Evaluation of Ultrasonic Snow Depth Sensors for U.S. Snow Measurements

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ABSTRACT

Ultrasonic snow depth sensors are examined as a low cost, automated method to perform traditional snow measurements. In collaboration with the National Weather Service, nine sites across the United States were equipped with two manufacturers of ultrasonic depth sensors: the Campbell Scientific SR-50 and the Judd Communications sensor. Following standard observing protocol, manual measurements of 6-h snowfall and total snow depth on ground were also gathered. Results show that the sensors report the depth of snow directly beneath on average within ±1 cm of manual observations. However, the sensors tended to underestimate the traditional total depth of snow-on-ground measurement by approximately 2 cm. This is mainly attributed to spatial variability of the snow cover caused by factors such as wind scour and wind drift.

After assessing how well the sensors represented the depth of snow on the ground, two algorithms were created to estimate the traditional measurement of 6-h snowfall from the continuous snow depth reported by the sensors. A 5-min snowfall algorithm (5MSA) and a 60-min snowfall algorithm (60MSA) were created. These simple algorithms essentially sum changes in snow depth using 5- and 60-min intervals of change and sum positive changes over the traditional 6-h observation periods after compaction routines are applied. The algorithm results were compared to manual observations of snowfall. The results indicated that the 5MSA worked best with the Campbell Scientific sensor. The Campbell sensor appears to estimate snowfall more accurately than the Judd sensor due to the difference in sensor resolution. The Judd sensor results did improve with the 60-min snowfall algorithm. This technology does appear to have potential for collecting useful and timely information on snow accumulation, but determination of snowfall to the current requirement of 0.1 in. (0.25 cm) is a difficult task.

1. Introduction

Snowfall and snow depth measurements are important to a variety of disciplines including commerce, transportation, winter recreation, and water supply forecasting. The western United States depends on snowfall for 75% of their annual water supply (Doesken and Judson 1997). For most of the United States outside of the high, mountainous regions of the West, the National Weather Service (NWS) is the primary source for snow measurements. Surface observations available from the NWS currently include several hundred airport weather stations across the country where observations of many weather elements are transmitted hourly. This network is supplemented by NWS historic Cooperative Observer Network (NRC 1998) with several thousand weather stations measuring temperature and precipitation once daily. In the early 1990s the NWS began deploying the Automated Surface Observing System (ASOS) at major U.S. airports in conjunction with the Federal Aviation Administration and the Department of Defense. The ASOS measures a variety of meteorological components including temperature, humidity, wind speed and direction, precipitation amounts, presence and type of precipitation, sky condition, visibility and obstructions to vision, and barometric pressure. ASOS does not measure traditional snow parameters, except for the liquid equivalent of snow. Since its beginning, ASOS has used a heated tipping-bucket rain gauge to record precipitation including rain and the water content of solid precipitation

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(Doesken and McKee 1999). The use of this type of gauge creates problems of underreporting precipitation particularly for snow falling at temperatures several degrees below freezing (Doesken and McKee 1999). However, ASOS is now converting the precipitation gauge to the all-weather precipitation gauge (AWPAG), which is a weighing-type gauge and more capable of measuring nonliquid precipitation (NWS 2004).

Prior to the recent deployment of ASOS, many cities had snowfall records dating back to the late 1800s. Many of these long-term snowfall station records were discontinued or transferred to stations some distance away that may not be representative (McKee et al. 2000). There is a definite need and interest in quality long-term snowfall records in the United States, yet Robinson (1989), who studied historic snowfall records, found that there are very few locations across the country with complete and accurate snow measurement records. Implementation of ASOS further magnified this problem. An ongoing study of snowfall trends in the United States has documented decades of observational inconsistency, even when only manual observations at long-term stations are considered (Kunkel et al. 2007). This study aims to evaluate the use of ultrasonic snow depth sensors to restore snowfall and snow depth measurements at ASOS and other automated stations and to potentially achieve a higher degree of data continuity.

a. *Traditional snow measurements*

The traditional NWS snow measurements consisted of gauge precipitation, snowfall, snow depth, and (at a subset of stations) snow water equivalent (SWE). *Gauge precipitation* is defined as the amount of liquid equivalent obtained by an NWS nonrecording, standard precipitation gauge (NWS 2006). *Snowfall* is defined as the maximum accumulation of new snow since the last observation and is customarily measured manually with a ruler on a snow measurement board. The measurement board is cleared after each observation. *Snow depth* is defined as the total depth of snow on the ground at the time of observation and includes both old and new snow on undisturbed surfaces. The measurement of snow depth may be the average of several total depth measurements to obtain a representative sample (NWS 1996). Gauge precipitation is measured to the hundredth of an inch, snowfall is measured to the tenth of an inch, and total snow depth is observed to the whole inch. Airport weather stations traditionally measured snowfall every 6 h, while Cooperative Observer Network stations typically measure once a day.

This evaluation of ultrasonic snow depth sensors for measuring total depth of snow on ground and fresh snowfall estimation from changes in total snow depth is done with respect to manual measurements assumed to be "ground truth." Uniformity and consistency in manual measurements were strongly encouraged within the team of cooperators who helped collect data from our test sites. However, there is inherent uncertainty in manual measurements due to the fact that snow melts, settles, blows, and drifts and does not accumulate uniformly on the ground. Depending on the time of day, the frequency, the measurement surface (i.e., grass, snow measurement board, etc.), the extent of nonuniformity in snow accumulation, and the overall care and detail of the individual observers, variability in manual observations must be expected. The authors are not aware of studies that have quantified this uncertainty in terms of measurement error, but would easily expect it to be in the magnitude of ±25%. The authors will quantify this in future research as it is not in the scope of the current study; however, it will impact a transition from manual to automated snow measurements.

b. *Ultrasonic snow depth sensors*

Ultrasonic depth sensors (USDS) have been under development since the early 1980s (Goodison et al. 1984) with recent implementation into the Snow Telemetry (SNOTEL) network (Lea and Lea 1998). These sensors send out an ultrasonic (50 kHz) sound pulse and measure the time it takes to reach the ground or snow surface and reflect back to the sensor. The ultrasonic pulse projects downward over a cone of 22° (Fig. 1). It is important to ensure that there is no interference with the 22° cone such as trees, wires, installation hardware, etc. The time for the pulse to return to the transducer is adjusted for the speed of sound in air based on measured air temperature, and the timing is converted to a distance via internal algorithms.

To adjust the speed of sound in air (V_{sound}) in meters per second for the ambient air temperature (T_a) in kelvins, Eq. (1.1) is used:

$$V_{\mathrm{sound}} = 331.4(T_a/273.15)^{0.5}. \tag{1.1}$$

The distance the sound pulse travels decreases as snow accumulates on the ground, thus reducing the time for the pulse to return to the sensor.

This study aimed to examine sensors already available "off the shelf" to local consumers. Here we explore how well these sensors work, as well as how and why they fail. Most importantly, we compare USDS measurements to traditional manual observations of snowfall and snow depth. Two manufacturers were tested in this study, the Judd Communications sensor and the Campbell Scientific SR-50 (Figs. 2 and 3).

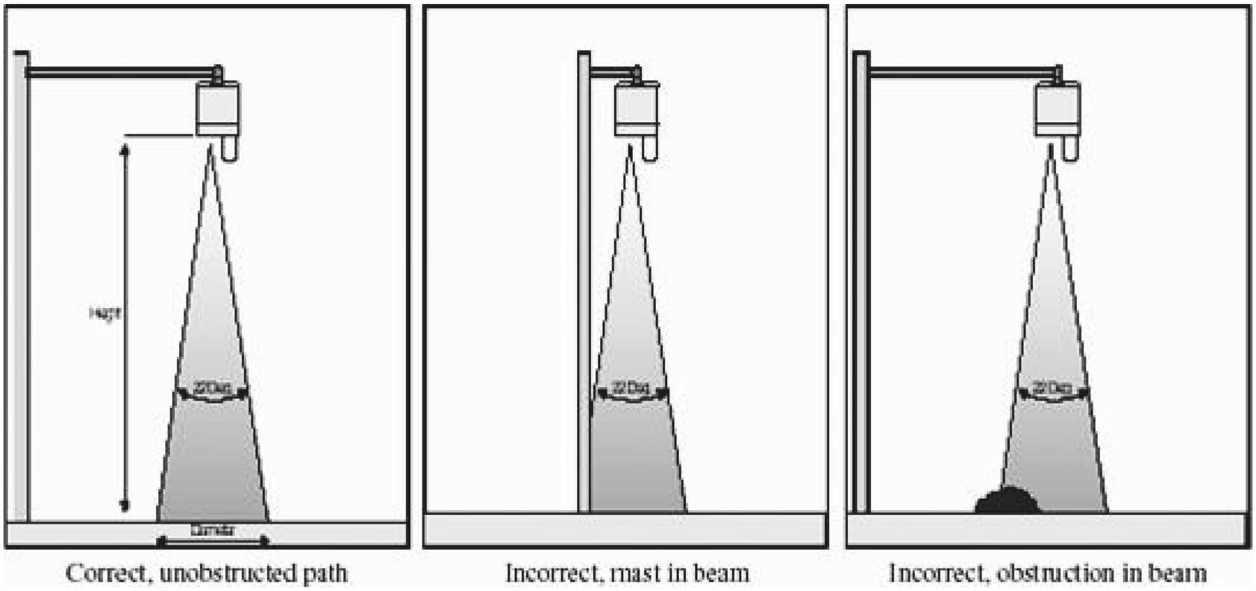

FIG. 1. Diagram showing the 22° cone utilized by the ultrasonic sensors (Judd 2005).

