AN ALGORITHM TO ESTIMATE TRADITIONAL SNOWFALL MEASUREMENTS FROM ULTRASONIC SNOW DEPTH SENSORS AT U.S. OBSERVING SITES

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ABSTRACT

The measurement of snowfall is a climatologically important variable measured at U.S. observing sites dating back to the late 1800's. Snowfall is inherently difficult to measure due to wind redistribution, compaction and melting that can occur prior to a snowfall measurement taking place. With automation of many U.S. observing sites in the 1990's, snowfall measurements were abandoned due to lack of technology to continue the measurements at many locations. This study aims to test the feasibility of restoring traditional snowfall measurements at automated stations using changes in snow depth from ultrasonic sensors. The ultrasonic sensors were installed in a triplicate configuration along with a Geonor precipitation gage and a wetness sensor for verification. Results show fairly good agreement between manual measurements and automated snowfall estimates. Differences are mainly due to low density snow that is not measured by the ultrasonic sensors and also does not register measureable precipitation in the Geonor gage. Wind driven events also cause problems for the algorithm, but overall these events were mainly less than 2.5 cm (1 inch) as manually measured but not estimated by the algorithm at all.
(KEYWORDS: snowfall, ultrasonic snow depth sensor, snowfall, snowboard, precipitation gauge)

INTRODUCTION

Snowfall is a measurement of the accumulation of new snow that falls during any given event. The National Weather Service (NWS) sets guidelines for snowfall measurements (NWS, 1996). The measurement is recommended to be taken from a white board made of PVC which is cleared after each measurement to reduce the effect of wind redistribution and compaction. The guidelines also state that snowfall measurements can be taken up to 4 times per day. Measuring more frequently than once every six hours can result in inflated snowfall values. All of these considerations are easily understood by a human observer that can see irregularities in the snow and account for them. These are not easily transmitted to a sensor that essentially is a point measurement of a highly variable element.

This study builds on previous investigations using ultrasonic sensors (Ryan, et al. 2008a and Ryan, et al. 2008b) for automated snowfall measurements. These previous studies tested the feasibility of using ultrasonic depth sensors by testing two manufacturers, Campbell Scientific SR50 and Judd Communications sensor. The SR50 was found to be more suitable due to better internal signal processing and thus higher data resolution which produced more accurate estimates for this purpose. These studies also found that both sensors are quite good at measuring total depth of snow on ground within 1 inch (2.5 cm) compared to the traditional manual snow depth measurements. In terms of the snowfall algorithm, these studies found that having verification of precipitation in the form of a weighing rain gage could help reduce "false alarms" of snowfall that are artificially created by the small scale variability in the sensor output.

Beginning with snow season 2011-12, three sites from the previous studies (Fort Collins, CO, Buffalo, NY and Aberdeen, SD) installed a Geonor vibrating wire precipitation gage and a wetness sensor to aid in algorithm development. Both of these measurements are taken at Climate Reference Network (CRN) sites which is where this study is targeted to restore snowfall measurements.

METHODS

At each of the site locations, Campbell Scientific SR50's were installed in triplicate. The measurement surface installed below the sensors is the same material as the standard NWS snowboard but larger in size. A temperature probe was installed in the middle of the array. This is the temperature used to correct the ultrasonic measurements for the speed of sound in air which varies with temperature. The Geonor was installed on a concrete

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pillar installed to frost depth for each location. A double alter wind shield and heater were installed with the Geonor. The Geonor uses vibrating wire technology to measure precipitation. The main concept is that the bucket hangs from vibrating wires, the frequency of those wires report changes with the weight of the bucket. As precipitation falls into the bucket the frequency of vibration changes and precipitation amounts can be determined. This study uses the Geonor algorithm developed by the National Climatic Data Center for the CRN network (Baker, et al., 2005). A Vaisala DRD11A rain detector was also installed. This sensor simply identifies if precipitation is present or not. Site photos are shown in Figure 1.

