JP1.25 AN EVALUATION OF TWO ULTRASONIC SNOW DEPTH SENSORS FOR POTENTIAL USE AT AUTOMATED SURFACE WEATHER OBSERVING SITES

Wendy A. Brazenec* and Nolan J. Doesken
Colorado State University, Fort Collins, Colorado

1. INTRODUCTION

Snowfall and snow depth measurements are important for a variety of disciplines including commerce, transportation and water supply forecasting as well as most daily activities. This measurement has traditional been performed by human observers here in the U.S. In the early 1990s the National Weather Service (NWS) first deployed the Automated Surface Observing System (ASOS) for airport weather observations. ASOS automated traditionally manual surface observations such as cloud cover, surface visibility, weather and obstructions to vision, and precipitation type and amount. Unfortunately, ASOS did not measure snowfall or depth because there was no suitable sensor available at that time. After ASOS was deployed, snow measurements were abandoned and many long-term weather stations, and climate records dating back as far as the late 1800s (McKee et al., 2000) were interrupted. Measurements of the water content of snow were also compromised since ASOS used a heated tipping bucket rain gage that has been shown to underestimate precipitation due to sublimation and wind-related effects (Doesken and McKee, 1999).

In recent years, ultrasonic depth sensors have been used to measure snow depth remotely in mountain environments. A study done by the NRCS at Mt. Hood, OR found that addition of depth sensors provided a valuable picture of snowpack dynamics that aided in snowmelt and runoff prediction (Lea and Lea, 1998). The SNOTEL network currently has over 400 operational ultrasonic snow depth sensors across the western U.S. Canadian interest in snow depth sensors dates back to the 1980s (Goodison, 1984). The NWS is currently exploring the possibility of using this measurement technology in ASOS and other surface observing networks.

2. ULTRASONIC SNOW DEPTH SENSORS (USDS'S)

USDS's consist of a transducer/receiver and a temperature probe. The transducer sends out a sound pulse which reflects off a targeted surface. The sound pulse then returns to the receiver. The time of travel for the sound pulse is corrected for the speed of sound in air (Equation 1) by multiplying by a correction factor. The adjusted snow depth is given by Equation 2.

$$V_{sound} = 331.4*(T_{Celcius}/273.15)^{0.5}\ (m/s) \qquad (1)$$

$$\text{Corrected Snow Depth} = D_s * (T_{Kelvin}/273.15)^{0.5} \qquad (2)$$

V_{sound} = *Velocity of sound in air (m/s),*
$T_{Celcius}$ = *Temperature Celcius,*
D_s = *Raw Snow Depth Reading,*
T_{Kelvin} = *Temperature Kelvin.*

The corrected time is then converted to a distance which is offset by the height of the sensor off the ground. As snow accumulates, the distance the sound pulse travels is reduced and the offset yields the height of snow under the sensor.

There are two main manufacturers of USDS's: Judd Communications and Campbell Scientific (Figure 1). The Judd Communications sensor is relatively inexpensive and includes both the transducer and the temperature probe in one unit. The Campbell Scientific sensor is more expensive than the Judd sensor and requires a separate temperature probe.

Figure 1: Two manufacturers of USDS's: Judd Communications (left) and Campbell Scientific (right).

3. OBJECTIVE

The main objective of this study is to test the performance of these sensors in diverse winter environments to see how well their outputs compare to traditional manual snowfall and depth

* *Corresponding author address:* Wendy A. Brazenec, Watershed Science Department, 1472 Campus Delivery, Colorado State University, Fort Collins, CO, 80523-1472; email: wab134@cnr.colostate.edu

measurements. We will also report on the status of an algorithm to derive six hour snowfall from the continuous snow depth reported by the sensors. The results will begin to show what potential these sensors may have to compliment existing NWS automated weather instruments.

4. SITE DESCRIPTIONS

Fourteen sites either volunteered or were invited to help with this study. Nine of these sites were NWS Forecast Offices. More sites were interested, but available instrumentation limited the study to 14 locations. To be considered, sites had to have the capability of measuring and reporting snowfall and depth manually at 6-hourly increments for all or the majority of the snowfall season.

The site locations are shown in Figure 2. All sites had adjacent open areas suitable for installation of USDS's. Ideally, all sites should have had at least one Judd and one Campbell Scientific USDS, to support intercomparisons, but limitations resulted in 4 sites having only one type or the other.

For ease of analysis, the sites have been broken into classes depending on the equipment they are testing. Class I sites have at least one Judd and one Campbell sensor, Class II have at least one Judd sensor only, Class III have at least one Campbell sensor only. A summary table is shown in Table 1. Grand Rapids, MI had a unique arrangement with multiple Judd sensors, some digital and some analog.

4.1 *Site Climate Classification*

The study sites span various climate types. The sites have been summarized using the Koeppen Climate Classification (FAO, 2005) shown in Table 2. Sites range from dry to temperate to cold. They also receive varying amounts of snowfall each year. Figure 3 shows the mean annual snowfall for each station (NCDC, 2005). Most of the sites receive greater than 24 inches (Table 3) of snow annually. Although we wanted to test in many climate regions, this project is a single-seaon intercomparison. Therefore, it was important to sample in many snowy areas to make sure we had a large sample of snow events to compare.