2. Study sites

This research project included nine sites (Fig. 4) throughout the coterminous United States that tested both the Judd Communications and Campbell Scientific depth sensors with manual measurements during the 2004/05 snow season (Table 1). Additional sites were a part of the study, but only those stations where Judd, Campbell, and manual observations were taken coincidently will be shown here. Six sites were located at NWS forecast offices. The Davis, West Virginia, site was an NWS Cooperative site whose observer volunteered for the project. Other non-NWS sites were Fort Collins and Steamboat Springs, Colorado. Sites were chosen on willingness to participate, although the amount of snow historically received was also taken into account. Because of technical problems, the use of the data from Caribou, Maine, and Indianapolis, Indiana, are limited.

FIG. 2. Judd Communications depth sensor (Judd 2005).

The siting of USDS is very important to achieving quality data. A site sheltered from wind effects (i.e., a forested clearing) would be an ideal condition; however, this is rarely available. Each individual site was responsible for mounting and installing the sensors and placing them as close to the customary observing point as possible to ensure similar exposure. The basic setup was similar for each site (Fig. 5).

The sensors were calibrated to read zero snow depth on a level, white expanded polyvinylchloride (PVC) snowboard under snow-free conditions. Snowboard sizes were either 81 cm × 61 cm or 122 cm × 122 cm depending on the height the sensors were mounted off the ground. Different sizes were used to ensure the 22° cone was completely within the bounds of the snowboards. Sensors were mounted perpendicular to the surface of interest at a height of 0.5 to 10 m off the ground depending on the historic maximum snow depth at each location. The sensors were mounted as close as possible to each other in order to minimize spatial variability and allow direct comparison of measurements. The sensors also needed to be far enough apart that the 22° cone of influence utilized by the ultrasonic pulses

FIG. 3. Campbell Scientific SR-50 sensor (Campbell Scientific, Inc. 2005).

did not overlap and interfere with the other sensor. The sensors were set up perpendicular to the leveled PVC snowboards. In some cases the snowboards were placed on the ground surface and leveled while others were framed with boards in order to avoid frost heaving by elevating the boards slightly off the ground surface. Frost heaving can potentially change the sensor to ground surface height due to the snowboard moving during freeze–thaw cycles. The sensors need to be rigidly mounted in order to minimize effects from strong wind, which can cause the sensors to vibrate and possibly return inaccurate snow depths.

3. Methods

a. Manual data

Snow measurements were made with an NWS snow measurement ruler, 10.2-cm (4 in.) diameter plastic all-weather precipitation gauge, 20.3-cm (8 in.) diameter standard precipitation gauge, and NWS expanded PVC snowboards. Expanded PVC is the chosen NWS material for snowboards and was implemented nationally in 2002; therefore, this study also used this material. The snow measurement ruler is made of metal labeled in increments of 0.25 cm (0.1 in.). The 10.2-cm plastic gauge was chosen to perform snow cores of SWE since it is considerably easier to use than the bulky NWS standard gauge. An NWS snowboard (in addition to larger snowboards beneath the sensors either 81 cm × 61 cm or 122 cm × 122 cm) was used to measure snowfall accumulation. The snowfall was measured every 6 h, snow was then cleared from each board, and boards were then repositioned on the surface of the snow. Six-hour measurements were taken only when snow was falling. The total snow depth observed at each site was the measurement provided from the customary observing point at each station. Total snow depth was measured at least once per day if snow was present on the ground. Multiple total depth samples were taken to obtain one integrated measurement when the observers felt it necessary, based on how spatially variable the snow cover was. The number of depth samples taken to obtain a representative sample was also recorded. The snow depth in the immediate vicinity of the USDS was also recorded. The snowboard beneath the ultrasonic sensors was never cleared. Notes were also made in reference to snow crystal type, wind speed, presence of blowing/drifting snow, etc.

The manual measurements of snowfall and snow depth were considered ground truth for this study since they are the traditional measurements. It is important to note that there may have been differences in techniques between sites, as well as among observers. The objective of the work was to test sensor performance and begin to develop a method to derive 6-h snowfall estimates from the continuous series of depth measurements from the USDS using traditional measurements as ground truth.

b. Automated data

The USDS measured snow depth every 5 min utilizing multiple echo processing (MEP). MEP is an internal sensor algorithm that sends multiple sound pulses and compares the measurements. If the measurements are not within ±1 cm another pulse is sent and the oldest is discarded until the measurements meet the precision criteria (Campbell Scientific, Inc. 2005; Judd 2005). Data were collected from the automated sensors at each site using a Campbell Scientific CR10X datalogger and downloaded with PC208W datalogger software using a laptop computer. The data outputs included date, time, battery voltage, Judd sensor depth, Judd temperature, Campbell sensor depth, and Campbell temperature. It should be noted that Cheyenne, Wyoming, and Milwaukee, Wisconsin, had one addi-

FIG. 4. Station locations for USDS study.

tional Judd sensor for which the depth and temperature were also output.

c. Factors affecting sensor performance

To identify factors affecting sensor performance the data were investigated both qualitatively and quantitatively. The main causes of errors with the ultrasonic sensors are listed in the manufacturer manuals as follows: "*the sensor is not perpendicular to the target surface, target is small and reflects little sound, target surface is rough and uneven, target is a poor reflector of sound (i.e. low density snow), and transducer is obstructed by ice/snow*" (Campbell Scientific, Inc. 2005; Judd 2005). Also, Goodison et al. (1984) suggested that moderate to heavy snowfall caused problems with sensor performance due to an attenuation of the sound pulse. They reported that the surface of the snow structure (loose powder versus hard packed crust) may cause the sensor to underestimate due to the signal penetrating the snowpack. In a performance update during the development of these sensors, Goodison et al. (1988) also identified that blowing and drifting snow caused anomalous measurements, but also commented on how they are easily quality controlled.

TABLE 1. Sensor inventory by site.

Site	Judd	Campbell
Buffalo, NY	1	1
Caribou, ME	1	1
Cheyenne, WY	2	1
Davis, WV	1	1
Fort Collins, CO	1	1
Indianapolis, IN	1	1
Marquette, MI	1	1
Milwaukee, WI	2	1
Steamboat Springs, CO	1	1

The factors that affect sensor performance are of importance because they cause erroneous data points that are easily identified and removed (Fig. 6a). Table 2 provides the percentage of these erroneous measurements (i.e., "spikes") for the entire season and of those that occurred during snow events. It is clear that these happen infrequently, and when they do occur it is most often during snow events. Caribou, Maine, and Steamboat Springs, Colorado, show high percentages of spikes due to malfunctioning equipment. For this study, once the erroneous data points were identified by date and time, the manual data were utilized to find possible causes of error. The manual data were only taken every 6 h with observers reporting anything over the entire 6-h period that could cause problems with sensor performance. The observations were assumed to be valid over the previous 6-h time period unless it was otherwise ascertained that the manual reports could not be the cause of degraded sensor performance.

d. Comparison of sensor snow depth to manual snow depth

An objective of this study was to quantify how accurately the sensors measure the depth of snow on the ground. Because of the nature of ultrasonic depth sen-

