-50 sensors). After 12 UTC on this date the SOG levels began to fall under all three sensors, before beginning to slowly rise on the second half of Dec 31st. Precipitation was still occurring while the SOG levels were falling (as indicated by the WxInd and Geonor curves), though the slope of the Geonor curve was small (thus indicating lighter precipitation was falling during this time period).

All the S3 algorithm curves indicated that SF occurred between 6 and 12 UTC on Dec 30th (between 2.8 cm and 4.5 cm versus 2.2 cm indicated by the climate observer). For the rest of the day none of the curves indicated that SF occurred. This certainly represents a limitation of this algorithm. However, as was discussed in the previous paragraph, the snow that fell over this time was very light. Note as well how near 19 UTC on Dec 30th the SOG beneath the SRa sensor increased near 3 cm within 30 minutes, before falling back to the level it was previously at. This is another example which shows the importance of constructing a "consensus" SF statistic using three SR-50 sensors. None of the S3 curves showed that snowfall occurred near this time period. This is a strength of the S3 algorithm.

A general trend that has been observed at Edmonton this winter (other examples not shown) is that the 0.5 cm step functions produce accumulative SF values greater than the algorithms which use 0.7, 0.8, and 1.0 cm as ST's. This can sometimes be an advantage as indicated by the light SF which occurred on Dec 31st where only the 0.5S3 algorithms captured this (SF amounts of 1.0 cm and 1.5 cm compared to zero cm for the other algorithms). In comparison, the SF observed by the climate observer on this date was 1.0 cm.

More often than not, however, using a 0.5 cm ST is too sensitive. Note how at the very end of the time period on Dec 31st only the 0.5S3GN gave a SF statistic of 0.5 cm. The Geonor curve at this time has a slope of zero, indicating little precipitation accumulation occurred near the end of the day. This SF statistic was probably the result of late day convective and/or turbulent mixing in the boundary layer (note the sinusoidal characteristics of the SR50 curves which all follow very closely to each other). The advantage of using the Geonor to help to verify SF accumulations greater than or equal to the ST is revealed in this example.

Finally, note that the 0.5S3GN algorithm produces the highest accumulative SF (i.e.; using a 0.5 cm ST and not using the Geonor). This point will be discussed further in section 7.

6. COMPARATIVE ALGORITHMS

In order to validate the S3 algorithm, other algorithms will be constructed to compare it and to the "Truth" (i.e.; 24 hour MSF values measured by the human observer). All these new algorithms will have similarities to either S3 algorithm, or the current crude method that EC uses to automate measurements of SF. Examining the results of these new algorithms will reveal a deeper understanding of how well the various parts of the S3 algorithm work.

The first new algorithm (Difference 6 Hours; DF6GY with the Geonor and DF6GN without the Geonor) is somewhat related to how EC presently takes automated measurements of SF (only one SR50 is used). Every 6 hours the values of SOG beneath each of the 3 SR50 sensors, and the measured weight of water captured by the Geonor, are subtracted from the values measured 6 hours earlier. If at least 2 of the 3 sensors have ∆ SOG levels > 0, and if the Geonor has indicated that precipitation occurred, then all the sensors which had positive ∆ SOG levels are averaged to produce a SF statistic.

It is important to note that since the DF6 algorithm uses a consensus of three SR50 instruments to produce an answer, this represents an improvement over using the measurements of just one sensor. The purpose of this algorithm is to prove that summing SF incrementally using discrete "step" values (as defined by the ST parameter) will yield a better answer than simply taking the time differential of snow depth observations.

The second new algorithm (One Sensor; S1) is a mixture of the S3 and DF6 algorithms. The purpose of the S1 algorithm is to prove the importance of using three SR50's to construct a consensus SF measurement. This algorithm treats each SR50 sensor independently, and indicates that SF occurred beneath one sensor if the ∆ SOG value crosses the ST using exactly the same methodology as the S3 algorithm. Every six hours this algorithm then sees if at least 2 of the 3 sensors had indicated that SF occurred. If the answer is yes, and if the Geonor has indicated that precipitation has also occurred, then a SF statistic is given using the same methodology presented in the DF6 algorithm.