Figure 1. Site photos from left to right: Buffalo, NY, Aberdeen, SD and Ft. Collins, CO

Data from the precipitation gage, snow sensors, temperature probe and wetness sensor were collected on a 5 minute time step during the 2011-2013 snow seasons. The precipitation gage data was sent via FTP to NCDC for calculation of precipitation from the official CRN algorithm. After retrieving the Geonor precipitation output from NCDC, simple quality control and smoothing procedures are performed on the snow sensor data to remove large data spikes and small scale noise from the transducer output. The algorithm checks that the change from one 5 minute time step to the next is within a reasonable range otherwise it uses the previous observation. Readings are checked to see if they are within a reasonable range of where the sensor is mounted, bad readings generally report the height of the sensor off the ground. Bad data is identifiable because the sensor essentially reads a zero which is then offset by the height the sensor is mounted. That height the sensor is mounted is generally the data "spike" that is reported by the sensors during times where measurements are difficult to obtain (intense snowfall and wind driven events).

Once the data is filtered it is run through both a median filter and a forward weighted 60 minute moving average before the actual snowfall algorithm begins. Using the smoothed 5 minute data the algorithm looks at the 5 minute change in snow depth and goes through several logic steps to make decisions. Before this portion of the algorithm runs, the user must input 2 parameters, the threshold 5 minute change in snow depth (ΔSD) and the threshold temperature (TT) for changing precipitation in the Geonor to snowfall.

The logical steps that the algorithm utilizes are listed below:

1.) If ΔSD> user set threshold AND Wetness sensor <500
    a. SF(x) = ΔSD
2.) Else If Air Temp (C)<=TT AND Geonor precipitation > 0
    a. SF(x) = (Geonor precip/ρ_{fresh})*1000
3.) Otherwise:
    a. SF(x)=0

If the ΔSD is greater than the defined threshold and the wetness sensor indicates precipitation, the ΔSD is used as the 5 minute snowfall amount. If that step fails, then the algorithm gets a little smarter. Because we deal with blowing and drifting snow, there may be events where snowfall occurs but does not accumulate on the boards. Step 2 attempts to remedy this situation by checking if the air temperature meets the TT criteria and if there is precipitation reported in the Geonor gage. If these criteria are met, a temperature based fresh snow density equation is utilized to estimate the density. That equation is called the Hedstrom-Pomeroy (Hedstrom and Pomeroy, 1998) fresh snow density equation in the form:

$$\rho_{fresh} = 67.92 + 51.25e^{(TempAirC/2.59)}$$

Using this equation and the precipitation from the Geonor gage, a snowfall estimate can be made during times where the ultrasonic sensors fail to measure an event. If step 1 and 2 fail to be true, the snowfall value is set to zero. These 5 minute values are then summed over either a 6 or 12 hour period (weather forecast office's measure every 6 hours whereas the Fort Collins station measures every 12 hours) to be compared to manual observations.

Before comparing to manual observations, compaction is considered. The problem of compaction arises because traditional manual snowfall observations are taken on a snow board which is cleared after each observation. This reduces the effect of compaction, blowing/drifting and snowmelt on snowfall measurements. The ultrasonic sensors do not clear the snow off the snowboard after each observation. Snow depth is continuously measured and compaction, redistribution and melt are included in those measurements. In order to account for this, compaction is calculated using the SNOTHERM model equation shown below for metamorphism (Jordan, 1991). Overburden compaction is not considered. This compaction is then added to the snowfall algorithm output to essentially nullify compaction occurring. There is uncertainty in using this method because 5 minute changes in snow depth are being considered instead of taking a 6 or 12 hour reading. The compaction routine is still being investigated to see if it improves algorithm results.

$$Compaction_{metamorphism} = 2.778x10^{-6} * C3*C4* e^{(-0.04*(273.15-TempK))}$$

TempK is the average temperature of the period in Kelvin. The variable C3 is a factor that accounts for how dense the snow is. The density here is calculated from the derived snowfall amount averaged for the three sensors and the Geonor output. If the fresh snow density is < 150 kg/m3 it is equal to 1, if it is > 150, then it increases C3 exponentially by:

$$C3 = e^{(-0.046*(density-150))}$$

C4 increases compaction under higher temperatures due to more rapid destruction of snow crystals. If the temperature is greater than 0C (273.15K) the factor is equal to 2, if it is lower it is equal to 1.

RESULTS

The results from the algorithm are quite encouraging, yet issues do exist particularly with low density snowfall and wind driven events. The biggest concern is small snowfall events with low density snow that do not register precipitation in the Geonor gage and snow either does not accumulate on the snowboards or the accumulation rate is near the compaction rate. Both the delta snow depth and threshold temperature parameters were treated as calibration factors. The combination that minimized error statistics was used. Results from 2012 and 2013 are shown.