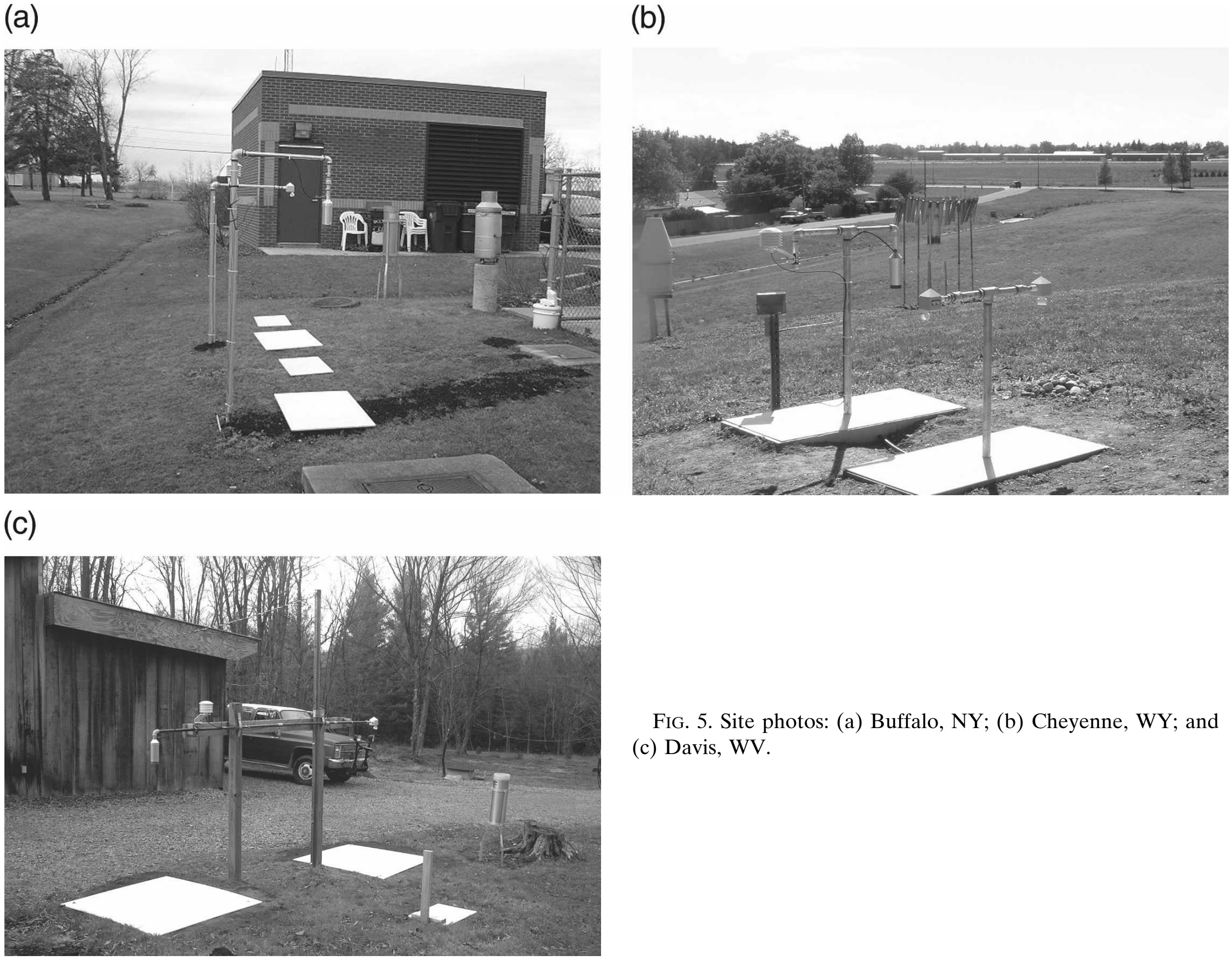

FIG. 5. Site photos: (a) Buffalo, NY; (b) Cheyenne, WY; and (c) Davis, WV.

sors having "noisy" data (Fig. 6b), moving averages were applied to create a smooth snow depth time series for comparison. Both 1- and 3-h moving averages were applied to the data to give a better understanding of which amount of smoothing worked best for each sensor at each site. The main reason for the data smoothing was the sensor data resolution, which for the Judd is 3 mm (Judd 2005) and the Campbell 0.1 mm (Campbell Scientific, Inc. 2005). The total depth of snow on the ground can be an average of several depth measurements to obtain a representative measurement, if spatial variability is deemed present. To minimize the effects of spatial variability, the snow depth on the boards beneath the sensors was also measured. Both of the measurements were then paired with the USDS reading. To describe errors associated with both measurements the average difference, standard deviation of difference, mean absolute error, and root-mean-square errors (RMSEs) were calculated for each comparison. The root-mean-square error for the measurements was normalized by the average snow depth at each location (J. zumBrunnen, Colorado State University, 2005, personal communication). This was done in order to compare the RMSE from site to site. For example, an RMSE at a site with 25 cm of annual snowfall is much more significant than the same RMSE at a site receiving 150 cm of annual snowfall.

e. Six-hour snowfall algorithm

To create a snowfall algorithm, 6-h snowfall was calculated from the 5-min sensor data. This calculation was done using two different methods, a 5-min snowfall algorithm and a 60-min snowfall algorithm. Using only the change in snow depth every 6 h would cause snowfall to be omitted if it accumulated and melted within the 6-h period.

1) FIVE-MINUTE SNOWFALL ALGORITHM (5MSA)

The first method used a 5-min time step for calculating snowfall according to Eq. (3.1) where t is time in

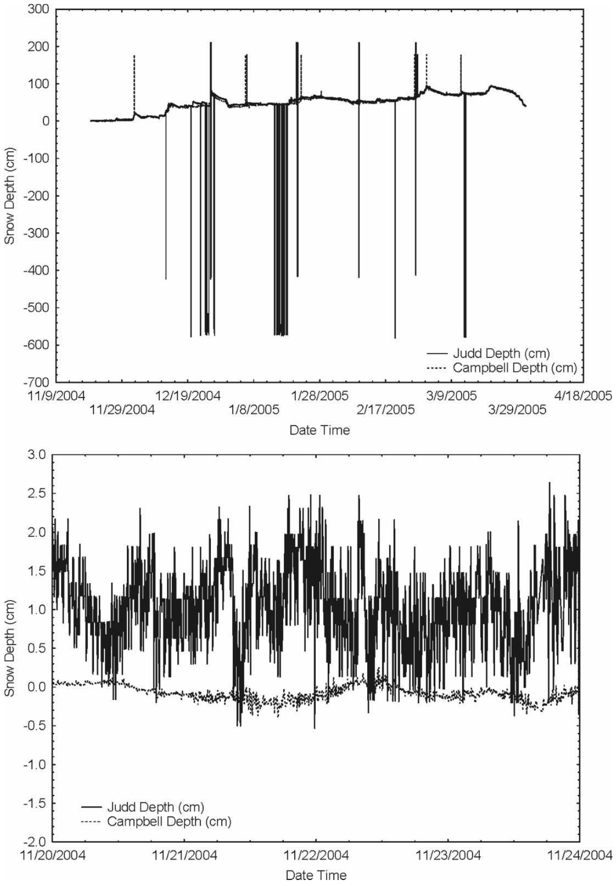

FIG. 6. Marquette, MI, example of raw sensor data (top) showing erroneous data points and (bottom) demonstrating normal variation.

minutes, i is time in hours, j is the number of 5-min intervals, and d_s is snow depth. If the sensor snow depth increased over the 5-min period the difference was taken and called 5-min snowfall. If the depth did not increase a zero was entered. The 5-min snowfall values were then summed over the 6-h observation intervals used by each site to obtain the 5-min snowfall algorithm for 6-h snowfall ($6\mathrm{HSF}_{5\mathrm{MSA}}$):

$$6\mathrm{HSF}_{5\mathrm{MSA}} = \sum_{i}^{i+6} \sum_{j=0}^{11} (d_{s_{t+5}} - d_{s_t}) \quad \text{for all} \quad (d_{s_{t+5}} - d_{s_t}) > 0. \tag{3.1}$$

2) SIXTY-MINUTE SNOWFALL ALGORITHM (60MSA)

The second method took the change in snow depth over a 60-min interval according to Eq. (3.2). The positive 60-min changes in snow depth were summed over the 6-h observation periods to create the 60-min snowfall algorithm for 6-h snowfall ($6\mathrm{HSF}_{60\mathrm{MSA}}$):

$$6\mathrm{HSF}_{60\mathrm{MSA}} = \sum_{i}^{i+6} (d_{s_{t+60}} - d_{s_t}) \quad \text{for all} \quad (d_{s_{t+60}} - d_{s_t}) > 0. \tag{3.2}$$

Both of these methods were performed on both 1- and 3-h moving averages in order to determine the effect of smoothing as well as the degree of smoothing required by each sensor to accurately estimate 6-h snowfall.

3) COMPACTION

Both of the above methods calculated snowfall over small time periods that do not take into account compaction of the snowpack over the longer 6-h period. Once the 6-h snowfall values were calculated, compaction by both metamorphism and overburden were considered. Metamorphism takes into account the breakdown of snow crystals resulting in a compacted snow depth, while overburden considers the weight of new snow overlying old snow. Temperature-based compaction equations were obtained from the SNTHERM.89 one-dimensional snowpack model by Jordan (1991), who modified Anderson's (1976) equations. This compaction model was chosen since temperature was readily available.

TABLE 2. Percentage of data spikes for the entire season and those occurring during snow events.

Site	Judd—entire season	Judd—during snow	Campbell—entire season	Campbell—during snow
Buffalo, NY	0.26	40.40	0.01	100.00
Caribou, ME	8.86	1.82	14.01	3.88
Cheyenne, WY	0.00	55.00	0.00	0.00
Davis, WV	0.04	94.44	0.00	0.00
Fort Collins, CO	0.05	86.96	0.13	20.31
Indianapolis, IN	0.00	0.00	0.00	0.00
Marquette, MI	2.54	13.58	0.18	65.67
Milwaukee, WI	0.00	4.17	0.00	0.00
Steamboat Springs, CO	6.24	3.13	17.85	31.94

TABLE 3. Summary statistics for sensor and manual depth below sensor comparison. Statistics were performed for both 1- and 3-h moving averages (1HRMA and 3HRMA, respectively) and include average difference in depth (AD), std dev of AD, number of observations (N), MAE, and RMSE standardized by average snow depth (RMSE/AVSD).