7. ALGORITHM VERIFICATION STATISTICS

7.1 *Overview Of The Statistics*

We propose to characterize the "goodness" of all three algorithms by calculating the average of the absolute value of differences (i.e.; the "Error") between 24 hour MSF (by a human observer) and 24 hour SF statistics produced by the algorithms (∑|MSF-S3|; ∑|MSF-DF6|; and∑ |MSF-S1|, all divided by the number of days comprising the statistics (N), respectively). In other words, how close are the algorithm derived SF values to the measurements taken by a human observer? This approach is a better method of calculating the variance than using the least squares method. The reason for this is that taking the square of a small number produces a number of a much smaller value (i.e.; causes distortion). The main reason why this approach is not used frequently in data analysis is because the absolute value function is not differentiable at zero.

The S3 and S1 algorithms are sub-categorized depending on the value of the ST they take, and whether or not they use the Geonor as verification for SF. An example of the notation used in the ALGORITHM column in Table 1 is 1.0SxGY. The "x" is to be interpreted as either being 3 or 1 (i.e.; S3 or S1).

To further identify the "goodness" of the algorithms, each of the possible aforementioned algorithm permutations (1.0S3GY, 0.8S1GN, etc.)

are subdivided into three classes. These classes will see how well the algorithms perform over all days comprising the data set (ALL N), days were SF ≥ 0.2 cm occurred (SF), and days where no precipitation of any type fell (NO SF). Days where trace SF occurred (14 days) were not included in either the SF or NO SF class. The magnitude of the 24 hour SF cases comprising the SF class ranged from 0.2 cm to 12.6 cm.

It is important to note that the DF6 algorithm does not use a ST. Therefore these statistics are only outputted twice (once when the Geonor was used and once when it was not). Other statistics were calculated, but these results are not discussed in this paper.

7.2 *Analysis Of The Statistics*

ALGORITHM	CLASS	∑|MSF-S3| /N	∑|MSF-S1| /N	∑|MSF-DF6| /N	DAYS (N)
1.0SxGY Or DF6GY	ALL N	0.48	1.32	0.51	79
	SF	1.58	4.34	1.45	24
	NO SF	0.00	0.00	0.07	41
0.5SxGY	ALL N	0.44	1.56		79
	SF	1.27	4.85		24
	NO SF	0.10	0.11		41
1.0SxGN Or DF6GN	ALL N	0.60	1.55	0.61	79
	SF	1.92	5.02	1.45	24
	NO SF	0.02	0.02	0.22	41
0.5SxGN	ALL N	0.83	2.06		79
	SF	2.02	5.25		24
	NO SF	0.23	0.46		41
0.7SxGY	ALL N	0.49	1.48		79
	SF	1.54	4.73		24
	NO SF	0.03	0.03		41
0.8SxGY	ALL N	0.43	1.38		79
	SF	1.38	4.51		24
	NO SF	0.00	0.03		41

Table 1. Average of the Absolute Value of Difference Statistics between 06 UTC daily measured snowfall (MSF) and various permutations of the 3 Sensor (S3), 1 Sensor (S1), and Difference 6 Hours (DF6) algorithms. The Class column comprise these statistics for all days in the data set (ALL N), days that snowfall ≥ 0.2 cm fell (SF), and days with no measurable precipitation of any type (NO SF).

To interpret the results of Table 1, one compares the numbers down a column (permutations of one algorithm), and across a row (comparing the different algorithms). The smaller the number, the better the average value of the difference between MSF and an algorithm produced SF value. A value of zero means a perfect score (i.e.; every single day the 24 hour MSF and algorithm SF values were exactly the same).

When examining the statistics of the S3 column, there are several interesting points to gleam. First, compare the numbers of the 1.0S3GY and 0.5S3GY algorithms. As was suggested in the second case study, using a 0.5 cm step function (i.e.; ST) does a better job of measuring SF when it occurs (ALL N and SF classes). However, if one compares the numbers of the NO SF class, using the 0.5 cm step can result in days of reporting SF where none occurred (the number is zero for 1.0S3GY). There were 4 days out of 41 where the 0.5S3GY algorithm indicated SF occurred when it did not.

Next compare the results of the 1.0S3GY and 1.0S3GN algorithms. No matter what class you look at, using a Geonor as verification to identify when periods of SF occurs helps to minimize false reporting errors. A similar trend is noted when comparing the 0.5S3GY and 0.5S3GN algorithms.