Buffalo, NY

The accumulated snowfall from both manual observations and algorithm output are shown in figure 2 below for both snow season 2012 and 2013. The snow depth delta was set to 0.03 and the threshold temperature to -0.5C.

The cumulative graphs show fairly good agreement between the manual observations and the algorithm output for much of the snow season. These graphics illustrate the algorithms ability to pick up on most storms, although the magnitude of the event reported can differ from manual observations. Manual observations are not taken directly beside the snow sensors at the Buffalo test site, they are taken closer to the WFO building. This may be sufficient to account for some of the differences between snowfall amounts, particularly during wind driven events. Figure 3 shows the linear regression for the algorithm with and without compaction. In both seasons, the use of the compaction routine ends up overestimating the seasonal total snowfall and in some cases event based snowfall as well. The R-squared values range from 0.83-0.87 for the algorithm without compaction over the two test seasons.

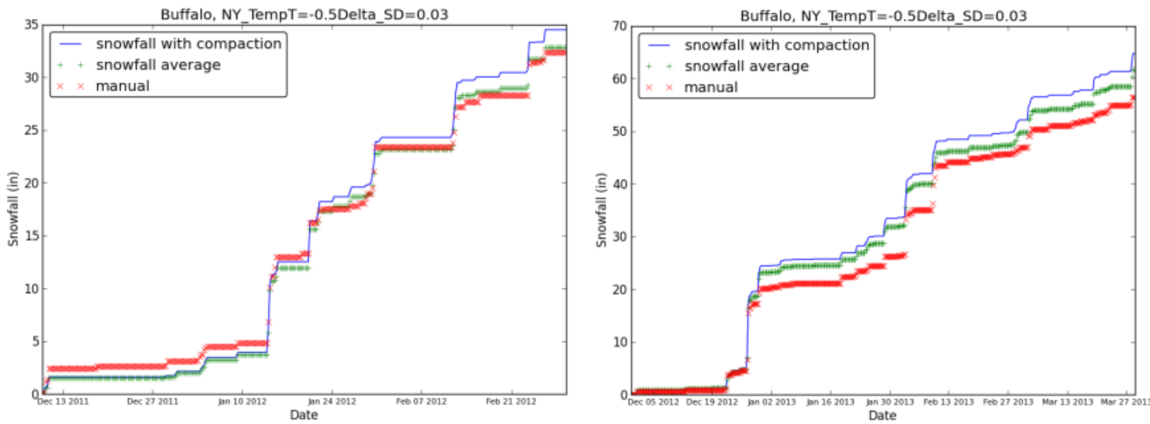

Figure 2. Buffalo, NY cumulative snowfall from 2012 (left) and 2013 (right).

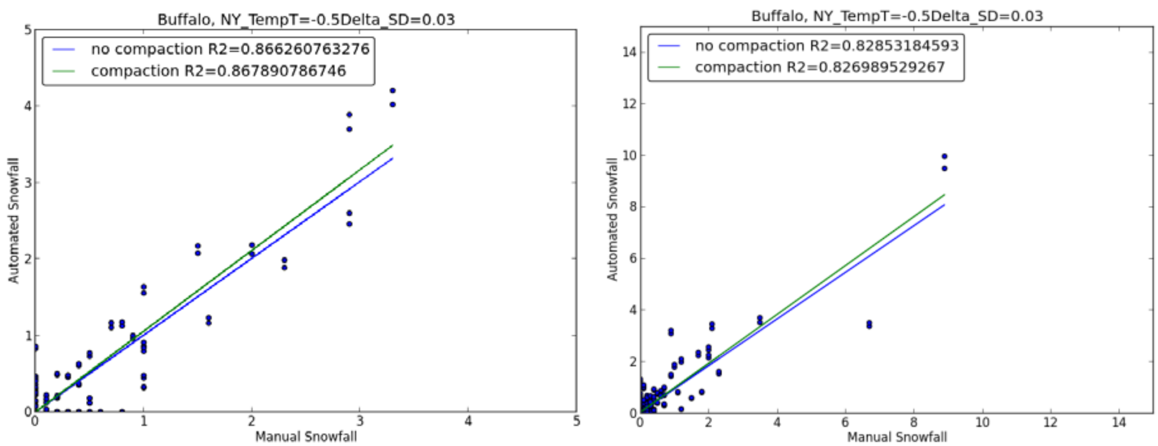

Figure 3. Linear regression of the algorithm output with and without the compaction routine applied vs. the manual readings for 2012 (left) and 2013 (right)

Fort Collins, CO

The results for the Fort Collins station are shown in Figure 4 and are similar to results seen in Buffalo. The compaction routine overestimates snowfall at this location as well. There is better overall agreement in measurements due to less wind driven events. The snow depth delta was set to 0.01 and the threshold temperature to +0.5C.