5. METHODS

5.1 *Automated Data Collection*

At all sites with multiple sensors, the USDS's were set up side by side at least 2 meters apart to make sure there was no sound wave interference. Each sensor fired a sound pulse every 15 seconds. The 15 second readings were then averaged over a 5 minute period and archived using onsite data loggers. The sensors target surfaces were expanded PVC snowboards, nearly identical to the snow measurement boards used by most NWS weather stations. The boards were larger in

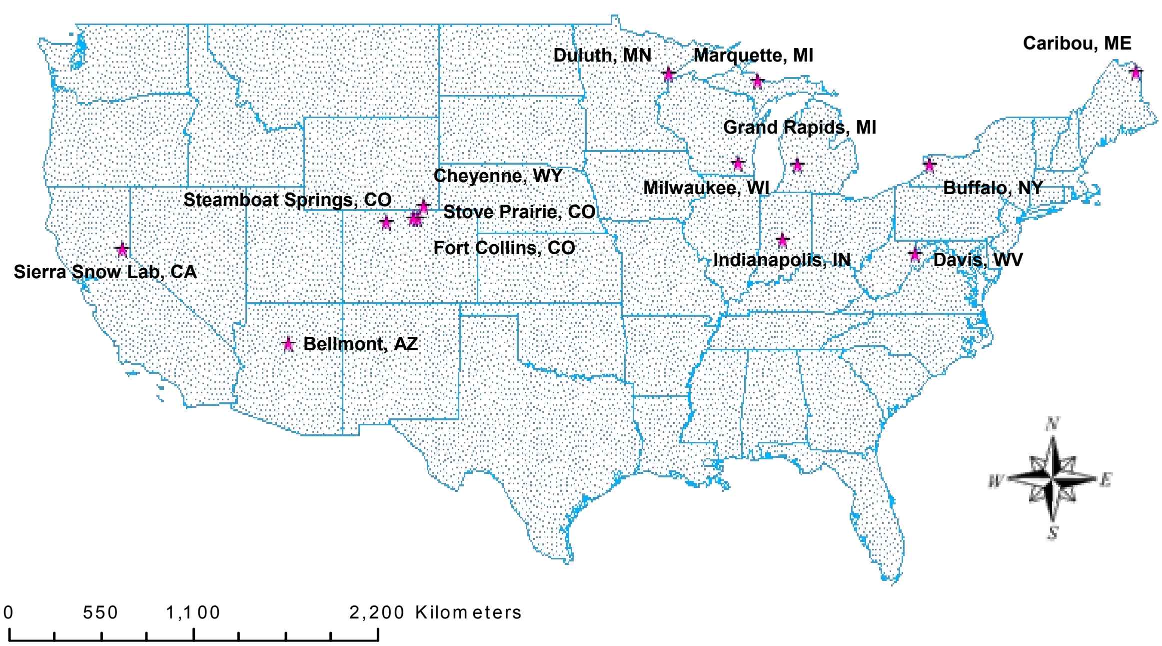

Figure 2: Sites Testing Ultrasonic Snow Depth Sensors.

Station	Class	Longitude	Latitude	Judd	Campbell
Bellmont, AZ	II	-111.82	35.23	1	0
Davis ,WV	I	-79.43	39.10	1	1
Sierra Snow Laboratory, CA	III	-120.37	39.32	0	1
Indianapolis, IN	I	-86.28	39.71	1	1
Steamboat Springs, CO	I	-106.75	40.45	1	1
Fort Collins, CO	I	-105.13	40.62	1	1
Stove Prairie, CO	II	-105.39	40.63	2	0
Cheyenne, WY	I	-104.81	41.15	2	1
Grand Rapids, MI	IV	-85.54	42.89	2 Digital, 2 Analog	0
Buffalo, NY	I	-78.72	42.94	1	1
Milwaukee, WI	I	-88.55	42.98	1	1
Marquette, MI	I	-87.55	46.53	1	1
Duluth, MN	I	-92.21	46.84	1	1
Caribou, ME	I	-68.01	46.87	1	1

Table 1: Class, location and equipment for each of the study sites.

Stations Included	Class	Description
Cheyenne, WY; Fort Collins, CO and Stove Prairie, CO.	**Bs**	Dry: Arid regions where annual evaporation exceeds annual ppt. High sunshine. S refers to vegetation type – steppe climate.
Davis, WV and Indianapolis, IN	**Cf**	Temperate: At least 30 mm of precipitation in driest month, < 3 times as much precipitation in wettest month than driest month.
Bellmont, AZ; Duluth, MN; Sierra Snow Laboratory, CA and Steamboat Springs, CO	**D**	Cold: Average temperature of warmest month >10°C and coldest month ≤ 3°C.
Buffalo, NY; Caribou, ME; Grand Rapids, MI and Milwaukee, WI	**Df**	Cold: At least 30 mm of rain in driest month. Less than 3 times amount of precipitation in wettest month than driest month.
Marquette, MI	**Dw**	Cold: Winter dry season- at least 10 times the precipitation in wettest month of summer as in driest month of winter.

