THESIS

EVALUATION OF ULTRASONIC SNOW DEPTH SENSORS FOR AUTOMATED SURFACE OBSERVING SYSTEMS (ASOS)

Submitted by
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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY WENDY ANN BRAZENEC ENTITLED EVALUATION OF ULTRASONIC SNOW DEPTH SENSORS FOR AUTOMATED SURFACE OBSERVING SYSTEMS (ASOS) BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

EVALUATION OF ULTRASONIC SNOW DEPTH SENSORS FOR AUTOMATED SURFACE OBSERVING SYSTEMS (ASOS)

In the 1990's the National Weather Service deployed automated surface observing systems at hundreds of airport locations across the country. Prior to the automation, human observers made snow observations every six hours. Once the automated systems were deployed, snow measurements ceased due to the lack of an automated sensor to measure snow. This study explored how well ultrasonic snow depth sensors compared to manual snow observations at nine sites across the country. This study had four objectives: 1.) Develop a method of quality assurance and quality control 2.) Identify factors which affect sensor performance 3.) Compare automated sensors to manual observations of snow depth 4.) Derive an algorithm to estimate six hour snowfall from automated sensor snow depth. A reliable data smoothing/processing technique was achieved using filtering of large variability and smoothing with a moving average to smooth small variations in snow depth. Factors found to affect sensor performance included: snow crystal type, wind speed, blowing/drifting snow, uneven snow surface, extremely low temperatures, and intense snowfall. The Judd and Campbell sensors both did a satisfactory job measuring snow beneath the sensor within ±0.4 inches. Two separate algorithms were created due to differing degrees of precision between the two sensors. It was found that the Campbell sensor did a better job at estimating six hour snowfall than the Judd using an algorithm that calculated snowfall over 5 minute periods and applying a temperature based compaction model to the estimated snowfall. The Campbell agreed with the manual data with an average mean absolute error between measurements of 0.23 inches. The Judd sensor results improved by using an algorithm which calculated snowfall using the change in snow depth over sixty minutes, however, the Campbell results were better using the five minute snowfall algorithm. Overall, both sensors accurately depicted the snow depth on the ground, however the Campbell sensor was more accurate at predicting six hour snowfall using the algorithms presented in this research.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 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 U.S. outside of the high mountain 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 1990’s the NWS began deploying the Automated Surface Observing System (ASOS) at most major airports across the U.S. in conjunction with the Federal Aviation Administration and the Department of Defense stating that:

> *The ASOS system serves as the nation's primary surface weather observing network. ASOS is designed to support weather forecast activities and aviation operations and, at the same time, support the needs of the meteorological, hydrological, and climatological research communities* (NOAA, 2005).

The ASOS system 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 snowfall or snow depth. Since its beginning, ASOS has used a heated tipping bucket rain gage to record precipitation including rain and the water content of solid precipitation (Doesken and McKee, 1999). The use of this type of gage creates problems of gage undercatch particularly for snow falling at temperatures several degrees below freezing (Doesken and McKee, 1999). (Note: the heated tipping bucket gage is currently being replaced with a high resolution weighing-type gage nationwide.)

Prior to the recent deployment of ASOS, many cities had snowfall records dating back to the late 1800's. 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 U.S., but a study of historic snowfall records found that there are very few locations across the country with complete and accurate snow measurement records (Robinson, 1989). Implementation of ASOS further magnified this problem.

1.1.1 Traditional Snow Measurements

The traditional NWS snow measurements consisted of gage precipitation, snowfall, snow depth and (at a subset of stations) snow water equivalent (SWE). *Gage precipitation* is defined as the amount of liquid equivalent obtained by a NWS standard precipitation gage. *Snowfall* is defined as the maximum accumulation of new snow since the last observation and is customarily measured on a snow measurement board. *Snow depth* is defined as the total depth of snow on the ground at the time of observation. The measurement of snow depth may be the average of several total depth measurements to obtain a representative sample (NWS, 1996). The number of measurements taken is at the discretion of the observer and depends on how spatially variable the snow cover is. There are no guidelines defining how many depth observations need to be taken. Gage precipitation is measured by melting the snow caught by a precipitation gage, and measuring the water content to the hundredth of an inch. Snowfall and snow depth are taken by inserting a ruler into the snowpack and reading the depth of snow. Snowfall is measured to the tenth of an inch while total snow depth is read to the whole inch. SWE is measured by taking a core sample of the total of all old and new snow remaining on the ground using the outer cylinder of a precipitation gage, melting the snow and measuring the liquid with the inner tube of the precipitation gage. First order staffed stations traditionally measured snowfall every six hours, while Cooperative Observer Network stations typically measure once a day.

1.1.2 Challenges of Snow Measurements

There are three properties of snow that make accurate and consistent snow measurements a challenge. Consistent, as it is used here, refers to both the comparability of snow measurements records as well as uniformity in measurement procedures. The first is that snow often melts as it lands or as it lies on the ground, both from warm soil below or from warm air, wind, or sunshine above (Doesken and Judson, 1997). This is particularly difficult when deciding what amount of snowfall to report. A trained human observer would report a trace of snow and note that the snow melted as it landed.

The second challenge is that snow settles as it lies on the ground. Depending on the initial density of fresh snowfall and on other coincident weather conditions, the snow may settle rapidly or very gradually. This can have profound effects on observations (Doesken and Judson, 1997). Snowfall measured once per day would differ greatly from snowfall measured every six hours due to compaction effects taking place over a longer time period. On average snowfall measurements taken every six hours measure 19% more snowfall than those taken only once per day (Doesken and McKee, 1999).

The third characteristic is that snow is easily blown and redistributed (Doesken and Judson, 1997). Snow will often blow and form deep drifts. This is important to keep in mind when selecting a site for measuring snow. An area that is sheltered from the wind is usually the best area, however not always available. ASOS stations are located at airports where natural shelter from the wind is not readily available.

Because of melting, settling and redistribution, the time interval between observations is important. In 1996, the NWS set new snowfall measurement guidelines in an effort to expand use and consistency of snow data from cooperative observers and ASOS stations. The guidelines stated "*this (snow) measurement should be taken minimally once-a-day (but can be taken up to four times a day). Never sum more than four 6-hourly observations to determine your 24-hour (snowfall) total*" (NWS, 1996). Prior to this guideline, snowfall measurements were taken at different time intervals at different types of stations. The amount of snow measured increases with increasing frequency of snowfall measurements (Doesken and McKee, 1999). Even though the guidelines were intended to improve consistency, a problem still exists with the flexibility in the measurement interval. Because of these challenges, there may be considerable error and inconsistency in manually measured snowfall and snow depth.

1.2 BACKGROUND

1.2.1 Review of Literature

Limited research has been performed on testing ultrasonic snow depth sensors (USDS) in a field setting.

One of the first models of USDS was tested in the early 1980's (Gubler, 1981). It was created as an inexpensive sensor for automation of snow depth measurements. The study found the absolute precision of the sensor to be ± 1.2 inches (± 0.03 meters). The system operated well for the entire season of testing. Soft surface layers were found to cause long periods of data loss, while blowing/drifting snow affected the data for only several minutes.

In 1984, the Hydrometeorology Division and the Data Acquisitions Services Branch of the Atmospheric Environment Service (AES) of Canada released an assessment on the use of an inexpensive remote snow-depth gage in Canadian snowpacks (Goodison et al., 1984). This study found the sensor to consistently under-measure the snowpack by 0.8 - 1 inch (2-3 cm). It was also found that intense snowfall and the snow surface structure (i.e. low density snow) caused problems with the sensors ability to report snow depth.

Another assessment of ultrasonic snow depth sensors was done in the deeper Sierra Nevada snowpack. This study found a high correlation (r = 0.99) between ground truth and this type of sensor measurements (Bergman, 1989).

The evolution of the Campbell® SR-50 has come a long way since the early versions. The Campbell SR-50 evolved by removing the built in temperature sensor and changing the power supply from earlier versions of the sensors (Labine, 1996). Measures were taken to minimize the amount of errors reported in the data. The sensor is also capable of measuring multiple targets and outputting quality numbers associated with the data. Overall, the Campbell SR-50 became more reliable under various conditions due to improved signal processing (Labine, 1996).

The Natural Resources Conservation Service (NRCS) field tested the Judd Communications® depth sensor during the 1997 water year near Mt. Hood, OR for use in the SNOTEL (Snow Telemetry) network. The sensor performed well, with the exception of high intensity snow events where the sound pulse would reflect off falling precipitation rather than the snow surface. They found that the addition of depth sensors would provide valuable information of snowpack dynamics to aid in snowmelt and runoff prediction (Lea and Lea, 1998). The SNOTEL network currently has around 400 operational Judd sensors in mountainous locations across the western U.S.

1.2.2 Automation of Snow Measurement

The automation of snow measurements started in the early 1970's. The use of snow pillows has been utilized since the 1970's to measure SWE mainly in mountainous areas where measurements are hard to obtain. The SNOTEL network has been in operation since the early 1980's replacing collocated snow courses in areas hard to access making the measurements more cost effective (Serreze et al., 1999). SNOTEL sites originally measured daily values of SWE and precipitation and have gradually added minimum/maximum temperature, wind speed and more recently snow depth. SNOTEL utilizes meteor burst technology which transmits data to a central location without having to be visited for measurements (Serreze et al., 1999).

1.2.2.1 Snow Pillows

A snow pillow is a thick plastic or thin metal bag filled with antifreeze that is placed level with the ground surface. Snow accumulates on the pillow and a pressure transducer measures SWE as the weight of the snow on the pillow (Serreze et al., 1999). Snow pillows come in a variety of shapes and materials. They are most effective in high snow environments. However, the bridging of snow from the surrounding snowpack can affect the measurement quality. Snow bridging refers to a physical connection between the surrounding snowpack and the snow on the pillow which affects the distribution of the weight of the snow on the pillow. Also, large animals can disturb or damage snow pillows (Pomeroy and Gray, 1995). Snow pillows are widely used in the SNOTEL network to measure SWE.

1.2.2.2 Ultrasonic Snow Depth Sensors (USDS)

Ultrasonic depth sensors were developed using the technology of ultrasound. Ultrasound originated from SONAR (sound navigation and ranging) which allowed submarines to measure distances to objects under water during World War I for navigation (Woo, 2002). Ultrasound consists of longitudinal disturbances that propagate through a medium (Halliday and Resnick, 1988). The velocity of ultrasound in any medium is a function of the density and elasticity of the material. The speed of sound in water is approximately four times the speed of sound in air due to this fact (Halliday and Resnick, 1988). High frequency waves can be used to detect small objects, while lower frequency waves can be used to detect larger objects (Halliday and Resnick, 1988). The use of ultrasonic depth sensors began by utilizing a Polaroid ultrasonic ranging kit (Goodison et al., 1984) and has evolved into the sensors available today.

Ultrasonic depth sensors (USDS) have been used since the early 1980's with recent implementation into the SNOTEL network. This study aimed to test two existing USDS, not the technology utilized by them. Two manufacturers were tested in this study (See Figures 1-1 and 1-2). The Judd Communications (Judd, 2005) sensor converts a digital sensor reading of snow depth to an analog signal for transmission to a datalogger, while the Campbell Scientific model SR-50 (Campbell, 2005) utilizes SDI-12 (serial data interface) output to send digital output to a datalogger. The Judd sensor may also be purchased as a digital sensor that connects directly to a computer.

Both sensors must be mounted perpendicular to the surface of interest. The sensors can be mounted 1.6 to 32.8 feet (0.5-10 meters) off the ground. The sensors send out an ultrasonic sound pulse at 50 kHz and measures the time it takes to return to the sensor. The ultrasonic pulse utilizes a cone of 22 degrees (Figure 1-3) in which it measures over. It is important that nothing such as: trees, wires, installation hardware, etc. interferes with the 22 degree cone. The time for the pulse to return to the transducer is then adjusted for the speed of sound in air based on measured air temperature, and the timing is converted to a distance via an internal algorithm. The Judd sensor has a built-in temperature probe and radiation shield. A temperature probe and radiation shield must be purchased separately for the Campbell SR-50 sensor.

To adjust the speed of sound in air (V_{sound}) for the ambient air temperature (T_a) in degrees Kelvin Equation 1.1 is used.

$$V_{sound} = 331.4*(T_a/273.15)^{0.5}\ (m/s) \quad (1.1)$$

The Campbell sensor uses this relationship to correct the measured snow depth according to equation 1.2.

$$D_s\ (corrected\ Campbell^{®}) = D_{s\ (raw)} * (T_{Kelvin}/273.15)^{0.5} \quad (1.2)$$

V_{sound} = *Velocity of sound in air (m/s)*

$T_{Celcius}$ = *Temperature Celsius*

$D_{s(raw)}$ = *Snow Depth Reading*

T_{Kelvin} = *Temperature in degrees Kelvin*

The Judd sensor runs an internal sensor algorithm with a simplified equation 1.3.

$$D_s\ (corrected\ Judd^{®}) = D_{s\ (raw)} * ((T\ {}^{o}C * 0.00183) + 1) \quad (1.3)$$

Equation 1.3 assumes a linear relationship between V_{sound} and T_a over the range -100º C to +100º C. The simplified Judd correction can add 0.4% error to the measurement readings. 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. The sensors were calibrated to read zero snow depth on a level, white expanded Polyvinylchloride (PVC) snowboard under snow free conditions.

1.3 OBJECTIVES

The specific objectives of this research project were:

i) Develop a reliable method of quality assurance/quality control.

ii) Identify factors affecting sensor performance.

iii) Compare manual measurements of snow depth to each USDS.

iv) Develop an algorithm to derive six hour snowfall from sensor snow depth.

It was hypothesized that ultrasonic snow depth sensors can be used to estimate six hour snowfall during snow events from the reported sensor snow depth for the entire 2004-2005 snow season.

Figure 1-1: Judd communications depth sensor. *(Judd, 2005)*

Figure 1-2: Campbell Scientific SR-50 sensor. *(Campbell Scientific, 2005)*

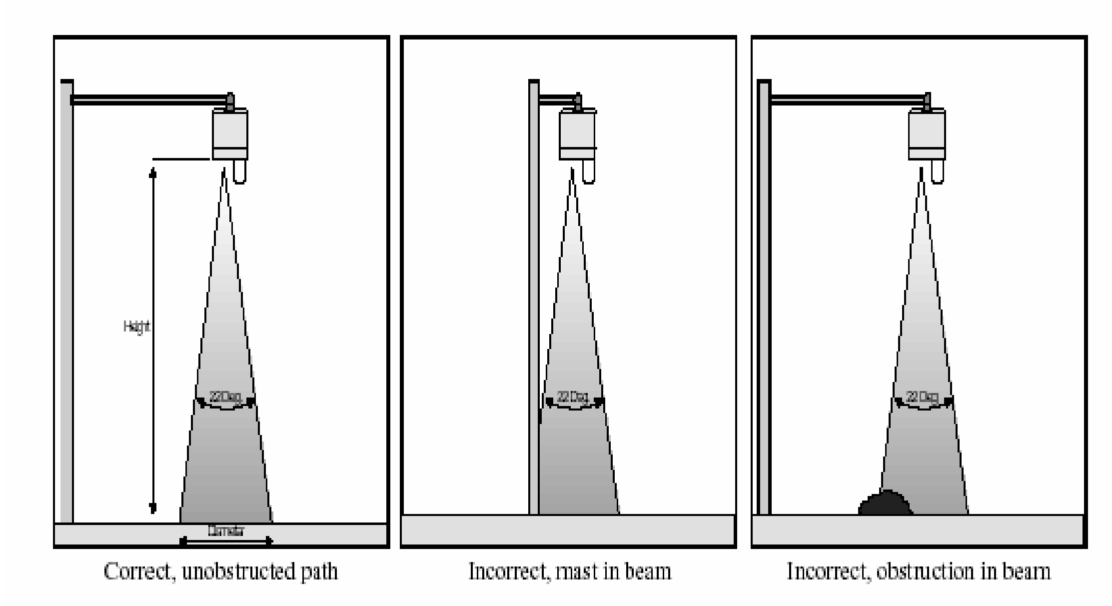

Figure 1-3: Diagram showing the 22 degree cone utilized by the ultrasonic sensors. (*Judd, 2005*)

CHAPTER 2: SITE DESCRIPTIONS

This research project included nine sites (Figure 2-1) throughout the coterminous U.S. that tested both the Judd Communications and Campbell Scientific depth sensors during the 2004-2005 snow season. Most sites were located at NWS forecast offices. One site (Davis, WV) was a NWS Cooperative site whose observer volunteered for the project. Other non-NWS sites included Fort Collins, CO and Steamboat Springs, CO. Table 2-1 shows the number of each sensor present at each site. Due to technical problems, the use of the data from Caribou, ME and Indianapolis, IN are limited.

Table 2-1: Sensor inventory by 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

2.1 SITE CONSTRUCTION

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. The basic setup was similar for each site. A detailed instruction packet was created and distributed which illustrated how to setup the datalogger to communicate with the sensors. Communication was enhanced between all sites by the use of a snow study email list for sites to express questions or advise others as each site was progressing through setup. Site photos are shown in Appendix A.

The sensors were mounted as close as possible to each other in order to minimize spatial variability in measurements. The sensors also needed to be far enough apart that the 22 degree cone of influence utilized by the ultrasonic pulses did not overlap and interfere with the other sensor. The sensors were setup perpendicular to the leveled PVC snowboards in order to receive a valid return signal. 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 once the ground begins to freeze. The sensors need to be rigidly mounted in order to minimize effects from strong wind which can cause the sensors to shake and return inaccurate snow depths.

For the purpose of this study Cheyenne, WY and Milwaukee, WI were important sites for comparison of wind effects. There was no snow fence installed to reduce wind at the Cheyenne, WY site. This was done for two reasons, the first was to retain comparability between manual and automated data and the second was to examine the effect of wind on sensor performance. Milwaukee, WI installed a double ring snow fence (See Appendix A Figure A-8) in order to minimize wind effects. Comparisons between these two sites provided insight into how valuable snow fences are for sensor performance. Steamboat Springs, CO served as a high snow site in order to compare sensor performance to most other sites that received intermittent and relatively low snowfall. These other sites provided useful data to understand how the sensors perform in different climates and site configurations.

2.2 CLIMATE CLASSIFICATION

The sites testing the sensors are found in climate zones including dry, temperate and cold according to the Koeppen Climate Classification (Table 2-2) (FAO, 1997). It was important to locate the test sites in areas receiving enough snowfall to be able to adequately evaluate the sensors for one winter of data collection. Average snowfall at the sites ranged from 24 to greater than 72 inches annually (Figure 2-3 and Table 2-3). In order to assess the data from the sensors, climatological factors such as: wind speed, snow crystal type, intense snowfall etc, were noted during manual measurements in order to identify which climate factors had an effect on sensor performance. Snow processes do not behave the same in all of the site locations because snow cover is highly variable and dependent on both the snowstorms themselves and the weather conditions between storms. The setup of each site was governed by their climate variables. For example, the sensor height from the ground was a function of the maximum snow depth at each site. The siting of the snow sensors also took into account prevailing wind direction. Some sites were known to be affected by blowing and drifting snow, and measures were taken to alleviate their effect with proper site selection.

Table 2-2: Description of Koeppen climate classes and station in each class.

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

Table 2-3: Summary of mean annual snowfall by station.

Stations	Mean Annual Snowfall (in)
Indianapolis, IN	24.1 - 36.0
Milwaukee, WI	36.1 - 48.0
Cheyenne, WY Fort Collins, CO	48.1 - 72.0
Caribou, ME Buffalo, NY Davis, WV Marquette, MI Steamboat Springs, CO	> 72.0

Figure 2-1: Station locations for USDS study.

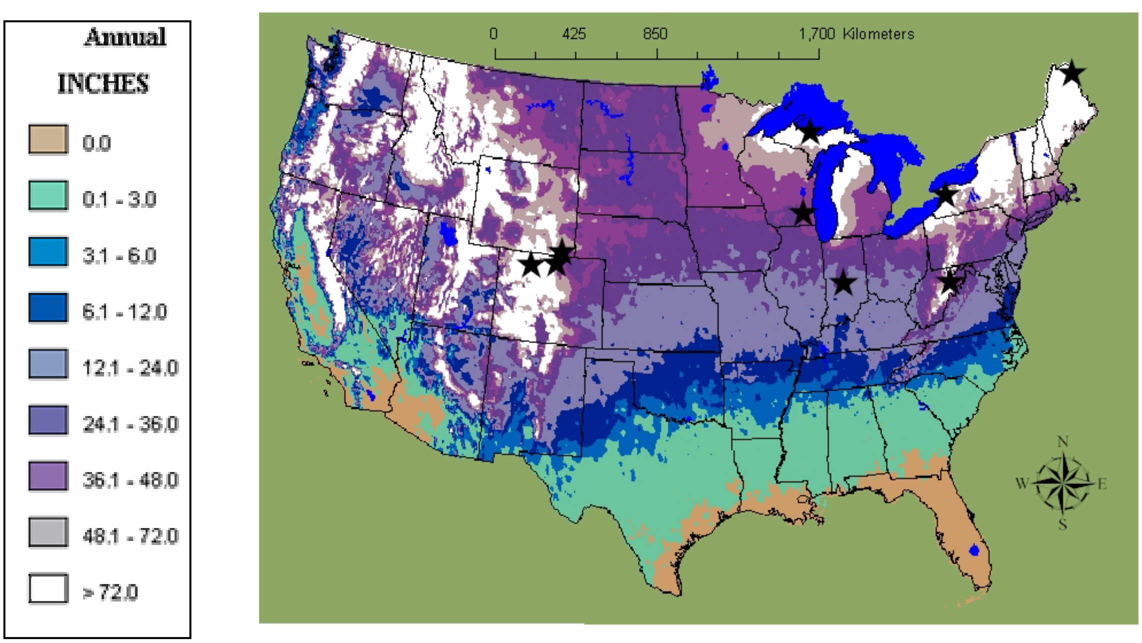

Figure 2-2: Mean annual snowfall (in) from *NCDC (2005)*.

CHAPTER 3: METHODS

3.1 DATA COLLECTION

The units of measurement used for this research were standard (or English) units. Standard units were chosen because they are the units of measurement used by the National Weather Service for measuring meteorological parameters.

3.1.1 Manual Data

Snow measurements were made with a National Weather Service (NWS) snow measurement ruler, a four inch plastic all-weather rain gage, eight inch standard rain gage (gage precipitation) and NWS expanded polyvinylchloride (PVC) snowboards. Expanded PVC is the chosen NWS material for snowboards. Therefore, this study also used this material. The snow measurement ruler is made of metal labeled to the tenth of an inch. The four inch plastic gage was chosen to perform snow cores of snow water equivalent (SWE) since it is considerably easier to use than the bulky NWS standard eight inch gage. A NWS snowboard (in addition to larger snowboards beneath the sensors either 32 in x 24 in or 48 in x 48 in) was used to measure six hour snowfall accumulation. The snowfall was measured every six hours, cleared, and repositioned to restart accumulation. 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. 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 ultrasonic depth sensors (USDS) was also recorded. The snowboard beneath the ultrasonic sensors was never cleared. SWE and gage precipitation measurements were made to the nearest hundredth of an inch using the inner core of the precipitation gage. SWE on the ground is the amount of water contained in a four inch gage core sample taken from the ground surface while gage precipitation refers to the amount of water contained in the snow captured by the four or eight inch precipitation gage. Notes were also made in reference to snow crystal type, wind speed, presence of blowing/drifting snow etc. The notes were taken in order to evaluate what may have caused problems with sensor performance. A summary of manual measurements is given in Table 3-1.

Table 3-1: Summary of manual measurements.

6 Hour Measurements
6 hour snowfall
Total depth of snow on the ground
Gage Precipitation
4” gage snow core off the 6 hour snowboard
Depth of snow nearest the Campbell sensor
Depth of snow nearest the Judd sensor
Number of measurements of total snow depth measurements.
Wind Speed
Snow Crystal Type: Dendrites, Columns, Needles, Plates, Sleet/Freezing Rain, Irregular
Presence of Blowing Drifting Snow
Observations of Snow Surface
Observations of Spatial Variability
Any other pertinent information that may have affected sensor performance.

A data website (Figure 3-3) was established to submit both manual and automated data (CSU, 2004). The observers at each study site were encouraged to maintain hard copy records of the manual data sheets and backups of electronic datalogger files. The manual data were submitted into forms directly on the website. Since online data submission sites can be prone to errors, it was requested that each site maintain hard copies of their manual data to be checked during quality assurance/quality control (QA/QC).

The manual measurements of snowfall and snow depth were considered ground truth for this study. It is important to note that this assumption may be flawed due to differences in techniques between sites as well as among observers. However, the manual measurements are the traditional measurements. The objective of the work was to test sensor performance and derive six hour snowfall from the USDS using traditional measurements as ground truth.

3.1.2 Automated Data

The USDS measured snow depth every five minutes utilizing multiple echo processing (MEP). MEP is an internal sensor algorithm which sends multiple sound pulses and compares the measurements, if they are not within ± 0.39 inches (± 1cm) another pulse is sent and the oldest is discarded until the measurements are satisfactory (Campbell, 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, WY and Milwaukee, WI had two Judd sensors for which the depth and temperature were also output.

3.2 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

One of the goals of this study was to assess sensor output stability and to find a reliable method of QA/QC. Sensor data illustrate both large (Figure 3-1) and small amplitude (Figure 3-2) variability. The use of the word variability in this thesis pertains to the precision of the instruments, however it is divided into two categories and described as variability in the measurements. The large amplitude variability consisted of occasional large data spikes which were easily filtered and removed. The small amplitude variability was inherent in the sensor data; data smoothing techniques, such as a moving average, removed most of it. The small amplitude variability consisted of variations of a few tenths of an inch between sensor measurements even with snow free conditions. Both forms of variability were addressed with data processing so that a smooth, continuous record of snow depth could be compared to manual measurements.

3.2.1 Sensor Quality Assurance/Quality Control (QA/QC)

To have uniformity in the sensor data files, all site data were quality assured and controlled using the same procedures. All QA/QC was done using the Microsoft Excel 2003 spreadsheet software. The first step in processing the sensor data was to identify large data spikes present in the USDS data. This was done with a conditional *(if)* statement that identified both large negative and positive data spikes that occurred when the sensors could not make a measurement. Data spikes are caused when the sensor does not receive the return ultrasonic pulse due to a variety of environmental factors; these will be discussed in detail in the following section. The threshold for a positive spike was dependent on the amount of snow received at each site. For most sites twenty inches was used, but for higher snow sites values differed by the maximum snow depth received at each of those sites, particularly Marquette, MI and Steamboat Springs, CO. These were chosen after examination of the data and choosing a threshold that would not filter out valid data points contributing to accumulation and ablation (i.e. melting) patterns. The value of the spikes is *usually* the offset value of the sensor height off the ground in the datalogger program, however this is not always the case. The threshold for negative values was the same magnitude as the positive threshold. This was to differentiate between large negative spikes and negative values due to small amplitude variability around zero so that the frequency of data spikes could be quantified. Once all the large spikes were removed corresponding time steps were marked as missing.

The next step was to set negative values to zero. Negative values occurred due to small amplitude variability when the snow depth was at or near zero. The marked missing values were then filled in using the value from the previous time step. This method was chosen because data spikes were not common.

The data were then checked for variability over the five minute periods. If the snow depth changed by more than ±0.5 inches in five minutes the data were flagged. The flagged data points were also filled in using the previous time step. This method worked well to remove the large amplitude variability from the data even though small amplitude fluctuations still existed in the data. The total number of data points that fell into the two main corrections are shown in Table 3-2, where correction one refers to the large data spikes, correction two refers to the ±0.5 inches check over 5 minute intervals and "n" refers to the total number of observations. Caribou, ME was not included because of problems in the data caused by malfunctioning equipment.

Table 3-2: Total number of data points flagged by each large amplitude variability correction.

		Judd		**Campbell**	
	n	**Large Data Spike Correction 1**	**±0.5 inch check Correction 2**	**Large Data Spike Correction 1**	**±0.5 inch check Correction 2**
Buffalo, NY	38811	99	635	1	160
Cheyenne, WY	55846	20	157	0	27
Cheyenne, WY	55846	90	298	N/A	N/A
Davis, WV	54063	18	655	1	195
Fort Collins, CO	50281	23	430	64	111
Indianapolis, IN	11825	0	49	0	20
Marquette, MI	38007	965	1452	67	312
Milwaukee, WI	21465	24	250	0	38
Milwaukee, WI	21465	53	273	N/A	N/A
Steamboat Springs, CO	35356	2205	781	6311	1255

Once the large amplitude variability was removed the data were further smoothed to remove small amplitude variability between the five minute time steps. Both one and three hour center weighted moving averages were applied to the data. Center weighting was utilized in order to retain the most information about the current depth of snow. One and three hour moving averages were initially chosen to determine the amount of smoothing required for the data as well as to evaluate if each sensor needed a different amount of smoothing. The data were also plotted and visually inspected after QA/QC to ensure the procedures worked properly. For example, to check that all data spikes were removed and large time periods were not filled in with the same value.

3.2.2 Manual Data QA/QC

Manual data were collected at each individual site and submitted to a central database via an online data submission website (CSU, 2004). Even though data were submitted online there was a need for QA/QC to ensure missing data points were properly labeled, typographical errors were identified and corrected, and the proper date and time were accompanying the data. In order to check the data submitted over the website, hard copies of the data sheets were obtained from each participating site. The hard copies were treated as truth and the data from the website was altered if different from the original data sheets. The use of the website was helpful for collecting the large amount of data and creating a central database for its storage. There were numerous errors associated with the electronic data which would not have been identified without the original data sheets. After QA/QC the manual data were compared to the automated data.

3.3 FACTORS AFFECTING SENSOR PERFORMANCE

In order 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: 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), transducer is obstructed by ice/snow, and strong winds blowing the echo out from under the sensor (Campbell Scientific, 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 vs. hard packed crust) may cause the sensor to underestimate due to the signal penetrating the snowpack. For this study, once the data spikes were identified by date and time the manual data were utilized to find possible causes of error. The manual data were only taken every six hours with observers reporting anything over the entire six hour period that could cause problems with sensor performance. The observations were assumed to be valid over the previous six hour time period unless it was otherwise ascertained that it could not be the cause. This assessment is highly speculative since six hour manual reports were used to assess five minute sensor data.