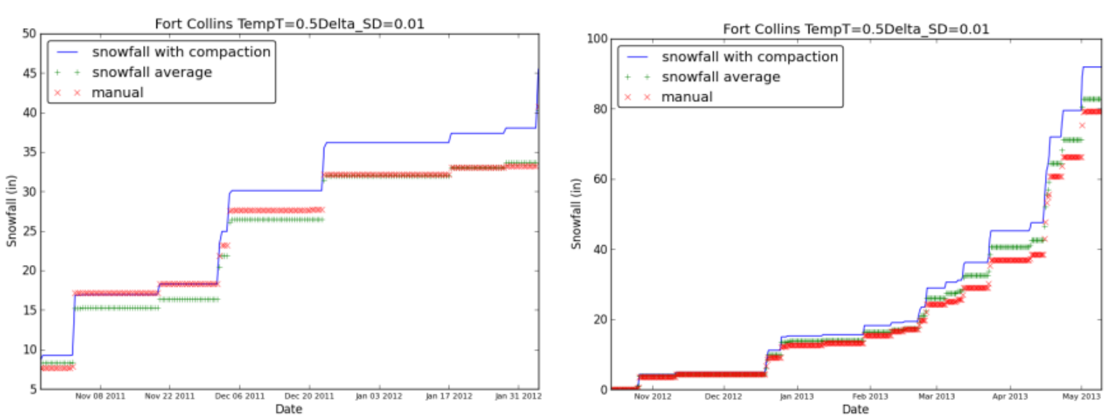

Figure 4. Ft. Collins, CO cumulative snowfall from 2012 (left) and 2013 (right)

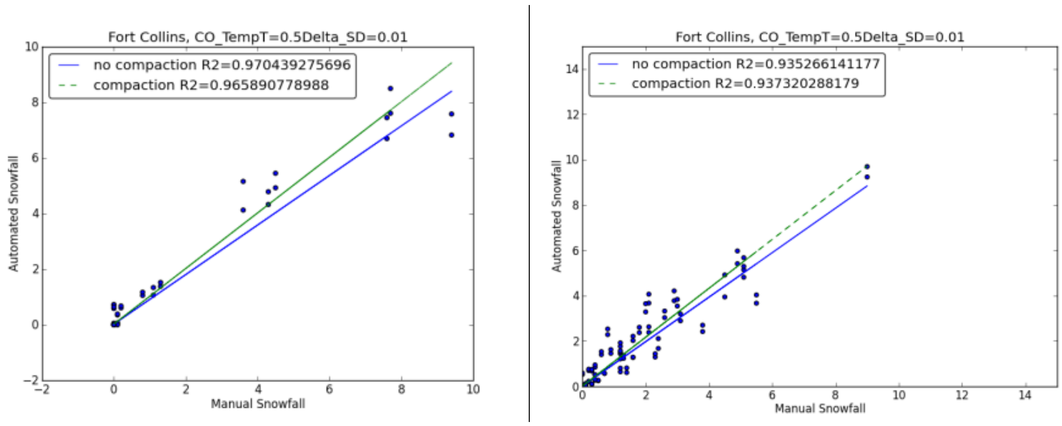

Figure 5. Linear regression of the algorithm output with and without the compaction routine applied vs. the manual readings for 2012 (left) and 2013 (right)

The linear regression is shown in figure 5 for both seasons and shows excellent agreement with the R-squared ranging from 0.94-0.97 without the compaction routine.

Aberdeen, SD

Only results for 2013 will be shown (Figure 6) since 2012 had an abnormally small sample of events to analyze. The R-squared is 0.84 suggesting fairly good agreement. The snow depth delta was set to 0.03 and the threshold temperature to 0.0C.