Site	Sensor and smoothing	AD (cm)	Std dev (cm)	N	MAE (cm)	RMSE/AVGSD
Buffalo, NY	Judd (1HRMA)	0.20	2.23	434	1.33	0.30
	Judd (3HRMA)	0.19	2.17	434	1.31	0.24
	Campbell (1HRMA)	0.23	2.03	434	1.24	0.24
	Campbell (3HRMA)	0.23	1.97	434	1.23	0.26
Cheyenne, WY	East Judd (1HRMA)	0.31	1.68	143	0.85	0.72
	East Judd (3HRMA)	0.22	1.66	151	0.85	0.71
	West Judd (1HRMA)	0.20	2.38	47	1.37	1.00
	West Judd (3HRMA)	−0.20	2.50	55	1.56	1.05
	Campbell (1HRMA)	−0.15	1.39	143	0.57	0.59
	Campbell (3 HRMA)	−0.23	1.40	151	0.59	0.60
Davis, WV	Judd (1HRMA)	0.43	11.03	201	5.78	0.88
	Judd (3HRMA)	0.39	11.02	201	5.81	0.88
	Campbell (1HRMA)	−0.01	10.99	201	5.96	0.88
	Campbell (3HRMA)	−0.03	10.98	201	5.96	0.88
Fort Collins, CO	Judd (1HRMA)	0.38	1.36	529	0.65	1.07
	Judd (3HRMA)	0.37	1.34	529	0.64	1.05
	Campbell (1HRMA)	0.15	1.35	529	0.50	1.03
	Campbell (3HRMA)	0.20	1.33	529	0.50	1.02
Marquette, MI	Judd (1HRMA)	−1.36	2.69	571	2.08	0.07
	Judd (3HRMA)	−1.36	2.72	571	2.08	0.07
	Campbell (1HRMA)	−4.30	3.15	571	4.55	0.12
	Campbell (3HRMA)	−4.30	3.16	571	4.55	0.12
Milwaukee, WI	Judd1 (1HRMA)	N/A	N/A	N/A	N/A	N/A
	Judd1 (3HRMA)	N/A	N/A	N/A	N/A	N/A
	Judd2 (1HRMA)	−0.08	1.06	244	0.70	0.14
	Judd2 (3HRMA)	−0.11	1.04	244	0.70	0.14
	Campbell (1HRMA)	0.49	2.17	220	1.25	0.30
	Campbell (3HRMA)	0.49	2.16	220	1.25	0.30
Steamboat Springs, CO	Judd (1HRMA)	−0.08	0.58	35	0.37	0.00
	Judd (3HRMA)	0.22	2.16	35	0.81	0.01
	Campbell (1HRMA)	−0.18	0.87	29	0.61	0.01
	Campbell (3HRMA)	0.15	2.32	29	1.02	0.01

4) STATISTICS

The statistics used to describe how well the algorithms performed included percent difference in total seasonal snowfall accumulation, a Nash–Sutcliffe R-squared (Nash and Sutcliffe 1970) on the cumulative seasonal snowfall, and MAE on the incremental 6-h snowfall measurements. The percent difference in seasonal totals describes how well the sensors did at measuring the total seasonal accumulations. The Nash–Sutcliffe R-squared described how well the cumulative sensor estimated snowfall modeled the cumulative manual snowfall pattern. A perfect Nash–Sutcliffe R-squared is 1.0 with negative values indicating that the observed mean manual 6-h snowfall is a better predictor than the model; it is a measure of the model efficiency. The MAE described how well the calculated sensor 6-h snowfall values matched the manual 6-h snowfall measurements. The errors of commission (CEs) and errors of omission (OEs) were also calculated to describe what proportion of time the algorithms correctly reported the occurrence or nonoccurrence of snowfall. The CEs illustrate the proportion of time the sensors reported snowfall when none was measured manually. The OEs illustrate the proportion of time the sensors reported no snowfall when snowfall was measured manually.

4. Results

a. *Comparison of automated and manual snow depth*

1) SENSOR COMPARISON TO DEPTH AT SENSORS

The statistics for the sensors compared to the depth in the immediate vicinity of the sensors are shown in Table 3. The descriptive statistics vary by site and sensor. The results were similar for the two degrees of smoothing investigated. The average difference in snow depth ranged from −4.3 to 0.5 cm; negative values indicated the sensors underestimated snow depth while

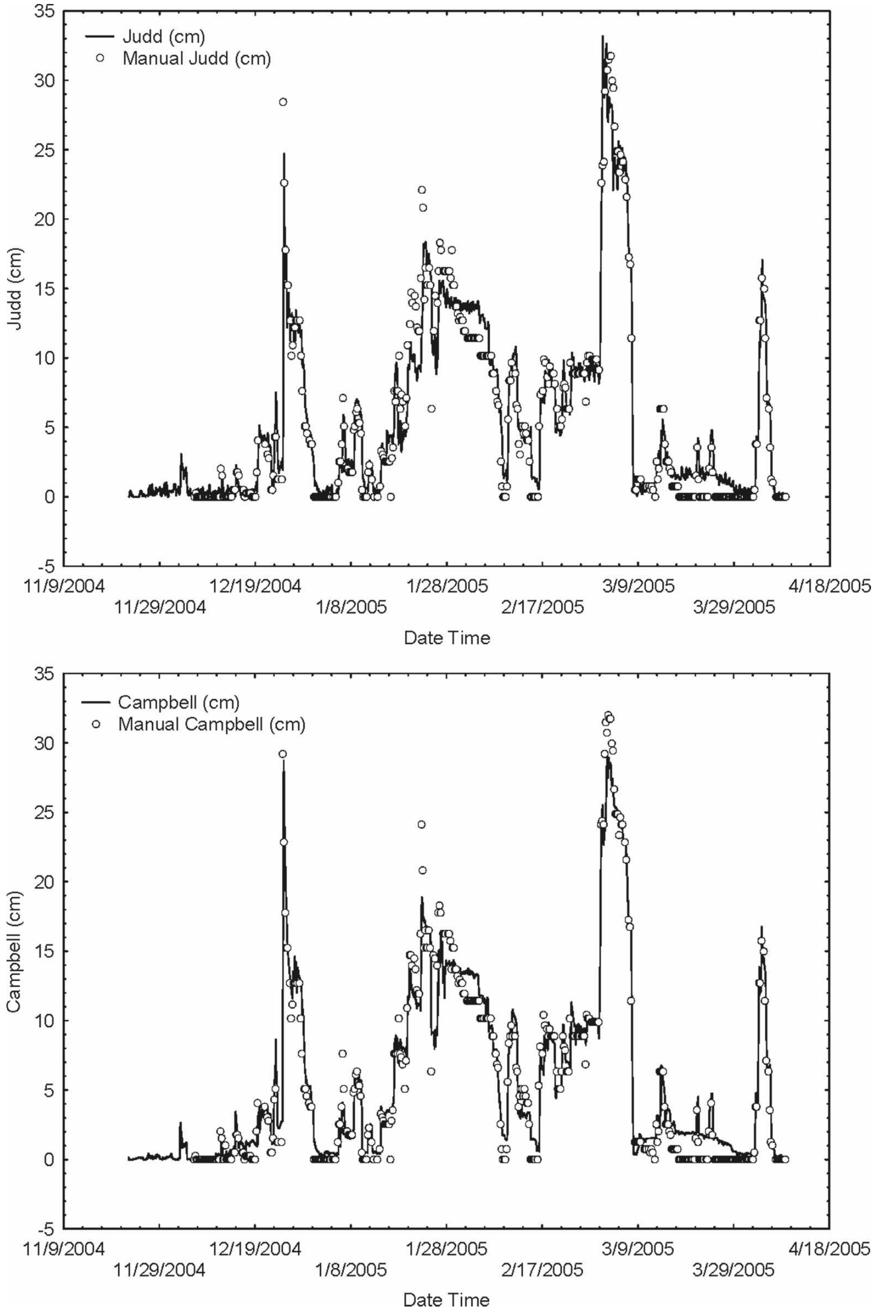

FIG. 7. Buffalo, NY, manual depth at sensors plotted with automated data for the (top) Judd and (bottom) Campbell sensors for the snow season 2004/05.

positive values indicated they overestimated. The standard deviation of average difference ranged from 0.58 to 11 cm. The mean absolute error (MAE) ranged from 0.37 to 6.0 cm. The normalized RMSE ranged from 0 to 1.1.

Figure 7 shows plots of Buffalo, New York, sensor snow depth plotted with manual snow depth next to each sensor. Both sensors overestimated the observed depth by an average of 0.2 cm with a standard deviation of 2.2 cm for the Judd and 2.0 cm for the Campbell. The MAE for the Judd was 1.3 cm and 1.2 cm for the Campbell. The normalized RMSE was 0.24 for both.

2) SENSOR COMPARISON TO TOTAL SNOW DEPTH

To illustrate the importance of using several depth measurements to obtain a representative total snow

TABLE 4. As in Table 3, but for summary statistics for sensor and manual total depth of snow comparison.