Table 2: Summary of Stations by Koeppen Climate Classification.

Mean Annual Snowfall (in)	Stations
24.1 - 36.0	Indianapolis, IN
36.1 - 48.0	Milwaukee, WI
48.1 - 72.0	Bellmont, AZ; Cheyenne, WY; Duluth, MN; Fort Collins, CO; Grand Rapids, MI
> 72.0	Caribou, ME; Buffalo, NY; Davis, WV; Marquette, MI; Sierra Snow Lab, CA; Steamboat Springs, CO; Stove Prairie, CO;

Table 3: Summary of Mean Annual Snowfall (inches).

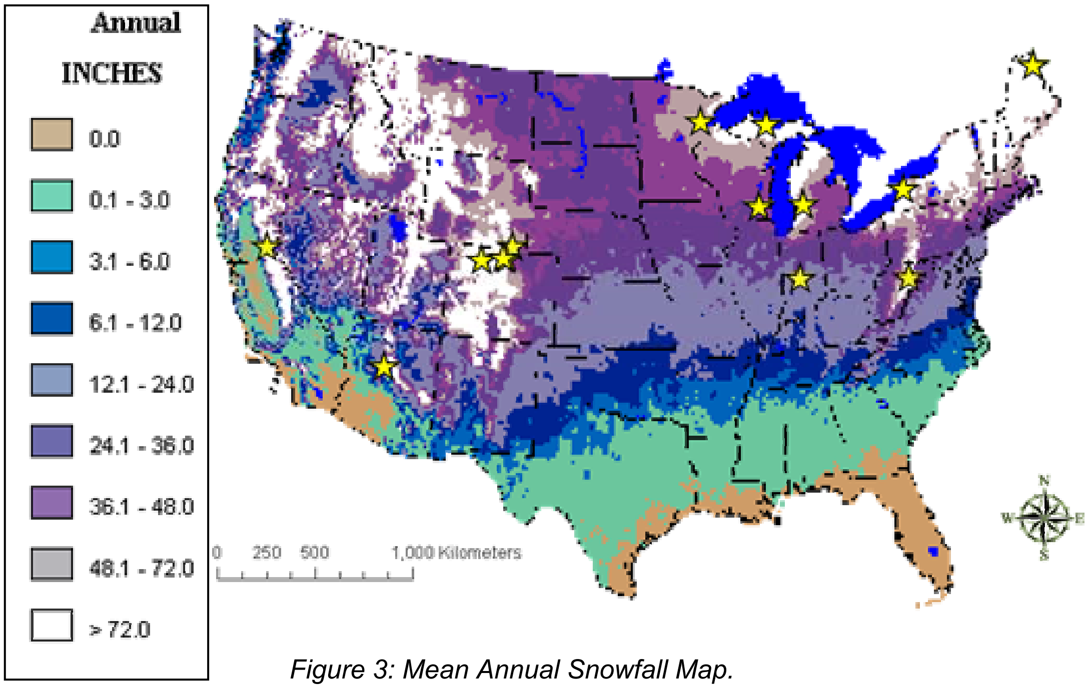

Figure 3: Mean Annual Snowfall Map.

areas known for deep snow accumulations and requiring taller mounting poles for USDS installation. The 5-minute elements recorded in the data logger were Judd sensor depth and temperature, Campbell sensor depth and temperature as well as battery voltage.

5.2 *Manual Data Collection*

Snow measurements were made with a NWS snow measurement ruler and expanded PVC snow boards using measurement procedures as specified by the 1996 National Weather Service snow measurement guidelines. Water content was measured using NWS standard rain gauges, recording gauges, or 4" plastic all-weather rain gauges. The 4" plastic gage was chosen to perform snow cores since it is considerably easier to use for core samples than the NWS Standard 8" gage. Two snowboards were used at most stations: one was a 6 hour snowboard; the other was a 24 hour snowboard. Each board was cleared during snow events after each measurement. The measurements off these boards included 6 or 24 hour snowfall and snow water equivalent (SWE). Six hour measurements were taken only when snow was falling. The 24 hour measurements were taken when it was snowing or when older snow remained on the ground. Snow depth readings were also taken in the immediate vicinity of each USDS, and total depth of snow on the ground was also reported. The ground snow depth was an average of several depth samples, the number depending on the spatial variability. Snowfall and snow depth measurements were made to the nearest one tenth of an inch. SWE and gage precipitation measurements were made to the nearest one hundredth of an inch using the inner core of the gage to measure the melted snow. Observations of wind speed, snow crystal type and any other pertinent information were also reported. Manual and automated observations were usually taken very close to each other, but co-location was not always feasible. A special data collection website was established at Colorado State University for all stations to log their data.

6. RESULTS

At the time of this report, data collection had just ended and analysis was just beginning. Results shown here are only preliminary findings.