3.4 COMPARISON OF SENSOR SNOW DEPTH TO MANUAL SNOW DEPTH

A major objective of this study was to quantify how accurately the sensors measure the depth of snow on the ground. 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. In order to minimize the effects of spatial variability the snow depth on the sensor boards beneath the sensors was measured. Both of the measurements were then paired with the USDS depth reading. In order to describe errors associated with both measurements the average difference, standard deviation of difference, mean absolute error, and root mean square errors were calculated for each sensor. Both one and three hour moving averages were used to give a better understanding of which amount of smoothing works best for each sensor at each site. This information was useful in the formulation of the six hour snowfall algorithm.

3.5 SIX HOUR SNOWFALL ALGORITHM

Two separate algorithms were tested in this study due differing degrees of small scale variability.

3.5.1 Calculation of Snowfall

In order to create a snowfall algorithm, six hour snowfall was calculated from the five minute sensor data. This calculation was done using two different methods, a five minute snowfall algorithm and a 60 minute snowfall algorithm. The calculation of six hour snowfall requires more than taking the change in snow depth every six hours. This method would cause snowfall to be omitted if it accumulated and melted within the six hour period. Figures 3-4 and 3-5 show plots of cumulative six hour snowfall plotted for Buffalo, NY and Fort Collins, CO. The snowfall was calculated by taking the change in snow depth over six hour intervals.

3.5.1.1 Five Minute Snowfall Algorithm (5MSA)

The first method used a five minute timestep for calculating snowfall according to equation 3.1 where t is in minutes, d_s is snow depth and i is in hours. If the sensor snow depth increased over the five minute period the difference was taken and called five minute snowfall. If the depth did not increase a zero was entered. The five minute snowfall values were then summed over the six hour observation intervals used by each site to obtain the five minute snowfall algorithm for six hour snowfall (5MSA-6HSF).

$$\begin{aligned} &\text{5MSA-6HSF} = \sum_{i}^{i+6} (d_{s_{t+5}} - d_{s_t}) && \text{if } (d_{s_{t+5}} - d_{s_t}) > 0 \\ &\text{5MSA-6HSF} = 0 && \text{if } (d_{s_{t+5}} - d_{s_t}) \le 0 \end{aligned} \qquad \textbf{3.1}$$

3.5.1.2 Sixty Minute Snowfall Algorithm (60MSA)

The second method took the change in snow depth over a sixty minute interval according to equation 3.2. The positive sixty minute changes in snow depth were then summed over the six hour observation periods to create the sixty minute snowfall algorithm for six hour snowfall (60MSA-6HSF). Both of these methods were performed on both one and three hour moving averages in order to determine the effect of smoothing as well as the degree of smoothing required by each sensor to accurately estimate six hour snowfall.

$$\begin{aligned} &\text{60MSA - 6HSF} = \sum_{i}^{i+6} (d_{s_{t+60}} - d_{s_t}) && \text{if } (d_{s_{t+60}} - d_{s_t}) > 0 \\ &\text{60MSA - 6HSF} = 0 && \text{if } (d_{s_{t+60}} - d_{s_t}) \le 0 \end{aligned} \qquad \textbf{3.2}$$

3.5.2 Compaction

Both of the above methods calculated snowfall over small time periods which do not take into account compaction of the snowpack. Once the six hour snowfall values were calculated, compaction by both metamorphosis and overburden were considered. Metamorphosis 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. The compaction equations are temperature based and were obtained from the SNTHERM.89 one-dimensional snowpack model by Jordan (1991) who modified Anderson's (1976) equations 3.7 and 3.8. This compaction model was chosen because temperature was readily available.

In order to use these compaction equations the density of the new snow was required. SWE and snow depth were components of the manual observations and could be used to compute snow density. Since there were not enough of these measurements to use for the entire season, four different temperature-based fresh snow density models were utilized. The results were compared to the manual observations of snow density at each site to obtain the best model for prediction of fresh snow density. Only sites with sufficient SWE and snow depth data were used for the comparison with at least one site from each climate zone. The four models included: Diamond-Lowry (1953), LaChapelle (1961), Hedstrom-Pomeroy (1998), and a particle shape equation (Fassnacht and Soulis, 2002), and are given as:

$$\rho_s(fresh)_{Diamond-Lowry} = 119 + 6.48 * T_a \qquad \textbf{3.3}$$

$$\rho_s(fresh)_{Alta} = 50 + 1.7 * (T_a + 15)^{1.5} \qquad \textbf{3.4}$$

$$\rho_s(fresh)_{Hedstrom-Pomeroy} = 67.92 + 51.25e^{(T_a / 2.59)} \qquad \textbf{3.5}$$

$$\begin{aligned}\rho_s(fresh)_{Fassnacht-Soulis} = 85 * [\ & (1 - 0.03 * \cos(0.33 * T_a + 0.418)) + \\ & 0.15 * \cos(2 * 0.331 * T_a + 0.418) \\ & - 0.029 * \cos(3 * 0.331 * T_a + 0.418) + 0.123 * \\ & \sin(0.331 * T_a + 0.418) + 0.009 * \sin(2 * 0.331 * T_a + 0.418) \\ & - 0.026 * \sin(3 * 0.331 * T_a + 0.418)\ ] * (-1.75) + 1\end{aligned} \qquad \textbf{3.6}$$

After calculating correlation coefficients for each model and the manual observations, the Hedstrom-Pomeroy equation was chosen to calculate fresh snow density using the average temperature over the six hour period of interest. Once the snow density was estimated the compaction equations could be applied. The equations are listed below for both metamorphism and overburden compaction (Jordan, 1991). The metamorphism equation is listed as equation 3.7 and the overburden compaction is equation 3.8. In the metamorphism equation γ_l refers to the bulk density of liquid water and γ_i refers to the bulk density of ice. Temperature is in degrees Kelvin.

$$\left|\frac{1}{\Delta z}\frac{\partial \Delta z}{\partial t}\right|_{metamorphi\ sm} = -2.778 * 10^{-6} * c3 * c4 * e^{-0.04(273.15-T)} \quad \textbf{3.7}$$

where $c3 = c4 = 1$ if $\gamma_l = 0$ and $\gamma_i \leq 150$ kg/m^3

$c3 = \exp^{[-0.046(\gamma_i - 150)]}$ if $\gamma_i > 150$ kg/m^3

$c4 = 2$ if $\gamma_l > 0$

$$\left[\frac{1}{\Delta z}\frac{\partial \Delta z}{\partial t}\right]_{overburden} = -\frac{P_s}{\eta_0} e^{-c5(273.15-T)} e^{-c6\rho_s} \quad \textbf{3.8}$$

where P_s = *snow load pressure in* (N/m^2)

$\eta_0 = 3.6 * 10^6\, N * s/m^2$

$c5 = 0.08\, K^{-1}$

$c6 = 0.021\, m^3/kg$

$$P_s(N/m^2) = 248.976 * SWE \quad \textbf{3.9}$$

The variables *c3* and *c4* in the metamorphism equation allow for different compaction rates depending on how wet or dry the snowpack is. The constant c4 in the metamorphism equation was set to 2 if the air temperature was greater than 32º F which doubles the compaction rate for wet snow. For the other two conditions the predicted fresh snow density was used to estimate c3 and c4. Once the metamorphism depth and the new density of snow were calculated, the new snow depth was entered into the overburden equation 3.8. The overburden compaction was only calculated if there was old snow underlying new snow.

3.5.3 Statistics Used for Algorithm Assessment

In order to compare the six hour snowfall algorithm to manual six hour snowfall measurements the cumulative snowfall was plotted for each. If missing data (i.e. automated data was not available for that period or a missed manual observation) existed in either the automated or manual data, that period was removed from both records. A Nash-Sutcliffe R-squared (Nash and Sutcliffe, 1970) was calculated for the cumulative snowfall along with percent difference in seasonal snowfall totals. Mean absolute error (MAE) was calculated for the incremental predictions of six hour snowfall compared to manual six hour snowfall measurements.

In order to assess how the occurrence or non-occurrence of snow was predicted by the sensors compared to manual, the errors of omission and commission were calculated for all degrees of smoothing on both sensors. The error of omission (OE) describes the proportion of the time when the sensors did not measure snow when it was measured manually. The error of commission (CE) describes the proportion of the time the sensors measured snow when no snow was measured manually.

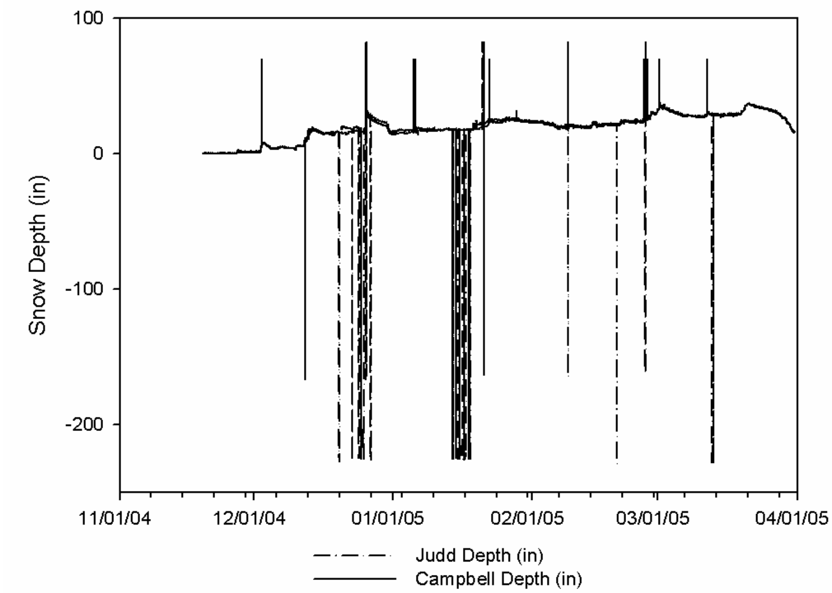

Figure 3-1: Example of large amplitude variability in sensor data from Marquette, MI.

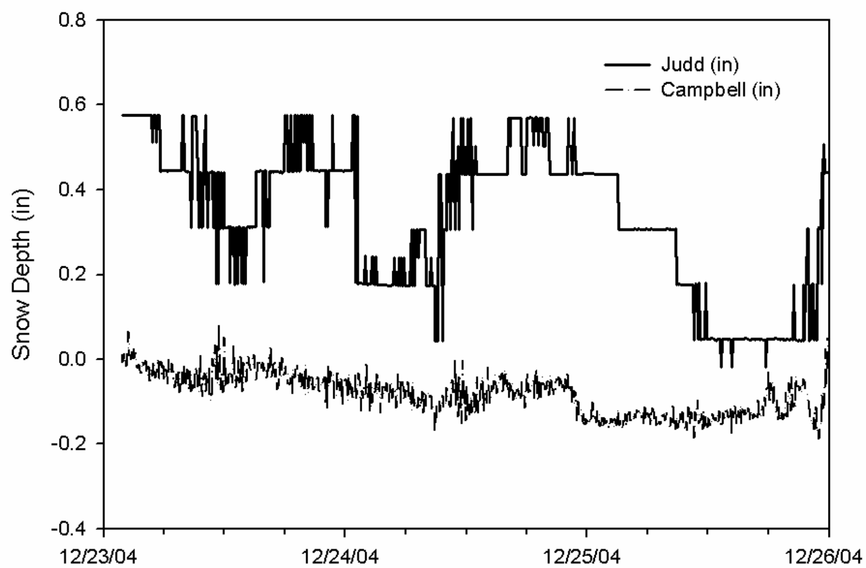

Figure 3-2: Example of small amplitude variability from Milwaukee, WI during a snow-free period.

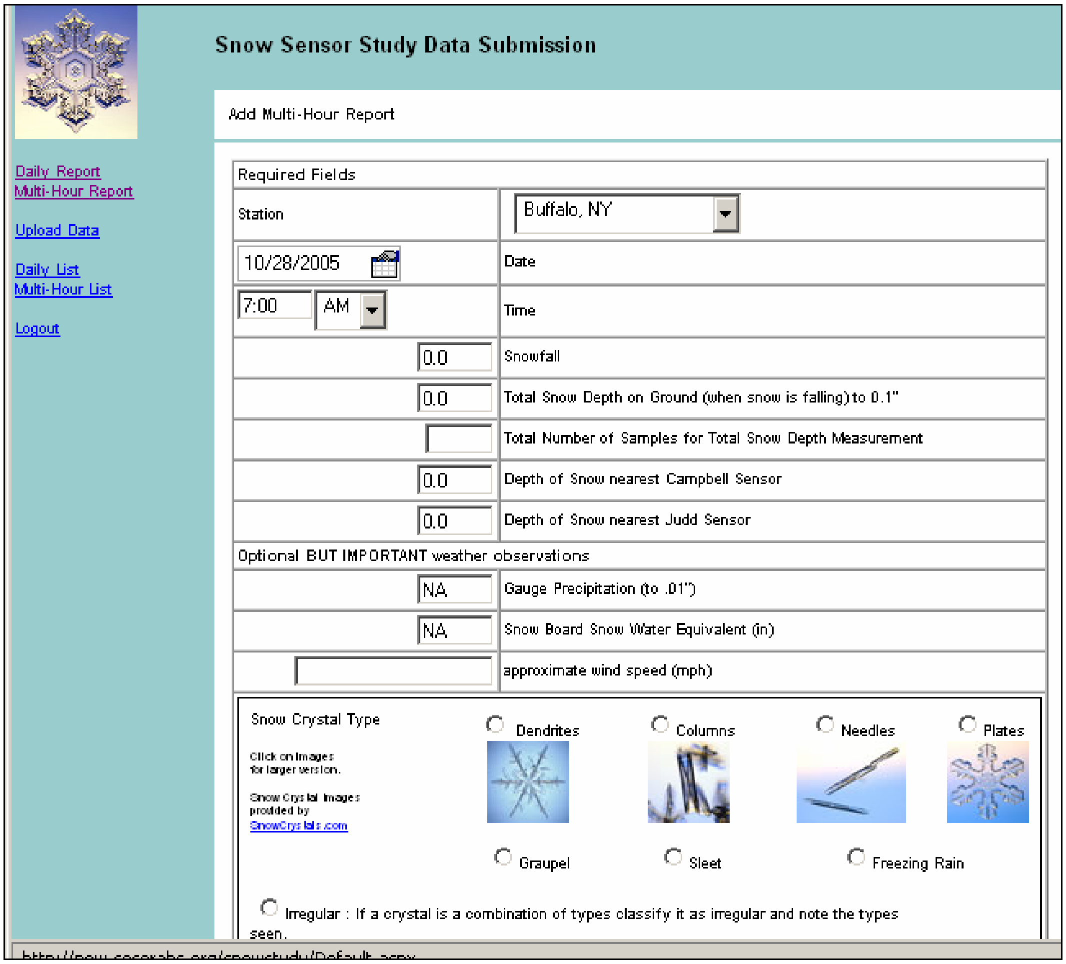

Figure 3-3: Screen capture of the snow study data submission site.

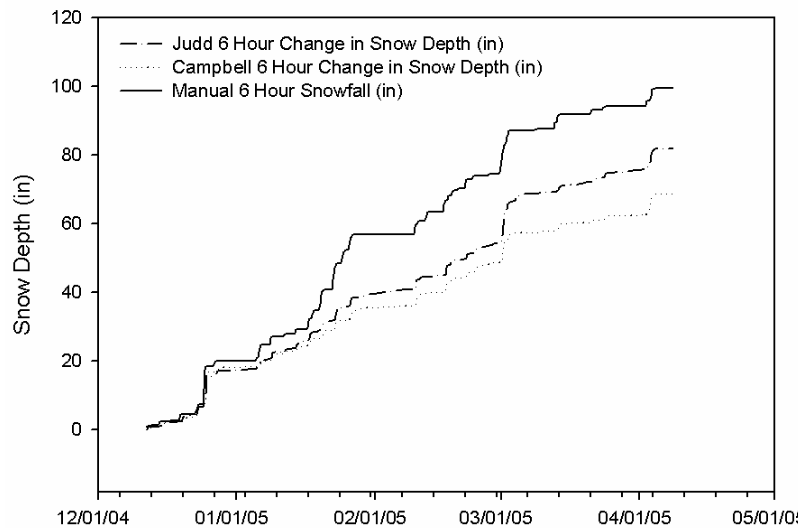

Figure 3-4: Buffalo, NY snowfall calculation taking six hour change in snow depth.

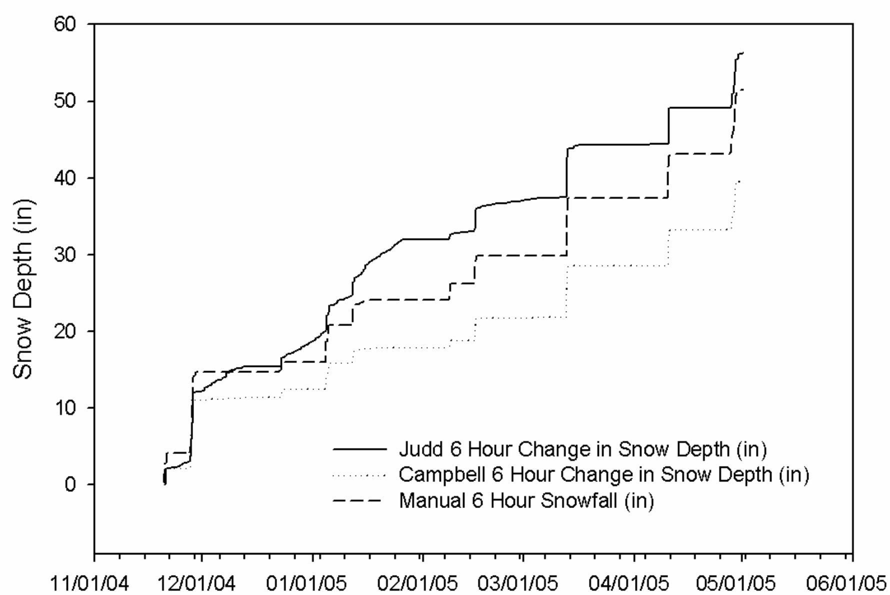

Figure 3-5: Fort Collins, CO snowfall calculation taking six hour change in snow depth.

CHAPTER 4: RESULTS

4.1 CHARACTERISTICS OF SNOW SENSOR DATA

Raw sensor data were not very precise and needed varying degrees of smoothing depending on sensor and site setup. A plot of unedited data for Buffalo, NY is shown in Figure 4-1.

4.1.1 Large Amplitude Variability: Qualitative Analysis of Data Spikes

For each site, the large amplitude variability (i.e. data spikes) was identified and compared to manual reports in order to determine the cause of the spikes. The spikes usually occur over distinct time periods. The spike or time period in which they occurred where recorded and then possible causes from the manual data were noted. The summary is shown in Appendix E. Sites with large amounts of data spikes due to malfunctioning equipment or limited amounts of manual data were omitted (i.e. Caribou, ME, Steamboat Springs, CO and Indianapolis, IN). In some cases no reports were entered and no cause of the spike was identified. The major causes of the spikes were snow crystal type, wind speed, intense snowfall, presence of blowing/drifting snow and extreme cold temperatures. Other causes that were speculated to be the cause of non-continuous data spikes included: possible observer interference, grass cutting, and snow falling off the sensors/structure causing an un-level snow surface. The causes found for large amplitude variability in this study are similar to results from the other snow sensor studies found in the literature review (e.g. Goodison et al., 1984). It is important to note that in some cases it is impossible to determine the cause of the spike because more than one possible cause was reported. The manual observations were taken every six hours and it was inferred that what was happening at the observation time could have occurred when the data spike occurred.

4.1.2 Large Amplitude Variability: Quantification of Data Spikes

The quantification of data spikes involved calculating the percentage of time spikes occurred and also the percentage of spikes that occurred during snowfall events. The percentage of time spikes occurred was found by summing the total number of spikes and dividing by the total number of observations and multiplying by 100%. The percentage of spikes that occurred during snow events involved an algorithm to decide if it was snowing or not. The algorithm looked at the five minute smoothed depth measurements before and after the data spike. If snow depth increased both before and after the data spike, it was said to be snowing. Once it was found to be snowing, those spikes occurring during snow events were divided by the total number of spikes and multiplied by 100%. The results are shown in Figures 4-2 and 4-3. Figure 4-2 illustrates how infrequent the data spikes are relative to the entire data record. Figure 4-3 shows that most often the spikes are occurring during snowfall events. Caribou, ME; Indianapolis, IN and Steamboat Springs, CO show low percentages during snowfall events but these sites were also plagued with more data spikes than most sites due to malfunctioning equipment. On average the Judd sensor produced spikes 0.4% of the time while the Campbell produced them 0.04% of the time.

4.1.3 Small Amplitude Variability

In order to quantify the amount of small amplitude variation found in each sensor without interference from snowfall, only periods of no snowfall were used. No snowfall periods were then broken into two categories: snow free and snow covered. Five sites were chosen for the assessment based on having suitable data to evaluate and included: Davis, WV; Marquette, MI; Fort Collins, CO; Buffalo, NY and Indianapolis, IN. Suitable data meant that they had an extended period of time where snow was present on the ground without additional snowfall. In each of the comparisons there are at least 500 data points for evaluation. If a negative trend due to compaction was present in the data, a trend was fit through the data and the residual difference between the original data and the trend data were used for the calculation of standard deviation. The standard deviation was used to get an idea of the variation present when the snow depth should have been near constant. For each of the periods the standard deviation in snow depth reported was calculated as well as the total number of observations (Table 4-1). The average standard deviation for the Judd with snow free conditions was 0.19 inches and with snow covered conditions was 0.18 inches. The maximum was 0.30 inches for the Judd with snow covered conditions. The average standard deviation for the Campbell with snow free conditions was 0.07 inches compared to the average with snow covered conditions of 0.11 inches. The Campbell sensor consistently shows less small amplitude variation under both snow free and snow covered conditions at all sites.

In order to quantify the extent the two degrees of smoothing (i.e. one or three hour moving average) removed the small amplitude variability the standard deviations were calculated (Table 4-2). The same time periods as the above snow free condition analysis were used. On average the one hour moving average reduced the small amplitude variability in the Judd to 0.10 inch (from 0.19 inch) and the Campbell to 0.03 inch (from 0.07 inch). The three hour moving average reduced the small amplitude variability in the Judd even further to 0.08 inch while the Campbell remained at 0.03 inch. A plot of Marquette, MI is shown in Figure 4-4 with both degrees of smoothing for each sensor.

Table 4-1: Standard deviation (in) of reported snow depth with no snowfall and a) snow free conditions and b) snow covered conditions.

Judd	No Snowfall and Snow Free	N	No Snowfall and Snow Covered	N
Davis, WV	0.15	1440	0.07	1440
Marquette, MI	0.23	1356	0.10	649
Fort Collins, CO	0.23	1698	0.28	1272
Indianapolis, IN	0.18	1009	0.30	1333
Buffalo, NY	0.15	566	0.15	649
Average	***0.19***		***0.18***	
Campbell				
Davis, WV	0.08	1440	0.00	1440
Marquette, MI	0.05	1356	0.08	649
Fort Collins, CO	0.10	1698	0.20	1272
Indianapolis, IN	0.08	1009	0.24	1333
Buffalo, NY	0.04	566	0.04	649
Average	***0.07***		***0.11***	

Table 4-2: Standard deviation (in) of raw snow depth under snow free conditions and a) one hour moving average and b) three hour moving average.

Judd	Raw Data	1HRMA	3HRMA
Davis, WV	0.15	0.09	0.08
Marquette, MI	0.23	0.14	0.11
Fort Collins, CO	0.23	0.13	0.12
Indianapolis, IN	0.18	0.09	0.08
Buffalo, NY	0.15	0.04	0.03
Average	***0.19***	***0.10***	***0.08***
Campbell			
Davis, WV	0.08	0.00	0.00
Marquette, MI	0.05	0.02	0.02
Fort Collins, CO	0.10	0.09	0.09
Indianapolis, IN	0.08	0.02	0.02
Buffalo, NY	0.04	0.02	0.02
Average	***0.07***	***0.03***	***0.03***

4.2 CLIMATE FACTORS AFFECTING SENSOR PERFORMANCE

After inspection of the sensor data, a variety of climate and non-climate factors were identified that affected sensor performance. The main causes of problems with sensor performance are discussed in the following sections. It is important to note that the identification of data spikes is limited by the amount of manual data to validate them with. In this case observations were taken in six hour intervals so reports were assumed to be occurring over the entire period in order to validate five minute data. It is also important to note that the cause of a data spike may stem from one or more of the factors below. Again, it is important to keep in mind that data spikes are not very common in the data occurring in the Judd 0.4% of the time and 0.04% of the time with the Campbell. This kind of variation in the data was easily identified, removed and smoothed. However, it was very valuable to understand what types of conditions caused problems with the sensors so that measures to minimize these errors can be taken.

4.2.1 Snow Crystal Type

Snow crystal type is one of the main causes of large amplitude variability (See Figure 4-5). Reports of dendrites, columns, plates and needles were the types that coincided most commonly with large amplitude variability. The other options for crystal type reports were graupel, irregular, sleet or freezing rain. Freezing rain and sleet did not appear to have any affect on sensor performance. Irregular crystals refer to a combination of different types of crystals, but most often these are the crystals which would form a uniform snow surface, unlike the other types of crystals listed. Figure 4-6 shows the distribution of snow crystal reports from Marquette, MI, with 58% of the reports being dendrites, followed by 17% of the reports being irregular crystals. The actual crystal types may not be accurate due to observers having limited experience identifying crystal types. It is important to note that this a qualitative assessment in order to better understand the causes of large amplitude variability in the sensor data.

4.2.2 Presence of Blowing/Drifting Snow

Another common cause of large amplitude variability was the presence of blowing/drifting snow (See Figure 4-7). The presence of blowing snow under the sensor can cause the same problems as low density snow crystals. The sound pulse can hit the blowing snow crystals before reaching the surface causing the signal to be scattered and unable to measure the snow depth accurately. The sensor needs a clear path beneath the transducer in order to send and receive a quality measurement. When blowing snow was present the path between the ground and sensor was obstructed causing the sensor to be unable to report an accurate snow depth measurement.

4.2.3 Intense Snowfall

The effect of intense snowfall was the same as presence of blowing snow. In Figure 4-9 (Extreme Temperatures) from Marquette, MI there is also a period where both sensors produced large amplitude variability from the evening of 25 December 2004 into 26 December 2004. This was due to a period of intense snowfall in the range of 3-5 inches/hour. The signal was attenuated by the presence of intense snowfall under the sensor and could not make an accurate measurement. The signals most likely reflected off the snow crystals or attenuated the sensor sound pulse.

4.2.4 Wind Speed

Wind speed was another factor which caused problems with the performance of the ultrasonic sensors. It is important to note that wind speeds can cause large amplitude variability even in the absence of blowing snow. During the course of this study it was qualitatively inferred that winds in excess of 15 mph could produce large amplitude variability when no blowing snow was reported. The cause of this may be due to the sound pulse being blown out from under the sensor. When the sensor never received a return signal the snow depth could not be calculated. High winds also caused the mounting structures to shake if they were not rigidly installed. If the sensor was shaking it may not have been able to accurately send or receive the return signal not allowing the sensor to accurately report snow depth.

4.2.5 Uneven Snow Surface

An uneven snow surface can cause the sensor to report imprecise measurements. The sensors operate over a beam radius of 22 degrees. The surface below the sensor must be level and unobstructed throughout the 22 degree cone in order to have reliable measurements. During the course of this study, observers reported animal tracks, uneven snow surface due to drifting, and uneven snow surface due to snow falling off mounting structures. Animal tracks under the sensor had little effect on the performance of the sensor. There was also no evidence of the animal present in the data but it may have been filtered out during multiple echo processing (MEP).

Snow falling off the mounting structure was reported in Fort Collins, CO on 13 March 2005 (Figure 4-8). This caused the Judd sensor to show large amplitude variability and gave variable depth information. After removing a linear compaction trend from both data series the standard deviation of the residuals were calculated. The Judd showed a standard deviation of 0.26 inches while the Campbell was only 0.15 inches over the same period. Large amplitude variability was removed for this calculation. Recall from Table 4-1 that the small amplitude variation for the Judd with snow on the ground was 0.18 inches, while the Campbell was 0.11 inches. The uneven surface appears to have added around at tenth of an inch variation in the Judd depth reported and affected the Campbell to a lesser degree. The difference in variation may be attributed to differing degrees of uneven surface below each sensor.

4.2.6 Extreme Cold Temperatures

The user manuals for both the Judd and Campbell sensors list the operating temperature range to be -22 º to +158 º F (-30 º to +70 º C). Between 24 December 2004 and 27 December 2004 in Marquette, MI the temperature dropped to -25 º F (Figure 4-9). The Campbell sensor did not suffer any data loss and continued working throughout the extreme cold temperatures. However, the Judd sensor was not operating properly at temperatures of approximately -10º F. Temperatures in Caribou, ME dropped to -15 º F and this problem was not seen. This problem may be site specific to the sensor in Marquette, MI.

4.3 COMPARISON OF AUTOMATED AND MANUAL SNOW DEPTH

The evaluation of how the sensors compared to manual measurements consisted of two comparisons. The first was the comparison of the sensor depth to manual depth measurements made in the immediate vicinity of the sensors. The second was the comparison of sensor depth to the total snow depth on the ground reported by observers. The total snow depth measurements were taken where each site historically measured it. The total depth of snow on the ground measurement can be an average of several depth samples depending on the spatial variability of the snowpack. The number and placement of depth measurements was at the discretion of the observer, while the sensor depth was a single point measurement.

4.3.1 Sensor Comparison to Depth at Sensors

Each site, as part of the manual observation protocol, took snow depth measurements next to each ultrasonic snow depth sensor. The reason for this was to achieve the best estimate of the depth of snow that the sensor was measuring. Each manual measurement of snow depth was then coupled with the corresponding sensor measurement at the time of the observation. This was done for both the one and three hour moving averages that were applied to the sensor data. Once the manual and automated measurements were paired the average difference, standard deviation of average difference, mean absolute error and root mean square error were calculated (Table 4-3). The root mean square error for the measurements was normalized by the average snow depth at each location (zumBrunnen, Per.Com., 2005). This was done in order to be able to compare the root mean square error (RMSE) from site to site because a RMSE at a site with 10 inches of annual snowfall is much more significant than the same RMSE at a site receiving 60 inches of annual snowfall. The descriptive statistics vary by site and sensor (4-3). Caribou, ME and Indianapolis, IN are not included in the comparisons due to problems with the data at these sites. However, the results were similar for the two degrees of smoothing investigated. The average difference in snow depth ranged from -1.7 to 0.2 inches. The standard deviation of average difference ranged from 0.2 to 4.3 inches. The mean absolute error (MAE) ranged from 0.2 to 2.4 inches. The normalized RMSE ranged from 0 to 1.1 inches.