Next note how the values of the S1 column are significantly higher than the S3 column. This result confirms the previously made assumption that the at Δ SOG value under one SR50 sensor can be due to effects other than SF. A consensus SF statistic using three sensors dramatically improves that accuracy of reporting

SF. Therefore, the S1 algorithm should not be used to derive a SF statistic.

The related statistics between the DF6 and S3 columns reveals several interesting facts. Begin by comparing the 1.03SGY and DF6GY algorithms. For the ALL N class, the S3 algorithm verifies better than the DF6 algorithm. However for the SF class, the DF6 algorithm statistically does better than the S3. Continuing the analysis, the NO SF class reveals once again that using a ST helps to prevent false reports of SF. There were 16 days where the DF6 algorithm gave a report of SF when none fell. To be fair most of these days gave trace SF values. However, a report of 0.8 cm was indicated for one of these days. Finally, comparing the NO SF class of the DF6GY and DF6GN algorithms shows again how not using the Geonor can lead to a higher incidence of false reports of SF.

While these results suggest that there may not be a significant advantage of using the 1.0S3GY algorithm over the DF6GY algorithm, it is important to remember the potential of erroneous reports if the magnitude of SF is large. As was shown in the second case study of section 5, the possibility that the ∆ SOG may increase dramatically before returning to the level it was previously at. By simply taking the ∆ SOG levels every 6 hours, one cannot be certain of the exact timing within the last 6 hours of this change, and why did this change occur. An incremental step function approach solves these problems. As well, the 1.0S3GY has zero cases of reporting SF when no SF occurred.

The reason to use the S3 algorithm is because of the step function (ST) it uses. As was previously discussed, taking a 0.5 cm threshold gives statistically a better answer of SF amounts than using a 1.0 cm step value when SF occurs. The problem of using this lower ST was the number of false events it records. By examining the results of the 0.7S3GY and 0.8S3GY algorithms, one can see that it is theoretically possible to find a midway point between accuracy when SF occurs, and the prevention of false reports of SF (i.e.; 0.8S3GY).

It is important to realize that this result could be an artifact of geographic location, the sample size of the data set (this may be why the statistics for the 0.7S3GY algorithm are worse than for the 0.8S3GY algorithm), or the ability of the human observer to accurately measure SF. More data will have to be collected before deciding on the “best” ST threshold to use. Nevertheless, the fact that it is possible to use a threshold smaller than the given precision of the SR50 instrument (±1.0 cm) is encouraging. Note how the statistics of all three classes of the 0.8S3GY algorithm are better than the DF6GY statistics.

7.3 *Analysis Of The Snowfall Class*

Examining the statistics of the SF class for the S3 algorithm (the reason for this study) confirm the aforementioned problems of using SOG measurements to construct a SF statistic (all values are greater than 1 cm). As previously mentioned, the 0.8S3GY gave the best answer (1.38 cm) of the average difference between the SF statistic produced by the algorithm and human observations of SF. This algorithm also gave no false reports of SF. It is one of two S3 algorithms shown in this study (0.5S3GY is the other; 1.27 cm) to have a better answer than the DF6 algorithm (1.45 cm). It is also only one of two S3 algorithms to produce an answer better than the precision of subtracting two values which have an uncertainty of ±1.0 cm (i.e.; ±1.41 cm).

The reasons for these relatively high numbers can be visually seen in Figure 3 for March 20th 2005.