6.1 *Data Quality and Sensor Performance*

A major part of this study was testing USDS performance in all types of weather, identifying conditions where sensors worked well, and determining the conditions where sensors worked poorly. Sensor output was found to vary even with no snow on the ground, so we did considerable testing of "false", anomalous, and diurnal variations and their possible causes. Sites in different climate classes were evaluated to see if external factors affect the sensors to the same degree. Early results show that strong winds (Figure 4) and low density snow crystals in the air or on the

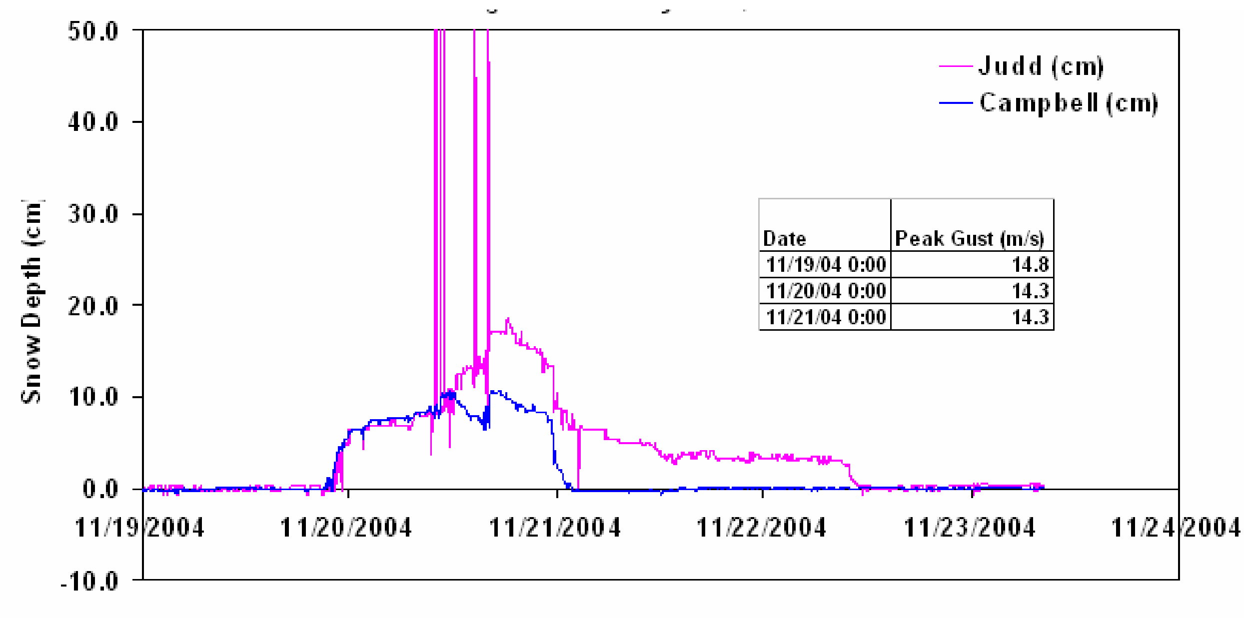

Figure 4: High Wind Effect on Sensor Performance Cheyenne, WY.

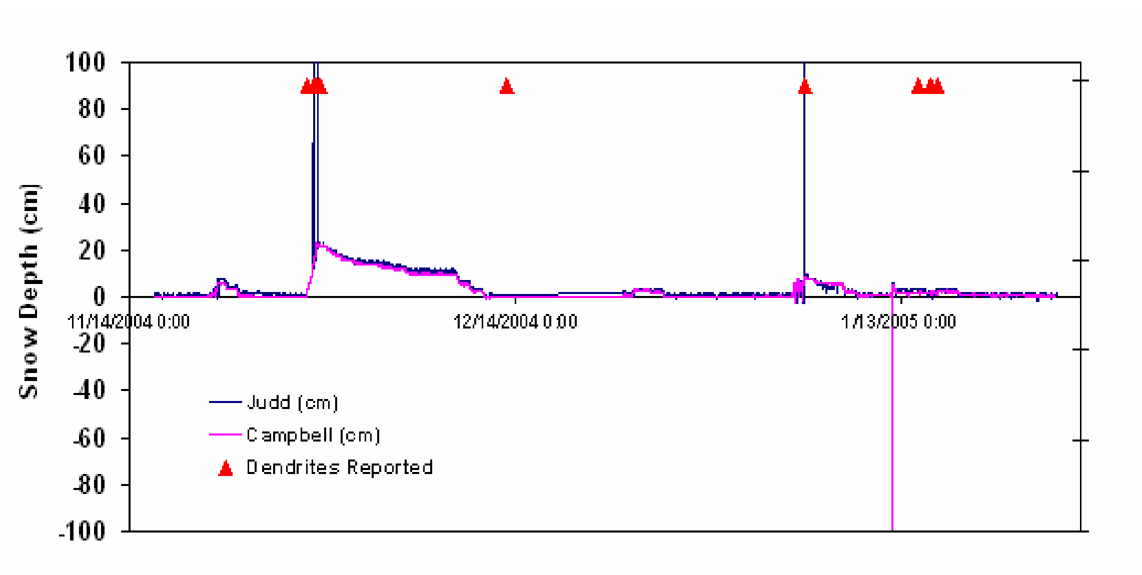

Figure 5: Dendritic Snow Crystals Effect on Sensor Performance Fort Collins, CO.

surface of the snow (Figure 5) cause “spikes” in the data due to scattering of the ultrasonic pulse. High winds or heavy falling snow or blowing/drifting snow can cause the sound pulse to be dispersed and attenuated, causing large errors. When the snow surface is covered with large, low-density conglomerate crystals, the sound wave was found to sometimes penetrate well into the snow before reflecting the wave.