Table 4-3: Summary statistics for sensor snow depth and manual sensor depth using 1 and 3 hour moving averages (1HMRA, 3HRMA respectively).

Buffalo, NY	**Average Difference (in)**	**Standard Deviation (in)**	**N**	**MAE (in)**	**RMSE (in)**	**Normalized RMSE (in)**
Judd (1HRMA)	0.08	0.88	434	0.52	0.88	0.30
Judd (3HRMA)	0.07	0.86	434	0.52	0.72	0.24
Campbell (1HRMA)	0.09	0.80	434	0.49	0.70	0.24
Campbell (3HRMA)	0.09	0.78	434	0.48	0.78	0.26
Cheyenne, WY						
East Judd (1HRMA)	0.12	0.66	143	0.33	0.67	0.72
East Judd(3HRMA)	0.09	0.65	151	0.33	0.66	0.71
West Judd (1HRMA)	0.08	0.94	47	0.54	0.93	1.00
West Judd (3HRMA)	-0.08	0.98	55	0.61	0.98	1.05
Campbell (1HRMA)	-0.06	0.55	143	0.22	0.55	0.59
Campbell (3 HRMA)	-0.09	0.55	151	0.23	0.56	0.60
Davis, WV						
Judd (1HRMA)	0.17	4.34	201	2.28	4.33	0.88
Judd (3HRMA)	0.15	4.34	201	2.29	4.33	0.88
Campbell (1HRMA)	0.00	4.33	201	2.35	4.32	0.88
Campbell (3HRMA)	-0.01	4.32	201	2.35	4.31	0.88
Fort Collins, CO						
Judd (1HRMA)	0.15	0.54	529	0.26	0.56	1.07
Judd (3HRMA)	0.14	0.53	529	0.25	0.55	1.05
Campbell (1HRMA)	0.06	0.53	529	0.20	0.54	1.03
Campbell (3HRMA)	0.08	0.53	529	0.20	0.53	1.02
Marquette, MI						
Judd (1HRMA)	-0.54	1.06	571	0.82	1.19	0.07
Judd (3HRMA)	-0.54	1.07	571	0.82	1.20	0.07
Campbell (1HRMA)	-1.69	1.24	571	1.79	2.10	0.12
Campbell (3HRMA)	-1.69	1.24	571	1.79	2.10	0.12
Milwaukee, WI						
Judd1 (1HRMA)	N/A	N/A	N/A	N/A	N/A	N/A
Judd1 (3HRMA)	N/A	N/A	N/A	N/A	N/A	N/A
Judd2 (1HRMA)	-0.03	0.42	244	0.28	0.42	0.14
Judd2 (3HRMA)	-0.04	0.41	244	0.28	0.41	0.14
Campbell (1HRMA)	0.19	0.85	220	0.49	0.87	0.30
Campbell (3HRMA)	0.19	0.85	220	0.49	0.87	0.30
Steamboat Springs, CO						
Judd (1HRMA)	-0.03	0.23	35	0.15	0.23	0.00
Judd (3HRMA)	0.08	0.85	35	0.32	0.84	0.01
Campbell (1HRMA)	-0.07	0.34	29	0.24	0.34	0.01
Campbell (3HRMA)	0.06	0.91	29	0.40	0.90	0.01

Figures 4-10 and 4-11 show plots of Buffalo, NY sensor snow depth plotted with manual snow depth next to each sensor. The Campbell sensor plotted is a one hour moving average while the Judd shows the three hour moving average. Since the small amplitude variation was larger in the Judd (0.2 inches compared to 0.1 for the Campbell), this led to the Judd requiring a larger degree of smoothing. The average difference between the depths for both sensors was overestimated by 0.1 inch with a standard deviation of 0.9 inches for the Judd and 0.8 inches for the Campbell. The MAE for both was 0.5 inches and the normalized RMSE was 0.2 inches.

4.3.2 Sensor Comparison to Total Snow Depth

In order to illustrate the importance of using several depth measurements to obtain a representative total snow depth measurement, the same statistics as the previous section were used to describe the difference between sensor snow depth and manual total snow depth (Table 4-4). Caribou, ME and Indianapolis IN are not included in the comparisons due to problems with USDS data. The average difference ranged from -2.2 to 1.3 inches. The standard deviation of the average difference ranged from 0.6 to 4.4 inches. The MAE ranged from 0.5 to 2.5 inches. The RMSE was again normalized by average snow depth and it ranged from 0.0 to 7.9 inches.

Table 4-4: Summary statistics between sensor depth and manual total depth of snow.

Buffalo, NY	**Average Difference (in)**	**Standard Deviation (in)**	**N**	**MAE (in)**	**RMSE (in)**	**Normalized RMSE (in)**
Judd (1HRMA)	-0.55	1.36	438	0.92	1.47	0.49
Judd (3HRMA)	-0.56	1.35	438	0.92	1.46	0.49
Campbell (1HRMA)	-0.51	1.38	438	0.89	1.47	0.50
Campbell (3HRMA)	-0.51	1.37	438	0.88	1.46	0.49
Cheyenne, WY						
East Judd (1HRMA)	-0.30	1.19	176	0.57	1.22	1.31
East Judd(3HRMA)	-0.31	1.18	184	0.56	1.21	1.31
West Judd (1HRMA)	-0.19	1.11	176	0.52	1.13	1.21
West Judd(3HRMA)	-0.20	1.12	184	0.54	1.13	1.22
Campbell (1HRMA)	-0.63	1.46	176	0.68	1.58	1.70
Campbell (3HRMA)	-0.63	1.46	184	0.69	1.58	1.70
Davis, WV						
Judd (1HRMA)	-1.02	4.44	256	2.50	4.55	0.93
Judd (3HRMA)	-1.03	4.44	256	2.50	4.34	0.88
Campbell (1HRMA)	-0.96	4.40	256	2.42	4.50	0.92
Campbell (3HRMA)	-0.96	4.40	256	2.42	4.50	0.92
Fort Collins, CO						
Judd (1HRMA)	0.05	0.67	554	0.32	0.67	1.29
Judd (3HRMA)	0.04	0.66	554	0.31	0.66	1.27
Campbell (1HRMA)	-0.06	0.70	554	0.30	0.71	1.36
Campbell (3HRMA)	0.01	0.69	554	0.30	0.70	1.35
Marquette, MI						
Judd (1HRMA)	-1.08	1.2	641	1.27	1.60	0.09
Judd (3HRMA)	-1.08	1.2	641	1.27	1.60	0.09
Campbell (1HRMA)	-2.25	1.2	641	2.32	2.54	0.15
Campbell (3HRMA)	-2.25	1.2	641	2.32	2.54	0.15
Milwaukee, WI						
Judd1 (1HRMA)	0.03	0.62	245	0.49	0.62	0.21
Judd1 (3HRMA)	0.03	0.62	245	0.49	0.61	0.21
Judd2 (1HRMA)	-0.41	0.74	245	0.57	0.85	0.29
Judd2 (3HRMA)	-0.42	0.74	245	0.57	0.85	0.29
Campbell (1HRMA)	-0.20	1.03	245	0.69	1.04	0.36
Campbell (3HRMA)	-0.20	1.03	245	0.69	1.04	0.36
Steamboat Springs, CO						
Judd (1HRMA)	1.25	1.47	113	1.52	1.56	0.02
Judd (3HRMA)	1.28	1.59	113	1.55	1.70	0.02
Campbell (1HRMA)	-1.48	1.70	113	1.85	2.25	0.03
Campbell (3HRMA)	-1.44	1.73	113	1.84	2.24	0.03

Figures 4-12 and 4-13 show the sensor snow depth for Buffalo, NY plotted with the manual total snow depth. Both sensors in Buffalo, NY tended to underestimate the total snow depth that was manually measured. The Judd underestimated by 0.6 inches with 1.4 inches standard deviation. The Campbell underestimated it by 0.5 inches also with a standard deviation of 1.4 inches. The MAE for both was 0.9 inches and the normalized RMSE was 0.5 inches.

4.4 SIX HOUR SNOWFALL ALGORITHM

The algorithms described for calculating six hour snowfall was applied to each sensor at each site using both a one and three hour moving averages. Figures 4-14 and 4-15 show the effect of the compaction routines on the six hour snowfall estimates and are plotted cumulatively for each sensor. The statistics calculated to describe how well the algorithms performed (Table 4-5) included percent difference in total seasonal snowfall accumulation, a Nash-Sutcliffe R-squared on the cumulative seasonal snowfall, and MAE on the incremental six hour 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 seasonal sensor accumulation modeled the seasonal manual accumulation of snowfall. A perfect Nash-Sutcliffe R-squared is 1.0 with negative values indicating that the observed mean is a better predictor than the model, it is a measure of the model efficiency. The MAE described how well the calculated sensor six hour snowfall values matched the manual six hour snowfall measurements.

Table 4-5: Summary statistics for both 5MSA and 60MSA including percent difference in seasonal snowfall, Nash-Sutcliffe r-squared and mean absolute error.

5 MINUTE SNOWFALL			
	% Difference	N-S R2	MAE (in)
BUFFALO			
Judd 1hrma	70.52	-0.42	0.37
Judd 3hrma	10.72	0.80	0.32
Campbell 1hrma	0.95	0.98	0.25
Campbell 3hrma	41.77	0.03	0.29
CHEYENNE			
Judd 1 1hrma	206.03	-18.11	0.20
Judd 1 3hrma	58.51	-0.20	0.12
Judd 2 1hrma	233.84	-23.13	0.21
Judd 2 3hrma	66.14	-0.71	0.11
Campbell 1hrma	11.35	0.77	0.09
Campbell 3hrma	37.58	-0.53	0.07
DAVIS			
Judd 1hrma	37.62	0.64	0.36
Judd 3hrma	11.61	0.56	0.28
Campbell 1hrma	7.13	0.58	0.28
Campbell 3hrma	29.03	0.00	0.25
FORT COLLINS			
Judd 1hrma	143.54	-24.10	0.18
Judd 3hrma	44.60	-2.05	0.11
Campbell 1hrma	33.64	-0.34	0.09
Campbell 3hrma	6.53	0.97	0.07
MARQUETTE			
Judd 1hrma	53.90	-0.07	0.45
Judd 3hrma	17.77	0.86	0.30
Campbell 1hrma	5.64	0.98	0.26
Campbell 3hrma	36.80	0.48	0.24
MILWAUKEE			
Judd 1 1hrma	154.52	-8.94	0.13
Judd 1 3hrma	55.86	-0.85	0.08
Judd 2 1hrma	179.84	-9.75	0.15
Judd 2 3hrma	58.03	-0.55	0.09
Campbell 1hrma	40.49	0.32	0.06
Campbell 3hrma	1.89	0.97	0.05
STEAMBOAT SPRINGS			
Judd 1hrma	37.62	0.38	0.75
Judd 3hrma	13.83	0.93	0.57
Campbell 1hrma	52.79	-0.23	0.79
Campbell 3hrma	3.60	0.99	0.60

60 MINUTE SNOWFALL			
	% Difference	N-S R2	MAE (in)
BUFFALO			
Judd 1hrma	38.19	0.65	0.32
Judd 3hrma	6.41	0.92	0.26
Campbell 1hrma	13.51	0.85	0.24
Campbell 3hrma	31.89	0.47	0.22
CHEYENNE			
Judd 1 1hrma	94.81	-2.96	0.14
Judd 1 3hrma	19.75	0.87	0.10
Judd 2 1hrma	108.68	-4.20	0.14
Judd 2 3hrma	23.95	0.80	0.09
Campbell 1hrma	35.36	-0.21	0.07
Campbell 3hrma	51.43	-1.27	0.06
DAVIS			
Judd 1hrma	0.62	0.79	0.30
Judd 3hrma	24.82	0.18	0.26
Campbell 1hrma	27.16	0.06	0.25
Campbell 3hrma	37.36	-0.32	0.24
FORT COLLINS			
Judd 1hrma	63.14	-4.90	0.12
Judd 3hrma	15.44	0.30	0.09
Campbell 1hrma	2.17	0.97	0.07
Campbell 3hrma	19.93	0.70	0.06
MARQUETTE			
Judd 1hrma	5.29	0.98	0.32
Judd 3hrma	35.73	0.51	0.28
Campbell 1hrma	30.01	0.65	0.26
Campbell 3hrma	45.10	0.21	0.25
MILWAUKEE			
Judd 1 1hrma	117.64	-2.10	0.12
Judd 1 3hrma	52.70	0.40	0.08
Judd 2 1hrma	135.96	-2.47	0.13
Judd 2 3hrma	58.31	0.34	0.09
Campbell 1hrma	7.13	0.96	0.04
Campbell 3hrma	19.93	0.92	0.04
STEAMBOAT SPRINGS			
Judd 1hrma	9.10	0.97	0.58
Judd 3hrma	28.45	0.72	0.52
Campbell 1hrma	5.76	0.96	0.64
Campbell 3hrma	19.65	0.87	0.56

4.4.1 Five Minute Snowfall Algorithm (5MSA)

The results from the 5MSA favor the Campbell sensor at every site. Figure 4-16 shows the cumulative 5MSA for the Judd sensor one and three hour moving averages (hereafter referred to as 1HRMA and 3HRMA) while Figure 4-17 shows both for the Campbell sensor. The percent difference in seasonal snowfall for the Judd 1HRMA and 3HRMA was 70.5 % and 10.7% respectively (Table 4-5). The percent difference for both the Campbell 1HRMA and 3HRMA was 0.95% and 41.8% respectively (Table 4-5). The Nash-Sutcliffe R-squared for the Judd 1HRMA and 3HRMA was -0.42 and 0.80 respectively (Table 4-5). For the Campbell 1HRMA and 3HRMA it was 0.98 and 0.03 respectively (Table 4-5). The MAE in the incremental snowfall measurements for the Judd 1HRMA and 3HRMA was 0.37 inches and 0.32 inches respectively (Table 4-5). The MAE for the Campbell 1HRMA and 3HRMA was 0.25 inches and 0.29 inches respectively (Table 4-5). The Campbell 1HRMA did the best at predicting 6 hour snowfall for Buffalo, NY using this method. The Campbell 1HRMA had the highest Nash-Sutcliffe R-squared as well as the lowest percent difference in seasonal total and MAE.

Another measure of how accurately the 5MSA performed was the calculation of the errors of commission (CE), which is the proportion of time the sensors measured snowfall when there was none manually measured (Figure 4-18). The ideal value of the CE is 0. 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, CO. The maximum CE was achieved by the Judd 1HRMA in Steamboat Springs, CO.

4.4.2 Sixty Minute Snowfall Algorithm (60MSA)

The results of the 60MSA differ by site and are not as consistent as the 5MSA. At some sites the results favor the Judd and at others they favor the Campbell. For Buffalo, NY the seasonal accumulation of the Judd 1HRMA and 3HRMA is shown in Figure 4-19 while the Campbell is shown in Figure 4-20. The percent difference in seasonal accumulation for the Judd 1HRMA and 3HRMA was 38.2% and 6.4% respectively. The percent difference for the Campbell 1HRMA and 3HRMA was 13.5% and 31.9% respectively. 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. The MAE for the Judd 1HRMA and 3HRMA was 0.32 and 0.26 respectively while the Campbell was 0.24 for the 1HRMA and 0.22 for the 3HRMA. In this case the Judd 3HRMA did the best job at predicting the six hour snowfall for Buffalo, NY with the largest Nash-Sutcliffe R-squared and the lowest percent difference in seasonal accumulation. The MAE was similar for each method and sensor.

Again, the CE was calculated for the 60MSA. The results are similar to the 5MSA (Figure 4-21). The Campbell 3HRMA consistently had the lowest CE (with the exception of Steamboat Springs, CO), 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, CO. The maximum CE was achieved by the Judd 1HRMA in Cheyenne, WY. The CE's suggest that the sensors are not measuring "no snow" very well. Figure 4-22 shows the number of occurrences for each range of snow depth that were reported manually as well as being estimated by the sensors for Marquette, MI using the statistically best model for each sensor. The sensors did not report nearly as many zero snow depths as were manually measured, they also overestimated the number of occurrences that fell in the 0.1-1.0 inch range. This is again due to small amplitude variability around zero causing 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 inch range.

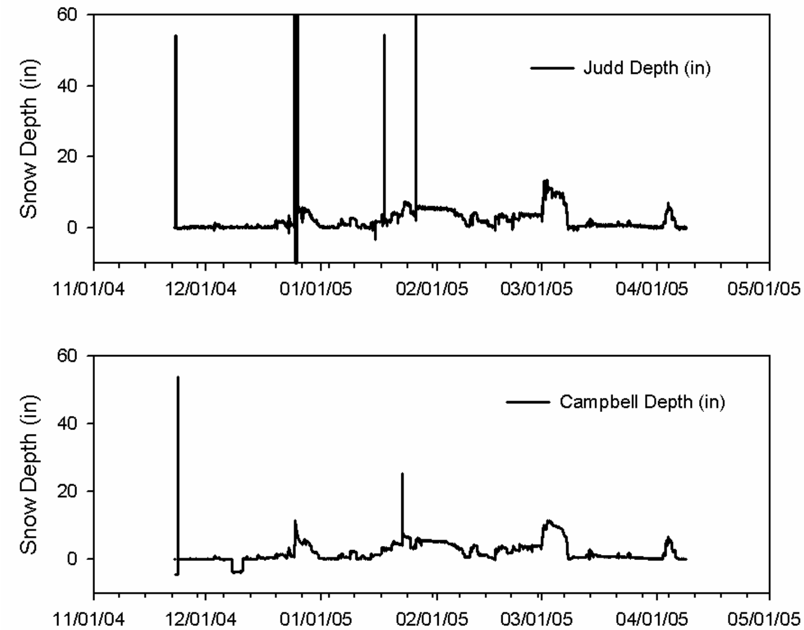

Figure 4-1: Buffalo, NY raw sensor data.

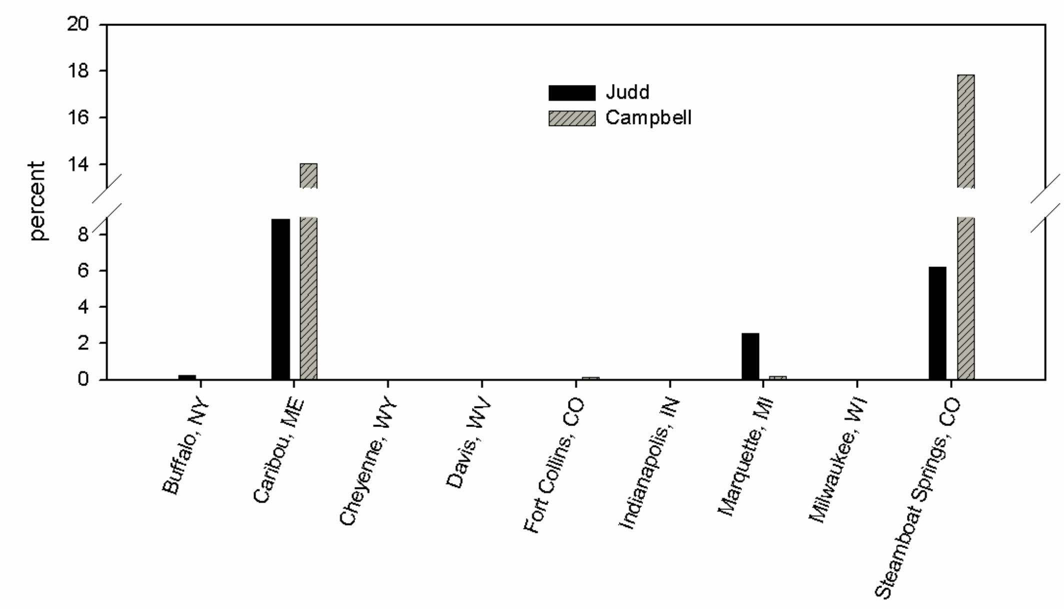

Figure 4-2: Percent of entire season spikes occurred.

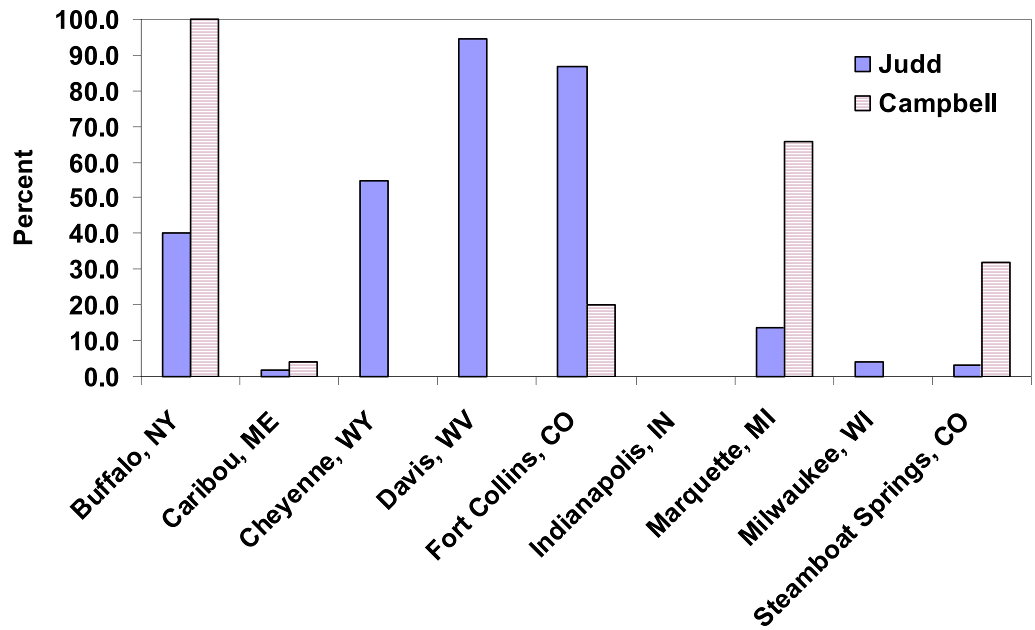

Figure 4-3: Percent of time spikes occurred during snowfall events.

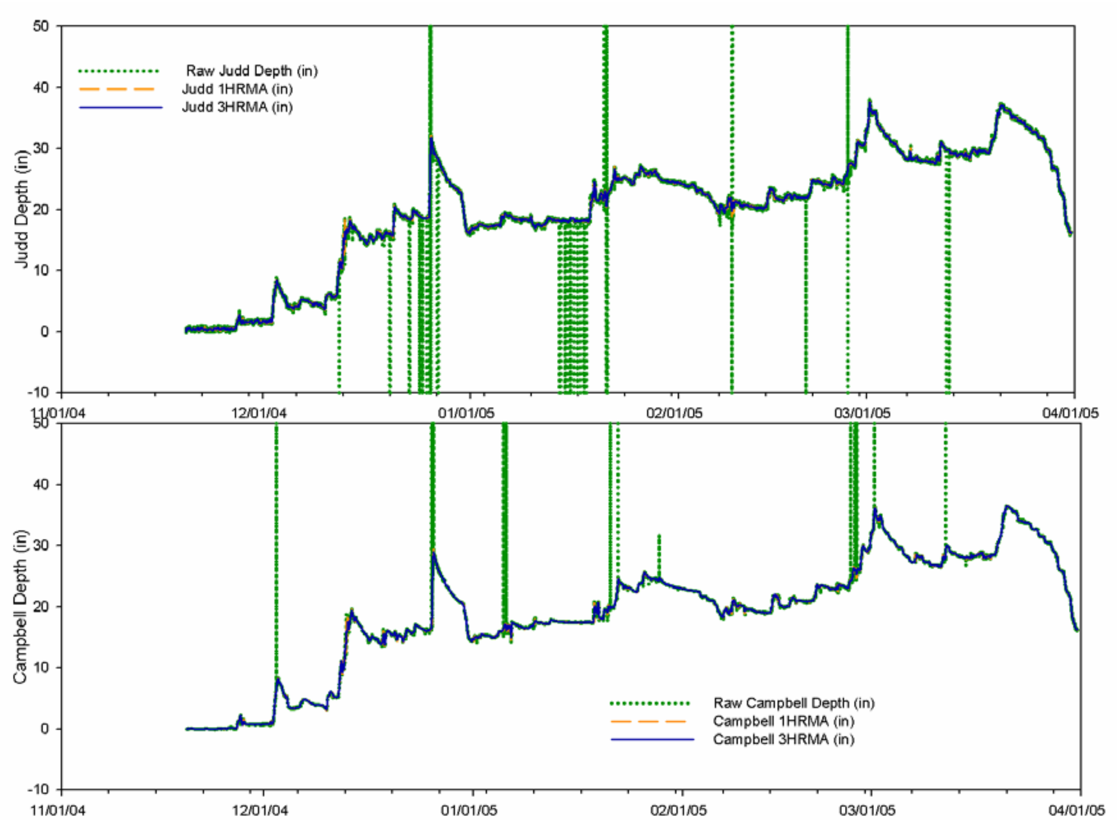

Figure 4-4: Raw and smoothed sensor depth (in) data from top to bottom: Judd and Campbell.

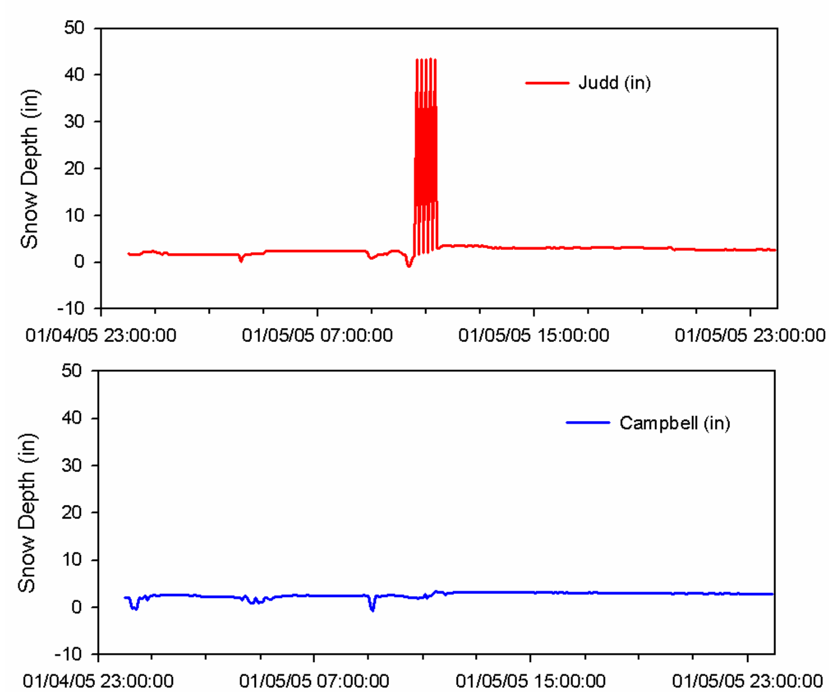

Figure 4-5: Snow crystal type effect on sensor performance.

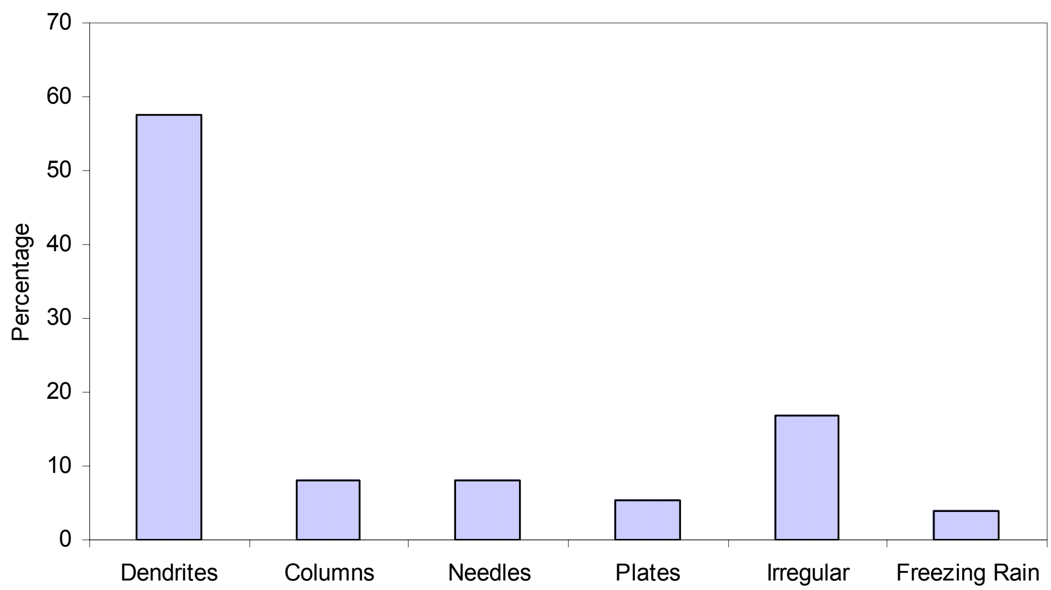

Figure 4-6: Percentage of reports of each crystal type from Marquette, MI.

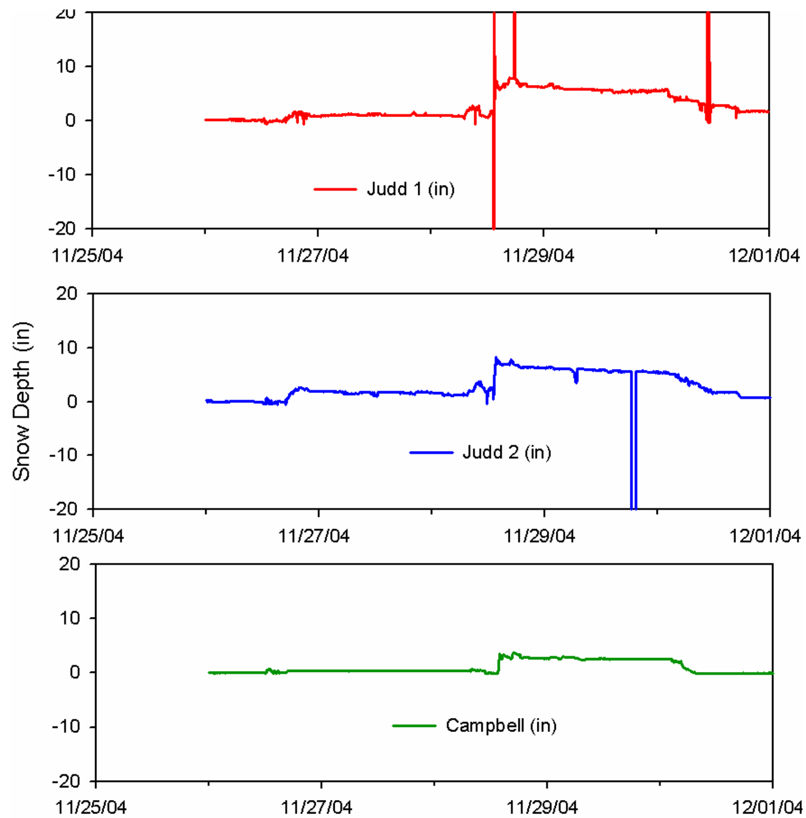

Figure 4-7: Blowing/drifting snow effect on sensor performance.

