Aurora

working to advance road weather information systems technology

Evaluation of the Hotplate Snow Gauge

http://aurora-program.org

Aurora Project 2004-01

Final Report
July 2005

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
Aurora Project 2004-01		

4. Title and Subtitle	5. Report Date
Evaluation of the Hotplate Snow Gauge	July 2005
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Jack Stickel, Bill Maloney, Curt Pape, Dennis Burkheimer	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Center for Transportation Research and Education Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664	11. Contract or Grant No.
12. Sponsoring Organization Name and Address	13. Type of Report and Period Covered
Aurora Program Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664	14. Sponsoring Agency Code

15. Supplementary Notes

Visit www.ctre.iastate.edu for color PDF files of this and other research reports.

16. Abstract

Winter precipitation (e.g., snow, ice, freezing rain) is poorly measured by current National Weather Service (NWS), Federal Aviation Administration (FAA), and State Departments of Transportation (SDOT) automated weather observation systems. The lack of accurate winter precipitation measurements, particularly snow, negatively impacts the ability of winter maintenance personnel to conduct snow and ice control operations. The inability to accurately measure winter precipitation is an ongoing problem that is well recognized by the meteorological community as well as organizations and industries dependent on accurate quantitative precipitation information.

The FAA recognized this limitation and its impact on the ability to conduct aircraft deicing operations, and began a research program in the 1990s to improve decision support for aircraft deicing. As part of this research effort, a new snow gauge was developed that was designed to be sensitive to typical snowfall rates, respond quickly, update each minute, and have very low maintenance characteristics. The new snow gauge was coined the "Hotplate" snow gauge because it measures the amount of heat necessary to melt and evaporate the snow that falls on its surface. The heat required to keep the sensor at a constant temperature is proportional to the liquid equivalent snowfall rate. This new sensor was successfully tested for several years as part of the FAA Aviation Weather Research Program and was recently commercialized.

The Aurora Program undertook this research project to test the overall accuracy of the Hotplate snow gauge and its utility for supporting snow and ice control operations. It is anticipated that knowledge of the real-time snowfall rate and liquid equivalent amount will aid tactical snow fighting operations. If real-time snowfall rate information is shown to be beneficial and the Hotplate technology practical, then the snow gauge could be added to automated Environmental Sensor Systems (ESS) or Road Weather Information System (RWIS) in the future.

17. Key Words	18. Distribution Statement
Hotplate snow gauge—winter road maintenance	No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	70	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

EVALUATION OF THE HOTPLATE SNOW GAUGE

Final Report
July 2005

Project Champion
Jack Stickel
Alaska Department of Transportation and Public Facilities

Co-Project Champions
Bill Maloney
The National Center for Atmospheric Research

Curt Pape
Minnesota Department of Transportation

Dennis Burkheimer
Iowa Department of Transportation

Authors
Jack Stickel, Bill Maloney, Curt Pape, Dennis Burkheimer

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its research management agreement with the
Center for Transportation Research and Education,
Aurora Project 2004-01.

A report from
Aurora Program
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-7684
Fax: 515-294-0467
www.aurora-program.org

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

The Aurora Program sponsored this research. The contents of this paper reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Aurora Board.

The project team is grateful for the support and leadership provided by the project champions, Jack Stickel (Alaska DOT), Curt Pape (Minnesota DOT), and Dennis Burkheimer (Iowa DOT).

EXECUTIVE SUMMARY

Winter precipitation (e.g., snow, ice, freezing rain) is poorly measured by current National Weather Service (NWS), Federal Aviation Administration (FAA), and State Departments of Transportation (SDOT) automated weather observation systems. The lack of accurate winter precipitation measurements, particularly snow, negatively impacts the ability of winter maintenance personnel to conduct snow and ice control operations. The inability to accurately measure winter precipitation is an ongoing problem that is well recognized by the meteorological community as well as organizations and industries dependent on accurate quantitative precipitation information.