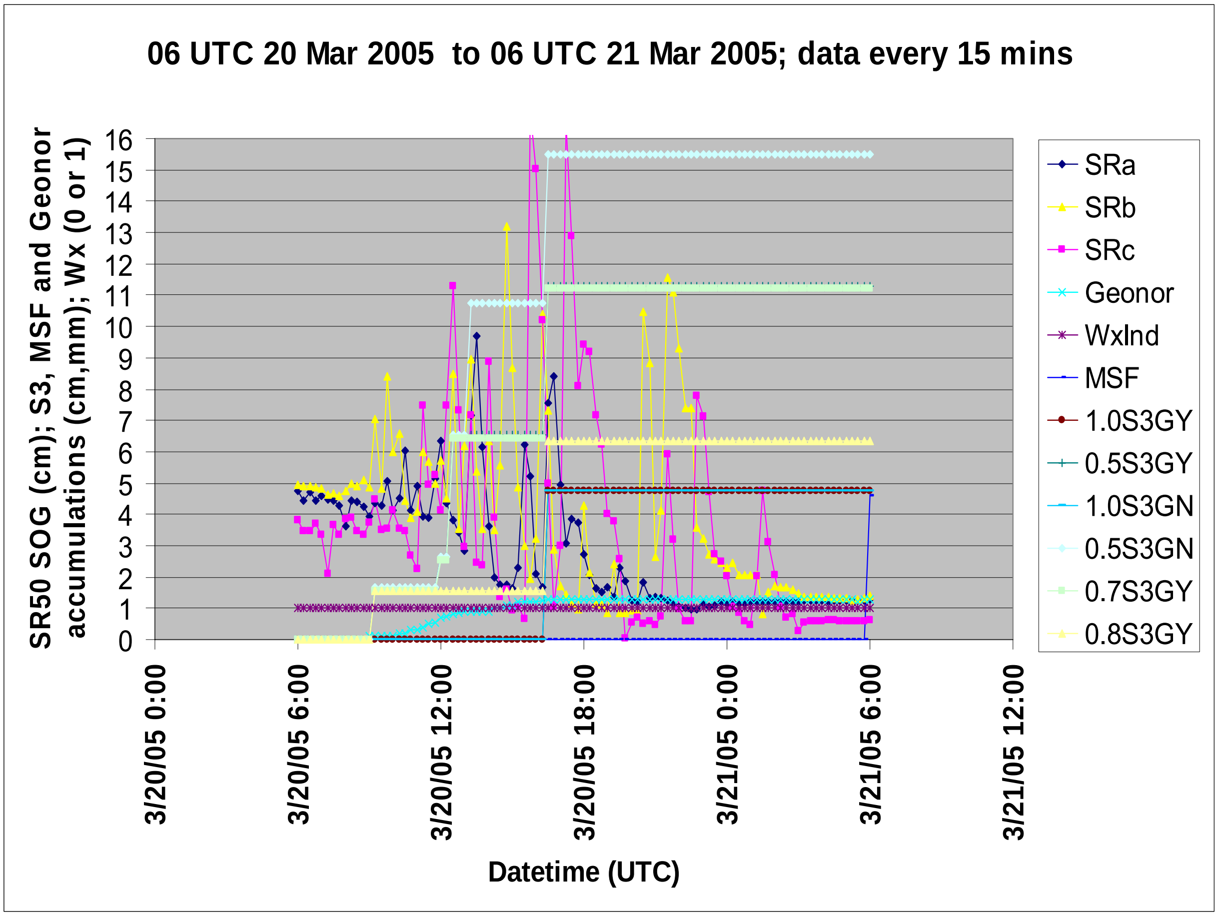


Figure 3. Same as Figure 1 for 20 March 2005.

It is obvious from this figure how difficult it would be calculating a SF statistic from these wildly fluctuating SOG values. Throughout March 20th SF occurred (note the WxInd) and the temperatures ranged from -9 ° C to -5° C. From 1430 UTC to 1630 UTC, the weather observer indicated blowing snow occurred. Additionally, from 2000 UTC to the end of the time period (06 UTC 21 March 2005), freezing drizzle was mixed with the SF. It is interesting to note that the SOG values for the SRc sensor placed above white landscape rock had larger fluctuations compared to the other two SR50 sensors.

Even the Geonor Total Precipitation Gauge had problems capturing the total SF which occurred on this date (1.3 mm compared to 4.6 cm). Of course this assumes that the human observer, and the devices used to capture falling snow accurately measured SF as well. Only the two 1.0S3 algorithms (both with and without the Geonor) gave a SF statistic close to the “real answer” (both 4.8 cm). All the other permutations of the S3 algorithm gave SF statistics much greater than the MSF. This example shows the difficulty of correctly choosing the ST one should use for this algorithm. Although the 0.8S3GY algorithm yields a better answer statistically for this data set, for this day one would get a better SF statistic by using the 1.0S3GY algorithm. This case also gives a reason why the statistics for the 0.7S3GY algorithm are worse than the 0.8S3GY algorithm (note the accumulative SF values of 11.2 cm versus 6.3 cm at 06 UTC 21 March 2005).