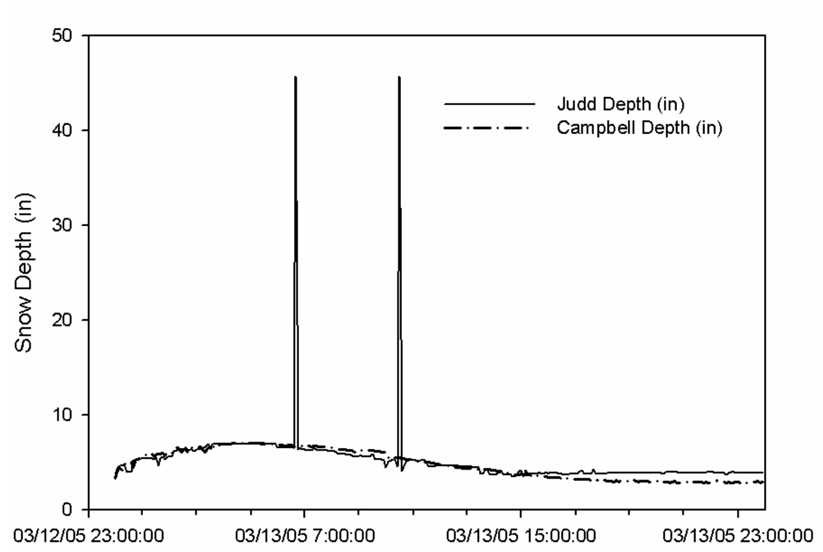

Figure 4-8: Fort Collins, CO uneven snow surface 13 March 2005.

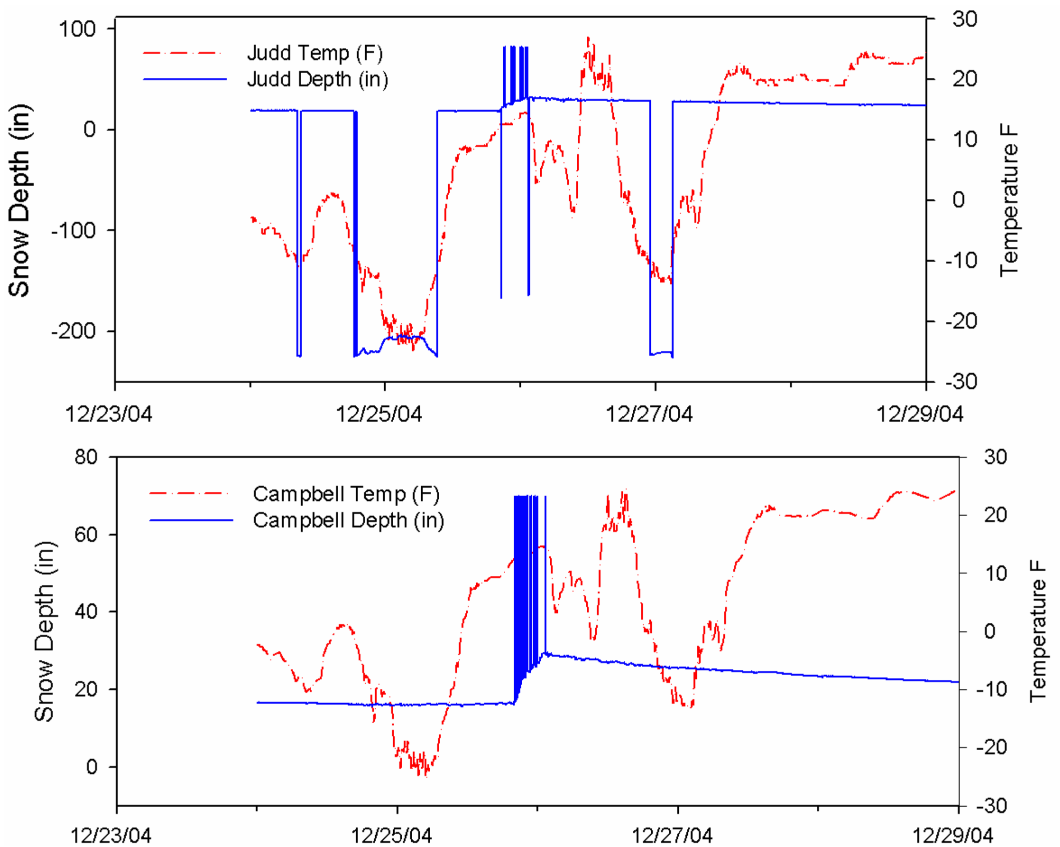

Figure 4-9: Marquette, MI extreme cold temperatures with Judd sensor failure.

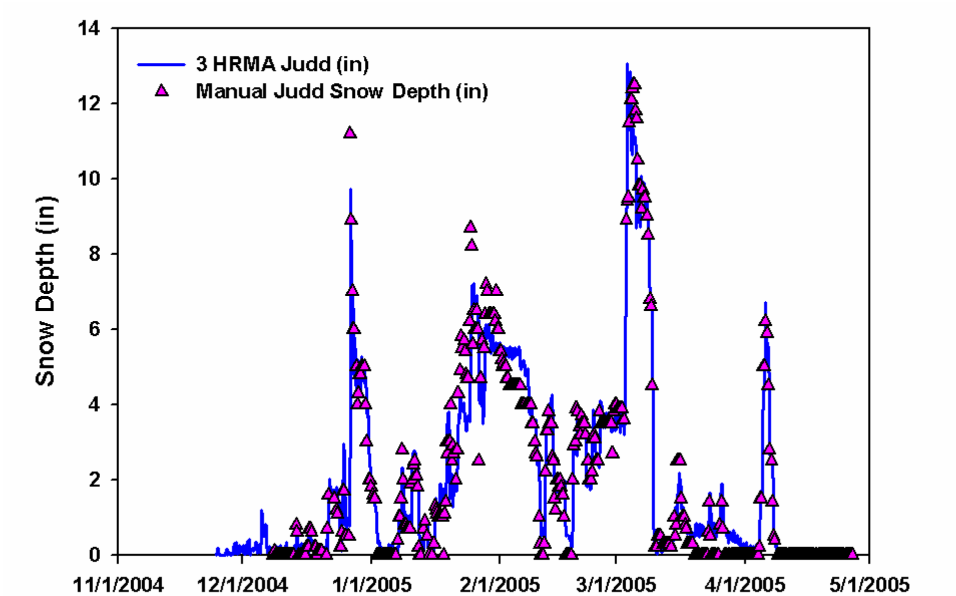

Figure 4-10: Buffalo, NY Judd sensor depth and manual depth next to Judd sensor.

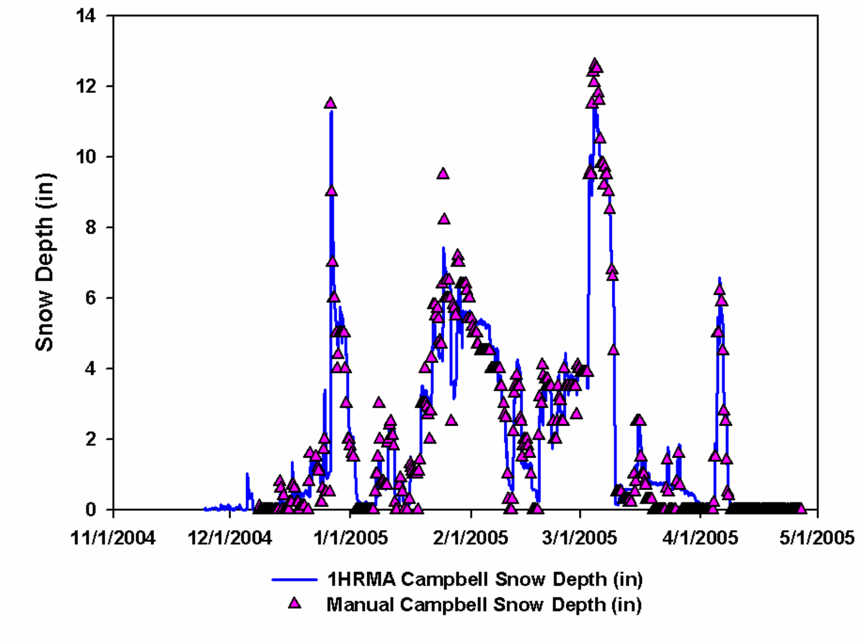

Figure 4-11: Buffalo, NY Campbell sensor depth and manual depth next to Campbell sensor.

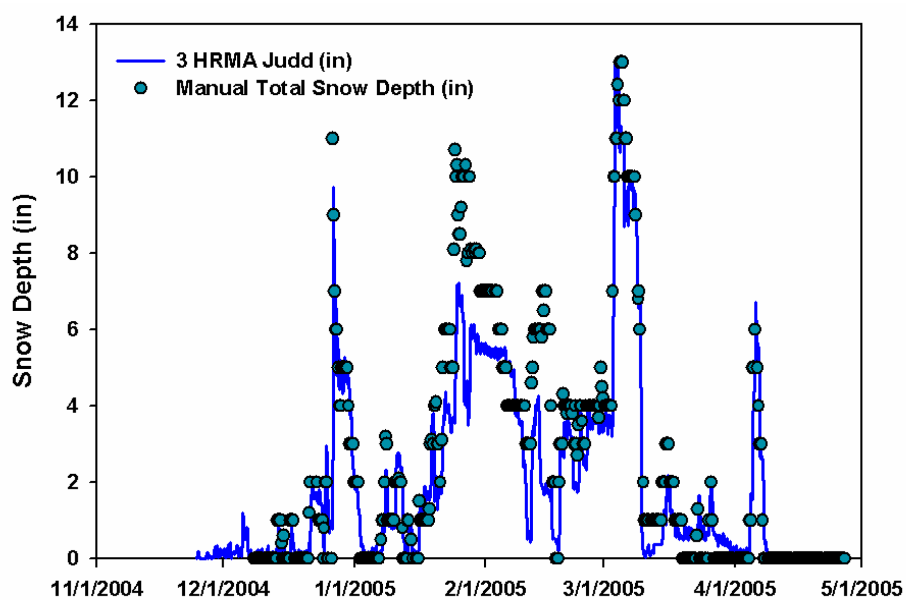

Figure 4-12: Buffalo, NY Judd sensor depth and manual total snow depth.

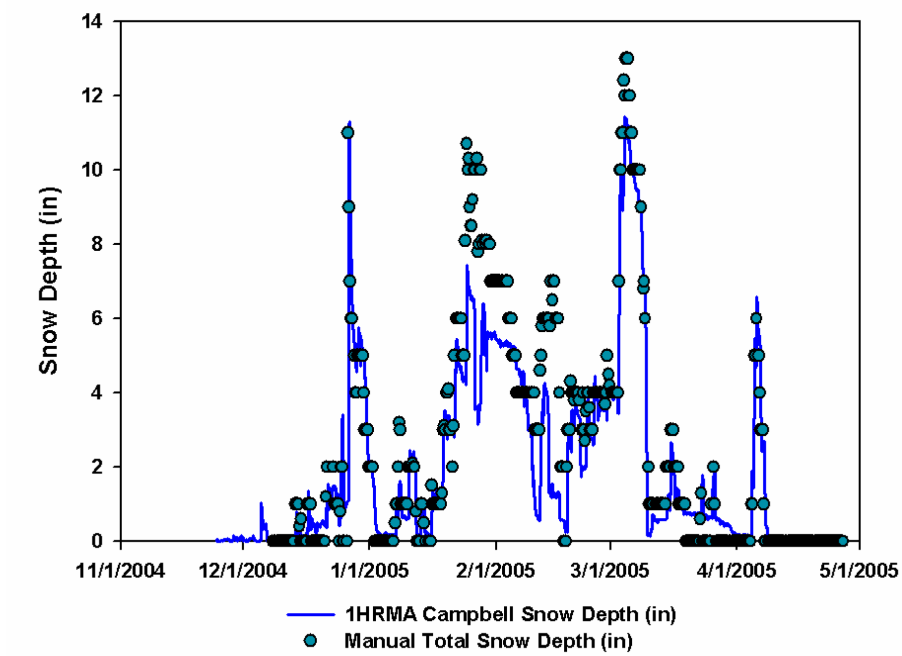

Figure 4-13: Buffalo, NY Campbell sensor depth and manual total snow depth.

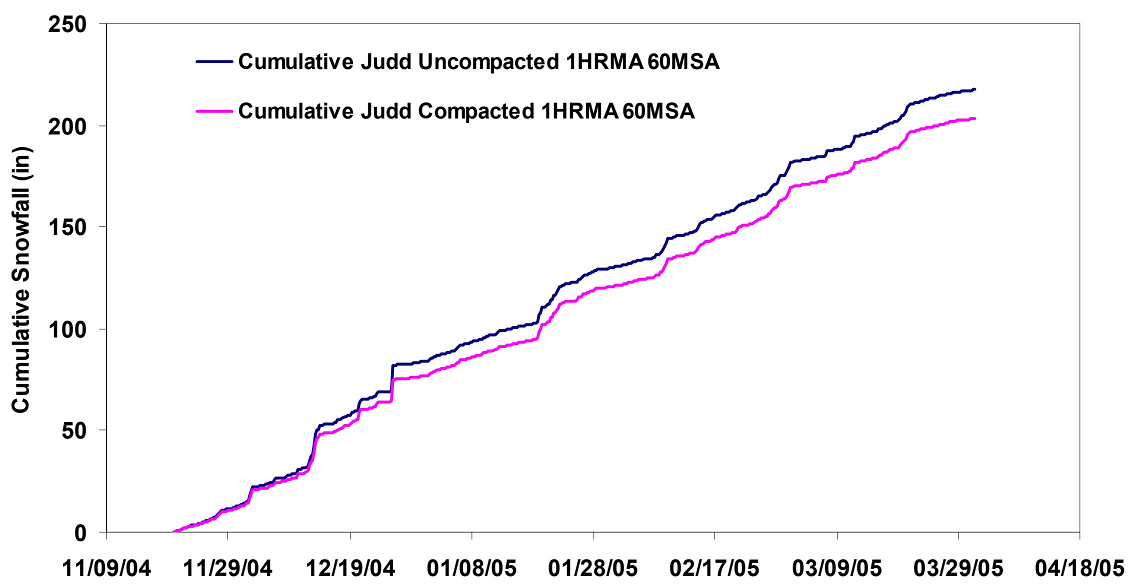

Figure 4-14: Marquette, MI Judd comparison of cumulative compacted and un-compacted snowfall.

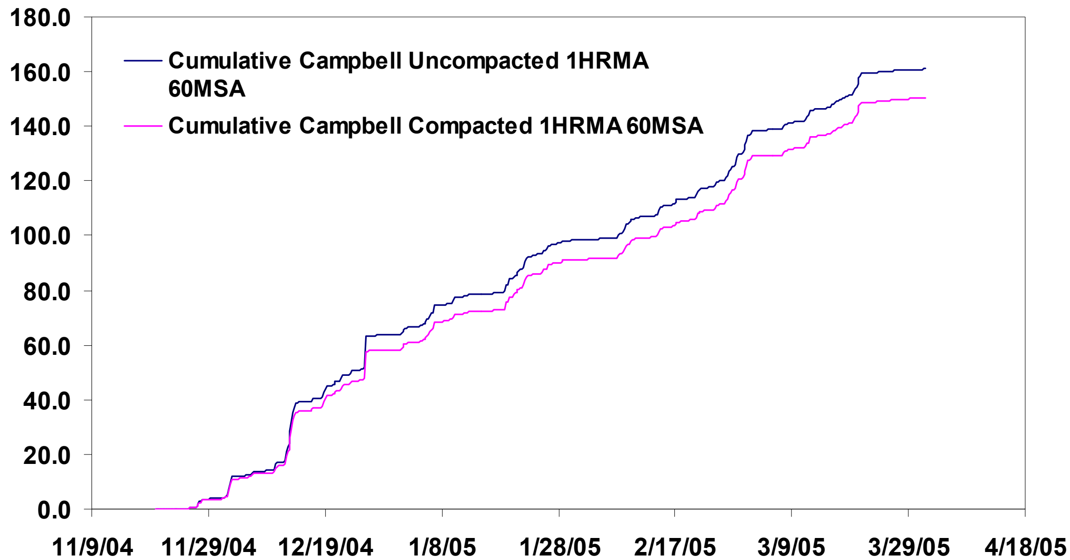

Figure 4-15: Marquette, MI Campbell comparison of cumulative compacted and un-compacted snowfall.

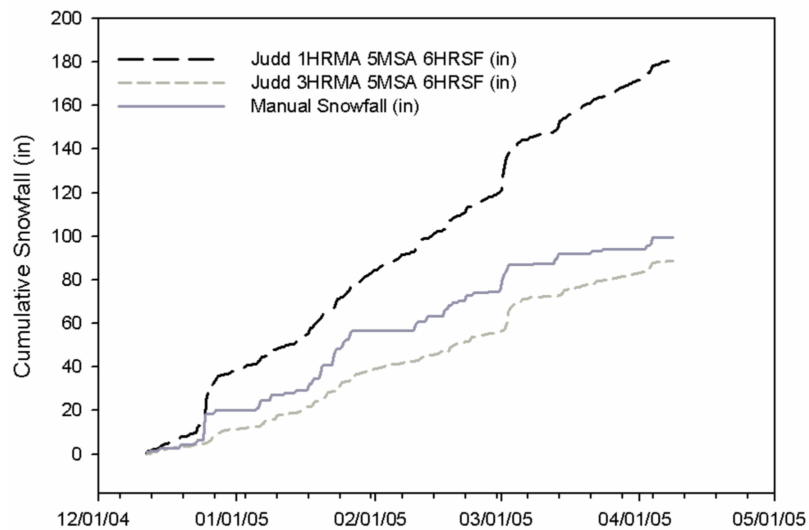

Figure 4-16: Buffalo, NY Judd sensor 5MSA using both 1HRMA and 3HRMA.

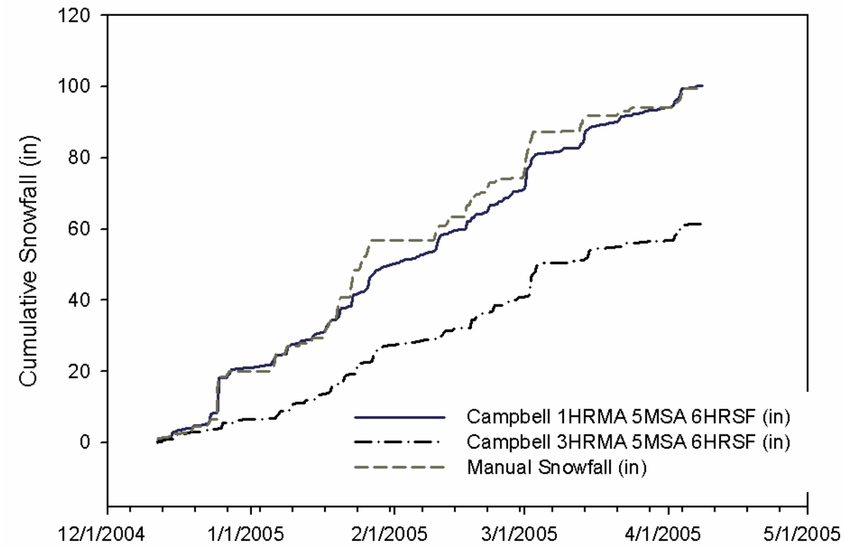

Figure 4-17: Buffalo, NY Campbell sensor 5MSA using both 1HRMA and 3HRMA.

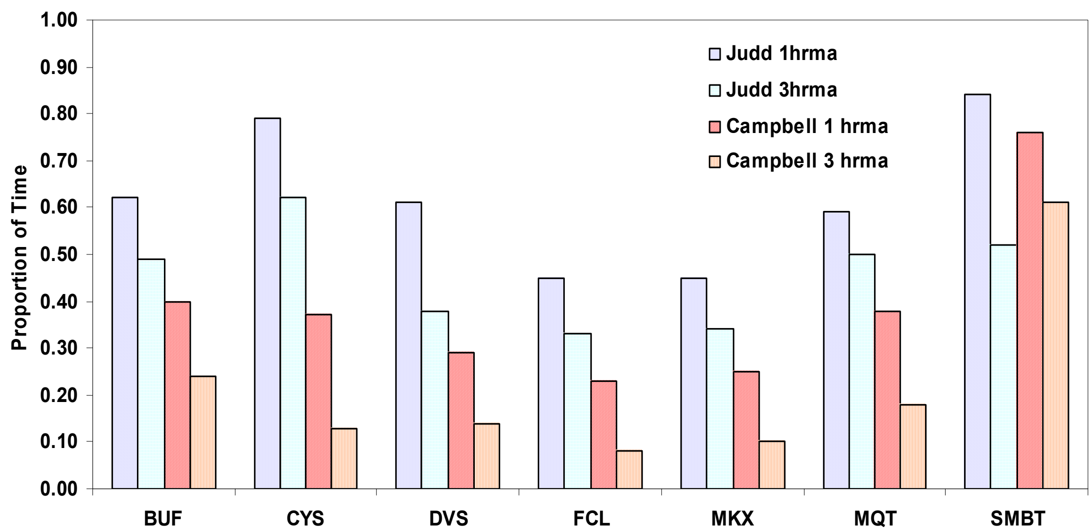

Figure 4-18: Commission errors for 5MSA.

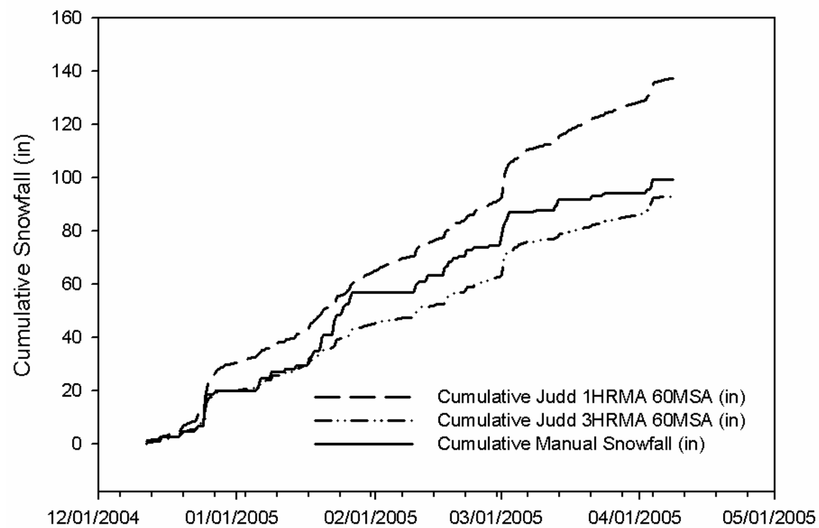

Figure 4-19: Buffalo, NY Judd sensor 60MSA using both 1HRMA and 3HRMA.

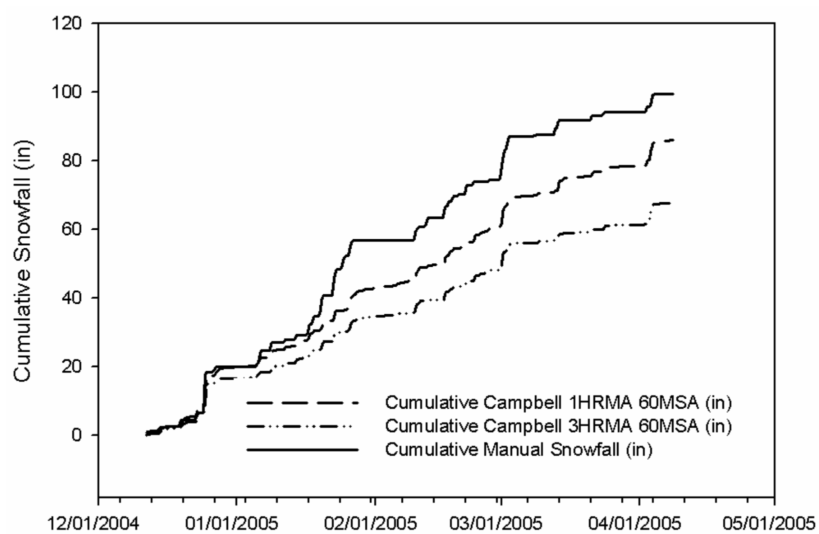

Figure 4-20: Buffalo, NY Campbell sensor 60MSA using both 1HRMA and 3HRMA.

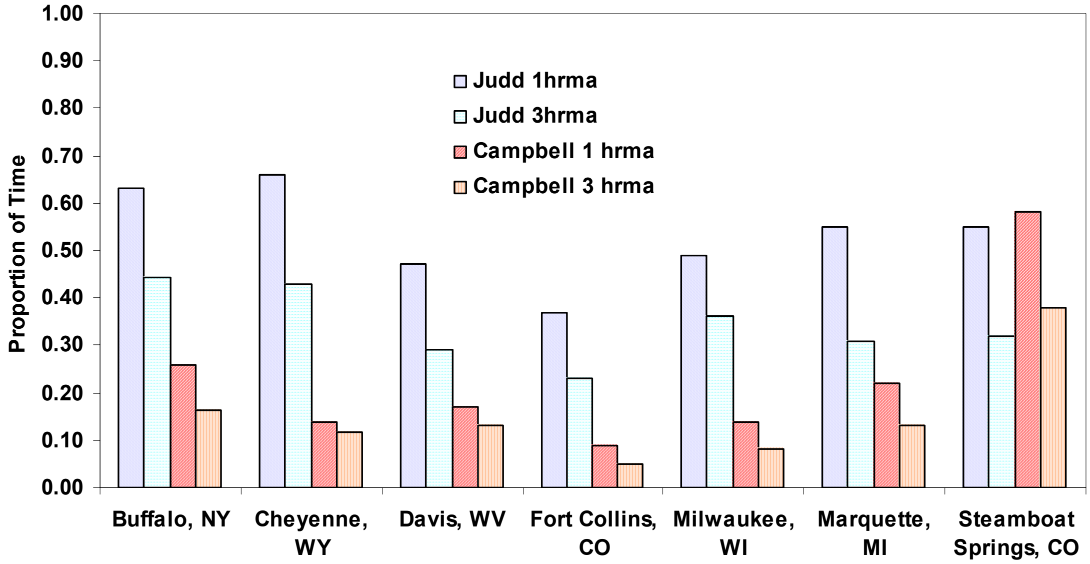

Figure 4-21: Commission errors for 60MSA.

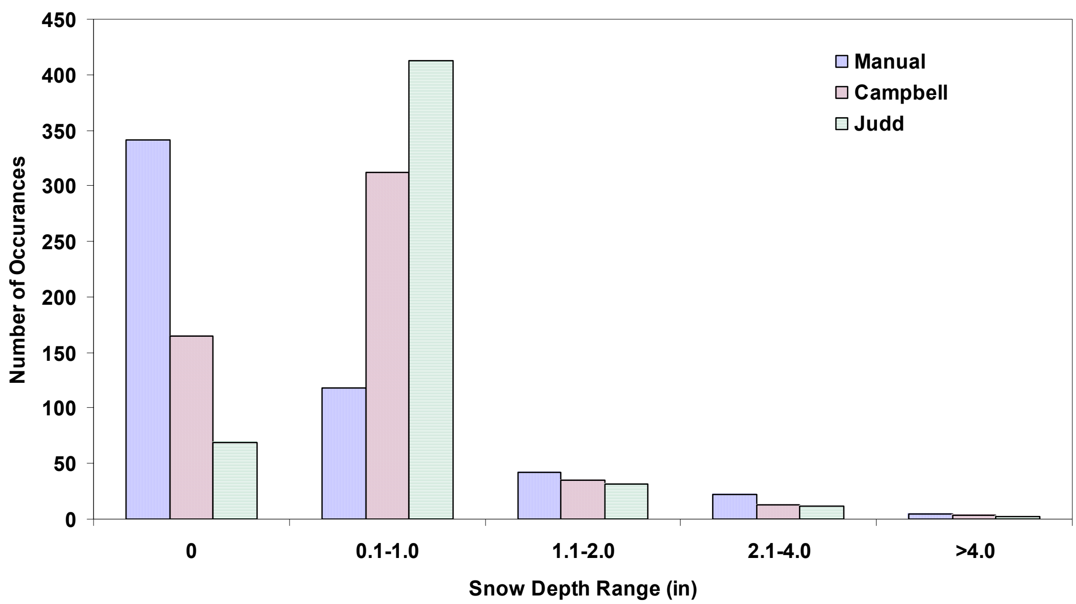

Figure 4-22: Number of estimated and measured six hour snowfall occurrences in each snow depth range.

CHAPTER 5: DISCUSSION

5.1 CHARACTERISTICS OF SNOW SENSOR DATA

5.1.1 Large Amplitude Variability

Large amplitude variability in the sensor data was infrequent and easily corrected. The large amplitude variability is created mainly by environmental factors such as low density snow crystals, blowing/drifting snow, strong wind speeds, intense snowfall, and extreme temperatures or by technical problems with the equipment. Large amplitude variability caused by environmental factors (i.e. not due to malfunctioning equipment) was infrequent. The Judd is more susceptible to large amplitude variability with it occurring on average 0.4% of the time, while the Campbell sensor produced large data spikes only 0.04% of the time (Figure 4-2). Both sensors appear to be more susceptible to large amplitude variability during snowfall events because most of the factors attributed to them are caused during snowfall events. Large amplitude variability is a small problem that is readily corrected, however it is important to understand what kinds of situations produce large amplitude variability in order to minimize their effects.