The FAA recognized this limitation and its impact on the ability to conduct aircraft deicing operations, and began a research program in the 1990s to improve decision support for aircraft deicing. As part of this research effort, a new snow gauge was developed that was designed to be sensitive to typical snowfall rates, respond quickly, update each minute, and have very low maintenance characteristics. The new snow gauge was coined the “Hotplate” snowgauge because it measures the amount of heat necessary to melt and evaporate the snow that falls on its surface. The heat required to keep the sensor at a constant temperature is proportional to the liquid equivalent snowfall rate. This new sensor was successfully tested for several years as part of the FAA Aviation Weather Research Program and was recently commercialized.

The Aurora Program undertook this research project to test the overall accuracy of the Hotplate snow gauge and its utility for supporting snow and ice control operations. It is anticipated that knowledge of the real-time snowfall rate and liquid equivalent amount will aid tactical snow fighting operations. If real-time snowfall rate information is shown to be beneficial and the Hotplate technology practical, then the snow gauge could be added to automated Environmental Sensor Systems (ESS) or Road Weather Information System (RWIS) in the future.

This project confirms the FAA project findings that the Hotplate snow gauge performs well and meets or exceeds the NWS performance criteria for snow gauges. Hourly comparisons were made between a GEONOR precipitation gauge (considered ground truth for this study) and the Hotplate for 18 precipitation events with varying precipitation types. The R value is a measure of correlation where zero means no correlation and one is a perfect match. The R value for this study was 0.978, which indicates excellent agreement between the sensors.

The Hotplate is able to measure liquid equivalent precipitation rates between 0.01 inches/hour (0.25 mm per hour) and 0.5 inches/hour (12 mm/hour) within 10% of the World Meteorological Organization (WMO) standard. The upper measurement limit of 0.5 inches/hour (12 mm/hour) is well above the normal liquid equivalent precipitation rate for snow events. Total liquid precipitation accumulation is calculated by integrating its one-minute precipitation rates over time.

The Hotplate snow gauge is virtually maintenance free. It has no moving parts, no fluids to change, and the heat it produces keeps it free from ice and insects, spider webs, etc.

The Hotplate does have some limitations including a drop off in performance when wind speeds exceed 30 miles per hour (mph) (15 meters per second). During high wind conditions (> 30 mph), the Hotplate gauge may under-report precipitation rates.

The Hotplate may also slightly over or underestimate precipitation rates during periods of mixed precipitation. Because the sensor, by itself, estimates precipitation type using air temperature, precipitation rate errors as high as 10% can occur when the system determines the wrong precipitation type (e.g., rain when snow is falling). This problem could be mitigated by taking advantage of sensors that directly measure precipitation type; the sensors are often part of ESS installations.

Even with these limitations, the Hotplate snow gauge performed very well. Its small footprint, one-minute update rate, and very low maintenance requirement, makes it quite attractive for weather sensing locations such as roadside ESS sites.

1. PURPOSE

This document describes the results of a research project to assess the accuracy of an advanced snow measurement gauge, herein referred to as the “Hotplate” snow gauge, to quantitatively measure liquid equivalent precipitation. The feasibility of the gauge to support winter snow and ice control operations is also discussed.

2. RELATED DOCUMENTS AND INFORMATION

For additional information on weather and road condition measurement and prediction capabilities, the reader is directed to the related documents listed in Table 1.

Table 1. Related Documents

Document and/or Web Sites	Primary Source
The Hotplate Snow Gauge 13th Symposium on Meteorological Observations and Instrumentation, Savannah, GA, 20-24 June, 2005, American Meteorological Society. A similar version of the report is provided in Appendix A	American Meteorological Society (AMS)
Mount Washington Observatory Research http://www.mountwashington.org/research/snowgauge.html	Mount Washington Observatory Organization
FAA Aviation Weather Research Program, Winter Weather Product Development Team http://www.faa.gov/aua/awr/prodprog.htm	Federal Aviation Administration (FAA)
World Climate Research Program, Workshop on Determination of Solid Precipitation on Cold Climate Regions, Fairbanks, AK, 9-14 June 2002. http://acsys.npolar.no/reports/archive/solidprecip/Contents.htm	World Climate Research Program
TPS-3100 Commercial Specification http://www.yesinc.com/products/data/tps3100/	Yankee Environmental Systems, Inc.

