Preliminary Results of Ultrasonic Snow Depth Sensor Testing for National Weather Service (NWS) Snow Measurements in the U.S.

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ABSTRACT

During the 2006-2007 winter season, 17 sites across the U.S. including Alaska tested an automated snow measurement system. This paper aims to describe successes and failures of this system and provide insight into data collected this season. The system was designed in collaboration with both Environment Canada and Snow Sensor Study participants during the summer of 2006. This system included three Campbell Scientific SR-50® sensors oriented 120° from one another and a temperature probe centered in the plot. Data collection efforts were successful with minimal amounts of data missing due to system or sensor failures. The system integrated automated retrieval of data from dataloggers, as well as automated file transfer protocol (ftp) to the study website for data archival and graphical display.

Overall, the sensors and installation worked well with only a few problems noted. The sensors compared well to both manual observations taken adjacent to each sensor as well as traditional total snow depth on ground measurements. The comparison to depths taken adjacent to the sensors allows for investigation of frost heave and indicates periods where the sensors were not functioning properly. The comparison to total snow depth on ground reveals problems with siting at some locations that are recommended to be remedied by re-installation or re-location of those sites prior to the 2007-2008 snow season. These results are preliminary and research will be ongoing for signal processing, snowfall algorithm development and optimal installation in preparation for the 2007-2008 snow season.

Keywords: Ultrasonic snow depth sensors, automated snow depth, manual snow measurement uncertainty.

INTRODUCTION

Snow depth is an important variable for hydrological, meteorological, and ecological studies. Previous studies have shown that ultrasonic technology shows excellent potential for measuring snow depth (Brazenec, 2005; Ryan *et al.*, 2007). Snowfall is the accumulation of new snow in a specified amount of time, and can be estimated from changes in the observed total depth of snow on ground (Brazenec, 2005; Ryan *et al*. 2007). In the 1990's the implementation of the National Weather Service (NWS) Automated Surface Observation System (ASOS) network replaced human observers with automated sensors. The measurements of snowfall and snow depth were not continued at many of these stations because automation of these measurements was not available. Therefore, there is interest to automate snow observations at selected surface weather observing sites in the United States.

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Ryan *et al*. (2007) provided an evaluation of different sensors and algorithms to estimate snowfall and related values. This paper subsequently provides an evaluation of the Campbell Scientific SR-50® (Campbell Scientific, 2005) as a tool for automation of U.S. snow measurements. This instrument was initially developed by Environment Canada for automating snow observations at remote, unmanned locations (Goodison *et al.*, 1984; Goodison *et al*., 1988). It was selected due to its modest cost, "off-the-shelf" availability, ease of use and maintenance, and reliable performance over a wide range of environmental conditions. It also provides the high resolution output required to estimate snowfall from continuous observations of total depth of snow on the ground.

From 2006 through 2007, a variety of background work was undertaken to understand the requirements from the instrument. These activities, accomplishments and key findings are presented herein, including discussions of site selection and network development, engineering and installation, data collection, site and sensor performance and comparisons between manual and automated snow parameters. The bulk of the effort during the past 12 months involved selecting sites for a representative nationwide evaluation, designing and installing a robust and consistent data collection system at all sites, and gathering automated data as well as coincident manual observations for comparison.

METHODS

Criteria for Site Selection

The first priority for this evaluation was to install, operate and test ultrasonic snow depth sensors in as many diverse climates as possible. Sites were selected based on several criteria. A necessary condition was that sites needed to be near NWS Weather Forecast Offices (WFO) where staff was available and willing to take coincident 6-hourly manual observations of precipitation and snowfall. The second criterion was that the WFO should be within approximately 1.6 km from an ASOS or some other complete surface weather observing site so that these data could be accessed and used in the evaluation of the sensors. The site also needed to be able to install the snow observing site within a reasonable distance of the office to utilize electricity and to facilitate direct comparison between manual and automated observations. The final criterion was an enthusiastic and willing participant from the WFO who would oversee and coordinate the efforts at their site.

Based on these criteria, the following list of the 2006-2007 participating sites was selected (Figure 1): Aberdeen, SD; Buffalo, NY; Cheyenne, WY; Fairbanks, AK; Flagstaff, AZ ; Fort Collins, CO; Grand Rapids, MI; Great Falls, MT; Indianapolis, IN; Johnstown, PA; Marquette, MI; McGrath, AK; Milwaukee, WI; Pittsburgh, PA; Salt Lake City, UT; Sterling, VA and Wilmington, OH. Of these sites most were WFO's except for Johnstown, PA and Sterling, VA which are NWS instrumentation test bed sites and Fort Collins, CO which is a long-term NWS cooperative observing site located at Colorado State University. Table 1 provides the three letter abbreviations for each of the sites which hereafter are used in both the text and figures to refer to individual sites.