5.1.2 Small Amplitude Variability

Small amplitude variability is important to consider for ultrasonic depth sensor (USDS) data and is the greatest challenge to accurate estimates of snowfall from changes in snow depth. The calculation of snowfall can be unduly inflated by small amplitude variations in USDS data. The small amplitude variability was observed under snow free and snow covered conditions. Five sites were chosen to investigate the variation (Table 4-1). The effects of compaction on the variability results were minimized by removing any negative trends that existed in the sensor data for the time periods examined. The maximum small amplitude variability was 0.30 inches (i.e. the standard deviation in snow depth), which occurred with the Judd sensor when snow was present on the ground. The Campbell sensor showed consistently lower small amplitude variation in the raw data than the Judd for both snow covered and snow free conditions. Under both snow covered and snow free conditions the Campbell variability on average was approximately 0.1 inch while the Judd was 0.2 inches (Table 4-1). The small amplitude variations needed to be minimized for creating an algorithm to calculate snowfall. The use of moving averages lessened the amount of small scale variability in both sensors (Table 4-2). Figures 4-16 and 4-19 illustrate how the Judd one hour moving average (1HRMA) snowfall algorithm continues to increase throughout the winter because of the small amplitude variation constantly being calculated as snowfall. This caused the Judd snowfall calculation to lose the accumulation pattern seen in the manual data. However, once the three hour moving average (3HRMA) was applied, the manual data pattern became more evident in the sensor data since more small amplitude variation was removed (Appendix D). It is important to remember that this did not affect the sensor ability to measure *snow depth*, it was a problem when calculating *snowfall*.

5.2 FACTORS AFFECTING SENSOR PERFORMANCE

The main climate factors that were found to affect sensor performance were snow crystal type, presence of blowing/drifting snow, intense snowfall, wind speed, uneven snow surface and extreme temperatures. Some of these may be alleviated by proper site selection and setup. One particularly interesting problem arose in Indianapolis, IN (See Figure 5-1) after they secured the snowboards to a frame approximately 12 inches above the ground surface. The elevation of the boards caused exposure to wind and sun resulting in premature melting and lack of accumulation. As with any other meteorological sensors the siting and setup of the sensors is extremely important for achieving quality and useful data.

5.2.1 Snow Crystal Type

There is little that can be done to alleviate the effects of low density snow crystals on sensor performance. The main types of snow crystals reported that affected USDS performances were: dendrites, plates, columns and needles (Figure 4-6). These types of crystals tend to create a greater and more complex scattering surface which allows the ultrasonic pulse to deflect more or penetrate deeper into the snowpack resulting in inaccurate measurements. Other classifications for crystal types that could be reported included irregular crystals and sleet/freezing rain. Irregular crystals referred to none of the typical forms and tend to form a more regular surface. However, crystal type assessment is very subjective and hence it is difficult to determine the exact form because observers were not carefully trained in determining crystal types.

5.2.2 Presence of Blowing/Drifting Snow

The presence of blowing/drifting snow can be minimized if the sensors are sited properly in an area naturally sheltered from wind. Trees act as a natural wind block without requiring installation of snow fences or other structures that may interfere with the accumulation of snow on the ground or operation of the sensors. Even though most ASOS stations are located at airport locations which are usually void of natural wind breaks it is crucial that all possible siting options be explored for the best possible results to be obtained. In an investigation of Marquette, MI it was found that 29% of all the reports included a comment on blowing/drifting snow. This illustrates the importance of proper site selection in order to reduce the effects of blowing/drifting snow.

It is important to measure total snow depth at several locations. If blowing/drifting snow is present and little shelter from the wind is available it is imperative to have more than a single point measurement to depict the average total depth of snow on the ground. A possible solution includes several rigidly mounted sensors in areas that would be least affected by wind. While the presence of blowing/drifting snow is not a large problem, it can result in the loss of quality data at critical times.

5.2.3 Intense Snowfall

It is difficult to solve the problems intense snowfall creates for the USDS. Intense snowfall obstructs the path between the transducer and the surface of the snow.

Mounting the sensor as close to the ground as possible can possibly reduce this problem, since the closer the sensor is to the measuring surface the less distance for the pulse to travel. However, it is as equally important to mount the sensor high enough to allow for an above average accumulation; data would be lost once the snow accumulation covered the sensor. Fortunately, USDS data were seldom affected by problems such as intense snowfall. Therefore, mounting the sensor high enough to avoid accumulation past the sensor is a higher priority than alleviating the effects of intense snowfall events. For example, the sensors in Steamboat Springs, CO needed to be mounted approximately 17 feet off the ground, which may explain some of the extra large amplitude variability in the data.

5.2.4 Wind Speed

As with the presence of blowing/drifting snow correct siting of USDS is imperative in minimizing wind speed effects on sensor performance. The "threshold" wind speed found from qualitative data inspection was approximately 15 mph. If sensors are properly sited in wind shielded areas, the effects of wind speed would be minimized. Also, constructing a rigid structure to mount the USDS's is important to reduce the amount of shaking caused by wind. Choosing a proper site for the sensors can greatly reduce wind effects on the sensors.

5.2.4.1 Snow Fences

The use of snow fences is not recommended as the best solution for reducing wind effects. If a naturally wind shielded site is available it should be used before constructing a snow fence. Milwaukee, WI used a snow fence for this study. The data from Milwaukee, WI did not greatly differ from any other site and in fact did not differ greatly with Cheyenne, WY which was a windy, non-fenced site. The mean absolute error (MAE) between sensor depth and total depth of snow on the ground ranged from 0.5 to 0.7 inches in Milwaukee and Cheyenne with all sensors (Table 4-4).

Another problem with snow fences is regular maintenance of the fences. Automated surface observing sites (ASOS) sites do not have observers present continuously and if a fence was damaged it could remain as such for long periods of time before the problem is identified when regular maintenance is performed. If a fence were to break it could possibly blow under the sensor creating problems for the sensor to accurately measure snow depth. 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, 1993). In addition to this, the fences may also reduce snow melt rates resulting in the snowpack persisting longer than the surrounding snowpack outside the fence. Multiple depth samples and proper siting are much more important to alleviate wind problems than the construction of snow fences.

5.2.5 Uneven Snow Surface

Uneven snow surfaces are not climatic factors, but this problem can be addressed with proper siting of the sensors. In the case where snow fell off the mounting structure the design of the structure should be changed. If snow cannot build up on the structure it also cannot fall off and introduce error into the data. Also, for cases where animals walked under sensors a fence (i.e. chain link, not a snow fence) can be installed around the measurement site at a distance to help keep out unwanted visitors.

5.2.6 Extreme Cold Temperatures

Even though the Judd user manual (Judd, 2005) rates the sensor at -22º to +158º F it did not appear to operate properly under the extreme cold conditions at one site in Marquette, MI (Figure 4-9). At temperatures colder than -10º F, the Judd sensor was not performing correctly while the Campbell sensor worked well throughout the extremely cold temperatures. Temperatures as low at -15 º F were also seen in Caribou, ME. The Judd did continue to work throughout this period, however it never got as cold as Marquette, MI. The problem that was seen in Marquette, MI is unexplained and unverified because temperatures this cold where not seen elsewhere. This is possibly a problem specific to the sensor in Marquette, MI. This is *potentially* a major concern if sensors are to be implemented in cold, northern or mountainous areas where extreme cold temperatures are not uncommon.

5.2.7 Summary

In most cases, climatic factors that can affect sensor performance can be reduced by proper site selection and setup. The sections above describe solutions to problems presented by climatic factors but this is not a complete list. Other problems may become evident once a site is in operation. Once a problem is identified measures should be taken to reduce the error introduced into the data.

5.3 COMPARISON OF AUTOMATED AND MANUAL SNOW DEPTH

Two comparisons of sensor to manual snow depth were performed. The depth manually measured next to the USDS was compared to the sensor depth. The total snow depth measurement at the sites normal snow measurement locations were compared to the sensor depth. The results of each comparison will be discussed in the following sections.

5.3.1 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. It is important to note that the depth taken was taken far enough away from the sensor as to not disturb the snow surface directly beneath the sensor or influence the 22 degree cone over which the USDS measured. Therefore, the results may be influenced by natural spatial variability of the snow depth.

The high snow site in Steamboat Springs, CO most accurately estimated the snow depth beneath the sensors for both the Judd and Campbell 1HRMA. The average difference between the sensor and manual sensor depths was 0.1 inch, with the Judd 1HRMA having a standard deviation of 0.2 inches and the Campbell 1HRMA of 0.3 inches. Previous studies of USDS's were mainly performed in mountainous snowpacks and have proven to test well with manual depth observations. The NRCS is currently using them at their snow telemetry (SNOTEL) sites (Lea and Lea, 1998). The amount of smoothing (i.e. 1HRMA and 3HRMA) had little effect on the performance results shown in Table 4-3 and will not be discussed.

The results between the two different sensors were similar at most sites when comparing manual to automated depth at six hour intervals. However, there are some differences between performances from site to site. The difference between performances at each site can be explained by site construction differences, different observers, and climate differences. Davis, WV showed large MAE and standard deviations of the average difference in measurements. This is most likely due to large spatial variability in snow depth at this site due to drifting patterns. The observer at Davis, WV was aware of this problem and took observations according to protocol (i.e. next to the sensor without disturbing it) although it was known that the reported depth did not match the sensor depth. In Marquette, MI it appears that the Campbell performed worse than the Judd. However, there was only one snow depth taken next to the sensors and was more representative of what the Judd sensor was reading than the Campbell (Figure 5-2).

Overall the sensors accurately represented the amount of snow depth beneath the sensors. On average both the Judd and Campbell measured within ±0.4 inches over the full range of conditions and sites. This value was found by averaging the MAE by sensor omitting results from Marquette, MI since there was only one manual measurement taken near the sensors, and Davis, WV due to problems with spatial variability at the site.

5.3.2 Sensor Comparison to Total Snow Depth

The results of the sensor to total ground snow depth comparison (Table 4-4) show that the sensors are usually underestimating the total snow depth measurement reported from each sites standard area for traditional snow measurements. The errors in this measurement are high at most sites with the MAE ranging from 0.30 to 2.5 inches. The results showed high standard deviations of the average difference between the depth measurements which ranged from 0.62 inches to 4.4 inches. The normalized root mean squared error (RMSE) ranged from 0.02 inches in Steamboat Springs, CO to 1.4 inches in Fort Collins, CO. These results are logical since the RMSE is normalized by the average snow depth at each location. The average snow depth in Steamboat Springs, CO was 68.5 inches compared to 0.5 inches in Fort Collins, CO. The normalized RMSE illustrates that the errors in measurements are much more important in areas that receive lower amounts of snow (i.e. low average snow depth).

The results presented in Table 4-4 illustrate the importance of integrating total ground snow depth measurements to obtain a representative sample. Obtaining a representative sample can be achieved by taking several depth measurements or by optimal siting in areas sheltered by wind effects. Milwaukee, WI used a snow fence to obtain a representative sample. However, the MAE still ranged from 0.49-0.69 inches and the normalized RMSE ranged from 0.21-0.36 inches. Even though the site used a snow fence to reduce wind effects and create an even snow surface, the measurements were still not representative of the manually measured total depth of snow on the ground.

On average the Judd measured within ± 0.7 inches while the Campbell was within ± 0.9 inches of the total depth of snow on the ground. The fact that the errors are around an inch illustrates the difficulty of perfecting snow measurements and suggests the need for multiple sensors to accurately represent the total snow depth.

5.4 SIX HOUR SNOWFALL ALGORITHM

There were two snowfall algorithms created for estimating six hour snowfall from the USDS depth measurements: five minute snowfall algorithm (5MSA) and sixty minute snowfall algorithm (60MSA). The two algorithms were created for the purpose of investigating over what interval snowfall should be calculated due to differing degrees of small amplitude variability in the sensor data. Each algorithm was then compared to the manual six hour snowfall measurements in which snowfall was measured every six hours followed by the snowboards being cleared to restart accumulation. Snowfall algorithms were not created for Caribou, ME and Indianapolis, IN due to problems with the data.

5.4.1 Five Minute Snowfall Algorithm (5MSA)

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, NY, Cheyenne, WY, Davis, WV and Marquette, MI all worked best with a 1HRMA while Fort Collins, CO, Milwaukee, WI and Steamboat Springs, CO 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. All of the sites that required a 1HRMA were rigidly mounted with large (~2 inch) pipe or 4 inch x 4 inch wooden posts to deter the structure from shaking in the wind. The sites that required more smoothing were less rigid in construction with the exception of Steamboat Springs, CO. The site in Milwaukee, WI used a snow fence and there were three sensors present. The sensor posts were not driven into the ground. They were attached to the snowboards under the sensors forming a structure that was more susceptible to shaking in the wind than other sites which may have added imprecision into the data. The Fort Collins, CO site was not as rigidly installed as the other sites and as well was more susceptible to shaking in the wind. As for Steamboats Springs, CO the data may have needed more smoothing because of malfunctioning of the Campbell sensor. The sensors in Steamboat Springs, CO accurately measured the snow depth beneath the sensors, however estimating snowfall from changes in USDS snow depth introduced more problems such as the small amplitude variability in the USDS. Overall, the Campbell sensor worked well to estimate six hour snowfall with a 5MSA. The MAE between six hour snowfall measurements were usually between 0.1 – 0.3 inches with the exception of Steamboat Springs, CO which was 0.6 inches and can be explained by malfunctioning equipment.

The commission errors (CE) for the 5MSA (Figure 4-18) illustrated what proportion of the time the sensors indicated increased snow depth when there was none manually observed. The CE drops as the moving average is increased from 1 to 3 hours in all cases with both sensors. However, even though the Campbell 3HRMA usually has the lowest CE, it is not always the best model for calculating six hour snowfall because the 3HRMA removes too much detail from the Campbell data and the snowfall cannot be accurately estimated.

5.4.2 Sixty Minute Snowfall Algorithm (60MSA)

The 60MSA results were not as clear as the 5MSA (Table 4-5). The best results were obtained with different sensors and differing degrees of smoothing from site to site. The use of a 60MSA removed some small amplitude variation from the sensors and the Judd obtained better results than with the 5MSA. However, taking the change over the longer

60 minute 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. Figures 5-3 and 5-4 show the omission errors for the Judd and Campbell sensors respectively. 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.

The reasons for the differences between sites are highly speculative and are attributed to both siting and sensors. Poor siting and installation can add more variation into the data which would need more smoothing. It has been illustrated that the Judd sensor does show more small amplitude variation and the effects of that variation could result in inaccurate estimates of *snowfall* at different sites.

The 60MSA errors of commission (CE) (Figure 4-21) illustrated that the Judd sensor has more small amplitude variability 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 CE decreases.

Because of the large CE the Buffalo, NY Judd three hour moving average data were investigated to see what effect a threshold for calculating snowfall had on the errors of omission (OE) and commission (CE). Figure 5-5 shows the cumulative snowfall for 0.05, 0.1, 0.15, 0.2 and 0.5 inch thresholds along with the manual snowfall. The results for the 0.15 inch threshold appear to do the best job calculating snowfall. Figure 5-6 shows the results for the OE and CE using thresholds of for calculating the 60MSA. The CE drops as the threshold is raised, however the OE increases as the threshold is raised.

Increasing the threshold caused the algorithm to omit snowfall events that actually occurred. Using a threshold for the Judd may allow for better estimates of snowfall from the USDS snow depth, however it also introduces OE because it is omitting valid snowfall events.

Figure 5-1: Site setup in Indianapolis, IN caused excessive wind scour and melting of the snow beneath the sensors.

Figure 5-2: Snow depth stake in Marquette, MI more representative of Judd than Campbell.

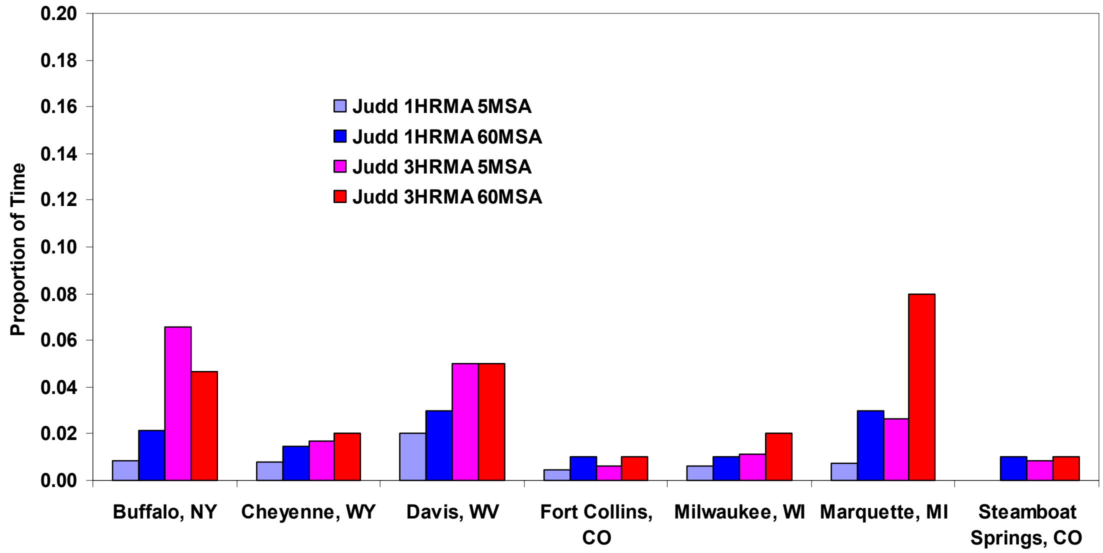

Figure 5-3: Judd sensor omission error changes between 5MSA and 60MSA.

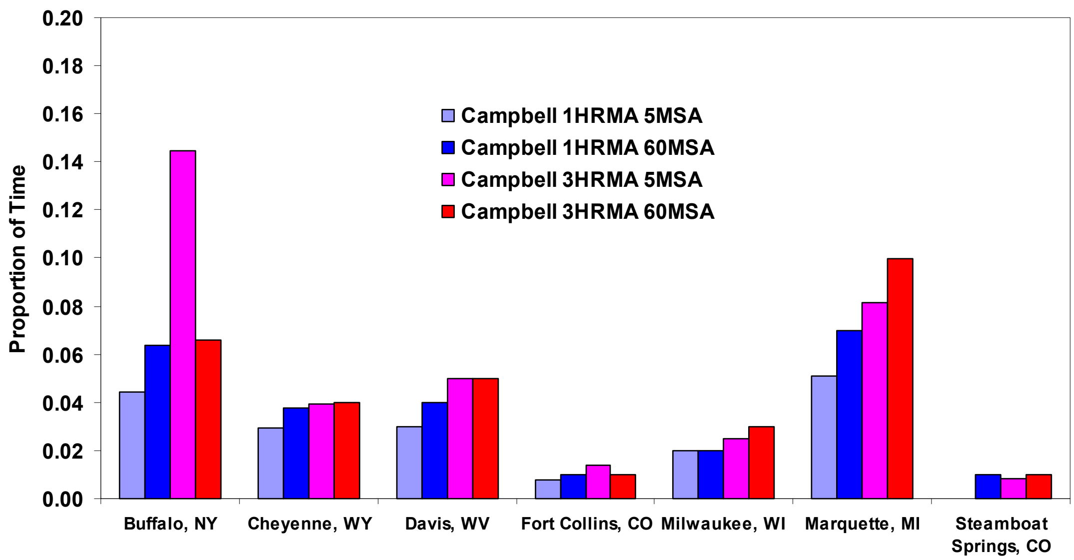

Figure 5-4: Campbell sensor omission error changes between 5MSA and 60MSA.

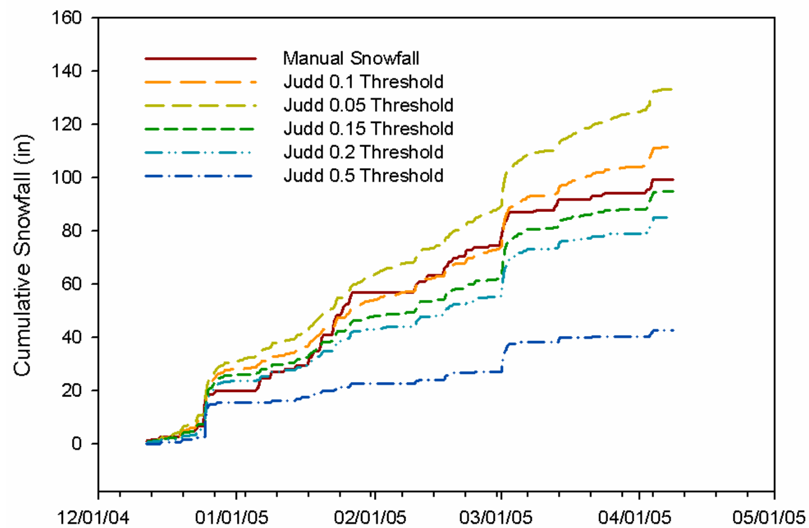

Figure 5-5: Buffalo, NY cumulative snowfall for Judd threshold snowfall calculations.

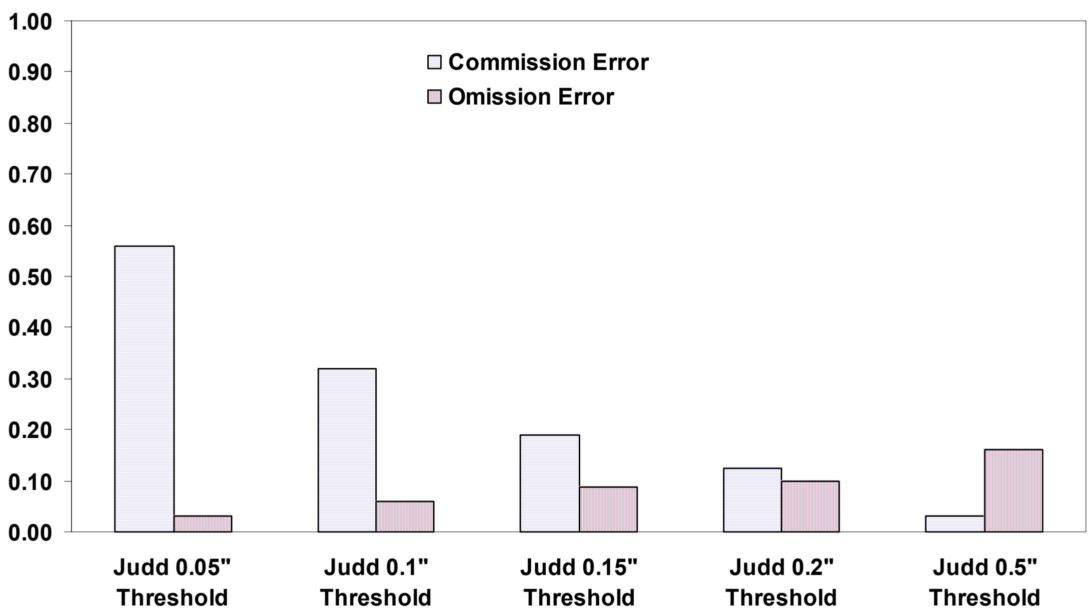

Figure 5-6: Buffalo, NY commission and omission error for Judd 3 hour moving average data using snowfall thresholds.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

6.1.1 Develop a reliable method of quality assurance/quality control (QA/QC).

After investigating different methods of data QA/QC a reliable method was developed and worked favorably at all locations. The large amplitude variability was easily filtered and removed, and accounted for a very small amount of the data, 0.4% with the Judd and 0.04% with the Campbell. The small amplitude variability was the most problematic characteristic of the snow sensor data because it affected snowfall estimation. It was found that at most locations a one hour moving average smoothed the Campbell sufficiently to give reliable results with both depth comparisons as well as the five minute snowfall algorithm. The Judd sensor usually needed a three hour moving average in order to give reasonable estimates of six hour snowfall, however depth comparisons were accurate with both sensors using either moving average.

The moving averages applied to the data in this study were center weighted. If these sensors are implemented in real-time a back weighted average is suggested. The effects of back-weighting can be minimized by using the smallest averaging period possible.

6.1.2 Identify factors affecting sensor performance.

Several factors affecting sensor performances were identified in previous studies of ultrasonic depth sensors were also found and confirmed in this study. The main causes included: snow crystal type, presence of blowing/drifting snow, intense snowfall, wind speeds in excess of 15 mph, uneven snow surfaces and extreme cold temperatures (colder than -10º F for the Judd). Other studies (Labine, 1996) also reported ice or rime build up on the sensors which affected the sensors ability to transmit and receive sound pulses, but this was not detected in the current study. Most of these factors can be substantially alleviated with proper siting and regular maintenance of the site and sensors.

If the sensors are implemented in an operational network, climate variables should be considered when installing the sensors. Sensors should be mounted parallel to the prevailing wind direction to minimize any shaking of the sensors. The sensors should be mounted far enough off the ground to ensure snow will not accumulate above the sensor. This height the sensor is mounted off the ground was based on annual total snowfall received at each site location. White expanded PVC snowboards worked well as a measuring surface and are recommended for use. They worked best when mounted to a wooden frame flush with the ground surface to prevent movement by wind and frost heaving.

6.1.4 Compare manual measurements of snow depth to each USDS

6.1.4.1 Sensor Comparison to Depth at Sensors

Both sensors measured the depth of snow beneath them with reasonable accuracy and reliability. On average both sensors measured within ±0.4 inches, with some larger problems due to siting, blowing snow, drifting, melting, etc. In order to achieve an accurate measurement of snow depth, proper siting is most important.

6.1.3.2 Sensor Comparison to Total Snow Depth

Both sensors tended to underestimate the total snow depth measurement taken at each sites historical snow measurement location. This was due to the point-nature of sensor measurement, and spatial variability of snow depth due to blowing, drifting, differential settling, melting, etc. On average the Judd measured within ±0.7 inches while the Campbell measured within ±0.9 inches of the total depth of snow on the ground measurement. Multiple sensors are suggested to overcome the error associated with spatially variable snowcover.

6.1.5 Develop an algorithm to derive six hour snowfall from sensor snow depth

Two algorithms were created to test how well the sensors could estimate six hour snowfall. The five minute snowfall algorithm worked best with the Campbell. With proper siting the Campbell could be used with a one hour moving average applied to the data. The Campbell most often depicted the correct pattern of snowfall accumulation throughout the season. The extra small amplitude variability seen in the Judd sensor usually caused overestimation of the six hour snowfall and did not accurately represent the manual data pattern.

The Judd sensor did provide more accurate results when the 60 minute snowfall algorithm was used. The 60 minute snowfall algorithm removed more of the small amplitude variability in the Judd and provided more accurate estimates of the manual data. However, the results for the 60 minute snowfall algorithm were not always in favor of one sensor over the other (Table 4-5). The results differed by site. Also, taking the difference in snow depth over the period of 60 minutes is compromising snowfall data (Figures 5-3 and 5-4). Taking the difference over such a large time period misses small snowfall events that may have come and melted/compacted within the 60 minute period. This may explain some of the variability in the 60 minute snowfall algorithm results. The plots of all estimates using both algorithms for six hour snowfall are provided in Appendix D.

There were no climate trends found which explained the degree of smoothing or sensor which gave more accurate results for the snowfall algorithms. There may be climate factors that exist, however the differences in site setup seem to have more of an effect on the degree of smoothing needed at each site.

6.2 RECOMMENDATIONS

In order to obtain accurate snow measurements from ultrasonic snow depth sensors proper site selection and installation are very important. Rigid installation of both sensors and snow measurement boards are recommended for best results. Site selection free from wind effects are recommended, but it is realized that this is often not available. More than one sensor may be needed in order to obtain representative snow measurements due to effects of wind on snow distribution. It is recommended that further research between sites with the same setup be conducted. Using the same setup will provide more comparable data than was present in this research due to differences between site setup and installation. It is also recommended that further tests of differences between climate zones be performed. In addition, the problem seen in Marquette, MI with the Judd sensor (Figure 4-9) should be further investigated to decide if the temperature range is a problem, or if the problem is site specific. The use of ultrasonic sensors can restore valuable snowfall and snow depth records at hundreds of automated surface observing system sites across the country providing data that is useful to a variety of disciplines.

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APPENDIX A: SITE PHOTOS

Figure A-1: Buffalo, NY

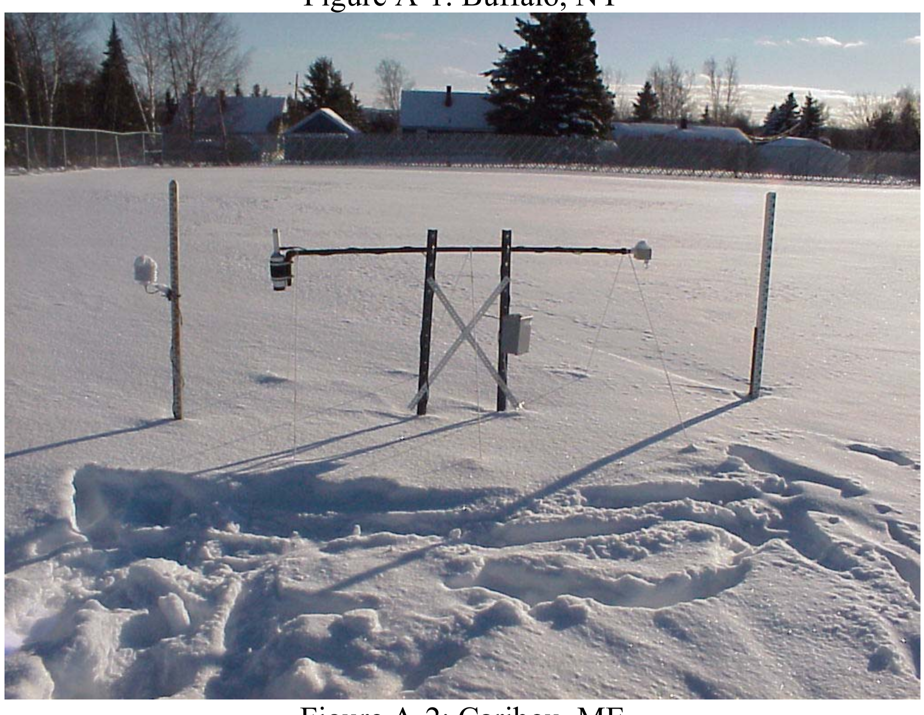


Figure A-2: Caribou, ME

Figure A-3: Cheyenne, WY

Figure A-4: Davis, WV

Figure A-5: Fort Collins, CO

Figure A-6: Indianapolis, IN


Figure A-7: Marquette, MI


Figure A-8: Milwaukee, WI


Figure A-9: Steamboat Springs, CO

APPENDIX B: SENSOR SPECIFICATIONS

Judd Communications Sensor Specifications

Power: +12 to 18 VDC, 50 Ma (maximum sample time 2.4 seconds)

Output: 0 to 2.5 or 0 to 5 VDC

Range: 0.5 to 10 meters (1.6 to 32.8 feet)

Beam width: 22 degrees

Accuracy: ± 1 cm or 0.4 % distance to target

Resolution: 3 mm (0.12 inches)

Temperature range: -30° to + 70°C (-22° to 158°F)

Size: 8 x 8 x 13 cm (3 x 3 x 5 inches)

Weight: .6 kg (1.3 lbs.)