3. PROBLEM STATEMENT

Winter precipitation (e.g., snow, ice, freezing rain) is poorly measured by current NWS, FAA), and SDOTs automated weather observation systems. The lack of accurate winter precipitation measurements, particularly snow, significantly impacts the winter road maintenance decision making process because decision makers are often unsure of the location, intensity, amount, and type of precipitation that is occurring in their region.

As part of the Federal Highway Administration (FHWA) Surface Transportation Weather Decision Support Requirements (STWDSR) process, winter road maintenance practitioners indicated that other than road temperature, current and predicted precipitation information were the most important weather elements for snow and ice control operations. SDOT personnel are committed to keeping roads safe and operating efficiently; therefore when there is any indication that winter weather conditions may exist, road treatment plans are prepared.

The inability to accurately quantify winter precipitation significantly impacts the winter road maintenance decision process and automated systems designed to provide treatment guidance such as the FHWA Maintenance Decision Support System (MDSS) (Mahoney and Myers, 2003). If winter precipitation is not identified when it is actually occurring, or is under reported roads may go untreated for significant periods, or they may be under treated .Both problems could lead to unsafe travel conditions and will certainly result in an inefficient winter maintenance operation.

Winter precipitation type and rate need to be measured more accurately, at more locations, and both the sensitivity and timeliness of the data need to be improved. NWS, FAA and SDOT weather observation systems should be upgraded to provide better measurements. The method(s) used to improve these measurements depend on the location and characteristics of the measurement site. The large, open, and secure areas (e.g., airports) typically chosen for NWS and FAA measurements lend themselves toward solutions that could include precipitation gauges that have larger footprints (e.g., weighing gauges with wind shields). SDOT weather observation sites, which are typically near the roadway and not surrounded by a security fence, will likely need a solution quite different from the FAA and NWS. The road environment, abrasives and the chlorides used for winter treatments must also be considered when exploring precipitation gauge technologies suitable for SDOT applications. Because precipitation rates can vary dramatically over short distances, a sufficient density of observations must be made to capture these important differences. SDOT RWIS networks are typically denser and cover a larger area than NWS and FAA networks. Equipping RWIS with improved precipitation measuring devices could dramatically improve the national observation network.

4. PROJECT BACKGROUND

The complexity and difficulty of conducting roadway and aircraft anti-icing and deicing operations has been recognized for decades. In 1990, the Society of Automotive Engineers (SAE) recognized that the weather information available to conduct safe aircraft deicing operations was not sufficient. Standard data sets included human observed and automated weather observation systems such as the Automated Surface Observing Systems (ASOS) and Automated Weather Observing Systems (AWOS), and basic radar data. In addition, NCAR studies conducted for the FAA concluded that NWS snowfall intensity reports (e.g., light, moderate, heavy) which are based on visibility measurements are misleading because there is not a strong correlation between visibility and liquid equivalent snowfall rates, which are important for determining when deicing/anti-icing chemicals will fail due to dilution (Rasmussen et al., 2002).

More recently, results of a study by NCAR conducted as part of the FHWA winter MDSS indicated that NWS ASOS and AWOS systems significantly under report winter precipitation amounts, which negatively impacts the ability of winter maintenance decision makers to gauge the intensity of winter events (NCAR, 2004).

As a result of these measuring deficiencies, the FAA Aviation Weather Research Program directed NCAR to develop advanced capabilities, including new snow gauges, which could be used to aid the aircraft deicing process. After several years of research, development, testing, and operational demonstrations, an aircraft deicing decision support system was completed. The resulting system, which is called the Weather Support for Deicing Decision Making System (WSDDM) (pronounced 'wisdom'), utilizes NWS Next Generation Radar (NEXRAD) data, standard surface weather observations from ASOS/AWOS, and real-time snow gauges (Rasmussen et al. 2001). The Hotplate snow gauge was developed as part of this research project.

5. RESEARCH GOALS AND OBJECTIVES

The primary goal of this project was to test the accuracy and utility of the Hotplate snow gauge for use in winter road maintenance. It is anticipated that knowledge of the real-time snowfall rate and liquid equivalent amount will aid tactical snow fighting operations. If real- time snowfall rate information is shown to be beneficial and the Hotplate technology practical, then the snow gauge could be added to automated Environmental Sensor Systems (ESS) or RWIS in the future.