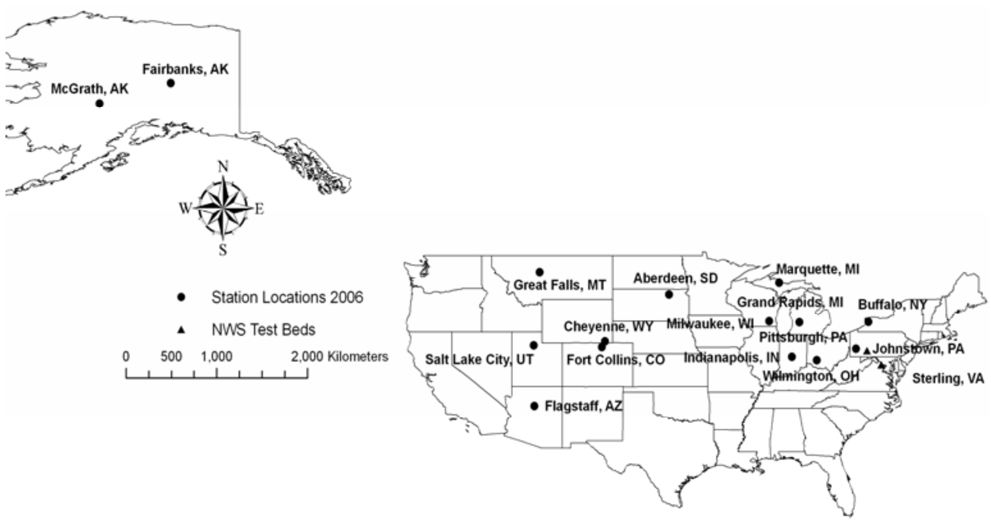

Figure 1. Map of the 2006-2007 site locations.

Table 1. Weather forecast office abbreviations.

Station Location	Abbreviation
Aberdeen, SD	**ABR**
Buffalo, NY	**BUF**
Cheyenne, WY	**CYS**
Fairbanks, AK	**FAI**
Fort Collins, CO	**FCL**
Flagstaff, AZ	**FGZ**
Grand Rapids, MI	**GRR**
Wilmington, OH	**ILN**
Indianapolis, IN	**IND**
Johnstown, PA	**JST**
McGrath, AK	**MCG**
Milwaukee, WI	**MKX**
Marquette, MI	**MQT**
Pittsburgh, PA	**PBZ**
Salt Lake City, UT	**SLC**
Sterling, VA	**SRD**
Great Falls, MT	**TFX**

Siting Criteria, Installation and Communications

Siting Criteria

Installation plans and siting criteria were developed in order to maintain standardization among sites. The following siting criteria were put in place prior to installation:

- Ideal location for snow measurement is open, level, grassy area naturally shielded from the wind in all directions.
- Where obstructions cannot be avoided, snow measurements should be taken a minimum of twice the distance from the obstacle as that obstacle is high.
- Avoid drainage areas or areas prone to flooding during heavy rain or snowmelt.
- Avoid slopes greater than 5°.
- Avoid south-facing slopes due to faster melt-out.
- Avoid, to the greatest extent possible, areas prone to drifting and wind scour.
- All sensors come with 61 meter cables which will restrict distance from power source.
- Dataloggers will be housed indoors in a heated and protected environment.

Installation and Communications

The general installation scheme was to place three Campbell SR-50 sensors 120° from one another with one sensor oriented to True North. The SR-50's were mounted on five centimeter galvanized steel posts sunk in concrete to 1 meter or frost depth (whichever was greater). Five cm galvanized steel was chosen based on its low expansion/contraction, as well as its stability to avoid vibrations due to wind. The height the sensor was mounted was a function of the historical maximum snow depth at each location. The ultimate goal was to choose the minimum height possible, however room for error must be allowed to ensure snow would not accumulate higher than the sensor was mounted. The function for the mounting height was (1.25*historical maximum snow depth) +32 cm (length of sensor) + 50 cm (50 cm was added because the SR-50 needs that distance above the surface to make an accurate measurement).

A temperature probe in a six gill radiation shield was placed in the center of the sensor plot at 75% of the height of the sensors off the ground. This was done in order to obtain a representative temperature measurement from the column of air utilized by the SR-50 sensors. The temperature measurement is needed to correct the SR-50 readings for the speed of sound in air.

The measurement surface chosen for the sensors was a 1.2 m x 1.2 m expanded PVC snowboard mounted flush with the ground surface, which was attached to either a sunken frame or sunken posts in order to avoid both frost heaving and movement of the board due to wind. These were to be installed with a slight tilt to the east to avoid water pooling on the target surface. Figure 2 provides photos of the final installation from a variety of sites.

Figure 2. Examples of site installations. Clockwise from upper left: Aberdeen, SD; Cheyenne, WY; Fairbanks, AK and Indianapolis, IN.

In order to assure convenient coincident manual observations and to make sure that stations had uniform and consistent station configurations, it was decided to use direct cabling from snow sensors to indoor dataloggers with a maximum cable length (manufacturer recommended) of 61 m. This meant that all sites could use standard power sources. However, this did restrict snow sensor siting options at some stations.