Mounting: 1/2 inch threaded pipe

Cable length: 7.6 meters (25 feet)

Maximum cable length: 304 meters (1000 feet)

Temperature Sensor Accuracy: ± 1°C, -40 to +85°C

Temperature Sensor Resolution: .5°C

Campbell Scientific Sensor Specifications

Power Requirements: 9-16 Volts DC

Power Consumption: 2mA (Quiescent)
250 mA (Measurement Peak)

Measurement Time: 0.6 Seconds (Typical)
3.0 Seconds (Maximum)

Output: SDI-12
Serial ASCII
Pulse Train

Measurement Range: 0.5 – 10 Meters

Accuracy: ±1cm or 0.4% distance to target (whichever is greater)

Resolution: 0.1 mm

Beam Acceptance Angle: 22 degrees (approximate)

Operating Temperature: -30 C to +50 C (extended temperature available)

Maximum Cable Length: 60meters (SDI-12 and ASCII)
300meters (pulse train)

Dimensions: Length = 31 cm
Diameter = 7.5 cm

Weight: 1.3 kg

APPENDIX C: 2004-2005 SNOW DEPTH DATA

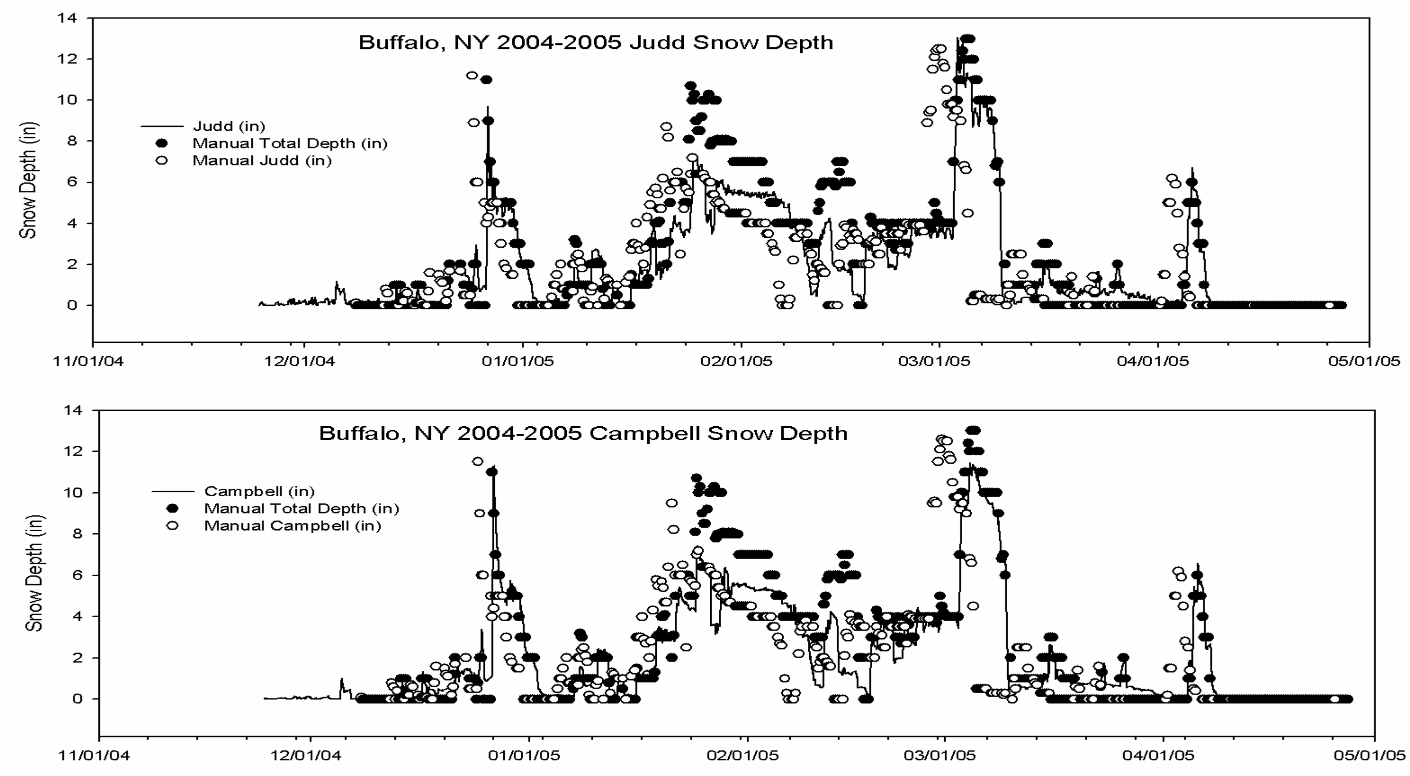
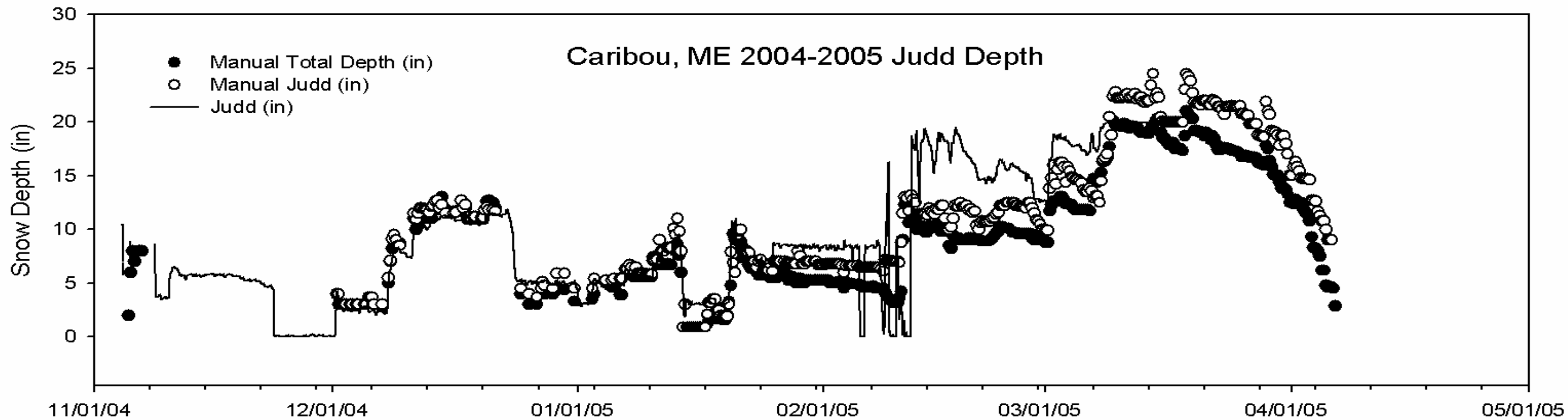


Figure C-1: Buffalo, NY 2004-2005 snow depth data. From top to bottom: Judd and Campbell.



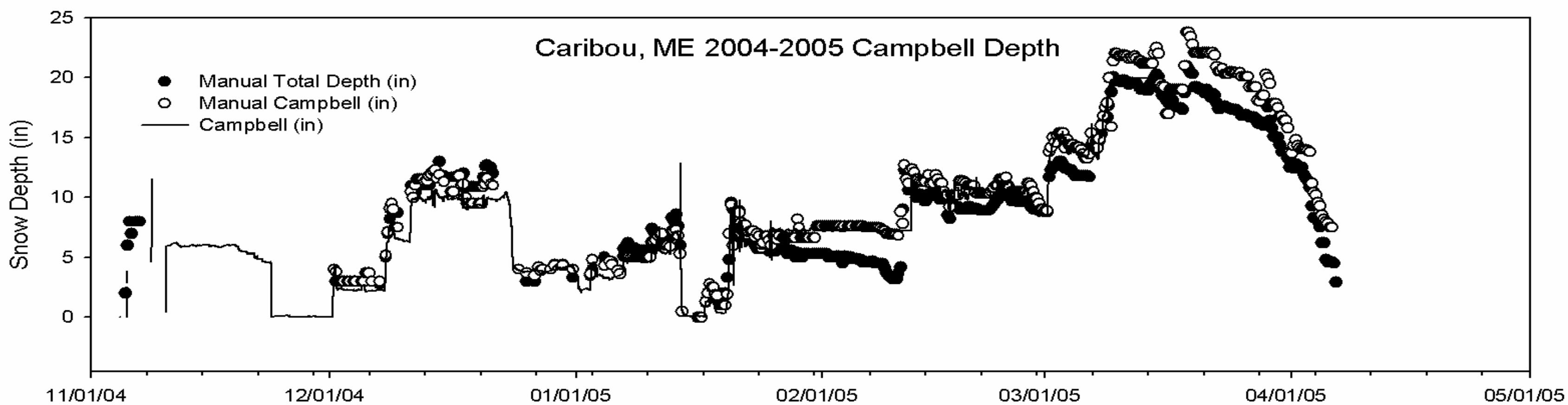


Figure C-2: Caribou, ME 2004-2005 snow depth data. From top to bottom: Judd and Campbell.

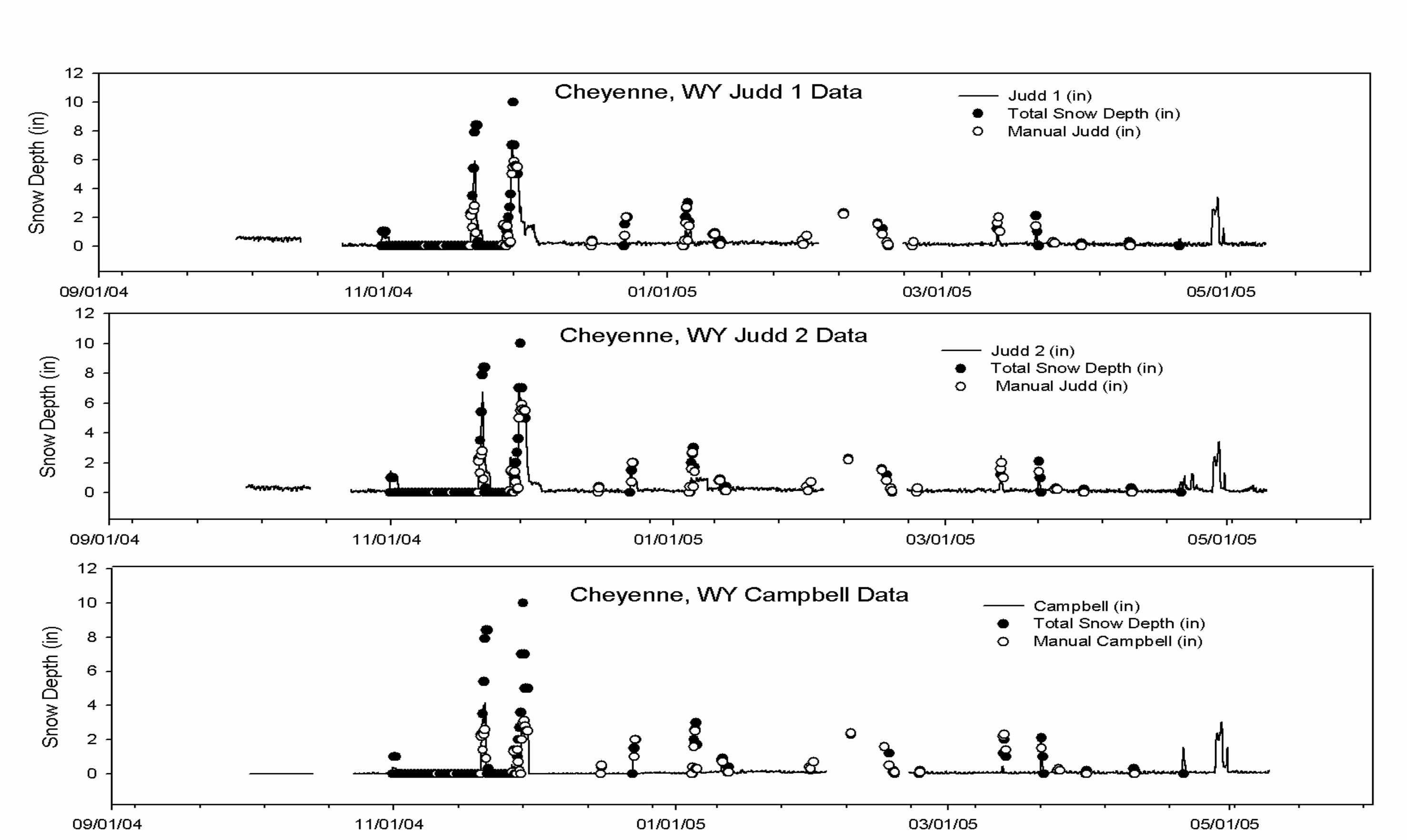


Figure C-3: Cheyenne, WY 2004-2005 Snow Depth Data. From top to bottom: Judd 1, Judd 2 and Campbell Data.

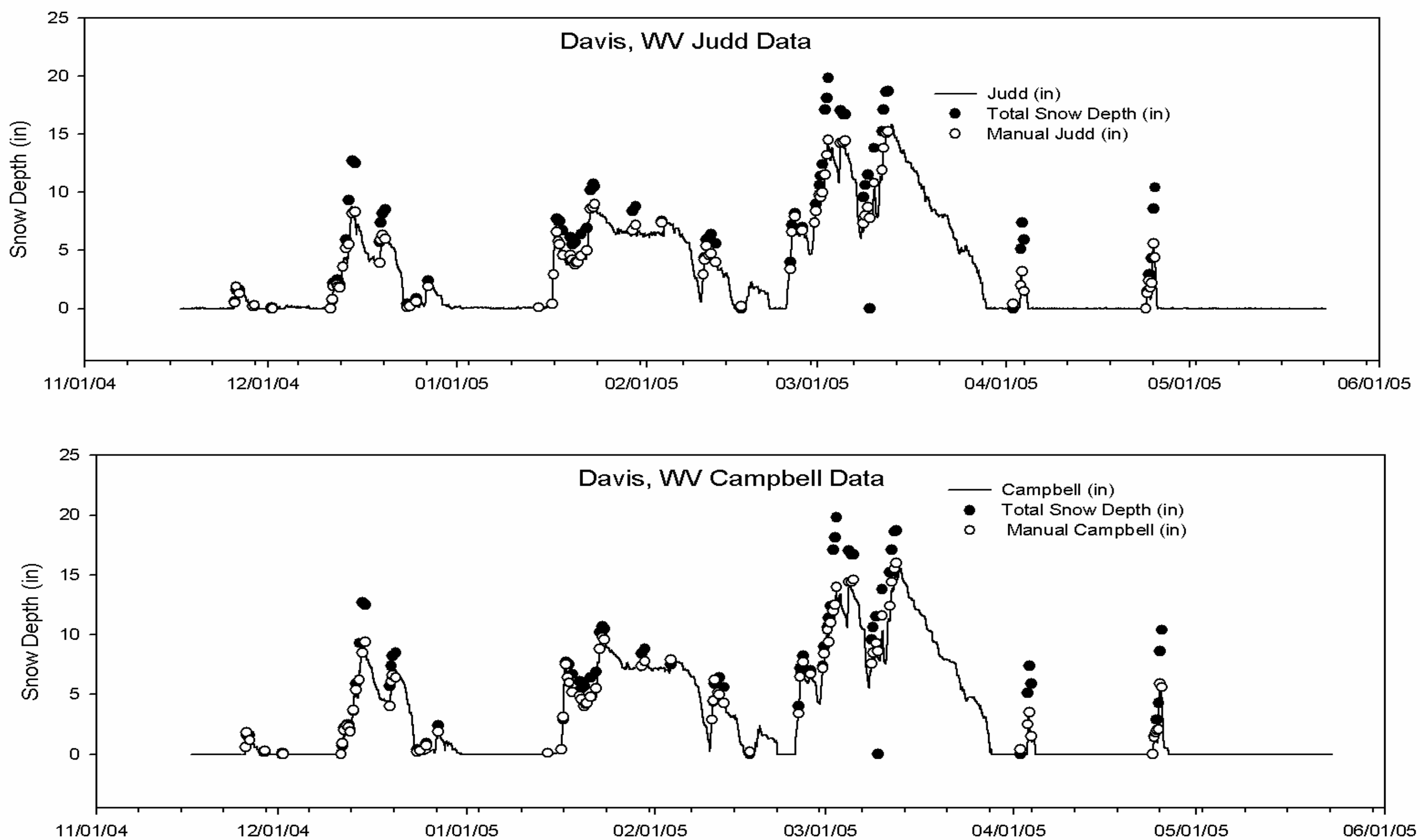


Figure C-4: Davis, WV 2004-2005 Snow Depth Data. From Top to Bottom: Judd, Campbell Data.

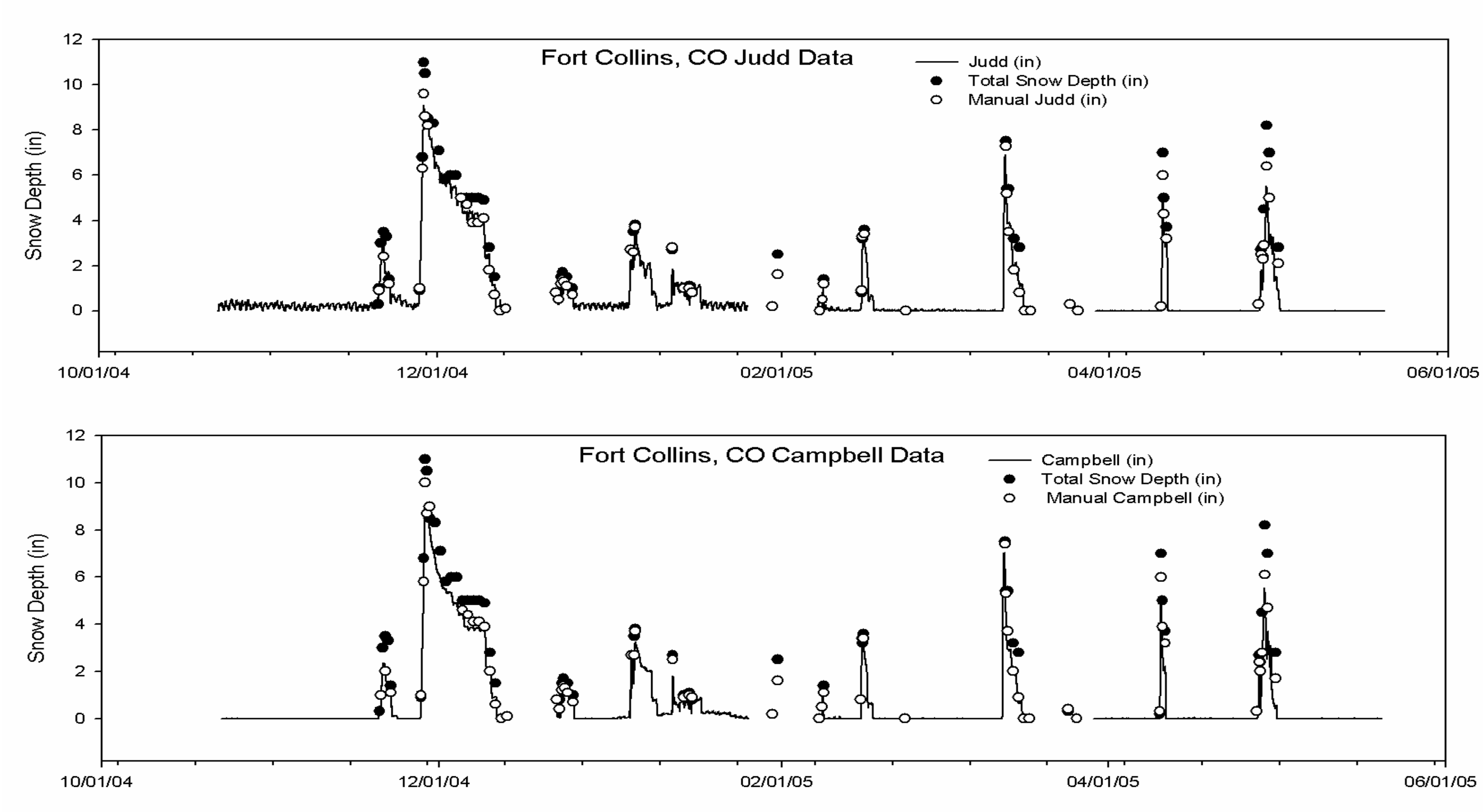


Figure C-5: Fort Collins, CO 2004-2005 Snow Depth Data. From Top to Bottom: Judd and Campbell.

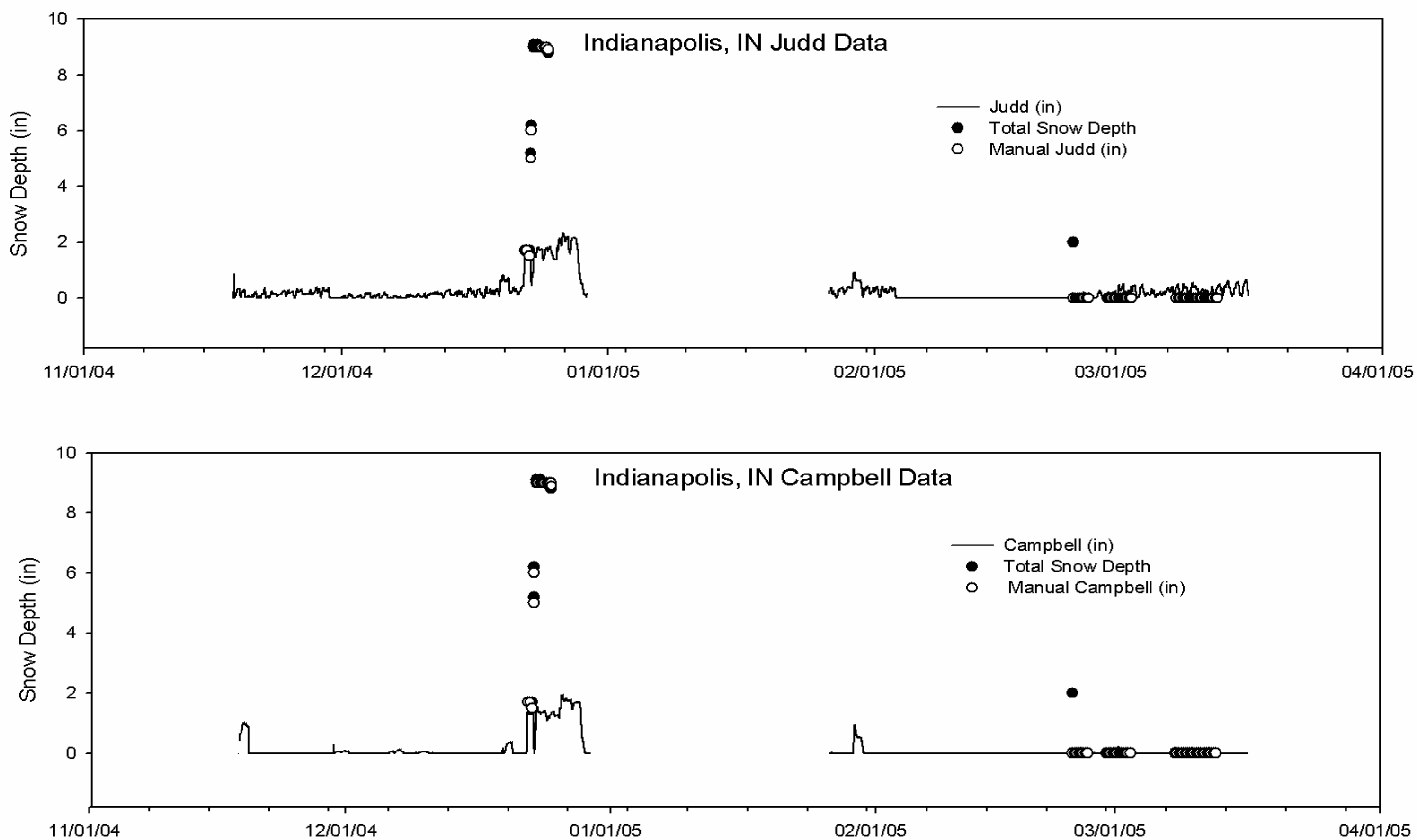
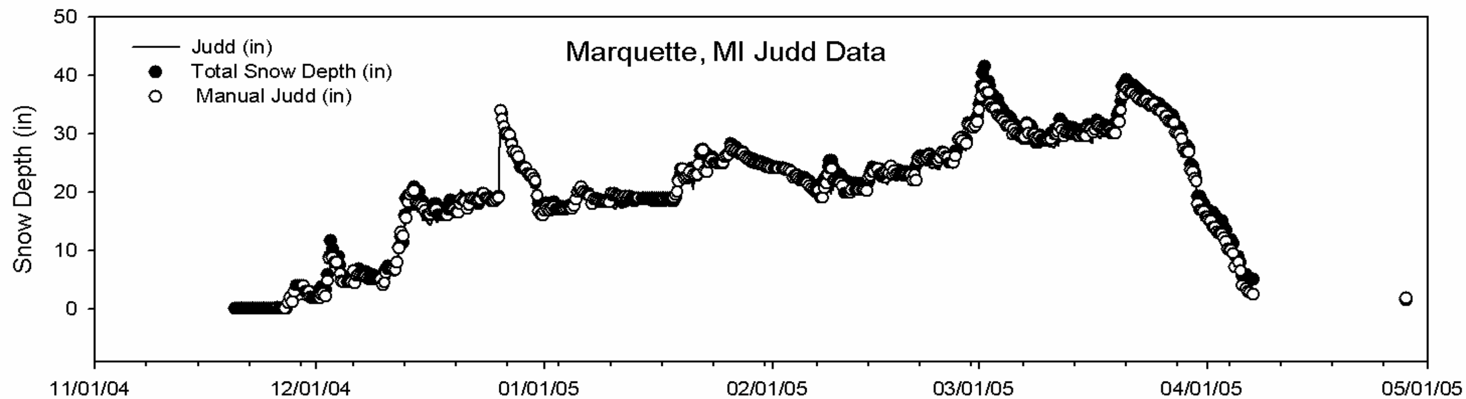


Figure C-6: Indianapolis, IN 2004-2005 Snow Depth Data. From Top to Bottom: Judd, Campbell.



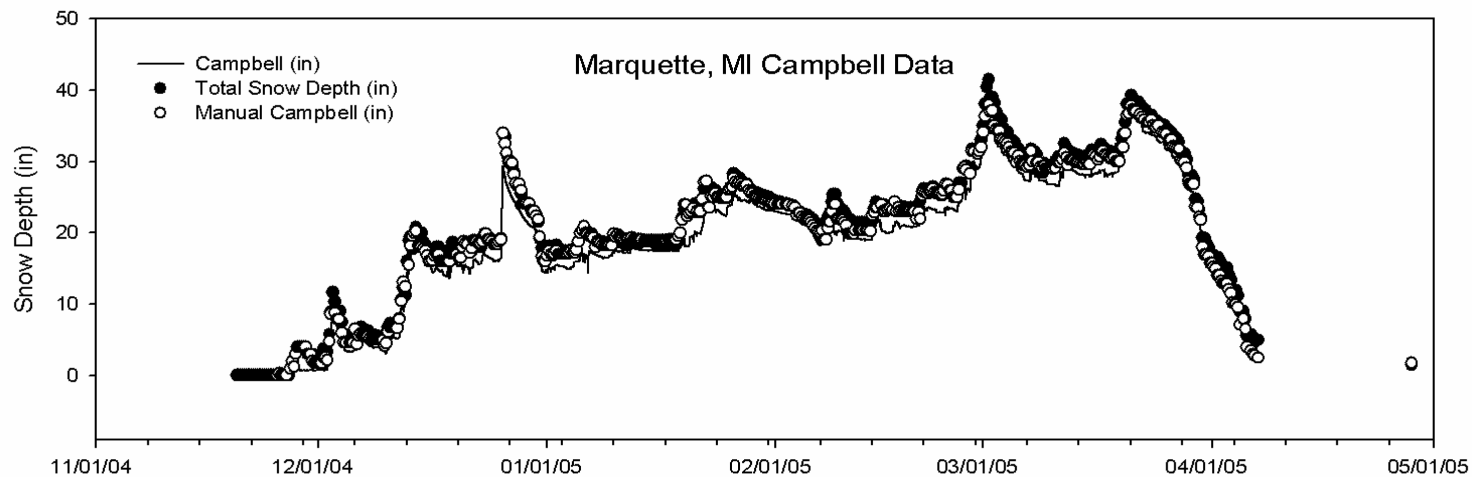


Figure C-7: Marquette, MI 2004-2005 Snow Depth Data. From Top to Bottom: Judd, Campbell.