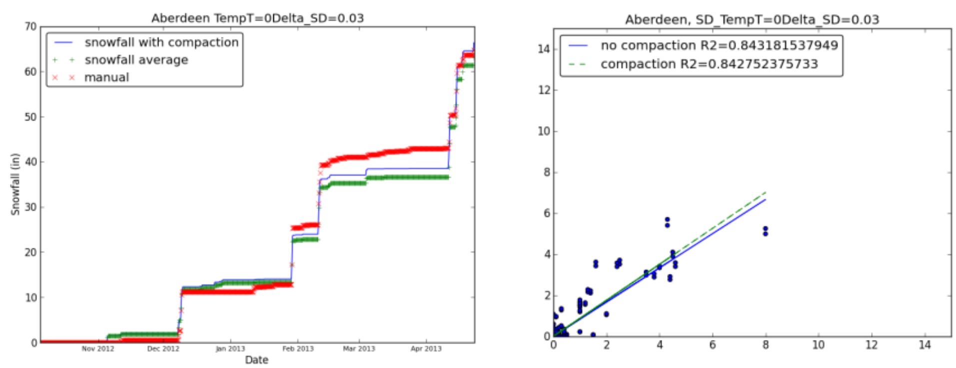

Figure 6. Aberdeen, SD cumulative snowfall (left) and linear regression (right) for the 2013 season

Table 1 provides statistics for the analysis. The mean absolute error, root mean squared error, omission and commission errors (OE and CE), the total number of observations (N) and number of snowfall events with no measureable precipitation are given. The OE show the fraction of time that the algorithm fails to estimate snowfall when it was observed manually, the CE show the fraction of time the algorithm erroneously estimated snowfall with none manually measured.

Table 1: Summary statistics are for the three sites for seasons analyzed. Mean Absolute Error (MAE) Root Mean Squared Error (RMSE), Omission and Commission Errors, number of events analyzed (N) and number of events without measurable precipitations are given.

Station	Buffalo, NY		Ft. Collins, CO		Aberdeen, SD
Year	**2012**	**2013**	**2012**	**2013**	**2013**
MAE (zeros not included)	0.3	0.4	0.4	0.4	0.6
RMSE (zeros not included)	0.4	0.7	0.7	0.6	0.8
Omission Error	15	17	1	2	21
Commission Error	14	17	4	7	11
N (analyzed events)	55	51	17	50	67
Events with no measureable precipitation	10	18	2	4	30

The statistical results are similar for all three sites in both years with the MAE ranging from 0.3-0.6” using only non-zero events. The RMSE which emphasizes the larger scale errors ranges from 0.4” to 0.8”. The OE and CE vary quite a bit by site. The large OE’s in Buffalo and Aberdeen are in part due to the large number of events without measureable precipitation. CE’s are attributed both to the threshold temperature and noise in the sensor data.

Table 2 shows the seasonal totals for the three sites for manual, each sensor, sensor average as well as the climate normal for the site. The percent difference in seasonal total between the manual observations and average of the three sensors is also given.

Table 2: Seasonal snowfall summary at the three test sites.

Station	Buffalo, NY		Ft. Collins, CO		Aberdeen, SD
Year	**2012**	**2013**	**2012**	**2013**	**2013**
Manual seasonal total	32.4	56.4	40.8	79.2	64.7
Sensor 1 total	32.3	63.3	39.1	84.9	64.7
Sensor 2 total	31.5	58.6	40.8	84.7	60.3
Sensor 3 total	34.8	63.2	41.3	79.1	64.2
Sensor average total	33.2	61.7	40.4	82.9	62.8
Normal seasonal total (1981-2010)	*94.7*	*94.7*	*55.8*	*55.8*	*38.4*
Percent difference (manual vs. sensor average)	2.5	9.4	-1.0	4.7	-2.9

DISCUSSION AND CONCLUSIONS

Overall, the algorithm is able to give reasonable estimates of station snowfall with some local calibration. The OE’s are mainly snowfall events less than 1.0” that are not being captured by the snow sensors and in most cases not by the precipitation gage either. The CE’s are mainly attributed to the threshold temperature changing precipitation to snow when it should not be. Measuring snowfall to the tenth of an inch with ultrasonic sensors may be unrealistic. Using error estimates, a more realistic resolution is around 0.5” (1.3 cm). In addition, the precipitation algorithm warrants further investigation due to the fact that there are many snowfall events without measureable precipitation. If the precipitation algorithm can capture those events, this algorithm can be improved upon as well.

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