Site	Sensor and smoothing	AD (cm)	Std dev (cm)	N	MAE (cm)	RMSE/AVGSD
Buffalo, NY	Judd (1HRMA)	−1.40	3.46	438	2.34	0.49
	Judd (3HRMA)	−1.41	3.43	438	2.33	0.49
	Campbell (1HRMA)	−1.30	3.52	438	2.26	0.50
	Campbell (3HRMA)	−1.30	3.49	438	2.25	0.49
Cheyenne, WY	East Judd (1HRMA)	−0.76	3.02	176	1.44	1.31
	East Judd (3HRMA)	−0.79	2.99	184	1.42	1.31
	West Judd (1HRMA)	−0.47	2.83	176	1.32	1.21
	West Judd (3HRMA)	−0.51	2.84	184	1.36	1.22
	Campbell (1HRMA)	−1.59	3.70	176	1.72	1.70
	Campbell (3HRMA)	−1.59	3.71	184	1.75	1.70
Davis, WV	Judd (1HRMA)	−2.60	11.27	256	6.34	0.93
	Judd (3HRMA)	−2.63	11.27	256	6.36	0.88
	Campbell (1HRMA)	−2.43	11.18	256	6.16	0.92
	Campbell (3HRMA)	−2.44	11.18	256	6.15	0.92
Fort Collins, CO	Judd (1HRMA)	0.12	1.70	554	0.80	1.29
	Judd (3HRMA)	0.11	1.67	554	0.80	1.27
	Campbell (1HRMA)	−0.16	1.79	554	0.75	1.36
	Campbell (3HRMA)	0.02	1.74	554	0.76	1.35
Marquette, MI	Judd (1HRMA)	−2.75	2.98	641	3.23	0.09
	Judd (3HRMA)	−2.75	3.00	641	3.23	0.09
	Campbell (1HRMA)	−5.71	3.02	641	5.88	0.15
	Campbell (3HRMA)	−5.71	3.02	641	5.88	0.15
Milwaukee, WI	Judd1 (1HRMA)	0.08	1.58	245	1.25	0.21
	Judd1 (3HRMA)	0.07	1.56	245	1.25	0.21
	Judd2 (1HRMA)	−1.04	1.89	245	1.44	0.29
	Judd2 (3HRMA)	−1.07	1.87	245	1.46	0.29
	Campbell (1HRMA)	−0.50	2.61	245	1.74	0.36
	Campbell (3HRMA)	−0.51	2.61	245	1.74	0.36
Steamboat Springs, CO	Judd (1HRMA)	3.17	3.74	113	3.87	0.02
	Judd (3HRMA)	3.24	4.04	113	3.93	0.02
	Campbell (1HRMA)	−3.76	4.33	113	4.71	0.03
	Campbell (3HRMA)	−3.65	4.39	113	4.68	0.03

depth measurement, the same statistics as in the previous section were used to describe the difference between sensor snow depth and manual total snow depth (Table 4). The average difference ranged from −5.7 to 3.2 cm. The standard deviation of the average difference ranged from 1.6 to 11 cm. The MAE ranged from 0.75 to 6.4 cm. The RMSE was again normalized by average snow depth and it ranged from 0.02 to 1.7.

Figure 8 shows the sensor snow depth for Buffalo, New York, plotted with the manual total snow depth. Both sensors in Buffalo tended to underestimate the total snow depth that was manually measured. The Judd underestimated by 1.4 cm with 3.4-cm standard deviation. The Campbell underestimated it by 1.3 cm with a standard deviation of 3.5 cm. The MAE for both was 2.3 cm and the normalized RMSE was 0.50.

In an effort to describe the error between manual and automated measurements during snow and snow-free periods, a few select sites were investigated to estimate error during these two periods. Figure 9 illustrates the MAE using data from Buffalo, New York; Fort Collins, Colorado; Marquette, Michigan; and Milwaukee, Wisconsin. These sites were chosen because they had large datasets as well as the lowest MAE from the overall analysis. Figure 9 shows in nearly every case that the error between the sensors and manual total snow depth is higher during snow events than when snowfall is not present (i.e., only snow on ground).

b. Six-hour snowfall algorithm

1) FIVE-MINUTE SNOWFALL ALGORITHM

The results from the 5MSA favor the Campbell sensor at every site (Table 5). Results for Buffalo, New York, are presented. Figure 10a shows the cumulative 5MSA for the Judd sensor 1- and 3-h moving averages (hereafter referred to as 1HRMA and 3HRMA) while Fig. 10b shows both for the Campbell sensor. The percent difference in seasonal snowfall for the Judd

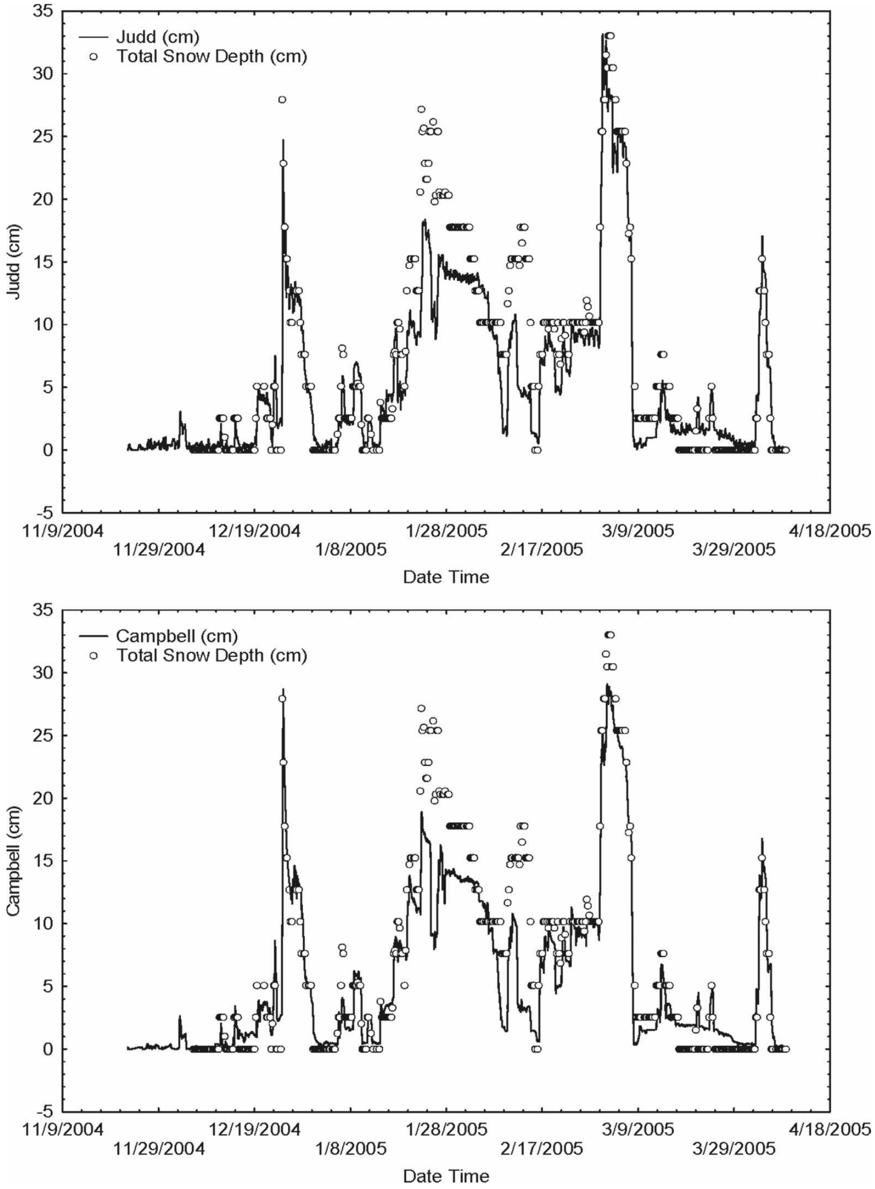

FIG. 8. Buffalo total snow depth plotted with automated data for the (top) Judd and (bottom) Campbell sensors for the snow season 2004/05.

1HRMA and 3HRMA was 70.5% and 10.7%, respectively (Table 5). The percent difference for both the Campbell 1HRMA and 3HRMA was 0.95% and 41.8%, respectively (Table 5). The Nash–Sutcliffe *R*-squared for the Judd 1HRMA and 3HRMA was −0.42 and 0.80, respectively (Table 5). For the Campbell 1HRMA and 3HRMA, the Nash–Sutcliffe *R*-squared was 0.98 and 0.03, respectively (Table 5). The MAE in the incremental snowfall measurements for the Judd 1HRMA and 3HRMA was 0.93 and 0.82 cm, respectively (Table 5). The MAE for the Campbell 1HRMA and 3HRMA was 0.64 and 0.73 cm, respectively (Table 5). The Campbell 1HRMA did the best at predicting 6-h snowfall for Buffalo using this method. The Campbell 1HRMA had the highest Nash–Sutcliffe *R*-squared as well as the lowest percent difference in seasonal total snowfall and MAE.

The CEs are shown in Fig. 11. The Campbell 3HRMA consistently had the lowest CE, followed by the Campbell 1HRMA, then the Judd 3HRMA and finally the Judd 1HRMA. The minimum CE was achieved by the Campbell 1HRMA in Fort Collins, Colorado. The maximum CE was achieved by the Judd 1HRMA in Steamboat Springs, Colorado.