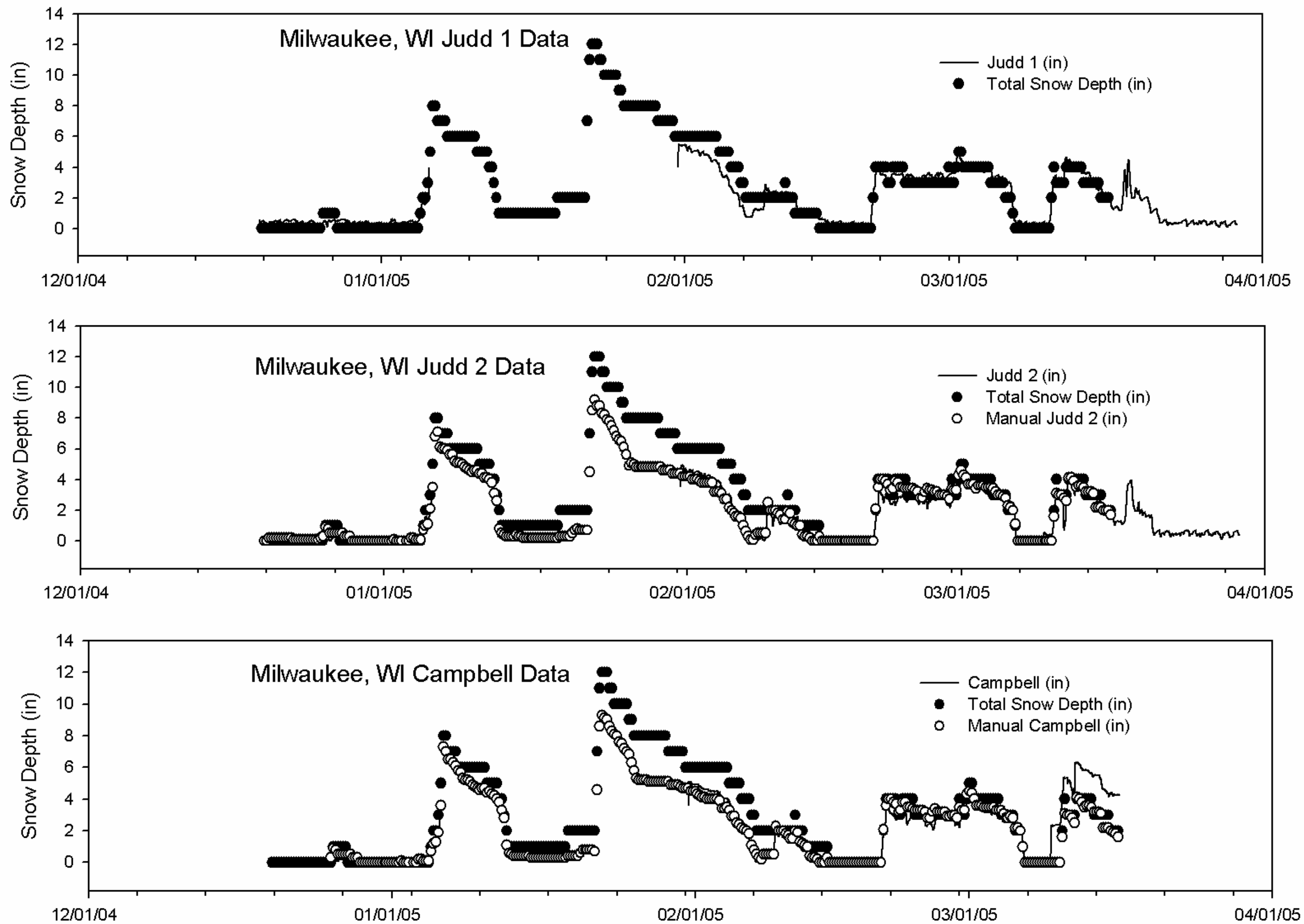


Figure C-8: Milwaukee, WI 2004-2005 Snow Depth Data. From Top to Bottom: Judd1, Judd2, and Campbell.

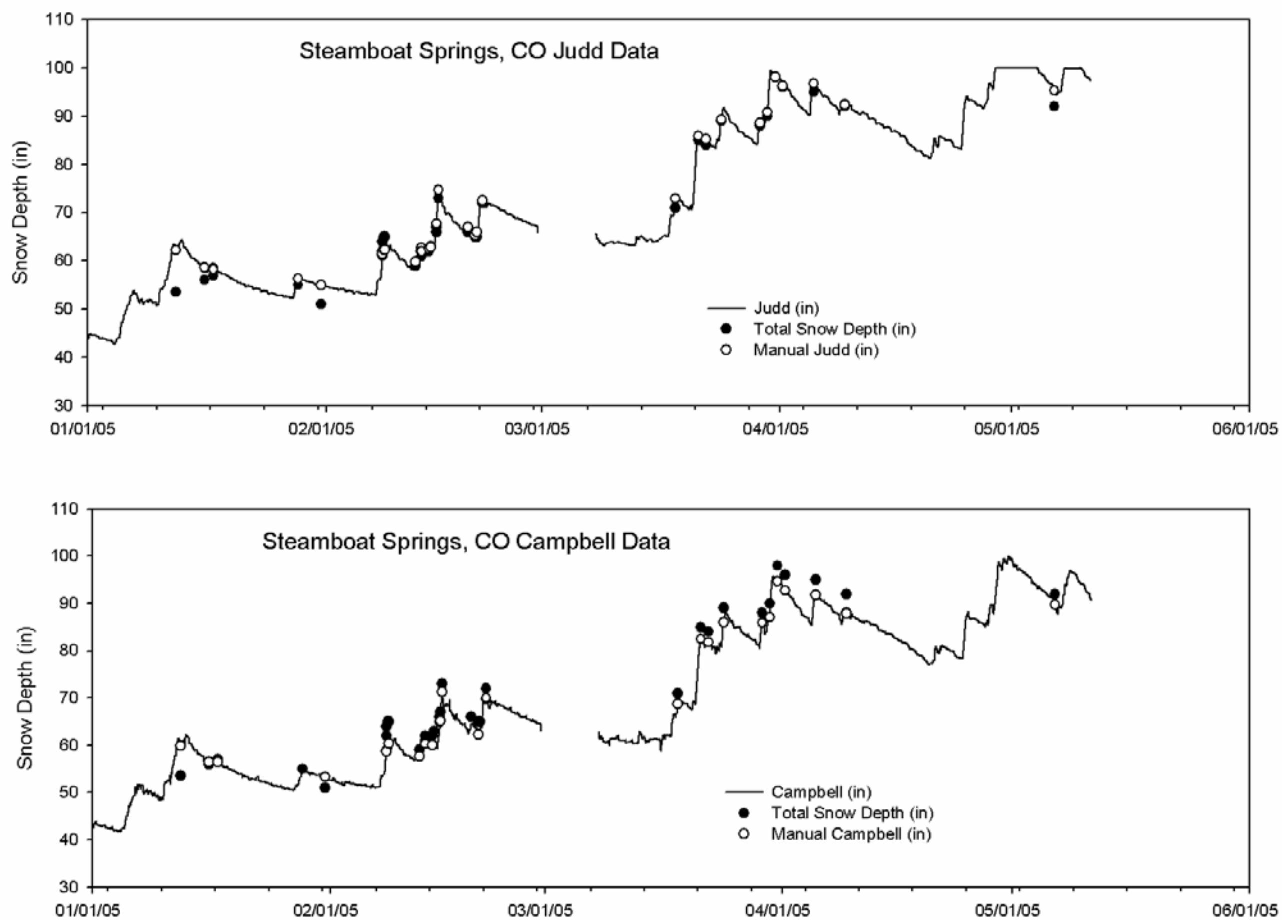


Figure C-9: Steamboat Springs, CO 2005 Snow Depth Data. From Top to Bottom: Judd, Campbell.

APPENDIX D: SIX HOUR SNOWFALL ALGORITHM PLOTS

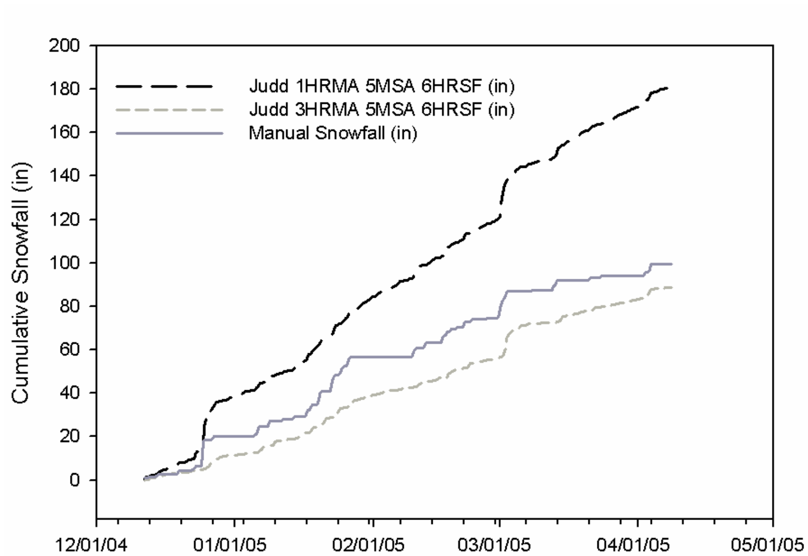


Figure D-1: Buffalo, NY Judd 5MSA.

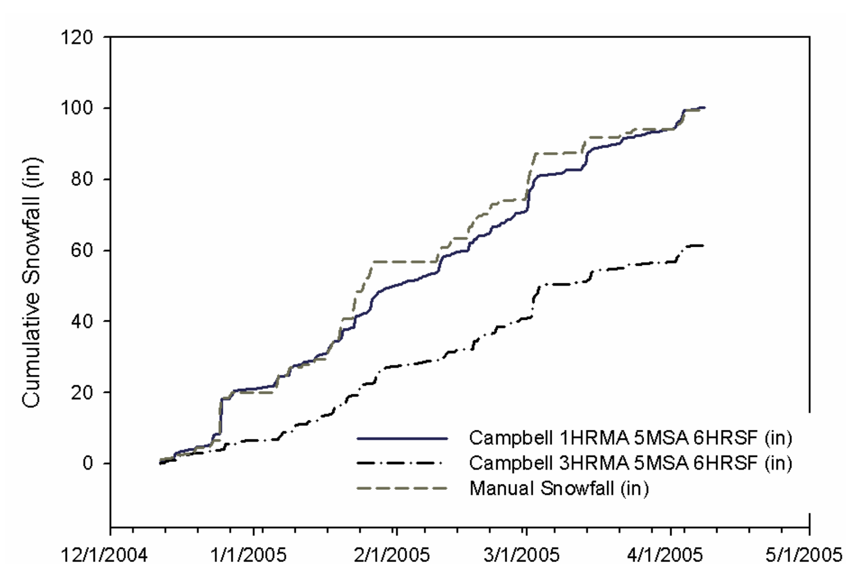


Figure D-2: Buffalo, NY Campbell 5MSA.

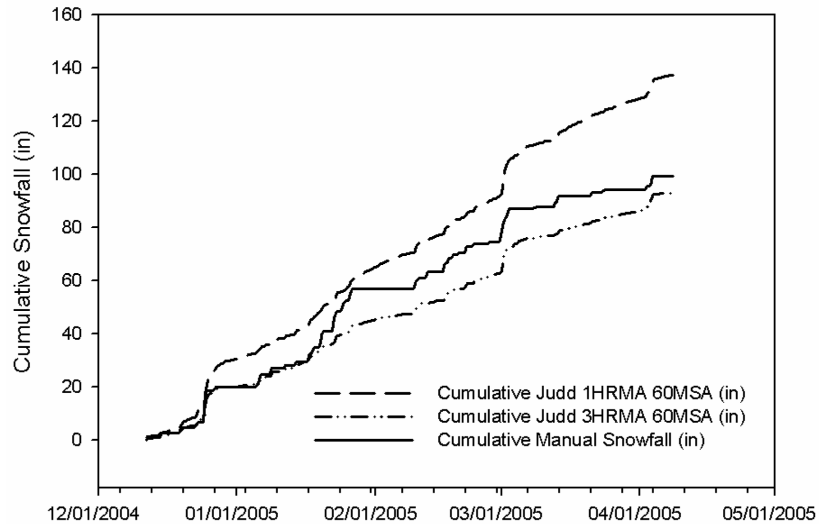


Figure D-3: Buffalo, NY Judd 60MSA.

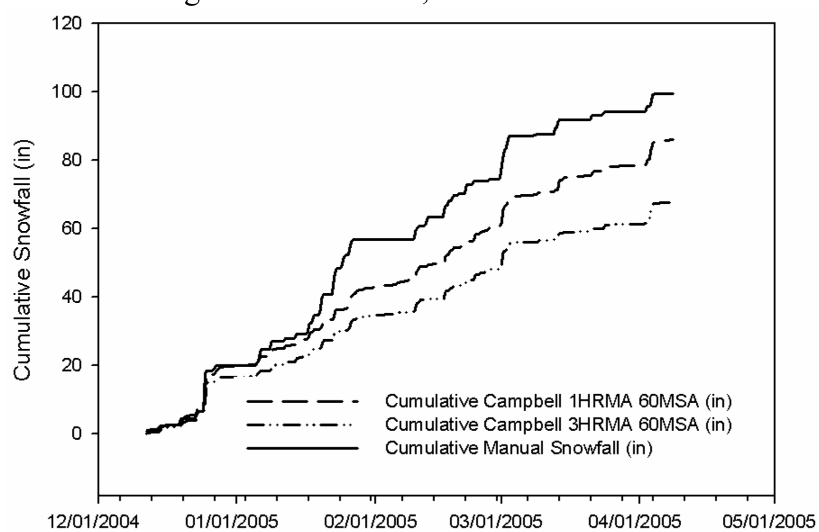


Figure D-4: Buffalo, NY Campbell 60MSA.

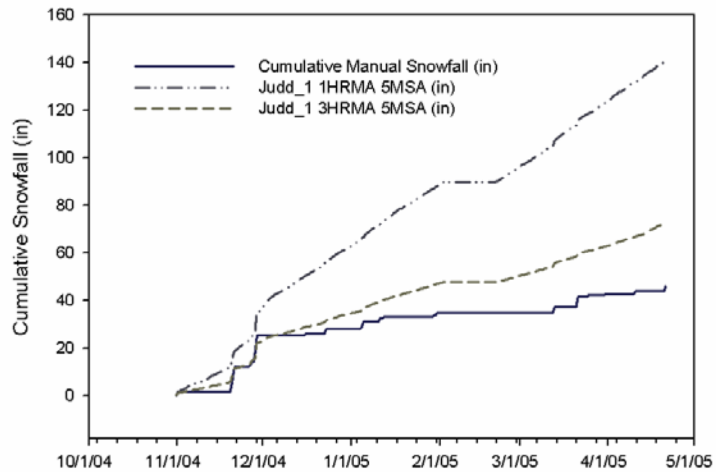


Figure D-5: Cheyenne, WY Judd 1 5MSA.

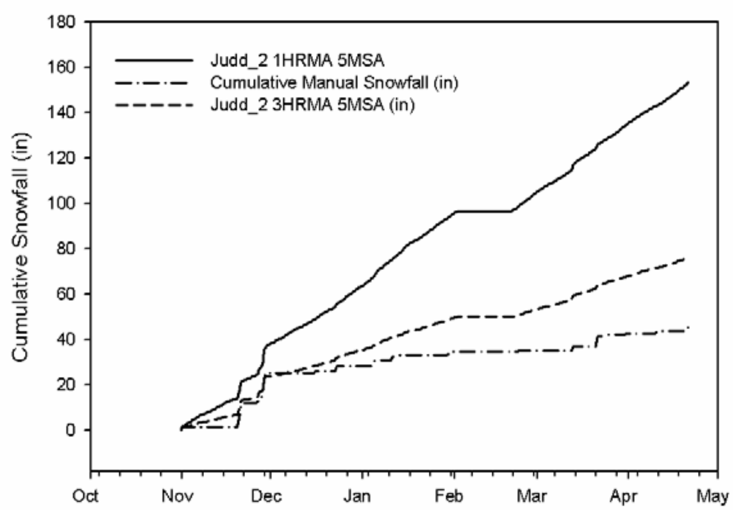


Figure D-6: Cheyenne, WY Judd 2 5MSA.

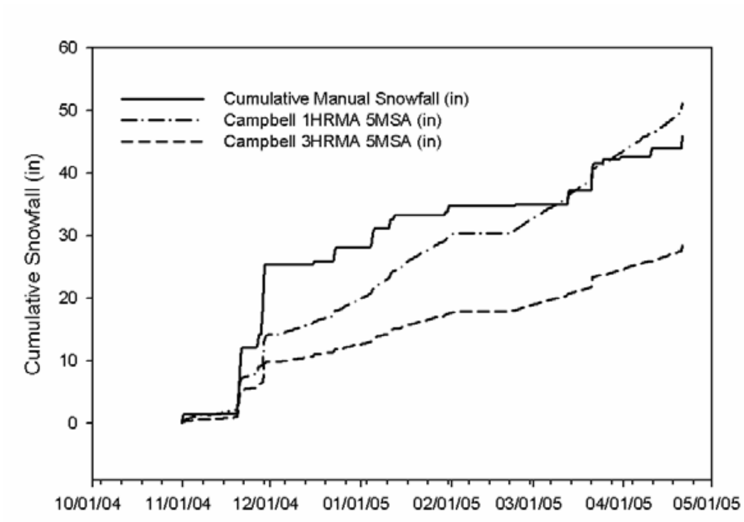


Figure D-7: Cheyenne, WY Campbell 5MSA.

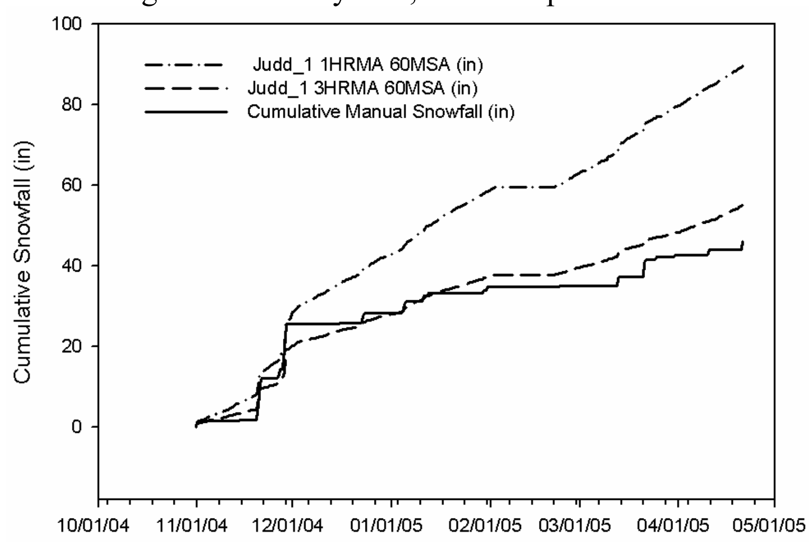


Figure D-8: Cheyenne, WY Judd 1 60MSA.

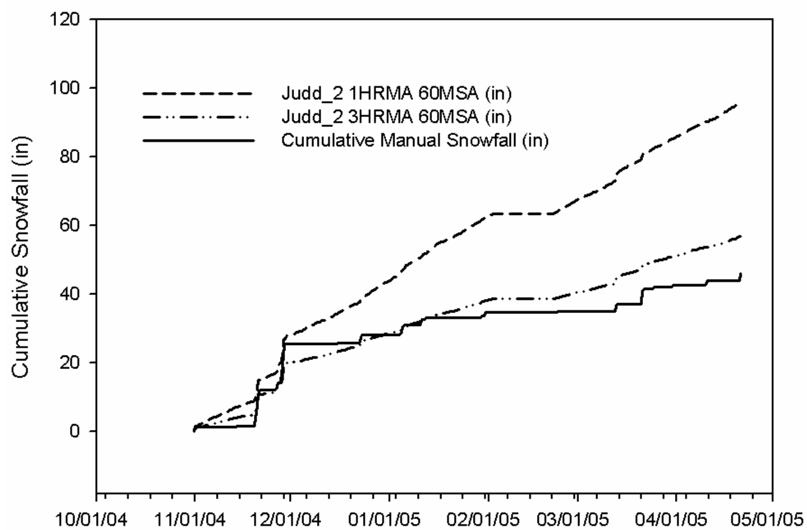


Figure D-9: Cheyenne, WY Judd 2 60MSA.

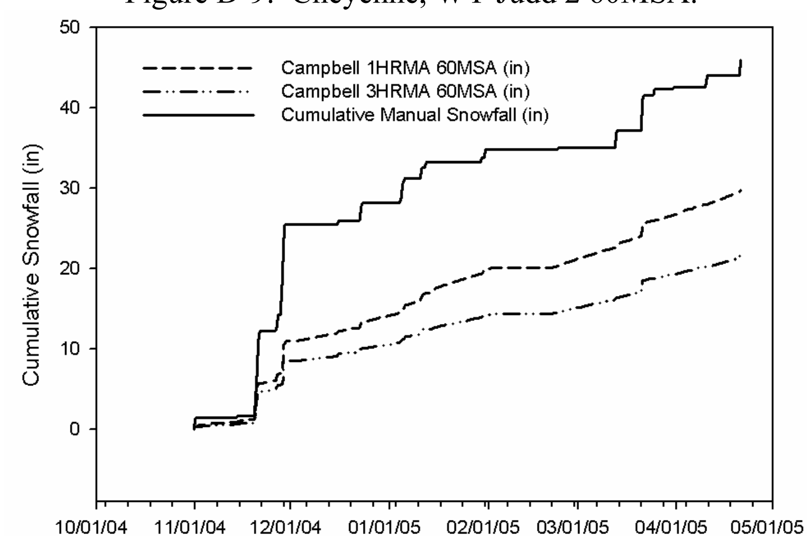


Figure D-10: Cheyenne, WY Campbell 60MSA.

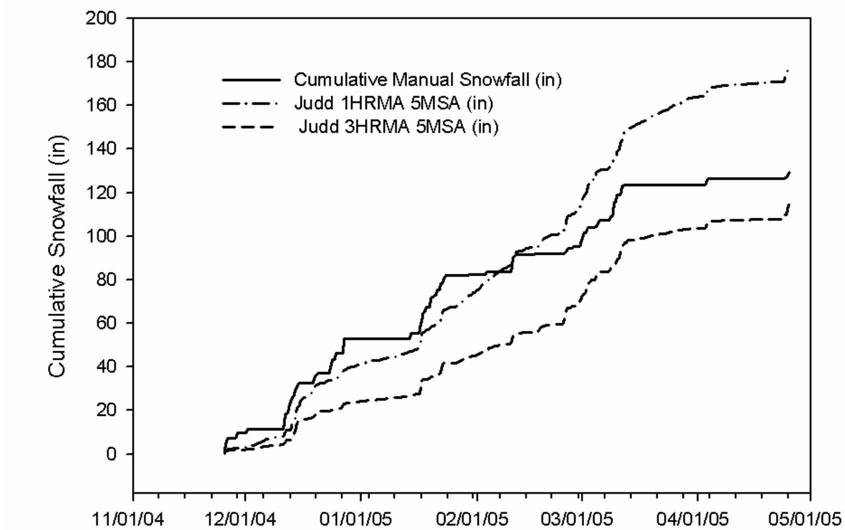


Figure D-11: Davis, WV Judd 5MSA.

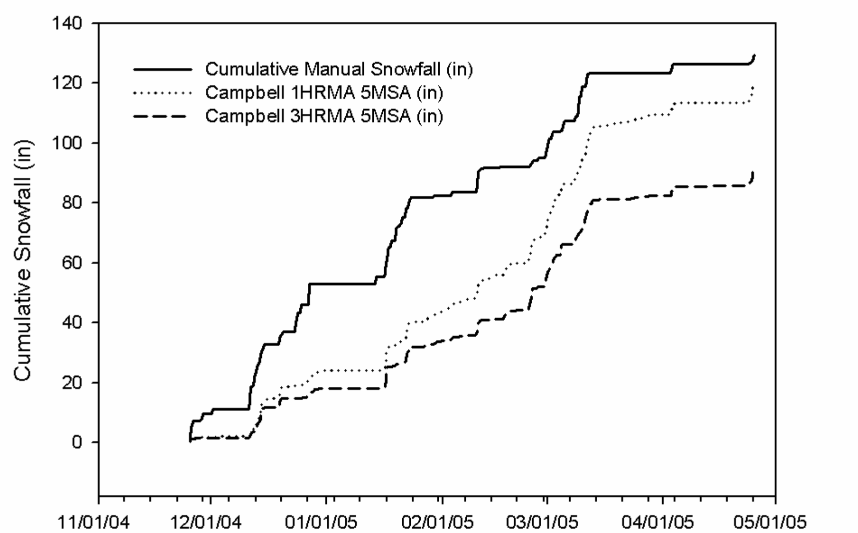


Figure D-12: Davis, WV Campbell 5MSA.

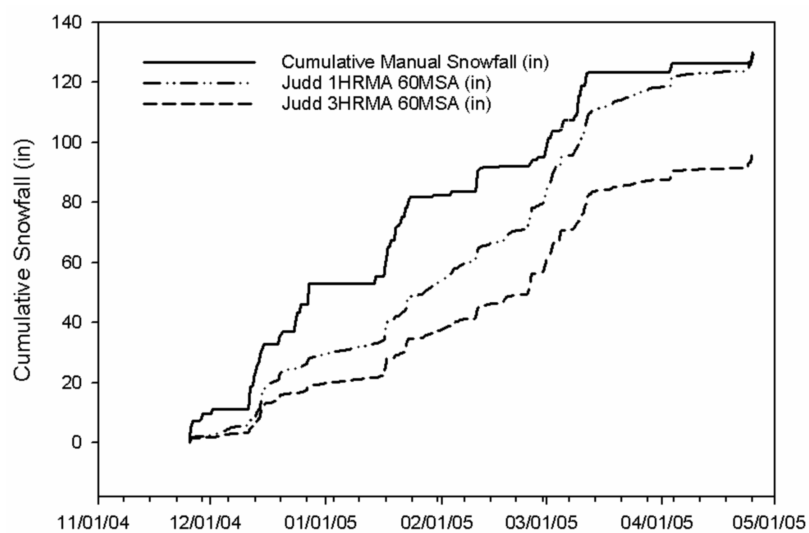


Figure D-13: Davis, WV Judd 60MSA.

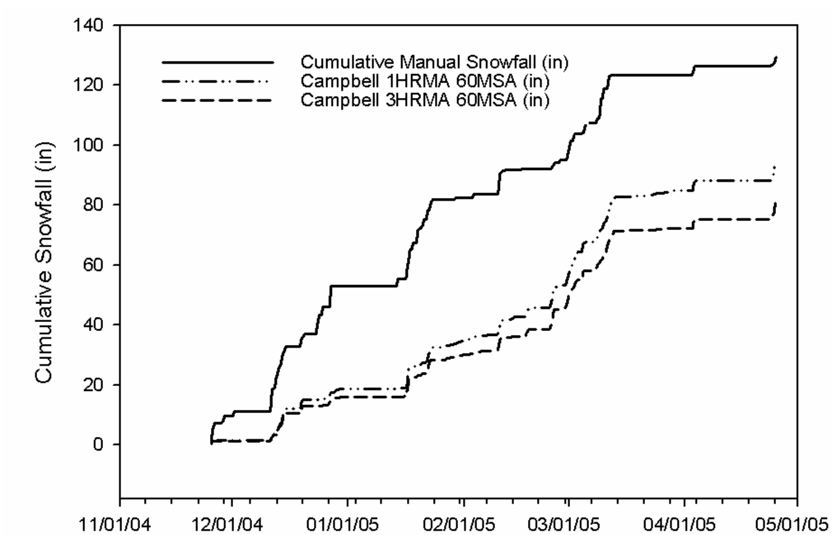


Figure D-14: Davis, WV Campbell 60MSA.

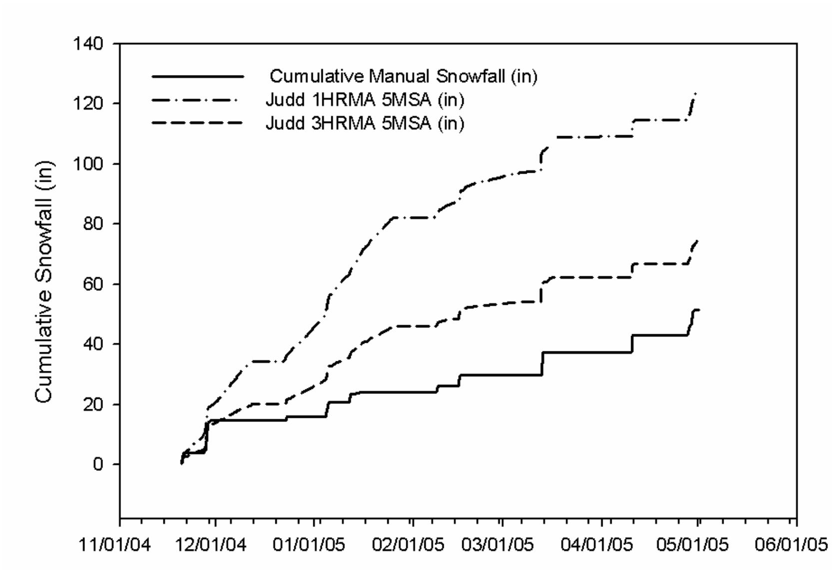


Figure D-15: Fort Collins, CO Judd 5MSA.

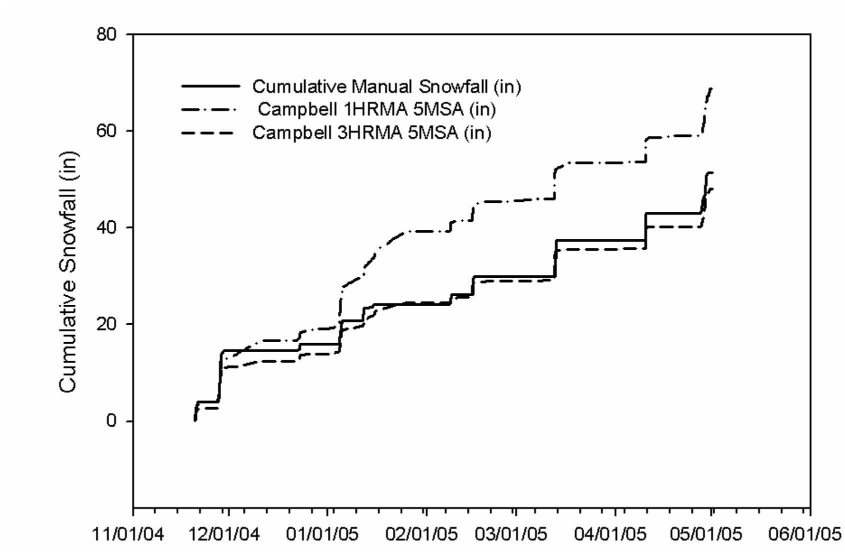


Figure D-16: Fort Collins, CO Campbell 5MSA.

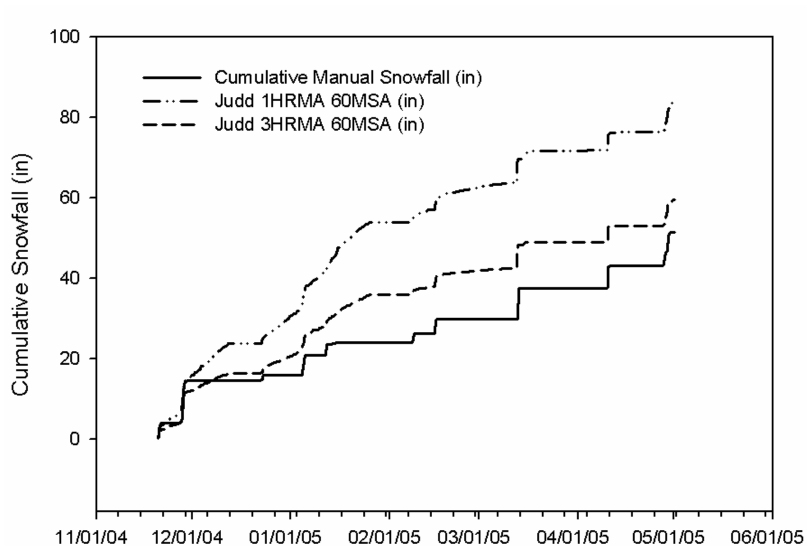


Figure D-17: Fort Collins, CO Judd 60MSA.