6. REVIEW OF PRECIPITATION MEASUREMENT METHODS

The standard method for observing precipitation is to use a gauge consisting of a collection container and a device or scale to determine the amount of precipitation that falls through the orifice. This technique has been employed for several hundreds of years (Middleton, 1969) and continues to be used today, although there have been distinct improvements in the instrumentation used to make the measurements. Today, there are numerous devices on the market designed to not only provide information on the *amount* of precipitation that has occurred, but the *rate* and *time* at which it fell and even the *type* of precipitation that occurred. However, most of the gauges in operation today were developed for climatological purposes. There has been relatively little emphasis placed on the importance of viewing these data in real time. In addition, the vast majority of devices used today are not well designed for measuring winter precipitation, particularly snow.

The NWS makes observations of precipitation accumulation at its ASOS stations each minute, but only reports the accumulations typically once each hour as a part of the standard aviation report. Precipitation gauges have evolved considerably over the years and now offer the prospect of providing high-resolution measurements available in real time. While these gauges are commercially available, relatively few have been integrated into existing observing networks.

Winter precipitation is defined as frozen or freezing precipitation that occurs in the form of snow, sleet (ice pellets), snow pellets, graupel, freezing rain or freezing drizzle. Various precipitation gauges have been developed over the years to measure rainfall accumulation and intensity. However, these same gauges perform poorly in snowfall. There are several reasons for this. The first is that snow tends to stick to the sidewalls of the gauge orifice rather than falling into the gauge as rain does. This results in a significant under measure of precipitation during the period when it is snowing, and a false over measure of precipitation when this snow melts and falls into the gauge at some later time. In extreme cases snow can actually “cap over” the opening of a gauge.
This effect is illustrated in Figure 1.

Figure 1. Precipitation gauge capped over by snow; (photo taken at NCAR's Marshall test site near Boulder, Colorado)

The second reason that snow is more difficult to measure than rain is that snowflakes are generally less dense than raindrops and are affected more by the distortions in airflow around the gauge. When air encounters an object, such as a gauge, it tends to flow around the object. Snowflakes follow similar trajectories and flow around the gauge rather than going into the gauge. This effect results in an under measure of snowfall that increases as the wind speed increases. Adding wind shields around a gauge can reduce this problem. A considerable effort has gone into determining the most effective wind shield. Rasmussen et al., 2001 demonstrated that gauges that are improperly shielded may record less than 25% of the true precipitation when wind speeds are on the order of 15 knots.

The World Meteorological Organization (WMO) has been very active in promoting intercomparison studies among gauges and wind shields used in countries around the world. There are numerous publications that present the results of these studies. A good reference for these studies is the *WMO Solid Precipitation Measurement Intercomparison Final Report* (Goodison, Louie and Yang, 1998).

The NWS and FAA operate and maintain approximately 900 automated surface weather-observing stations (ASOS and AWOS) across the U.S. Most of these stations are located at airports. ASOS stations record precipitation accumulation using a tipping bucket gauge that is heated during the winter. The resolution of the measurement is 0.01 inches, but for reasons listed above, the measurements during winter are very poor. The NWS announced in 2000 that it will replace many of these gauges with improved systems (weighing gauges). The NWS also uses an optical device called the Light-Emitting Diode Weather Identifier (LEDWI) to determine precipitation type. LEDWI is currently able to distinguish between rain and snow at precipitation rates greater than 0.01 inches, although during windy conditions (> 25 knots) a vibration develops that causes rain to be reported as snow and snow to be reported as rain. ASOS stations also have icing sensors that are able to tell when freezing precipitation, freezing fog or frost is occurring. Currently the NWS reports freezing rain when the icing sensor indicates icing and LEDWI says rain is occurring. However, freezing drizzle is not reported. ASOS does report freezing fog, but the report is not based on the observation that ice is detected on the icing sensor, but rather freezing fog is reported when the temperature is at or below freezing and the visibility is less than 5/8 mile. ASOS collects data each minute, but reports only hourly or when a change in conditions dictates that a "special" observation be reported.
During the past 10-15 years, SDOTs have purchased and installed roadside weather and road condition measurement systems (e.g., ESS or RWIS). Most of these installations include

measurements of road temperature, road wetness (yes/no), and chemical concentration. They also measure air temperature, dew point temperature and/or relative humidity, wind direction and speed. Some have visibility sensors, present weather sensors, and precipitation type sensors. There is considerable variation in the sensors used by various companies. At present little is known about the quality of these measurements.