8. CONCLUSIONS

There are three definitive conclusions that can be drawn from the results of this study. First, using a triple configuration of SR50 Ultrasonic Ranging Sensors to produce a consensus snowfall statistic yields a more precise answer than using just one SR50. Second, using a Geonor Total Precipitation Gauge as a verification check to identify periods of snowfall helps to minimize false reports of snowfall. Third, using a minimum threshold value where the snow on ground levels beneath an SR50 sensor must become greater than or equal to before considering the possibility that snowfall occurred, helps to minimize false reports of snowfall.

This study has introduced and statistically qualified an algorithm which incorporates the points identified in the previous paragraph. While this algorithm has shown promise, more work will have to be done to minimize the average difference between the magnitudes of snowfall produced by the algorithm and measured snowfall by a human observer. More data from other sites with different snowfall climatologies will have to be collected and analyzed to ensure that the results presented in this study are not an artifact of geographic location. Finally, more analysis will be needed to identify the value of the minimum threshold where one can be almost certain that no false reports of snowfall are produced.

9. REFERENCES

Baker, C. B., R. Buckner, W. Collins, and M. Phillips, 2005: Calculation of Official USCRN Precipitation from Geonor Weighing Precipitation Gauge. NOAA Technical Note NCDC No. USCRN-05-1, 27 pp.

Brazenec W. A., and N. J. Doesken, 2005: An Evaluation of Two Ultrasonic Snow Depth Sensors for Potential Use at Automated Surface Weather Observing Sites. *13th Symposium on Meteorological Observations and Instrumentation*, June 19-23, Savannah, GA.

Campbell, C. and C. D. Smith, 2005. The Bratt's Lake Precipitation Intercomparison Project: Estimating the Systematic Errors in Measuring Precipitation Using the Geonor Accumulating Precipitation Gauge, CMOS Bull. SCMO, Vol. 33, No. 2, 47-51.

CSD 2003: (http://www.campbellsci.com/documents/manuals/sr50.pdf) Campbell Scientific, Inc. Document. Accessed 21 October 2005.

Ferguson, S. A., M. B. Moore, R. T. Marriott, and P. Speers-Hayes, 1990: Avalanche weather forecasting at the northwest avalanche center, Seattle, WA. *J. Glaciol*., **36,** 57-66.

Fritsch, J. M., and Coauthors, 1998: Quantitative precipitation forecasting: Report of the Eighth Prospectus Development Team, U.S. Weather Research Program. *Bull. Amer. Meteor. Soc.*, **79,** 285-298.