Data at each participating site were collected over 5 minute intervals and included the following parameters: julian day, time, battery voltage, 5 minute average temperature of 10 second samples, 5 minute instantaneous snow depth for each sensor taken at zero seconds into a 5 minute interval, a coincident manufacturer quality number (QN) to accompany the 5 minute instantaneous snow depth as an indicator of signal quality, and 5 minute average snow depth for each sensor (10 second samples). An automated FTP utility was created to FTP data from each site into the study website (http://snowstudy.cocorahs.org) for data archival and display.

Technique for Evaluation of Sensor Performance

In an effort to describe how well the sensors performed, data quality flags were produced for the following situations. The first parameter was a five minute standard deviation (Stdev). Stdev checked for a 5 cm jump in the data from one five minute report to the next. Additional checks are needed due to the fact that there could be several bad data points in succession. Therefore in addition to Stdev, there is a check for large negative spikes (Neg spike). A QN check (QN<-210) looked at the manufacturer QN for each 5 minute sample. The QN is a unitless indicator of the volume of the return pulse to the sensor that varies from 0 to -600. A measurement >-210 is considered to be of good quality. A QN of zero indicates the sensor failed to make a measurement, which is the final check (QN=0).

Comparison to Manual Observations of Snow Depth

Two comparisons were made to the automated data in order to quantify how well these sensors depict snow depth. The first comparison made was to manual snow depth taken just adjacent to each sensor, without disturbing the sensor. The second comparison was to the traditional element of total snow depth on ground (TSD). Historically, manual observers have taken several TSD samples and averaged those to obtain a representative TSD measurement.

The manual observations were paired with automated data in order to make goodness of fit comparisons. The mean absolute error (MAE) and root mean squared error (RMSE) were calculated to describe how well the sensors depicted the manual observations. The RMSE has been normalized by average snow depth at each location. This was done because a RMSE at a location with 25 cm average snow depth is more significant than a location with 150 cm of average annual snow depth.

Manual Snow Measurement Uncertainty

In order to quantify how well the automated sensors depict traditional manual snow measurements of snowfall and snow depth, the manual observations are treated as "truth". However, even the manual measurements of snowfall and snow depth are fraught with problems such as: time of observation, time period between observations, compaction, wind redistribution, melting, and spatial variability. Kunkel, *et al.* (2007) describes the difficulties of identifying trends in snow variables due to nonclimatic factors like frequency of observation, time of observation, and use of 10:1 ratios. All of these things contribute error into the traditional manual observations which has not been quantified. Work is being done to analyze these manual observations using a high-density network of trained volunteer observers that report daily snowfall and snow depth. Only areas believed to be relatively homogenous were analyzed. Additional work will be performed at one site with several observers measuring the exact same snow field.

RESULTS

Snow Conditions

In order to describe the snow sensor performance, it is important to know what types of snow conditions were present at each site for the test season. Table 2 gives a summary by site of: total number of 6 hour periods with snowfall, number of 6 hour periods with snow on ground, number of days with snow on ground at 12Z, monthly snowfall totals and monthly maximum snow depth from the manual data entries. Marquette, MI (MQT) received the highest seasonal snowfall at 563.4 cm of snowfall from November through April. Pittsburgh, PA (PBZ) received the lowest amount of seasonal snowfall at 35.8 cm from December through April. MQT had the highest number of 6 hour periods with snowfall and snow on ground at 162 days and 515 days, respectively. MQT also saw the maximum snow depth for the season of 86.4 cm. Fairbanks, AK (FAI) had the greatest number of days with snow on the ground at 12 Z with 166 days. Johnstown, PA (JST) and Sterling, VA (SRD) do not have complete statistics because they do not have a complete manual dataset due to manual observations only being taken during storm events when observers are able to get to the sites. Due to FAI and McGrath, AK (MCG) not being traditional WFO's, they only took daily snowfall readings, therefore some statistics are also missing for the two AK sites. Fort Collins, CO (FCL) number of days with snow on ground at 12Z is actually based on observations taken at 14Z due to that being the traditional observation time at that site. The average seasonal snowfall for each site is also shown in Table 2 and was included for a general comparison. It is important to note that the seasonal total values for this season are only based on time periods when the snow sensors were in operation. Overall, snow conditions were favorable for creating a robust dataset that will provide useful information as to the conditions that cause the ultrasonic snow depth sensors to fail and succeed.

Table 2. 2006-2007 Snow conditions summary for periods with Snowfall (SF) and Snow on Ground (SOG), Days with SOG and snowfall and snow depth statistics.