RWIS systems do not measure liquid equivalent precipitation rate, which is important for winter maintenance operations. The Hotplate snow gauge described in this report is a candidate sensor for sensing liquid equivalent precipitation rate.

7. DESCRIPTION OF THE HOTPLATE SNOW GAUGE

The Hotplate snow gauge was jointly developed by Roy Rasmussen of NCAR and John Hallet of the Desert Research Institute (DRI) beginning in 1995. This work was funded by the FAA's Aviation Weather Research Program. The overall objective of the research project was to develop a decision support system for improving aircraft deicing operations. The resulting system is called the Weather Support for Deicing Decision Making (WSDDM) System (Rasmussen et al. 2001). The system required real-time liquid equivalent precipitation information. It was discovered that no suitable real-time snow gauges were available to meet this requirement, so a new snow gauge was developed.

There was a desired design requirement to develop a snow gauge requiring no moving parts, no fluids, and no wind shielding. The Hotplate snow gauge was designed to measure 1-minute liquid equivalent snowfall rates and accumulations. Between 1995 and 2005, improvements were made to the Hotplate based on testing that was conducted at NCAR's Marshall test site near Boulder, Colorado. In late 2003, a license was granted to Yankee Environmental Systems, Inc. (YES) to begin manufacturing the Hotplate under the name TPS-3100. The TPS-3100 is now commercially available for purchase (www.yesinc.com). A sample YES advertisement for the TPS-3100 is provided in Appendix B.

The Hotplate snow gauge (shown in Figure 2) consists of two identical heated plates, one facing upwards and exposed to precipitation and the other facing downwards just below the top plate. The lower plate is insulated from the top plate and is designed to serve as a reference plate that is only affected by wind and not by precipitation. The two plates are heated to nearly identical constant temperatures (~ 70 °C), which is hot enough to melt and evaporate small snow particles striking the plate in less than a second and large snowflakes in a few seconds. The plates are maintained at constant temperature during wind and precipitation conditions by increasing or decreasing the electrical current to the plate heaters. During conditions without precipitation, the plates cool nearly identically due to their identical size and shape. During precipitation conditions, the top plate cools due to the melting and evaporation of precipitation while the bottom plate is only affected by the wind.

The calculation used to derive the liquid equivalent precipitation must also take into account the precipitation type so that the latent heat of melting can be taken into account. Because the standalone device measures air temperature, the air temperature is used to estimate precipitation type. For air temperatures above 4^oC (39^oF), the precipitation type is assumed to be rain. For air temperatures of 0^oC (32^oF) or lower, the precipitation type is assumed to be snow. For air temperatures between 0^oC (32^oF) and 4^oC (39^oF), the latent heat factor is adjusted linearly. Because of these simplifying assumptions and the fact that the air temperature during rain/snow transitions can vary between 0^oC (32^oF) and 4^oC (39^oF), the reported liquid equivalent precipitation rate may be slightly higher or lower during these transitions. An example of this behavior is illustrated later in this report. Hotplate gauges that are integrated with weather sensors that measure precipitation type have the advantage of knowing the precipitation type eliminating this limitation.

The difference between the power required to cool the top plate compared to the bottom plate is proportional to the precipitation rate. Three concentric rings are placed orthogonal to each plate in order to prevent snow particles from sliding off the top hotplate during high wind conditions. Due to its streamline shape, the hotplate has minimal effect on the airflow around it, and thus does not require a wind shield. In addition, since the falling snow melts and evaporates, it does not require any glycol or oil, making it very low maintenance. The hotplate snowgauge has undergone five years of testing at NCAR, two years of testing at Mt. Washington, New Hampshire, and two winters of testing at Denver International Airport. Ames, Iowa, and Worthington, Minnesota became test sites as part of this research.