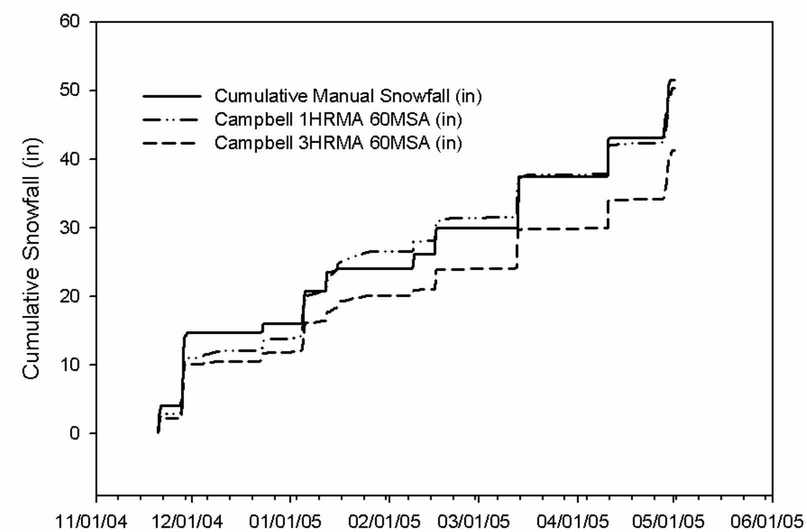


Figure D-18: Fort Collins, CO Campbell 60MSA.

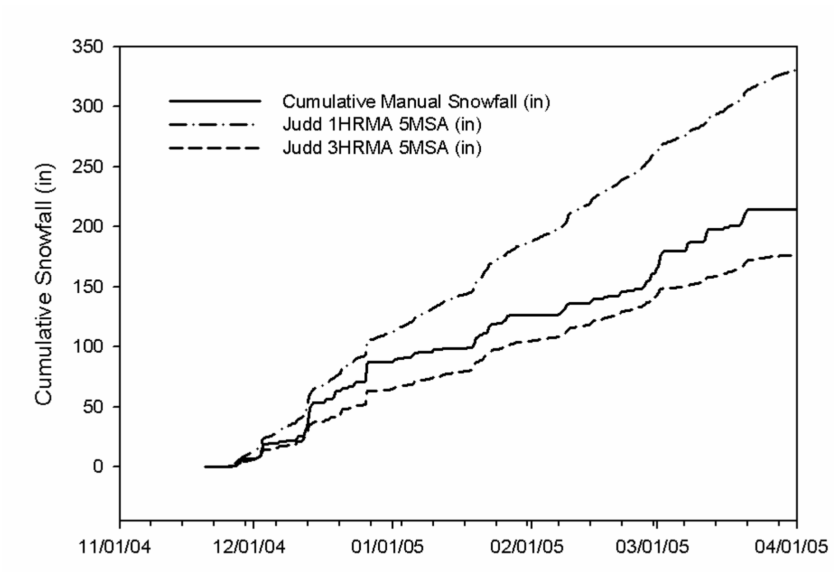


Figure D-19: Marquette, MI Judd 5MSA.

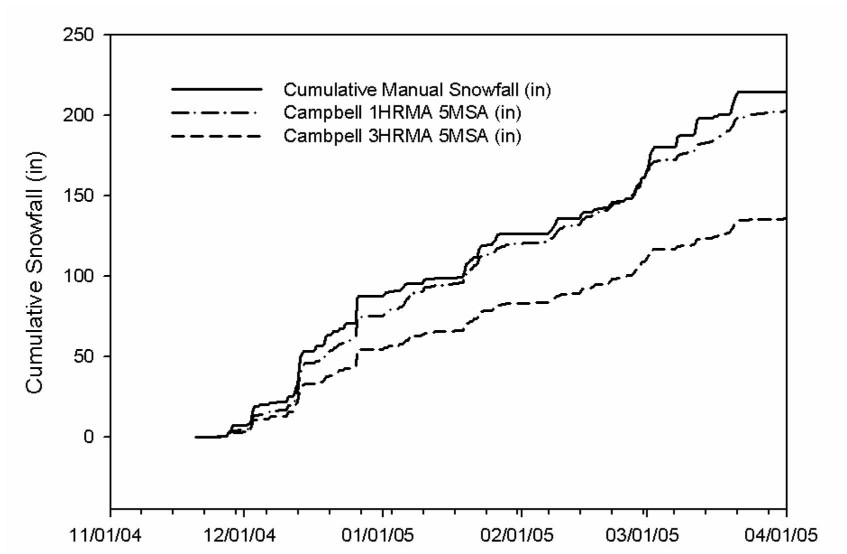


Figure D-20: Marquette, MI Campbell 5MSA.

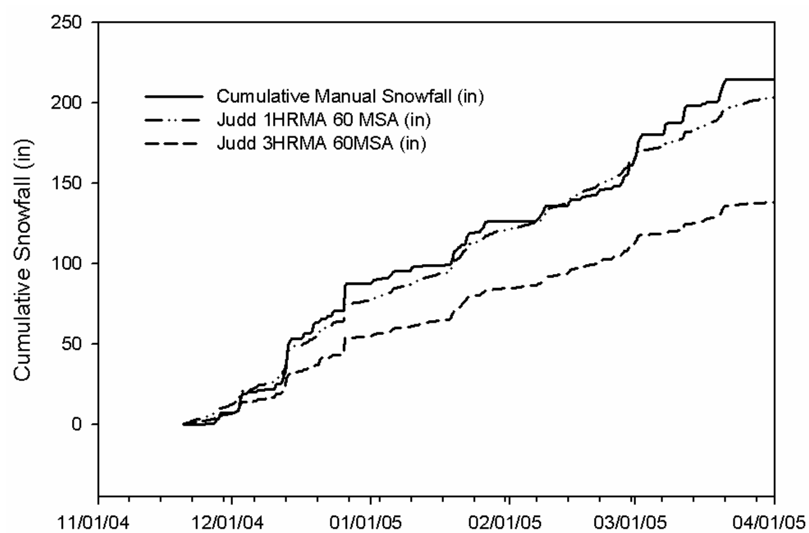


Figure D-21: Marquette, MI Judd 60MSA.

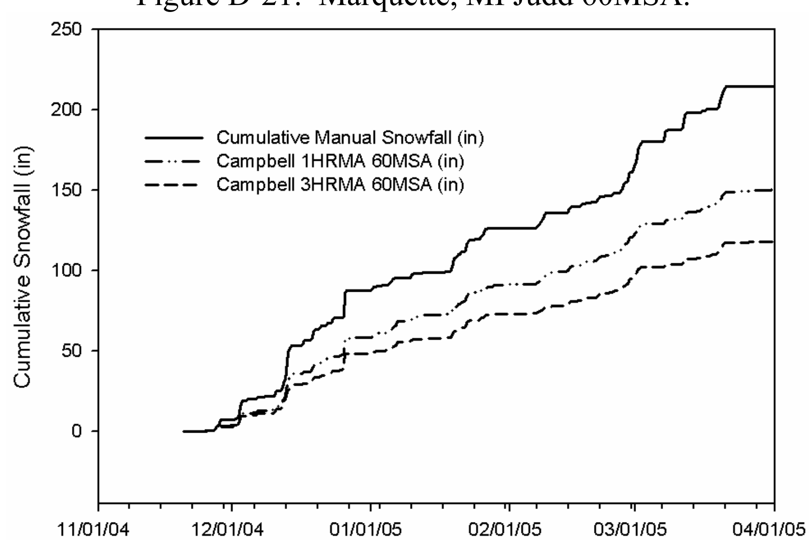


Figure D-22: Marquette, MI Campbell 60MSA.

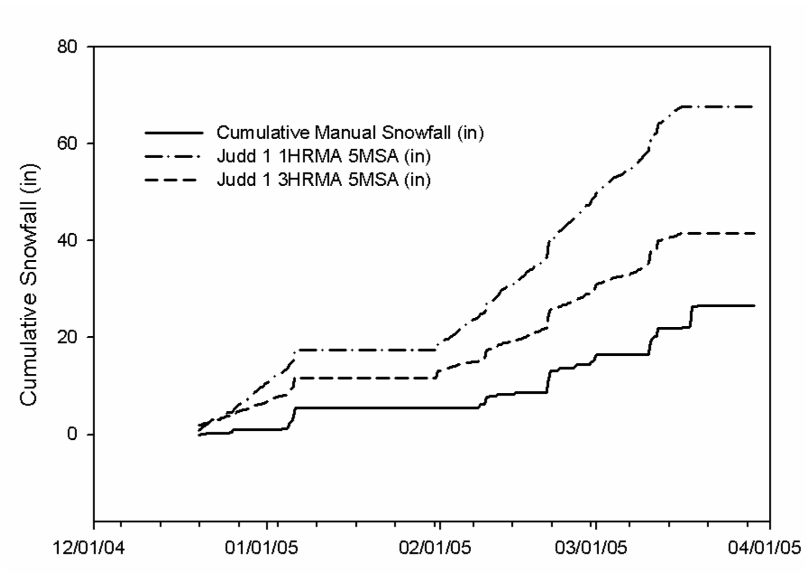


Figure D-23: Milwaukee, WI Judd 1 5MSA.

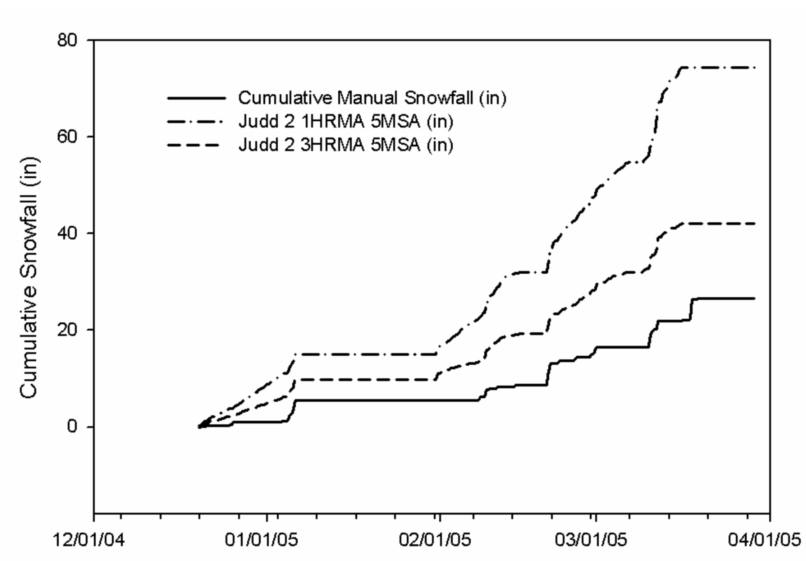


Figure D-24: Milwaukee, WI Judd 2 5MSA.

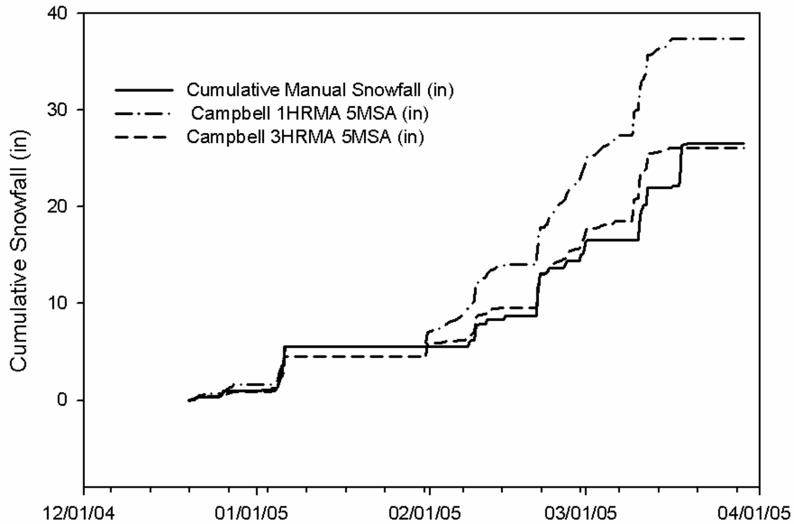


Figure D-25: Milwaukee, WI Campbell 5MSA.

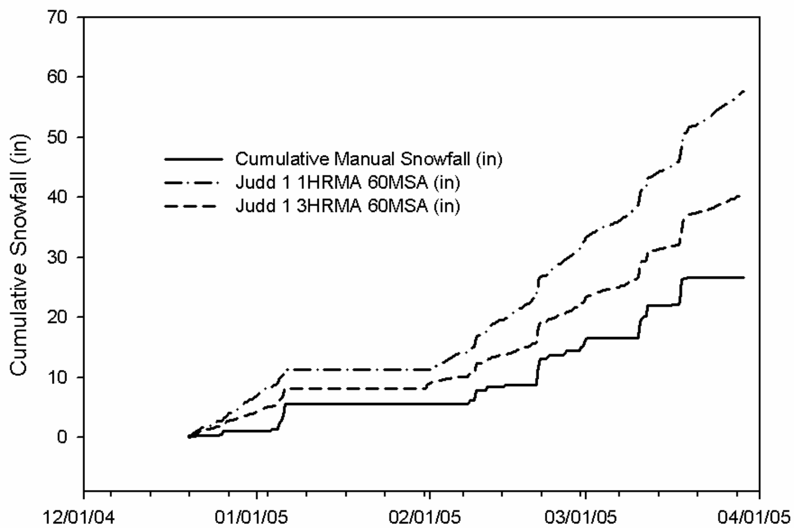


Figure D-26: Milwaukee, WI Judd 1 60MSA.

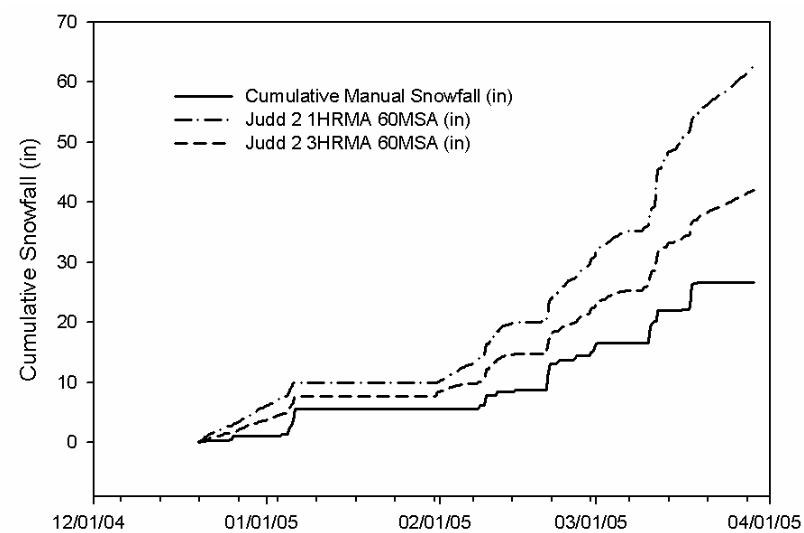


Figure D-27: Milwaukee, WI Judd 2 60MSA.

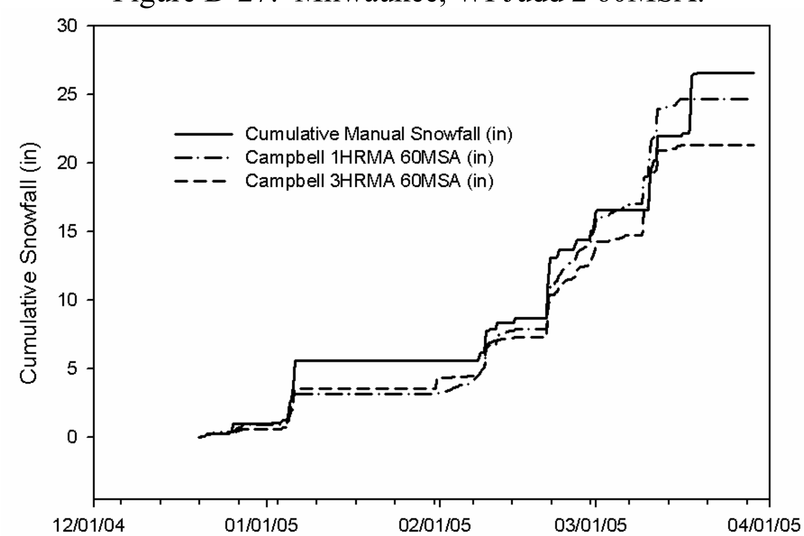


Figure D-28: Milwaukee, WI Campbell 60MSA.

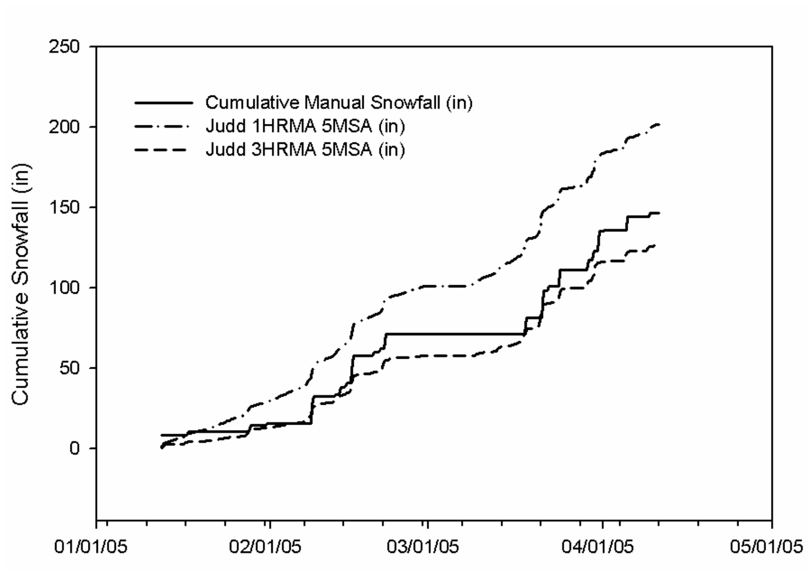


Figure D-29: Steamboat Springs, CO Judd 5MSA.

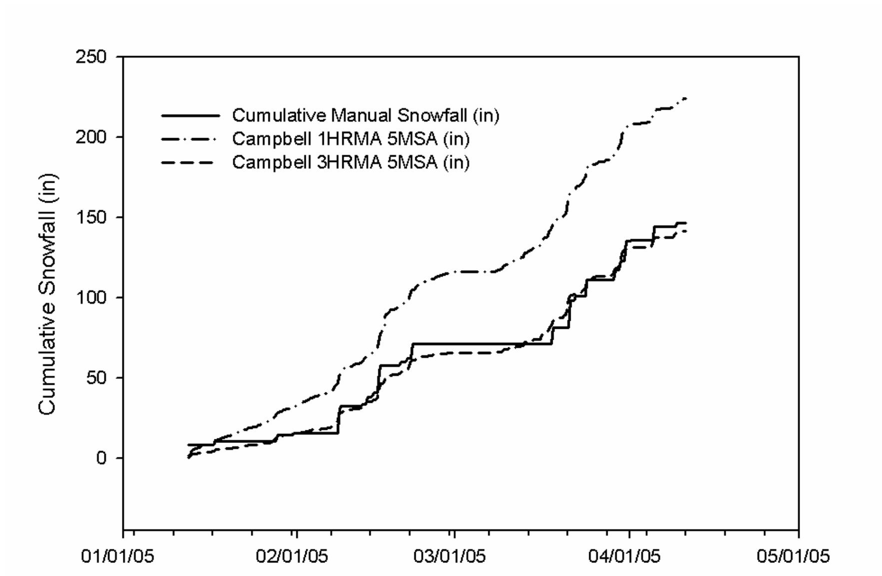


Figure D-30: Steamboat Springs, CO Campbell 5MSA.

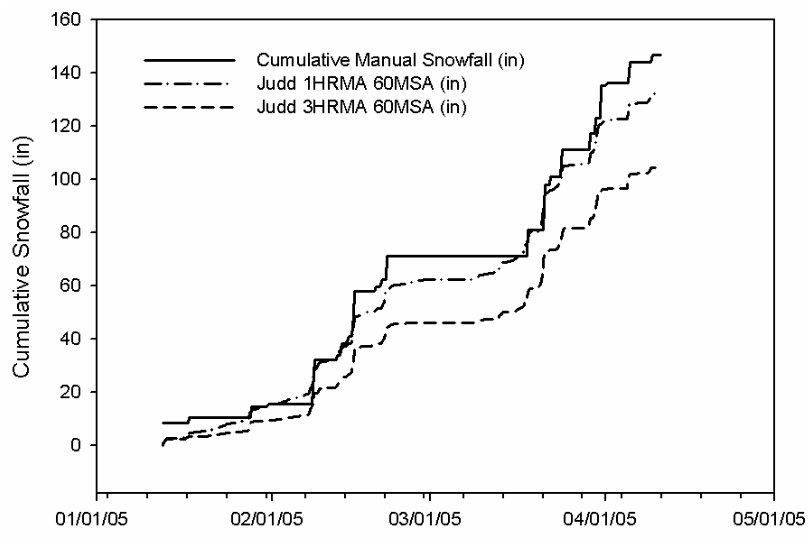


Figure D-31: Steamboat Springs, CO Judd 60MSA.

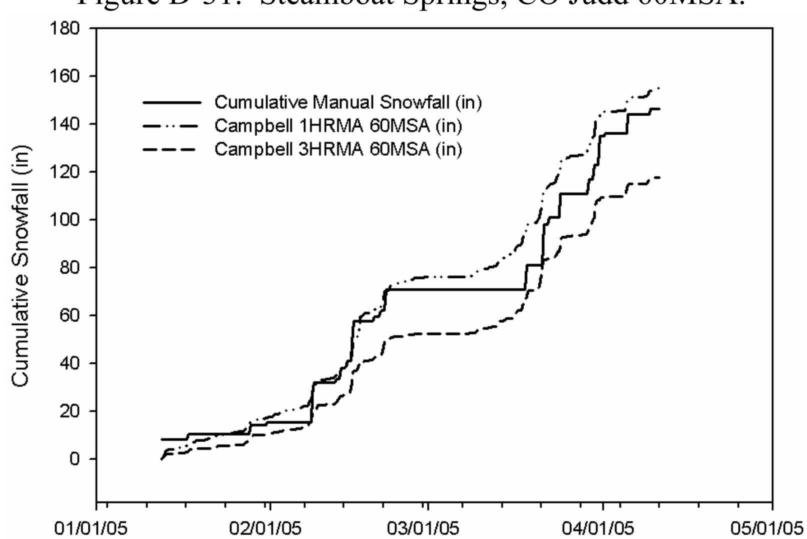


Figure D-32: Steamboat Springs, CO Campbell 60MSA.

APPENDIX E: QUALITATIVE ASSESSMENT OF DATA SPIKES

Table E-1 Buffalo, NY Data Spike Record.

	Buffalo, NY	
	Date	Reported Possible Causes
Judd	11/22/04 22:10 - 11/23/04 0:30	Calibration Period
	12/24/04 19:00 - 12/25/04 14:45	Dendrites and Light Fluffy Snow Reported Throughout "Spikey" Period
	1/17/2005 22:50	Lots of blowing/drifting at 1900 observation
	1/26/2005 7:05	Unexplained Single Spike
Campbell	1/22/2005 17:45	Single Spike Dendrites Reported @ 19:00 along w/ 15 mph winds

Table E-2: Cheyenne, WY Data Spike Record.

	Cheyenne, WY	
Judd 1	11/20/04 1:45 -16:05	dendrites and needles with blowing snow
	11/28/04 13:25-17:50	blowing/drifting snow
	11/30/04 10:55 - 11:15	NO REPORTS
	4/20/05 21:20 - 21:40	plates reported as wet snow melting as it lands
	4/28/2005 5:45	dendrites reported
Judd 2	11/20/04 9:55 - 16:05	dendrites/needles/blowing snow
	11/29/04 18:30 - 19:20	dendrites/blowing snow (time period continuously erroneous)
	12/23/04 17:45 - 21:50	dendrites/blowing snow (time period continuously erroneous)
	1/5/05 20:15 - 21:30	dendrites WS ~ 10mph (time pd continuously erroneous)
	3/13/2005 0:25	dendrites/needles/blowing snow
	4/20/05 21:25 -21:30	plates WS 9mph (same time pd as other Judd)
	4/29/2005 1:50	Columns with WS 7mph
Campbell	NONE	

Table E-3: Davis, WV Data Spike Record.

	Davis, WV	
Judd	12/14/04 11:05- 21:40	plates, possible NWS visitor interference
	1/16/2005 21:40	plates reported
	2/10/2005 17:00	14 mph winds reported
	2/24/05 18:20 - 19:10	needles/dendrites reported @ 12:40
	2/24/2005 22:05	plates/dendrites reported 2/25 07:00
	3/10/05 6:25 - 7:00	plates w/ winds 10 mph
	3/11/05 3:10 - 4:55	Crystals reported to be larger and softer than snow pellets?
	3/11/2005 16:30	needles/plates
	3/12/2005 23:10	17 mph winds
	4/3/2005	unexplained spike
	4/22/2005 3:25	no snow possibly windy conditions
Campbell	3/1/2005 23:00	drifting snow reported @ 18:35

Table E-4: Fort Collins, CO Data Spike Record.

	Fort Collins, CO	
Judd	11/28/05 7:00 - 7:35	intense snowfall
	11/28/2004 14:35	dendrites reported
	1/5/2005 10:40 - 11:20	dendrites reported
	2/15/05 13:55-14:55	irregular crystals reported
	3/12/05 22:00 - 23:05	No snow or wind (grass cutting?)
	3/13/05 6:40 - 10:30	slushy snow fell of sensor structure causing uneven surface
	4/10/05 10:00 - 13:00	high winds 12- 20 mph
	4/30/05 9:40 - 10:00	unexplained perhaps grass cutting
Campbell	1/21/05 5:25 - 5:55	dendrites and plates
	3/12/2005 22:00	slushy snow fell of sensor structure causing uneven surface
	4/3/05 14:55 - 15:30	15 mph winds no snow
	4/4/05 10:05 - 13:20	14 - 20 mph winds no snow
	4/7/05 14:45 - 15:25	17 mph winds no snow
	4/10/05 10:30 - 14:20	12-20 mph winds with wet snow
	4/28/05 4:20 - 4:50	needles
	4/28/2005 17:15	irregular wet crystals
	4/30/05 6:40 - 7:35	Unexplained perhaps grass cutting

Table E-5: Marquette, MI Data Spike Record.

	Marquette, MI	
Judd	12/12/04 8:45	dendrites and light winds
	12/19/04 21:45 – 22:50	needles, significant blowing/drifting
	12/22/04 19:50 – 20:35	needles
	12/24/04 8:20 – 8:55	winds around 15 mph
	12/24/2004 18:25 – 12/25/04 9:10	Temps < -10 F Caused Judd to Malfunction
	12/25/04 20:35 – 12/26/04 01:25	Intense snowfall 3-5"/hr
	12/26/04 23:05 – 12/27/04 03:00	Temps < -10 F Caused Judd to Malfunction
	1/14/05 05:20 – 1/14/05 9:20	Temps < -10 F Caused Judd to Malfunction
	1/15/05 00:10 – 1/15/05 9:50	Temps < -10 F Caused Judd to Malfunction
	1/15/05 19:00 – 1/16/05 09:50	Temps < -10 F Caused Judd to Malfunction
	1/16/05 21:00 – 1/17/05 06:25	Temps < -10 F Caused Judd to Malfunction
	1/17/05 19:40 – 1/18/05 05:00	Temps < -10 F Caused Judd to Malfunction
	1/20/2005 21:45 – 21:55	intermittent, dendrites reported at 19:00
	1/21/05 04:25 – 05:25	continuous, dendrites reported at 07:00
	1/21/05 07:15 – 07:55	nearly continuous, dendrites reported at 07:00
	2/8/05 21:00 – 23:45	intermittent, no report for this time, but surrounding obs. Reported dendrites
	2/19/05 22:25 – 22:45	intermittent, no reports of snow or wind
	2/26/05 04:15 – 04:40	nearly continuous, 10 mph winds with light
	3/12/05 21:55 – 3/13/05 07:50	Temps < -10 F Caused Judd to Malfunction

Campbell	12/2/04 19:40	dendrites and light wind reported @ 19:00
	12/25/04 20:50 – 01:20	intermittent spikes, plates reported at 1:00
	1/5/05 11:50	dendrites reported at 13:00
	1/5/05 21:10 – 21:30	intermittent, plates reported at 1/6/05 01:00
	1/21/05 5:25 – 5:45	intermittent, dendrites reported @ 07:00
	1/22/05 9:20 -9:30	intermittent, transition from synoptic to lake effect during this period
	2/25/05 20:55 – 21:00	dendrites reported at 19:00
	2/26/05 10:50 – 18:50	off and on spikes, dendrites reported at 13:00 and 19:00 obs
	3/1/05 8:45	dendrites and 25 mph winds reported at 07:00
	3/11/05 22:30	dendrites and 30 mph winds reported at 3/11 1900 and 3/12 07:00 (missing 01:00)

Table E-6: Milwaukee, WI Data Spike Record.

Judd 1	**Milwaukee, WI**	light, wet snow, winds 12mph
	2/20/05 10:50	possible observer interference (happened around obs time)
	3/21/05 5:35 - 6:10	12 mph winds
	3/22/05 3:50 - 5:00	
Judd 2		No apparent cause in manual data
	2/9/05 2:10 - 3:05	light, wet snow, winds 12mph
	2/20/05 10:30 - 13:05	light snow and snow pellets 12 mph winds
	3/10/05 14:20 - 14:40	13 mph winds from N
	3/11/05 1:35 - 1:55	15 mph winds from WNW
	3/11/05 10:50 - 10:55	18 mph winds from WSW
	3/11/05 19:10 - 22:15	14 mph winds from NW
	3/12/05 13:20	14 mph winds from W
	3/13/05 13:25	light snow with 12 mph winds from ENE
	3/17/05 20:30 - 22:45	
Campbell		
	NONE	