Data spikes and anomalous readings occurred an average of 0.56% of the time from the Judd USDS while the Campbell reported a “spike” only 0.06% of the time based on sample results from 6 of the 14 stations (See Figures 4 and 5 for examples of “spikes”). Nonetheless, the “spikes” happen rarely enough and are easily corrected for either USDS over a few 5-minute time periods.

The raw data from the sensors can be noisy and show high frequency variations of as much as a few centimeters even under calm conditions and with no snow on the ground. Without special processing, the output of the Judd sensor showed more of this type of noise. The Campbell sensor showed less scatter and less high frequency variations, but some of this was due to differences in signal processing between the two systems. Smoothing of the 5-minute readings was necessary for optimal data display and interpretation. After investigation of different moving average periods, a centered weighted three hour moving average was used (Figure 6). Other types of smoothing are also being explored.

6.2 Comparison to Manual Observations

The sensors were compared to each other as well as to the manual data. These comparisons showed how well the USDS measurements depicted the total depth of snow on the ground. The first analysis (Figure 7) compared USDS data with manual observations of snowfall and depth at the

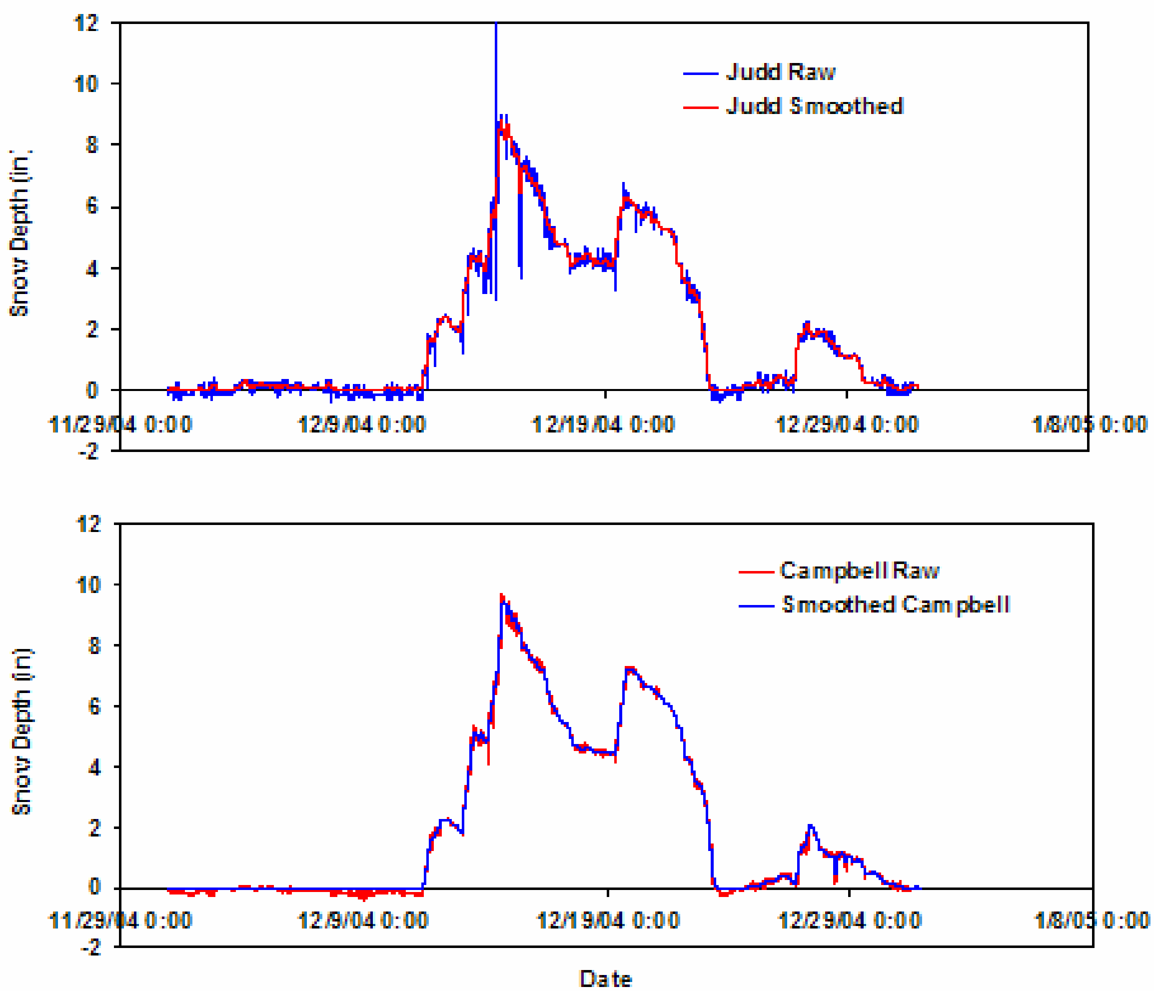

Figure 6: Raw and Smoothed Sensor Data for Davis, WV December, 2004

Marquette, MI National Weather Service Forecast office. Manual data for this comparison came from their customary site for surface observations a fairly short distance from where the USDS's were installed. Some snowfall and depth manual readings were the average of several samples, as deemed appropriate by the local observer when there was spatial variability in snowfall and depth. The USDS, however, was simply the depth at their respective fixed locations. Figure 7 shows the smoothed sensor data for Marquette, MI compared to the manual total depth of snow on the ground measurements taken in 6 and 24 hour intervals.