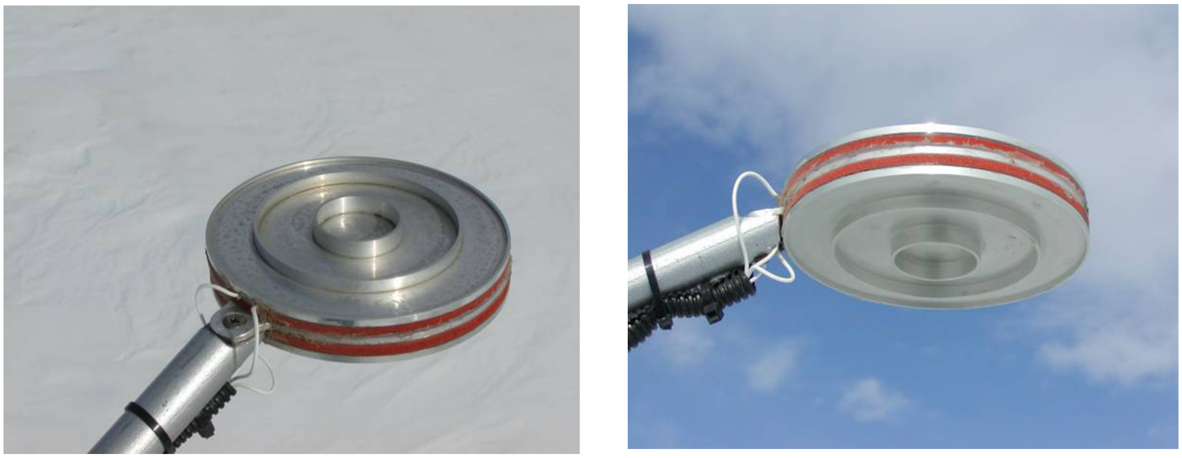


Figure 2. Top (left) and bottom (right) views of the Hotplate snow gauge; (the diameter of the plate is 13 cm [5 inches])

8. TEST SITE CONFIGURATION

A suite of environmental sensors were installed in December 2003 at the Iowa DOT maintenance garage at Ames, Iowa, and at an RWIS site near Worthington, Minnesota. During the winter of 2003-2004, the sensor suite was used primarily to support the FHWA MDSS project. Sensors included temperature, humidity, propeller-driven anemometer, pyranometer, sonic snow depth sensor, and a GEONOR precipitation gauge. A photo of the sensor suite at the Ames DOT garage site is shown in Figure 3. The Worthington site was similarly equipped.

Figure 3. Photo of environmental sensor suite installed at the Ames, Iowa, DOT garage to support the testing and verification of the hotplate snow gauge; (individual sensors are labeled as shown)

Iowa Department of Transportation - Ames Maintenance Garage Weather Site

Anemometer/
Wind Vane

Pyranometer

Alter Shield

GEONOR Snow Gauge

Electronics Box

Temp/RH (hidden from view)

Snow Depth Sensor (Ultrasonic)

During the fall of 2004, a 2/3 size Double Fence Intercomparison Reference (DFIR) wind shield was installed around the Ames weather sensor site to improve the collection efficiently of the GEONOR snow gauge, which was used as ground truth for the Hotplate gauge. A photo of the Ames, Iowa site with the 2/3 DFIR wind shield is shown in Figure 4. A full-size DFIR shield is considered the best wind shield for measuring winter precipitation according the WMO, but the site was too small to support a full size configuration. A higher confidence was placed in the accuracy of the GEONOR measurements for measuring snow, with its correction for wind speed, than the routine hourly precipitation measurements made at the Ames, Iowa airport METAR site.

In January 2005, a Hotplate snow gauge, provided by NCAR, was installed at each site and integrated into the data processing system and network. The data were transmitted to NCAR using the Internet and made viewable in real time on an NCAR website.