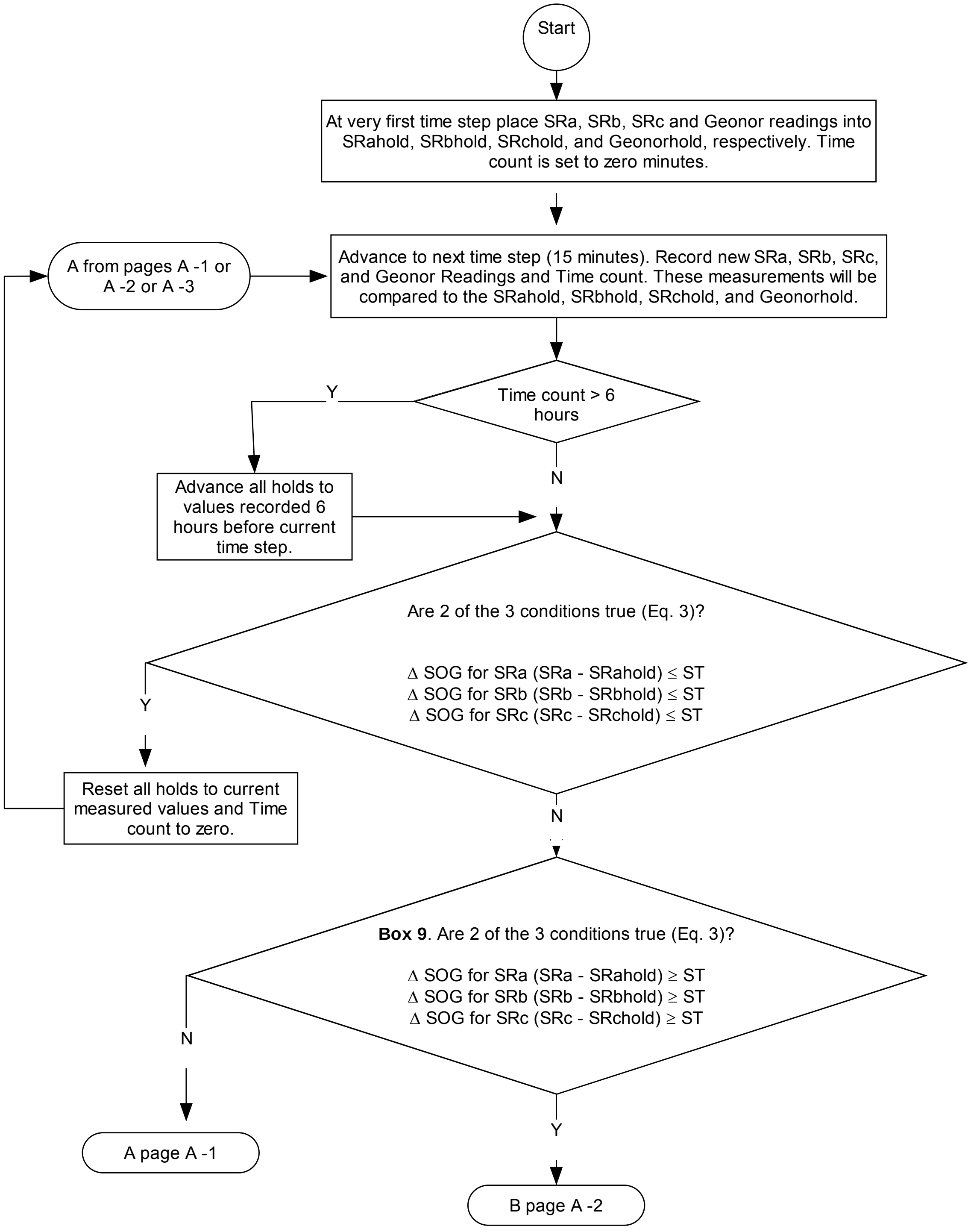
Goodison, B.A., B. Wilson, K. Wu, and J. Metcalfe, 1984: An Inexpensive Remote Snow-Depth Gauge: An Assessment. *Proceedings of the 52nd Annual Western Snow Conference,* April 17-19, Sun Valley, ID.