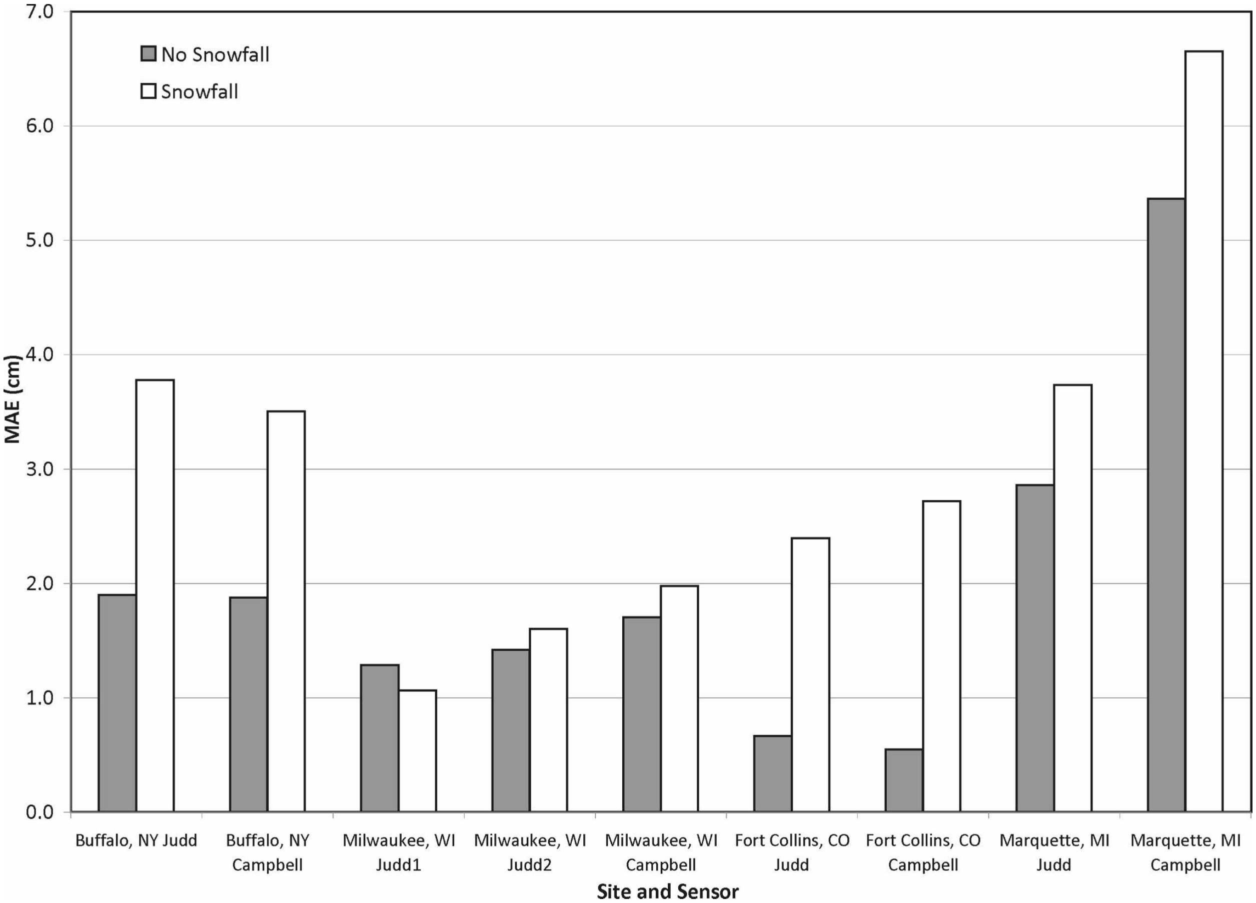

FIG. 9. Comparison of MAE between automated and manual total snow depth during periods where snowfall is present and snowfall is not.

2) SIXTY-MINUTE SNOWFALL ALGORITHM

The results of the 60MSA differ by site and are not as consistent as the 5MSA (Table 5). At some sites the results favor the Judd and at others they favor the Campbell. For Buffalo, New York, the cumulative seasonal snowfall for the Judd 1HRMA and 3HRMA is shown in Fig. 12a while the Campbell is shown in Fig. 12b. The percent difference in seasonal snowfall for the Judd 1HRMA and 3HRMA was 38.2% and 6.4%, respectively (Table 5). The percent difference for the Campbell 1HRMA and 3HRMA was 13.5% and 31.9%, respectively (Table 5). The Nash–Sutcliffe for the Judd 1HRMA and 3HRMA was 0.65 and 0.92, respectively, while the Campbell 1HRMA and 3HRMA was 0.85 and 0.47, respectively (Table 5). The MAE for the Judd 1HRMA and 3HRMA was 0.82 and 0.67 cm, respectively, while the Campbell was 0.61 cm for the 1HRMA and 0.55 cm for the 3HRMA (Table 5). In this case the Judd 3HRMA did the best at predicting the 6-h snowfall for Buffalo with the largest Nash–Sutcliffe *R*-squared and the lowest percent difference in seasonal snowfall. The MAE was similar for each method and sensor (Table 5).

Again, the CEs were calculated for the 60MSA (Fig. 13). The results are similar to the 5MSA. The Campbell 3HRMA consistently had the lowest CE (with the exception of Steamboat Springs, Colorado), followed by the Campbell 1HRMA, then the Judd 3HRMA, and finally the Judd 1HRMA. The minimum CE was achieved with the Campbell 3HRMA in Fort Collins, Colorado. The maximum CE was achieved by the Judd 1HRMA in Cheyenne, Wyoming.

The errors of omission for the Judd and Campbell sensors are shown in Figs. 14a and 14b. The omission errors depict the proportion of time the manual data measured snow and the sensors did not. At most sites the omission errors increased from the 5MSA to the 60MSA. This illustrates that the 60MSA is omitting snowfall events by taking the difference in snow depth over the longer time period.

TABLE 5. Summary statistics for the 5-min (5MSA) and 60-min (60MSA) snowfall algorithms using both 1-h (1HRMA) and 3-h (3HRMA) moving averages. The statistics include percent difference in seasonal snowfall, Nash–Sutcliffe R-squared (NS R^2), and MAE.

Site	Sensor and smoothing	5MSA (%)	5MSA NS R^2	5MSA MAE (cm)	60MSA (%)	60MSA NS R^2	60MSA MAE (cm)
Buffalo, NY	Judd 1HRMA	70.52	−0.42	0.93	38.19	0.65	0.82
	Judd 3hrma	10.72	0.80	0.82	6.41	0.92	0.67
	Campbell 1HRMA	0.95	0.98	0.64	13.51	0.85	0.61
	Campbell 3hrma	41.77	0.03	0.73	31.89	0.47	0.55
Cheyenne, WY	Judd 1 1HRMA	206.03	−18.11	0.51	94.81	−2.96	0.35
	Judd 1 3hrma	58.51	−0.20	0.30	19.75	0.87	0.25
	Judd 2 1HRMA	233.84	−23.13	0.54	108.68	−4.20	0.35
	Judd 2 3hrma	66.14	−0.71	0.29	23.95	0.80	0.23
	Campbell 1HRMA	11.35	0.77	0.23	35.36	−0.21	0.18
	Campbell 3HRMA	37.58	−0.53	0.18	51.43	−1.27	0.16
Davis, WV	Judd 1HRMA	37.62	0.64	0.92	0.62	0.79	0.77
	Judd 3HRMA	11.61	0.56	0.72	24.82	0.18	0.67
	Campbell 1HRMA	7.13	0.58	0.70	27.16	0.06	0.64
	Campbell 3HRMA	29.03	0.00	0.63	37.36	−0.32	0.61
Fort Collins, CO	Judd 1HRMA	143.54	−24.10	0.45	63.14	−4.90	0.32
	Judd 3HRMA	44.60	−2.05	0.27	15.44	0.30	0.23
	Campbell 1HRMA	33.64	−0.34	0.22	2.17	0.97	0.18
	Campbell 3HRMA	6.53	0.97	0.17	19.93	0.70	0.16
Marquette, MI	Judd 1HRMA	53.90	−0.07	1.14	5.29	0.98	0.82
	Judd 3HRMA	17.77	0.86	0.75	35.73	0.51	0.72
	Campbell 1HRMA	5.64	0.98	0.66	30.01	0.65	0.65
	Campbell 3HRMA	36.80	0.48	0.61	45.10	0.21	0.63
Milwaukee, WI	Judd 1 1HRMA	154.52	−8.94	0.34	117.64	−2.10	0.30
	Judd 1 3HRMA	55.86	−0.85	0.19	52.70	0.40	0.21
	Judd 2 1HRMA	179.84	−9.75	0.39	135.96	−2.47	0.33
	Judd 2 3HRMA	58.03	−0.55	0.22	58.31	0.34	0.23
	Campbell 1HRMA	40.49	0.32	0.16	7.13	0.96	0.11
	Campbell 3HRMA	1.89	0.97	0.11	19.93	0.92	0.10
Steamboat Springs, CO	Judd 1HRMA	37.62	0.38	1.90	9.10	0.97	1.48
	Judd 3HRMA	13.83	0.93	1.44	28.45	0.72	1.32
	Campbell 1HRMA	52.79	−0.23	2.00	5.76	0.96	1.63
	Campbell 3HRMA	3.60	0.99	1.52	19.65	0.87	1.42