In this example, manual observations consistently exceeded USDS snow depths. For the month of December, the Judd USDS averaged about 0.7 inches less depth than manual readings whereas the Campbell averaged about 2.1 inches less. These differences were most likely the result of local variations in depth rather than systematic differences, biases or errors in measurements.

Figure 8 shows a similar comparison but this time the manual depth readings were taken at a single point immediately adjacent to the USDS's. This time, the readings compared slightly better. The Campbell showed 1.8 inches less snow depth than manual readings for the month as a whole, while the Judd showed 0.5 inches less. While a small sensor bias is possible, or the zero offset could have been off slightly, differences were again most likely the result of local spatial variability.

Overall, for all stations and situations examined so far, the USDS data usually compare favorably to manual depth measurements and are very well correlated. However, difference can occur, especially during windy periods. Based on our experiences, differences in depth are a common result of drifting and uneven accumulation of snow. This points out the extreme importance of proper instrument siting and exposure to assure representative results.

6.3 *Six Hour Snowfall Algorithm – Preliminary Findings*

The USDS's report total depth of snow on ground and do not report "snowfall" as has traditionally been measured and reported. "Snowfall" is a popularized measurement of the new snow that has fallen in the recent past (6-hour or current day). The measurement, when taken properly, is the maximum observed accumulation of fresh snow prior to melting or settling.

If USDS's are to become a part of NWS observing systems, it is deemed desirable that traditional "snowfall" totals on 6 and 24-hour intervals can be derived from changes in the observed depth. This section shows preliminary results from a very simply method that computes the change in depth over specified time intervals and sums these depth changes to produce estimated snowfall

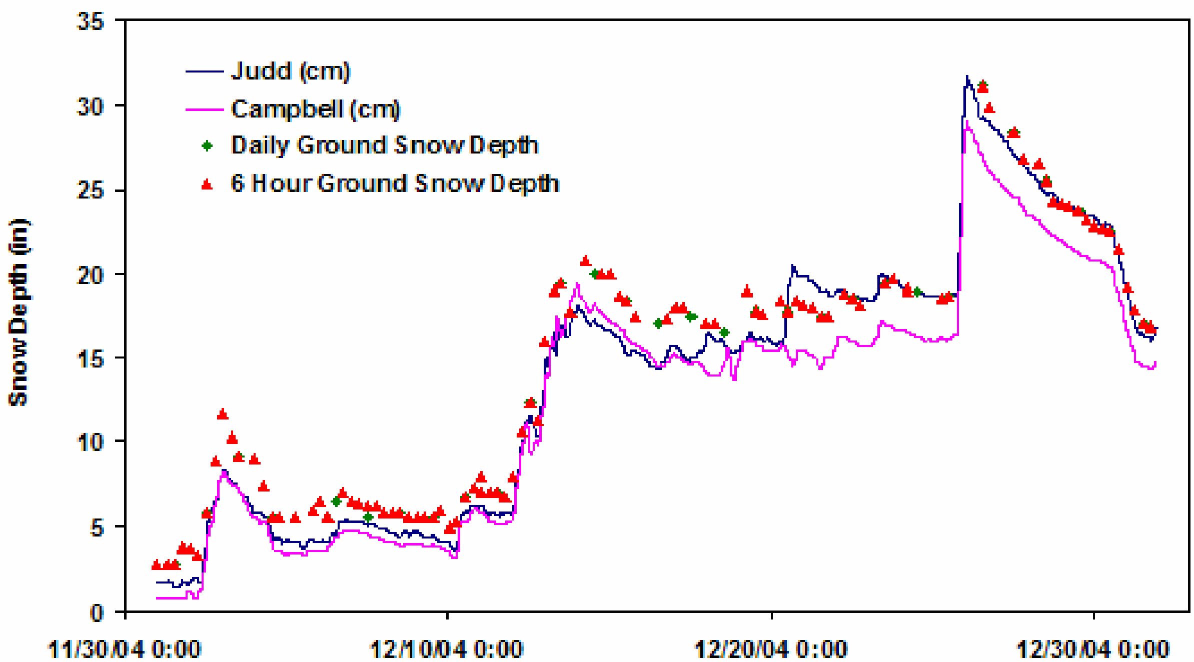

Figure 7: Marquette, MI Total Depth of Snow on the Ground vs. Sensor Depth (in)