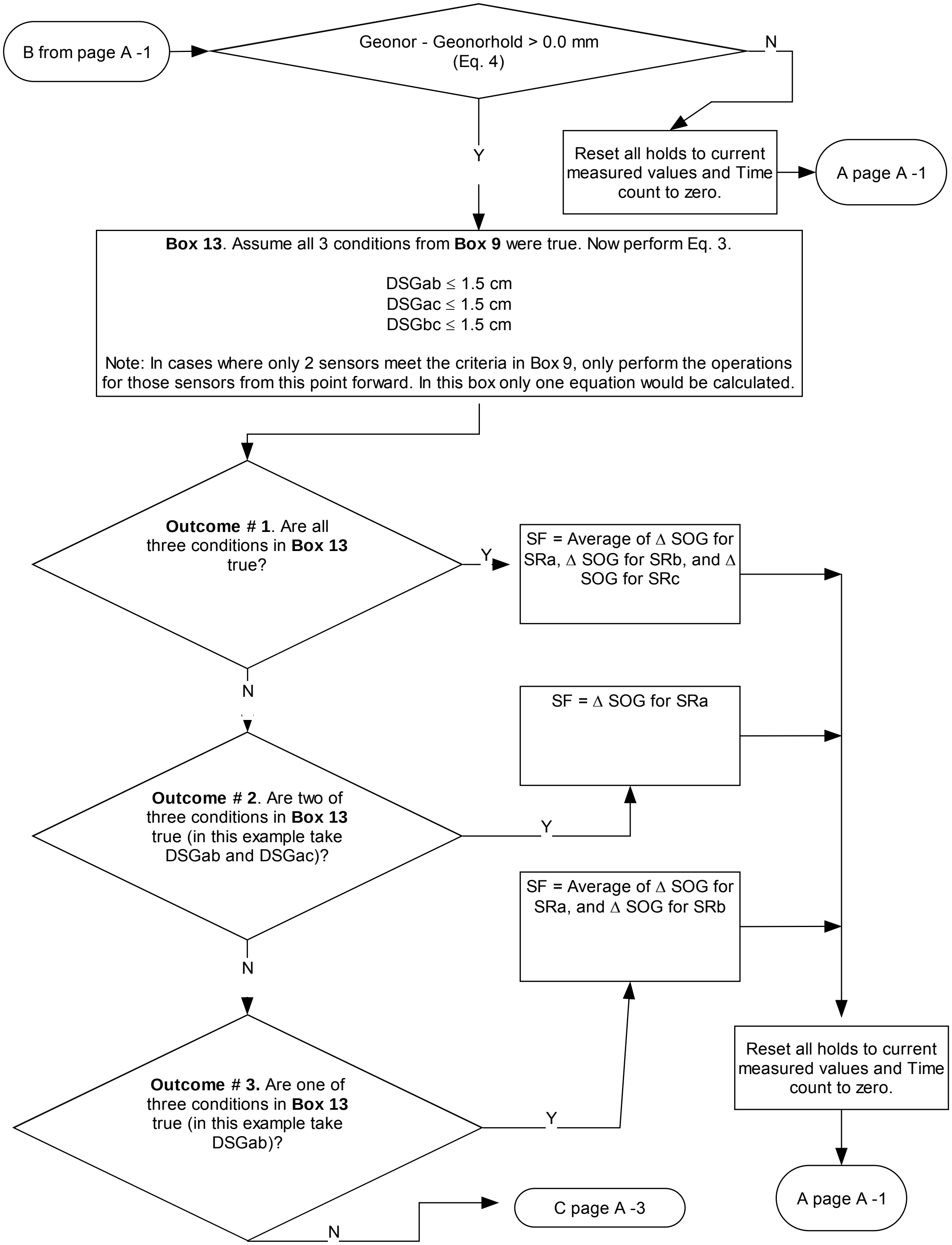
Gray, D. M., and D. H. Male, 1981: *Handbook of Snow: Principles, Processes, Management and Use*. Pergamon Press, 776 pp.

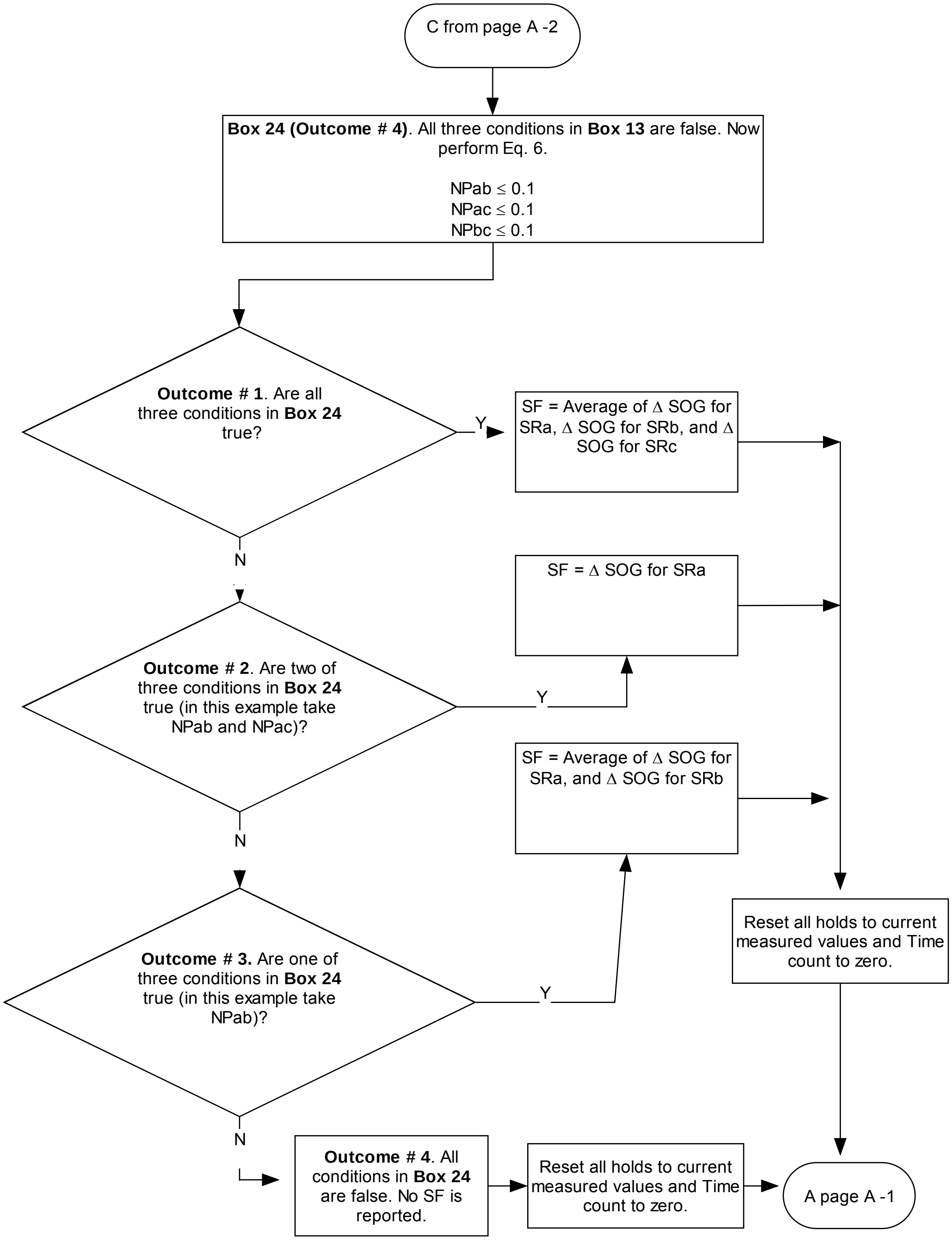
McKee, T.B., N.J. Doesken, C.A. Davey, and R.A. Pielke, Sr., 2000: Climate Data Continuity with ASOS, Report for Period April 1996 through June 2000. Climatology Report 00-3, Dept. of Atmos. Sci., CSU, Fort Collins, CO, November, 82 pp.