5. Discussion

a. *Factors affecting sensor performance*

After inspection of the sensor data, a variety of climate and nonclimate factors were identified that affected sensor performance. The main factors that affected sensor performance included snow crystal type, blowing or drifting snow, intense snowfall, wind speed, and uneven snow surface. The snow crystals that most affected sensor performance included dendrites, needles, columns, and plates. These crystal types created a snow surface that was not ideal for reflecting the sound pulse causing degraded sensor performance for short periods of time. Blowing and drifting snow as well as intense snowfall both caused degraded performance due to an attenuation of the sound pulse. In either case, the path between the sensor and target surface became obstructed and limited the performance of the sensor for short periods of time. Strong winds (approximately 24 km h^{-1}) also caused degraded sensor performance. The problems caused by strong wind are attributed to one or more of the following: winds cause the mounting structure to vibrate affecting the ability of the sensor to retrieve the sound pulse, winds cause a distortion of the sound pulse, which affects its ability to return to the sensor, or the wind is producing noise, which may affect the sensor's ability to capture the return sound pulse. Uneven snow surfaces caused imprecise measurements from the sensors. Uneven snow surfaces were most often caused by animals walking below the sensors and snow falling off the sensor-mounting structure causing an uneven measurement surface.

The factors found to affect sensor performance are by no means intended to be a complete list. Once a site is in operation other factors may be identified that also affect the sensor performance. The factors that were found to affect sensor performance are not easy to al-

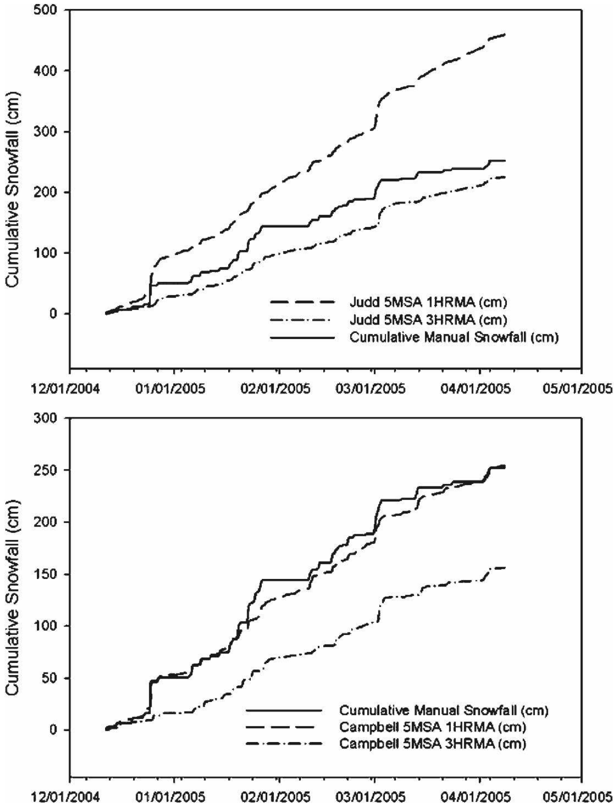

FIG. 10. Buffalo cumulative 5-min snowfall algorithm results for (top) Judd and (bottom) Campbell sensors using both 1-h (1HRMA) and 3-h (3HRMA) moving averages.

leviate. Snow crystal type and intense snowfall caused an attenuation of the sound pulse and little can be done to correct for these. The problems caused by wind speed and blowing/drifting snow can be alleviated by better site selection. Areas free of wind effects are the most desirable but not always available. The use of snow fences is not recommended due to problems they may cause if not regularly maintained. Also, if the fence is not constructed or sited properly it may accumulate more snow than actually falls, such as is the design for transportation-type snow fences (Tabler and Jairell 1993). The effects caused by uneven snow surfaces can easily be eliminated by installing a fence (i.e., chain link) to keep out unwanted visitors. In addition to this, using a mounting structure for the sensors that will not accumulate snow would keep snow from falling off the structure and creating an uneven surface below the sensors as was seen in this study.

b. *Comparison of automated and manual snow depth*

1) SENSOR COMPARISON TO DEPTH AT SENSORS

The comparison of sensor depth to manual depth of snow in the immediate vicinity of the sensors proved to be useful in estimating how well the USDS measured the snow depth. Overall the sensors accurately represented the amount of snow depth beneath the sensors. On average both the Judd and Campbell measured within ±1.0 cm over the full range of conditions and sites. This value was found by averaging the MAE by sensor omitting results from Marquette, Michigan, since there was only one manual measurement taken near the sensors, and Davis, West Virginia, due to major wind drifting problems experienced at the site and expressed by the observer.

2) SENSOR COMPARISON TO TOTAL SNOW DEPTH

The comparison of sensor snow depth to manual total snow depth illustrated that the sensors underestimated this measurement. On average the Judd measured within ±1.8 cm while the Campbell was within ±2.3 cm of the total depth of snow on the ground. The

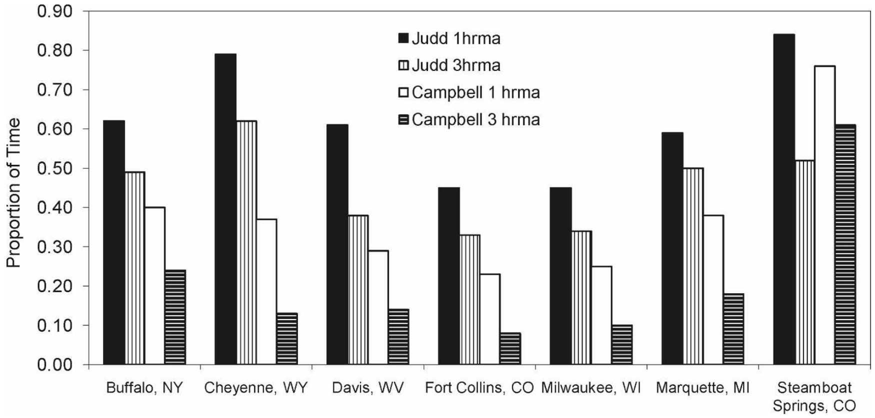

FIG. 11. Commission errors for the 5-min snowfall algorithm for both sensors using 1-h (1HRMA) and 3-h (3HRMA) moving averages.

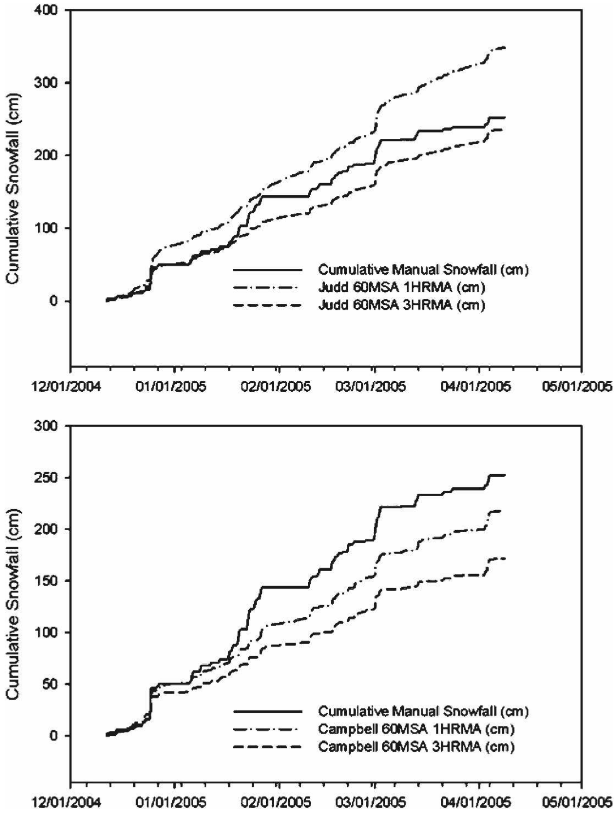

FIG. 12. Buffalo cumulative 60-min snowfall algorithm results for (top) Judd and (bottom) Campbell sensors using both 1-h (1HRMA) and 3-h (3HRMA) moving averages.

underestimation is mainly attributed to spatial variability. The manual total snow depth measurement is taken in the historical measurement location at each site. This measurement may also be an integration of several total depth measurements to achieve a representative sample. The fact that this measurement was underestimated illustrates that multiple sensors may be needed to obtain a representative measurement. The proper siting of the sensors is also important to obtaining a reliable total snow depth measurement.

c. *Six-hour snowfall algorithm*

1) FIVE-MINUTE SNOWFALL ALGORITHM

The best results for the 5MSA were obtained with the Campbell sensor at every site. However, the amount of smoothing needed varied from site to site. Buffalo, New York; Cheyenne, Wyoming; Davis, West Virginia; and Marquette, Michigan, all worked best with a 1HRMA while Fort Collins, Colorado; Milwaukee, Wisconsin; and Steamboat Springs, Colorado, all worked better with a 3HRMA. The reason for these differences is not fully understood but is thought to be mostly due to site construction and sensor. Overall, the Campbell sensor worked well to estimate 6-h snowfall with a 5MSA. The MAE between 6-h snowfall measurements were usually between 0.3 and 0.8 cm with the exception of Steamboat Springs, which was 1.5 cm and can be explained by malfunctioning equipment.