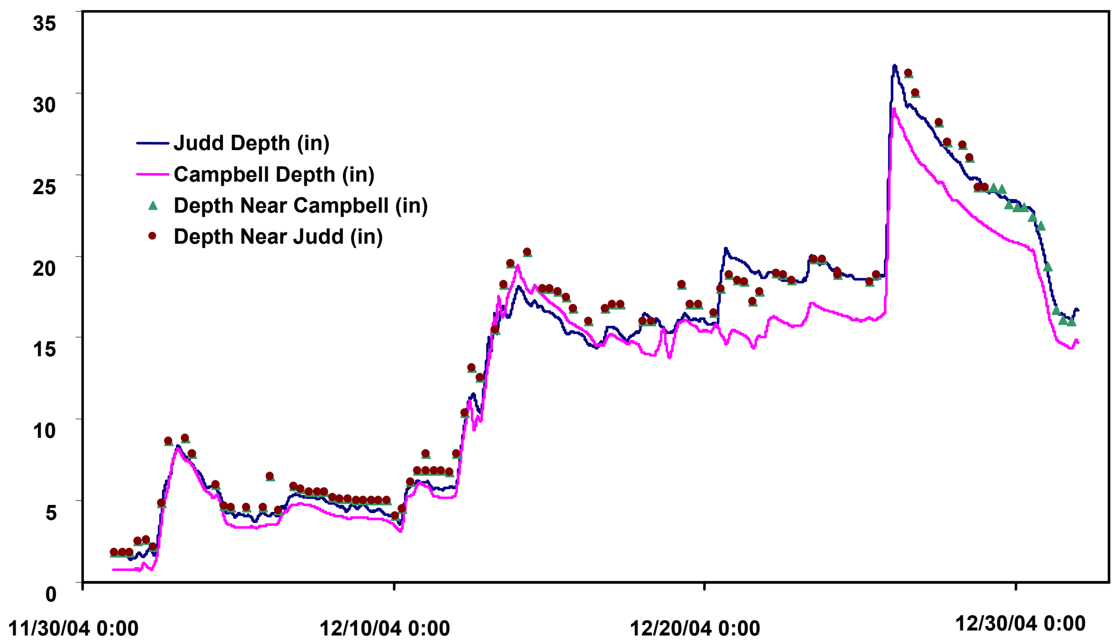

Figure 8: Sensor Depth and Depth of Snow near each Sensor.

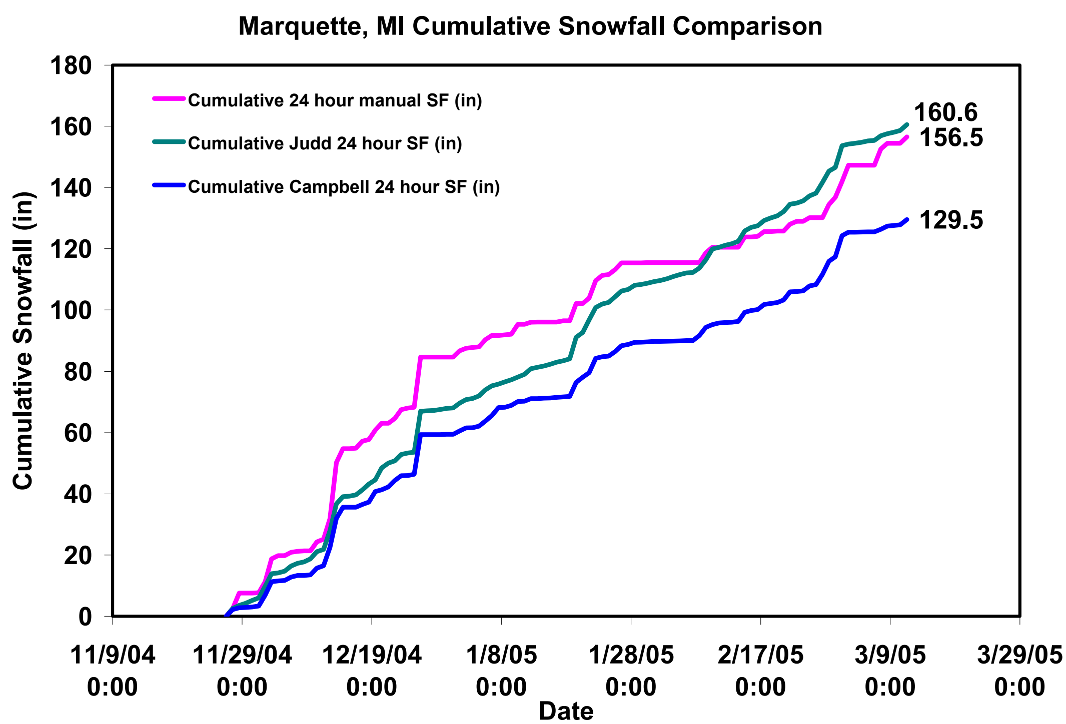

Figure 9: Cumulative Snowfall (in) in Marquette, MI of 6 hour manual snowfall, 24 hour manual snowfall, 24 hour snowfall estimation from both sensors and 6 hour snowfall estimation from both sensors.

totals. This part of the research has just begun and remains a work in progress. Eventually, our methodology must account for melting and settling of the existing snow. For this to work well, high frequency variations and noise must be accounted for.