Figure 4. Weather sensor suite with the 2/3 Double Fenced Intercomparison Reference (DFIR) Shield at the Iowa DOT garage at Ames, Iowa; (the Hotplate snow gauge was located outside the DFIR wind shield as indicated)

An NCAR manufactured Hotplate gauge was used because the commercial version was still undergoing production testing. A photo of the Worthington, Minnesota site is shown in Figure 5. The Worthington site was configured with a double Alter wind shield because the site was unable to support a DFIR wind shield. The Alter wind shield improved the collection efficiency of the GEONOR precipitation gauge, but was not as effective as the 2/3 size DFIR used at Ames, Iowa. The Hotplate gauge is highlighted in Figure 5.

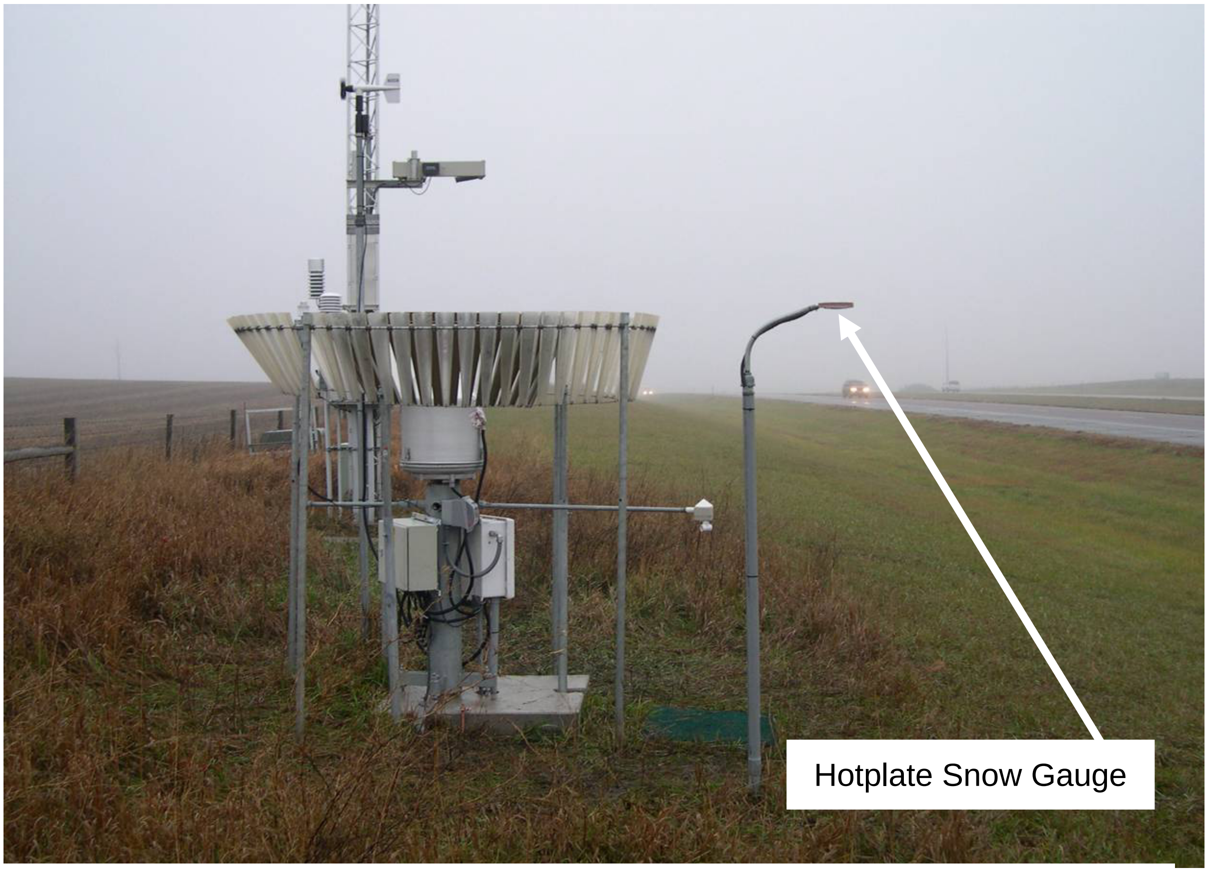


Figure 5. Worthington, Minnesota weather sensor suite along Interstate 90

The locations chosen for the installation of the Hotplate gauges at both Ames and Worthington sites were not ideal, but this was not known until a few cases were analyzed. Ideally, the hot plate gauges would be installed up and away from any obstructions including those associated with the rest of the sensors. The Hotplate gauges were too low to the ground and too close to the other sensors. When the wind blew from particular wind directions the sensor suite disrupted the flow impacting the collection efficiency of the Hotplate. This issue, which is discussed in more detail later in this report, was resolved by applying software corrections for certain wind directions. A better location for the Hotplate gauges would have been 3-4 feet above and approximately 25 feet away from the rest of the sensor suite.

9. LIQUID EQUIVALENT PRECIPITATION MEASUREMENTS

The sensitivity of the Hotplate gauge has been optimized for normal liquid equivalent snowfall rates, so typical snowfall rates fall into the measurement range of the Hotplate. Based on extensive testing for several years at numerous sites (NCAR, Mount Washington, New Hampshire, and Denver International Airport), it has been determined that the Hotplate snow gauge has a minimum detectable liquid equivalent precipitation rate of 0.25 mm/hr (0.01 inches/hr), which corresponds to light snow.

The maximum precipitation rate that the Hotplate can measure is dependent on wind speed and the temperature of the sensor head. This is typically around 12.5 mm/hr (0.50 inches/hr), which corresponds to an extremely high and rare liquid equivalent snowfall rate. A liquid equivalent precipitation rate of 12.5 mm/hr (0.50 inches/hr) is typically associated with moderate rain.