				Snowfall Totals (cm)								Monthly Maximum Snow Depth (cm)					
SITE	# OF 6HR PDS WITH SF	# OF 6HR PDS WITH SOG	# OF DAYS WITH SOG @ 12Z	Nov	Dec	Jan	Feb	Mar	Apr	Season	Average seasonal snowfall (cm)Ŧ	Nov	Dec	Jan	Feb	Mar	Apr
ABR	12	87	83	0.0	19.1	8.6	45.5	14.7	29.2	117.1	98.0	0.0	17.8	15.5	27.9	35.6	12.2
BUF	68	212	53	N/A	N/A	26.4	78.2	13.7	1.8	120.1	246.4	N/A	N/A	8.1	20.8	9.9	1.3
CYS	40	53	14	3.3	52.6	19.3	10.2	5.8	2.0	93.2	153.2	2.5	17.8	5.8	6.6	5.1	1.5
FAI**	N/A	N/A	166	3.6	19.8	22.4	4.1	9.1	0.0	58.9	171.2	10.2	25.4	38.1	35.6	43.2	38.1
FCL***	40	170	79	19.1	74.9	24.1	12.4	3.8	0.5	134.9	148.8	15.5	45.7	36.8	28.4	2.5	0.3
FGZ	36	124	34	N/A	N/A	31.8	27.9	2.3	7.4	69.3	278.9	N/A	N/A	17.8	12.7	2.5	4.6
GRR	37	75	9	0.0	3.8	10.9	61.0	N/A	N/A	75.7	183.4	0.0	12.7	15.2	38.9	N/A	N/A
ILN	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	74.2	N/A	N/A	N/A	N/A	N/A	N/A
IND	31	123	32	N/A	2.3	14.0	46.2	2.0	0.0	64.5	68.6	N/A	0.0	8.9	31.5	8.9	0.0
MCG**	N/A	N/A	N/A	0.0	45.2	64.5	3.3	0.3	0.0	113.3	233.2	N/A	N/A	N/A	N/A	N/A	N/A
MKX	59	285	72	2.5	24.4	38.6	61.2	21.3	11.4	159.5	133.1	2.5	22.9	20.3	40.6	27.9	12.7
MQT	162	515	127	21.1	91.2	134.9	64.3	113.3	136.1	563.4	468.6	7.6	22.9	43.2	53.3	86.4	50.8
PBZ	30	70	25	0.0	0.0	18.5	17.3	0.0	0.0	35.8	103.1	0.0	0.0	7.1	19.3	0.0	0.0
SLC	37	246	68	20.6	18.5	29.7	27.7	6.1	0.0	102.6	159.3	17.3	7.6	13.5	10.2	6.9	0.0
TFX	59	136	37	N/A	N/A	14.2	52.3	3.0	32.8	102.4	154.7	N/A	6.9	18.3	11.9	7.1	6.1

*JST AND SRD LEFT OUT OF SOG STATS DUE NON-UNIFORM OBSERVING METHODS (i.e. obs taken only during events).
** USED 24 HOUR DATA.
***FCL DAYS WITH SOG AT 12Z ACTUALLY AT 14Z.
Ŧ 30 year station normals (1971-2000)

Sensor Performance

Overall, the sensor performance was quite well with nearly no missing data except for periods where individual sensors went down. The automated FTP of data was successful for archiving a complete dataset from each location. Table 3 provides the start and end dates of data collection, the total number of automated five minute samples and the total percentage of flagged data using the criteria listed in the Methods section for each sensor at each station. The average of the three sensors is also provided for overall evaluation. Most sites did not have greater than 8% data flagged. The criterion which flagged the most data at most stations was the quality number and the most coincident element with degraded quality number was the presence of snowfall. There are some numbers in the table that are exaggerated due to individual sensor problems and include: MCG- North sensor, BUF-SE sensor and GRR-North sensor. There also appears to be some orientations (i.e. N, SE, SW) at some locations that caused higher amounts of flagged data than the other sensors at the same site. Those sites include: SRD-SW sensor, JST-SW sensor, MKX-SW sensor, FGZ-SE sensor, ABR-SE sensor, TFX-SE sensor, FCL-SW sensor, SLC-North sensor, MQT-North sensor and FAI-North sensor. These differences can be explained by siting, which suggests that there is no true "best" orientation for all sites. The optimal orientation is dependent upon the siting and exposure of each individual site and needs to be investigated further.

Table 3. Start date, end date, total number of samples (N) and total percentage of flagged data from each sensor at each site with an overall average.

				SENSOR			
	Start Date	End Date	N	NORTH	SE	SW	AVERAGE
CYS	10/25/2006	4/30/2007	58142	0.4	0.2	0.9	0.5
SRD	1/30/2007	4/30/2007	25908	0.6	0.9	1.6	1.0
PBZ	12/11/2006	4/30/2007	40977	1.8	1.3	1.2	1.4
ILN	1/2/2007	4/30/2007	33722	1.5	2.0	1.6	1.7
JST	12/7/2006	4/30/2007	41593	2.1	1.9	4.7	2.9
MKX	11/6/2006	4/30/2007	50359	2.2	2.3	4.6	3.1
IND	11/13/2006	4/30/2007	48181	3.4	2.5	3.3	3.1
FGZ	12/18/2006	4/30/2007	36390	3.7	4.4	2.7	3.6
ABR	10/30/2006	4/30/2007	52589	3.4	6.4	1.5	3.8
TFX	11/2/2006	4/30/2007	51734	3.2	8.8	4.9	5.6
FCL	10/23/2006	4/30/2007	54625	4.4	5.7	7.3	5.8
GRR	11/20/2006	4/30/2007	46510	9.1	4.9	3.6	5.9
SLC	11/2/2006	4/30/2007	51813	9.5	5.7	6.2	7.2
MQT	11/1/2006	4/30/2007	52125	10.8	4.8	8.0	7.8
BUF	1/2/2007	4/30/2007	33944	1.7	26.5	5.0	11.1
FAI	11/2/2006	4/30/2007	51658	24.7	11.1	9.5	15.1
MCG	12/15/2006	4/30/2007	38193	72.1	11.1	8.1	30.4