Neumann, N. N., C. Derksen, and B. E. Goodison, 2004: Relationships Between Point Snow Depth Measurements and Snow Distribution at the Landscape Level in the Southern Boreal Forest of Saskatchewan. *Proceedings of the 61st Annual Eastern Snow Conference,* June 9-11, Portland, ME.

10. APPENDIX 1: FLOWCHART OF THE S3 SNOWFALL ALGORITHM




B from page A -1
Geonor - Geonorhold > 0.0 mm
(Eq. 4)
N
Y
Reset all holds to current measured values and Time count to zero.
A page A -1
Box 13. Assume all 3 conditions from **Box 9** were true. Now perform Eq. 3.
DSGab ≤ 1.5 cm
DSGac ≤ 1.5 cm
DSGbc ≤ 1.5 cm
Note: In cases where only 2 sensors meet the criteria in Box 9, only perform the operations for those sensors from this point forward. In this box only one equation would be calculated.
Outcome # 1. Are all three conditions in **Box 13** true?
Y
SF = Average of Δ SOG for SRa, Δ SOG for SRb, and Δ SOG for SRc
N
SF = Δ SOG for SRa
Outcome # 2. Are two of three conditions in **Box 13** true (in this example take DSGab and DSGac)?
Y
SF = Average of Δ SOG for SRa, and Δ SOG for SRb
N
Outcome # 3. Are one of three conditions in **Box 13** true (in this example take DSGab)?
Y
Reset all holds to current measured values and Time count to zero.
A page A -1
N
C page A -3


C from page A -2
Box 24 (Outcome # 4). All three conditions in Box 13 are false. Now perform Eq. 6.
NPab ≤ 0.1
NPac ≤ 0.1
NPbc ≤ 0.1
Outcome # 1. Are all three conditions in Box 24 true?
Y
SF = Average of Δ SOG for SRa, Δ SOG for SRb, and Δ SOG for SRc
N
SF = Δ SOG for SRa
Outcome # 2. Are two of three conditions in Box 24 true (in this example take NPab and NPac)?
Y
SF = Average of Δ SOG for SRa, and Δ SOG for SRb
N
Reset all holds to current measured values and Time count to zero.
Outcome # 3. Are one of three conditions in Box 24 true (in this example take NPab)?
Y
N
Outcome # 4. All conditions in Box 24 are false. No SF is reported.
Reset all holds to current measured values and Time count to zero.
A page A -1