Results of a simple computation are shown in Figure 9. Each 5-minute increase in snow depth was summed over 6 and 24 hour time periods for Marquette, MI from early November 2004 through March 2005, encompassing most of their snow accumulation season. All methods, manual and automated showed qualitatively similar results, However, total snow accumulation ranged from a low of 129.5 inches based on Campbell cumulative 24 hour snowfall to a high of 160.6 inches for Judd cumulative 24 hour snowfall. The method for estimating 6 and 24 hour snowfall from the sensors were nearly the same differing only in the time period where snowfall was summed. Therefore the 6 and 24 hour estimates for each sensor respectively are nearly identical.

The noisier signal from Judd sensors poses a problem for short-duration snowfall estimation and explains the continuous accumulation of small snowfall amounts, even on obviously dry days. This problem can likely be reduced by filtering the noise more effectively. The Grand Rapids NWS WFO developed their own algorithm for smoothing and were quite satisfied with Judd output. Spatial variation between the two sensors and manual observations also needs to be taken into consideration when trying to estimate snowfall from point measurements. Confidence in the manual measurements is also an issue. The definition of snowfall is the maximum accumulation over the observation period. However, if the observer was not present at maximum accumulation, the observed value becomes speculative. In practice, many observations are simply the depth of snow on the snowboards at the time of the observation. Even so, the sensors are constantly measuring snow depth which should allow for a fairly accurate estimate of six hour snowfall.

Based on this initial work, we are quite optimistic that realistic estimates of daily snowfall will be possible very soon.

7. CONCLUSIONS

Based on one winter of data collection at sites across the U.S., the USDS's did a good job of representing the amount of snow present on the ground. Both the Judd and the Campbell Scientific USDS's performed reliably over large ranges of weather conditions with relatively few equipment problems. At the sites that have been analyzed so far, automated depth measurements tended to report less snow on the ground than was observed manually. The sensors agreed more closely with the amount of snow reported in their immediate vicinity than what was manually measured at the conventional observing site. This pointed out just how important siting and exposure are for consistent and comparable measurement.

The non snow-depth related scatter and noise in USDS data is problematic, and must be considered. Fortunately, the high level scatter such as spikes from windy or low density snow situations are easily identified and filtered out. The small scale scatter is still of concern, especially when trying to calculate snowfall values based on increasing or decreasing depth of snow. For the purposes of this study, a centered three hour moving average was used to smooth the data, but for real-time operations, better sampling and smoothing algorithms will be needed. Smoothing makes it difficult to detect in real time when snow first begins to accumulate, but it reduces the large number of "false snow accumulation" reports. Many applications would already find the raw data produced by USDS's very useful, but real-time snow depth measurements will be most important for forecasting, transportation and snow-removal applications.

Based on this study, we are confident that estimates of traditionally reported "snowfall" will be possible from the USDS data. Data continuity studies will be required, however, and improvements in the snowfall algorithm will be necessary to account for melting, settling and possibly even drifting. It is still to be determined if a single sensor configuration will suffice, or if multiple sensors will be preferred in order to better account for spatial variability in snow accumulation.

After just one season of detailed testing, it soon becomes apparent how informative continuous snow depth time series such as those shown in Figures 7 and 8 can be. These data are very instructive and quickly show many characteristics of snow accumulation, distribution, densification and melting that would have immediate applications in many fields. USDS data would quickly become a valued attribute to the climate record.

8. ACKNOWLEDGMENTS

This research was supported by the NWS Office of Climate, Water and Weather Services under CIRA Cooperative Agreement NOAA grant NA17RJ1228 Amendment 24. We would also like to thank all our WFO's and Co-operative observers for their contributions to this study. Their dedication made this research possible.

9. LITERATURE CITED

Doesken, N.J. and McKee, T.B. 1999: Life After ASOS (Automated Surface Observing System) – Progress in National Weather Service Snow Measurement. *Postprints, 8th Annual Western Snow Conference*, April 18-20, Port Angeles, WA.

FAO, 1997: (http://www.fao.org/waicent/faoinfo/sustdev/ EIdirect/climate/EIsp0002.htm) FAO SDRN Agrometeorology Group. Date accessed 23 January 2005.

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

Lea, J. and Lea, J. 1998: Snowpack Depth and Density Changes during Rain on Snow Events at Mt. Hood Oregon. *International Conference on Snow Hydrology: The Integration of Physical, Chemical and Biological Systems*, October 6-9, Brownsville, VT.

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

NCDC, (http://www.ncdc.noaa.gov/olca/), NCDC Online Climate Atlas. Accessed 4 February 2005.