Comparison to Manual Observations of Snow Depth

Depth Adjacent to Sensors

Figures 3 and 4 show the MAE and normalized RMSE for each sensor compared to manual observations taken just adjacent to each sensor. For most sites, the MAE is less than 2 cm, which is most likely due to variability on the snowboards from where the measurements were taken and the sensor was measuring, because the sensors will report the highest depth in their measurement area. However, both ILN and PBZ illustrate higher errors than most sites, and this is attributed to a variety of reasons. ILN has a very small dataset for evaluation with only 23 manual observations for comparison. This site also reported siting issues creating large differences in snow depths. The errors for PBZ are attributed both to siting and resolution of manual observations. The PBZ site was installed on a slope which created differential accumulation along the slope which is the main cause of the difference. Also, PBZ reported the depth next to the sensors to the nearest 2.5 cm (1 inch), whereas most other locations measured this depth to the nearest 0.25 cm (0.1 inch). The normalized RMSE plot exaggerates these errors compared to the other sites. Both ILN and PBZ have been recommended for reinstallation in areas with more suitable exposure for snow measurements.

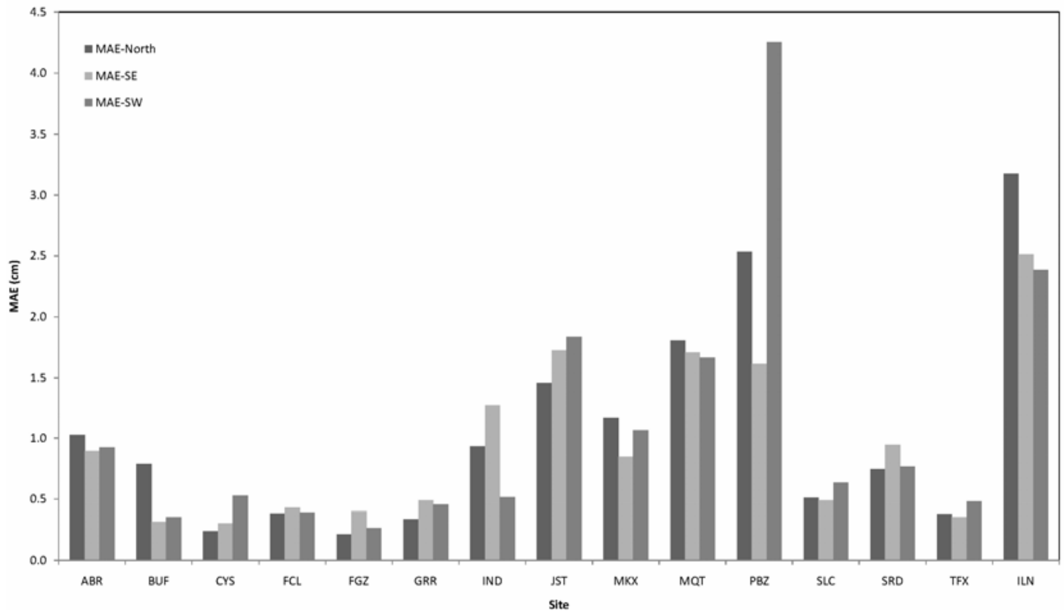

Figure 3. Mean absolute error (cm) for sensors vs. the manual depth at each sensor by site.

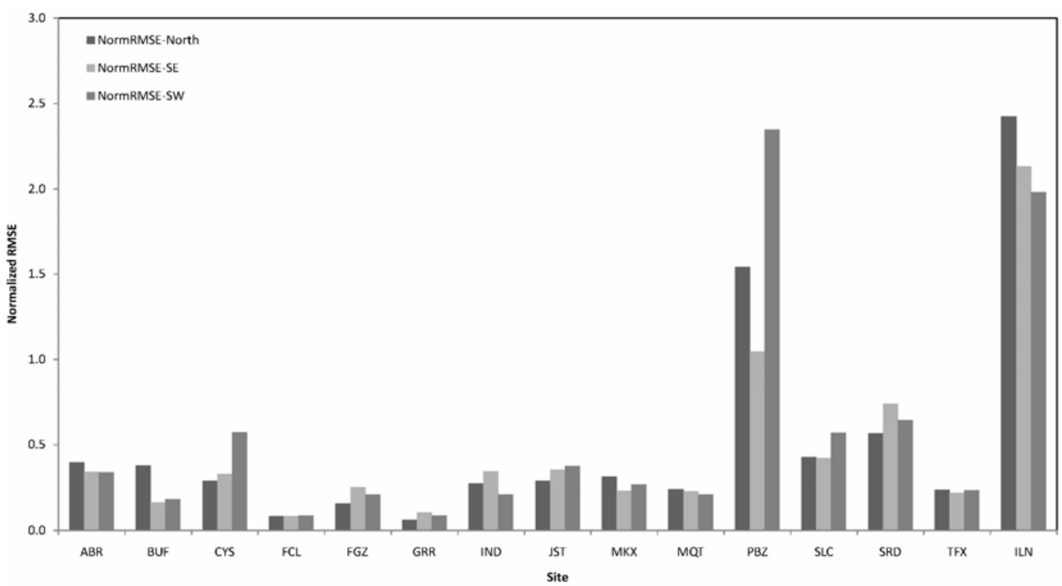

Figure 4. Normalized root mean squared error for sensors vs. manual depth at each sensor by site.