The CEs dropped as the moving average was increased from 1 to 3 h in all cases with both sensors (Fig. 11). However, even though the Campbell 3HRMA usually has the lowest CE, it is not always the best model for calculating 6-h snowfall because the 3HRMA removes too much detail from the Campbell data and the snowfall cannot be accurately estimated.

2) SIXTY-MINUTE SNOWFALL ALGORITHM

The use of a 60MSA removed some false reports of snowfall from the sensors and the Judd obtained better

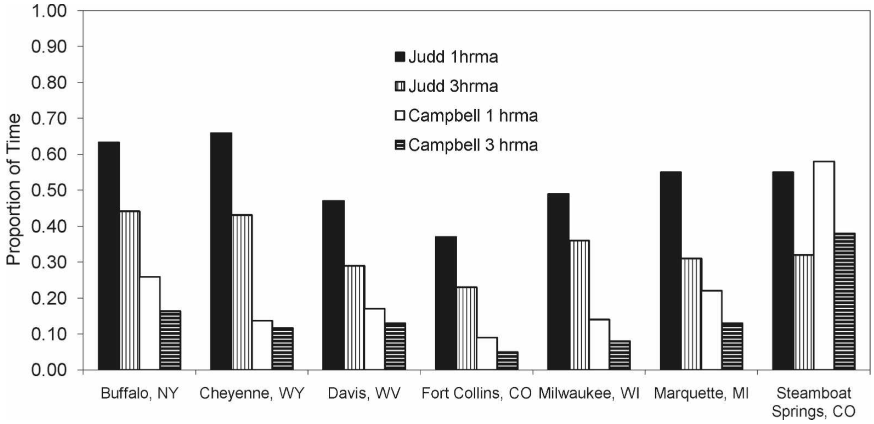

FIG. 13. Commission errors for the 60-min snowfall algorithm for both sensors using 1-h (1HRMA) and 3-h (3HRMA) moving averages.

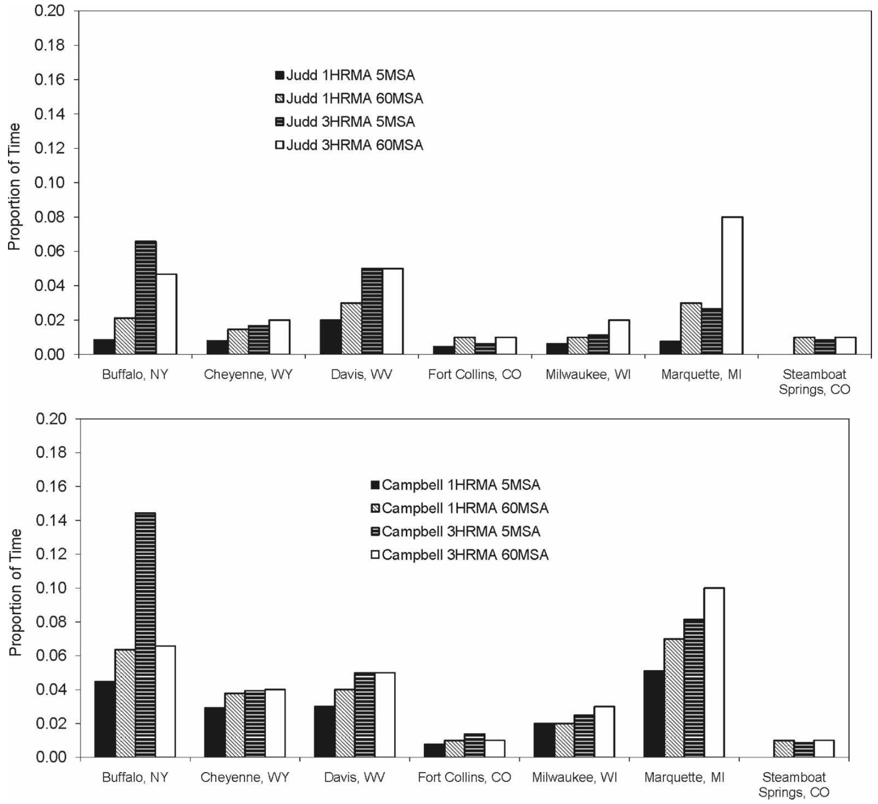

FIG. 14. Omission errors for (top) Judd and (bottom) Campbell algorithms (both 5- and 60-min algorithms using 1- and 3-h moving averages) by site.

results than with the 5MSA. However, taking the change over the longer 60-min period may omit small events that occurred over that time interval and would not accurately depict the actual snowfall at a site where this algorithm is used. The omission errors illustrated this point (Figs. 14a,b).

The reasons for the differences in algorithm performance between sites are highly speculative and were attributed to both siting and sensors. Poor siting and installation can add more variation into the data, which would need more smoothing. The sensor resolution introduces problems into calculating snowfall. The Campbell sensor has a finer data resolution that does not produce as many false snowfall reports as the Judd. The errors of commission illustrate this point. The 60MSA CEs (Fig. 13) illustrated that the Judd sensor has a coarser data resolution that allows it to appear to accumulate snow even under snow-free conditions. The patterns are consistent with the 5MSA; as the amount of smoothing increases the CEs decrease.

The CEs suggest that the sensors are not measuring "no snow" very well. Figure 15 shows the number of occurrences for each range of snowfall that was reported manually as well as being estimated by the sensors for Marquette, Michigan, using the statistically best model for each sensor. The sensors did not report nearly as many zero snow depths as were manually measured, and they also overestimated the number of occurrences that fell in the 0.1–1.0-cm range. This is again due to sensor resolution, which caused the sensors to measure snow when there was none manually reported. The reports that were supposed to be placed in the zero range for the sensors actually fell in the 0.1–1.0-cm range.

6. Conclusions

This evaluation of ultrasonic snow depth sensors has shown promising results that these sensors can be used to restore snow measurements at hundreds of automated sites across the United States and add more objectivity to a measurement often known to be subjective. Even though both sensors did accurately measure the snow depth below them, the underestimation of the total snow depth measurement illustrates the need for proper siting as well as the need for multiple sensors to obtain a representative measurement. Even though several factors were identified that affected sensor per-

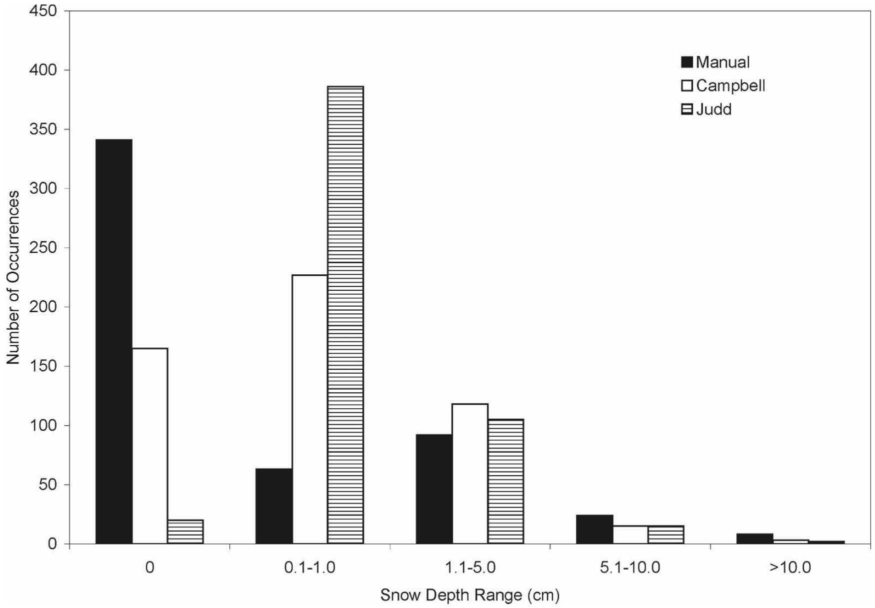

FIG. 15. Number of occurrences of snowfall in each incremental snow depth range for the manual snowfall and both Judd and Campbell predicted snowfall from Marquette, MI.

formance, simple data processing techniques can be used to filter and smooth out erroneous data points.

The estimation of 6-h snowfall is still a work in progress. Favorable results were obtained in this study, mainly with the Campbell sensor using the 5-min snowfall algorithm. The Campbell sensor has a finer data resolution, which allows more accurate estimates of 6-h snowfall than with the Judd sensor. The coarser Judd resolution caused more false reports than the Campbell sensor; however, some of these were removed by using a higher degree of data smoothing as well as using the 60-min snowfall algorithm. Future work must include standardization of site installation as well as stating clear guidelines for choosing site locations. Verification of compaction routines used in this study should also be investigated. The use of ultrasonic snow depth sensors provides useful information about snow accumulation, settling, and melting patterns that can add a much needed constant to snow measurements across the United States.

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