Total Snow Depth

Figures 5 and 6 provide the MAE and normalized RMSE for each sensor compared to the traditional manual total snow depth measurement. There are many sites with MAE larger than 2 cm and most of these errors are due to wind redistribution. Figures 7 and 8 illustrate data for FCL and CYS, respectively with manual total snow depth on ground plotted with the sensor data for the entire season. These plots show the differences that can be seen due to site exposure. The problems with ILN and PBZ listed above also hold true for this comparison. BUF had problems with wind redistribution as well. The North sensor was a bit more shielded and matched closer to the manual observation than either the SE or SW sensors. The MAE for GRR is higher for the North and SW sensors. This is mainly attributed to blizzard conditions in February where the SE tracked closer to observed snow depth. It is also important to note that GRR measures snowfall and snow depth within a double ring snow fence, which may affect the manual observations at this site. JST is located at an airport near the top of a ridge which makes it highly prone to wind scour and redistribution which caused high errors between the sensors and manual observations. This fact illustrates that automated snow measurements for airport locations may need to be taken off the main weather station to a satellite location with better exposure. MQT also illustrates large MAE's, which are mainly attributed to spatial variability in a deep snowpack. The manual observations tracked the pattern of accumulation and ablation well. The North sensor tracked closest to the magnitude of depth for most of the snow season until April when the SW tracked closest to the magnitude of the manual observations. The manual snow depth at MQT was also only reported to the nearest 2.5 cm, which contributes some of the error. The remaining sites had MAE's less than 2 cm which falls within the NWS requirement of 2.5 cm for snow depth. The RMSE's point to nearly the same locations as the MAE as well as highlight the large errors at ILN and PBZ.

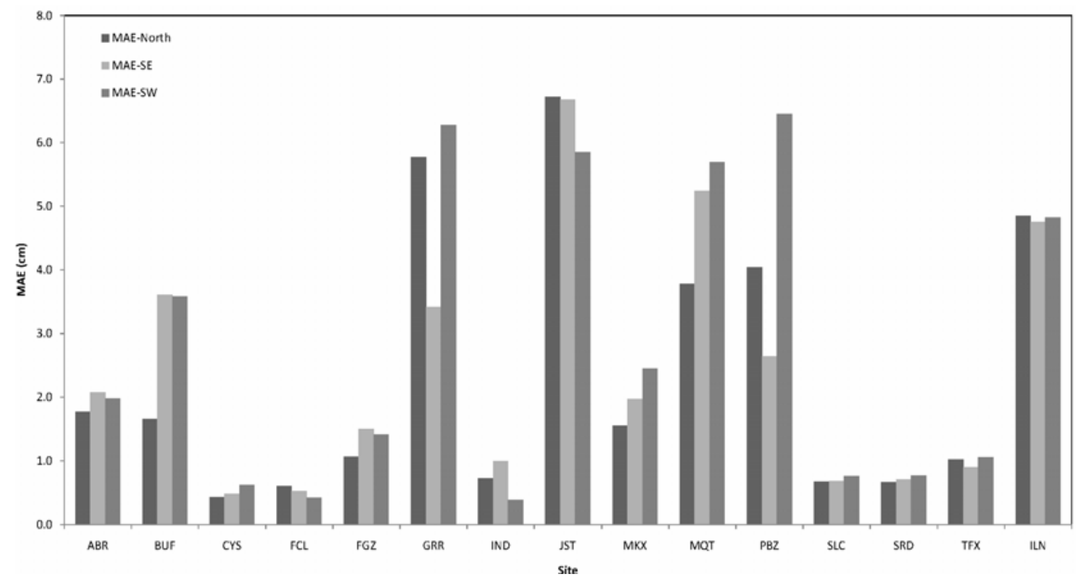

Figure 5. Mean absolute error (cm) for sensors vs. manual total snow depth by site.

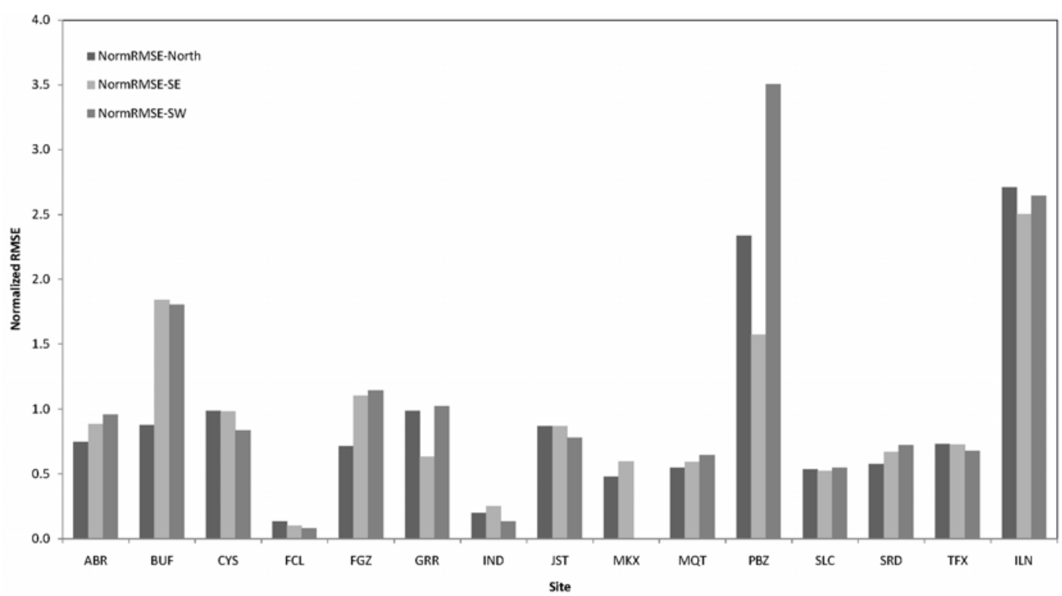

Figure 6. Normalized root mean squared error for sensors vs. total snow depth by site.

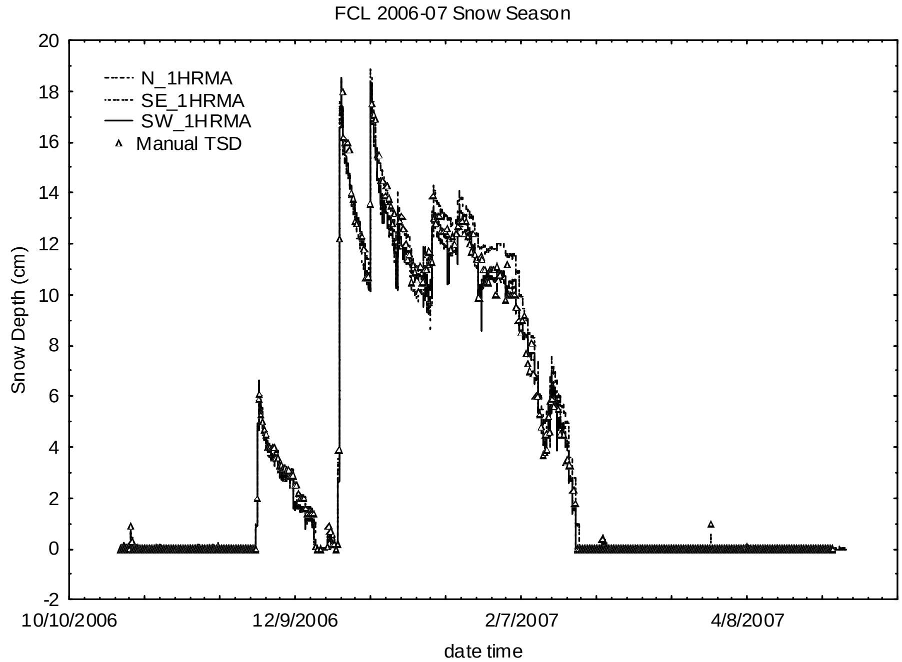

Figure 7. Fort Collins, CO (FCL) sensor data (lines) with manual total snow depth readings (triangles).

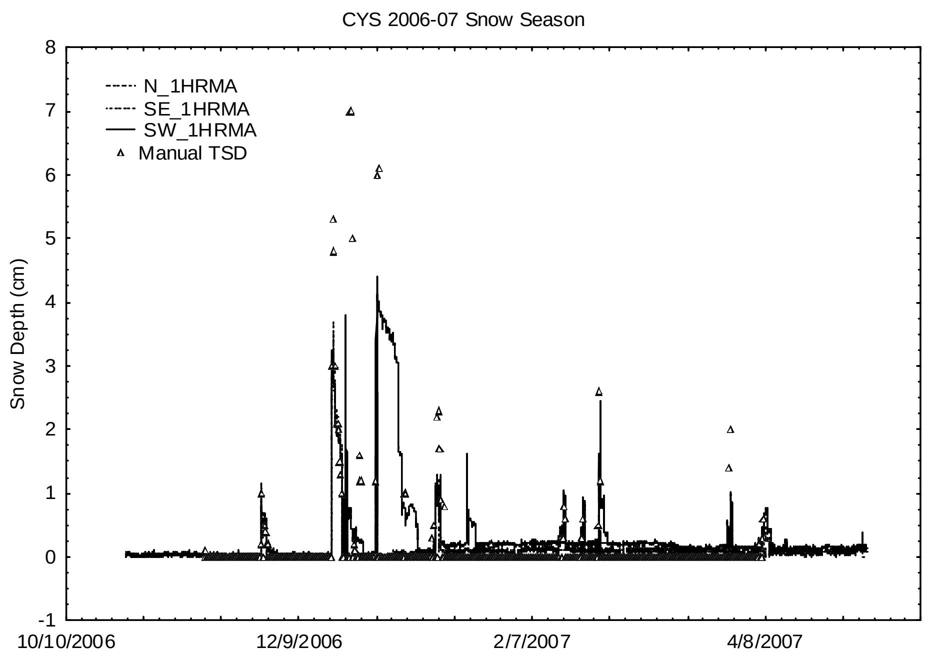

Figure 8. Cheyenne, WY (CYS) sensor data (lines) with manual total snow depth readings (triangles).

Manual Snow Measurement Uncertainty

A major assumption of this work is that manual observations are the "ground truth" measurement; however, snow measurements can be quite subjective and that is amplified even further with storm magnitude and wind-blown snow. Manual observations can vary from site to site and observer to observer creating biases in the data. A small investigation was done using a high density observing network of volunteer weather observers called CoCoRaHS (Cifelli *et al.,* 2005). Only locations that were known to be highly homogenous (small area, many observers) were used. Figure 9 shows the results from Denver County, CO with a high density of observers. Overall, results showed that reported snowfall and snow depth standard deviations increased as snow storm size increased. Storms ranging from 13-25 cm had a snowfall standard deviation of 2 cm while snow depth standard deviation was 8 cm. There are only a few observations on the higher end of the snow range, which is due to the fact that these storms are more uncommon than the smaller storms. This type of analysis illustrates that even though manual observations have been the historic standard, it may not be appropriate to call manual observations “ground truth” due to the inherent subjectivity of the measurements. Automated measurements can alleviate the some of the uncertainty of a rather subjective measurement. Much more work is anticipated on this evaluation of errors associated with manual snow measurements.

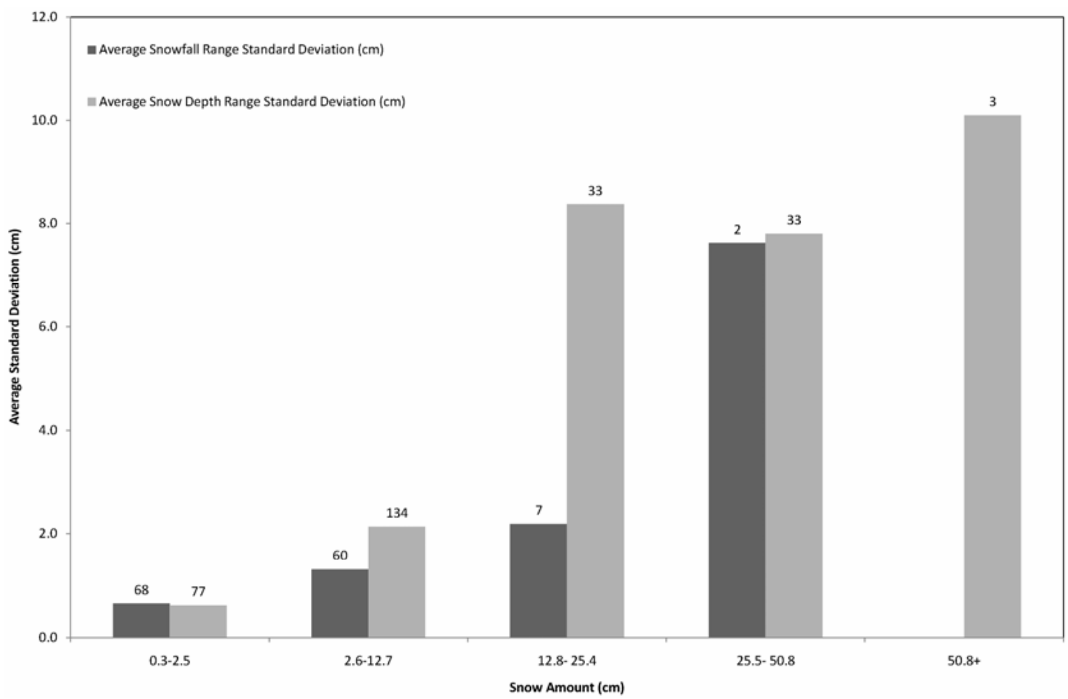

Figure 9. Denver county, CO average manual snowfall and snow depth standard deviation by snow amount. The number of storms in each snow amount is given above the columns.

CONCLUSIONS

Error analysis showed that the majority of sites represented the snow under the sensor within 2 cm, while the total snow depth measurement had errors up to 7 cm, but most sites were within 2 cm of the manual total snow depth measurement. Higher total snow depth errors are explainable by siting, wind redistribution and resolution of manual data. The primary source of error is simply the variability in snow accumulation from point-to-point and the challenge of positioning the sensors in representative locations to capture and hold snow comparable to surrounding areas. Even with significant winds and open exposures, most snow events were reasonably indicated at most sites. In an effort to put these errors in better context, work on manual observation uncertainty is being performed and preliminary results suggest that errors associated with manual observations can be as high 10 cm in some cases. Much more data needs to be analyzed to confidently apply the manual observation error bars to the sensor analysis. This work is on-going and will continue through the 2007-2008 season.

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