The Hotplate, by itself, does not sense precipitation type. The Hotplate assumes precipitation type (rain/snow) based on ambient air temperature and corrects the rate based on the collection efficiency of the gauge for wind speed and assumed precipitation type. This may cause a slight over reporting for freezing precipitation types like freezing rain or freezing drizzle because the gauge assumes that the precipitation type is frozen when air temperatures are below freezing and the latent heat of melting is factored into the precipitation rate calculation.

Precipitation rates may also be under reported when the precipitation type is hail, graupel (spongy hail), or ice pellets because some of the precipitation may bounce off of the Hotplate.

Wind has an effect on the collection efficiency of snow on the Hotplate. If no correction is taken into account, the Hotplate measures liquid equivalent snowfall similar to a GEONOR (weighing snow gauge) in a single Alter shield. The Hotplate measures the ambient wind speed and temperature to determine a collection efficiency multiplier to correct the rate. Once the rate is corrected based on the collection efficiency multiplier, the Hotplate rate and accumulation measurement is comparable to a GEONOR in a DFIR wind shield. This measurement is considered to be the truth measurement by the WMO.

9.1 Example of Colorado Testbed Comparisons

A comprehensive study was performed on the Hotplate during the winter of 2001 (Rasmussen et al. 2005) to determine how well it compares to the truth gauge. Of the 137 hours of precipitation that occurred during the test period, the Hotplate passed all the NWS ASOS Program Office criteria for a snow gauge. The criteria required hourly accumulations of the Hotplate to be within 0.02 inches per hour or 4% of the hourly total of the truth gauge (whichever is greater). The Hotplate also needed to report no measurable precipitation during non-precipitation events.

During the winter of 2004-05, two Yankee Environmental Systems TPS-3100 Hotplates were deployed at the NCAR Marshall test site (see: http://www.rap.ucar.edu/projects/marshall/). These Hotplates were deployed along with a GEONOR in a DFIR shield. Figure 6 shows a heavy snow event between April 27th and 29th for which the Hotplates showed excellent agreement with the GEONOR in the DFIR shield. The total liquid equivalent accumulation was 24 mm (~1.0 inch). The two Hotplate gauges reported 23 mm and 22 mm, which was within 10% of the total reported by the GEONOR.

During this event, the R.M. Young (propeller) anemometer at the site froze and stopped reporting the wind speed. Using the Hotplate derived wind speed, the wind data for this event was recovered as illustrated in Figure 7.

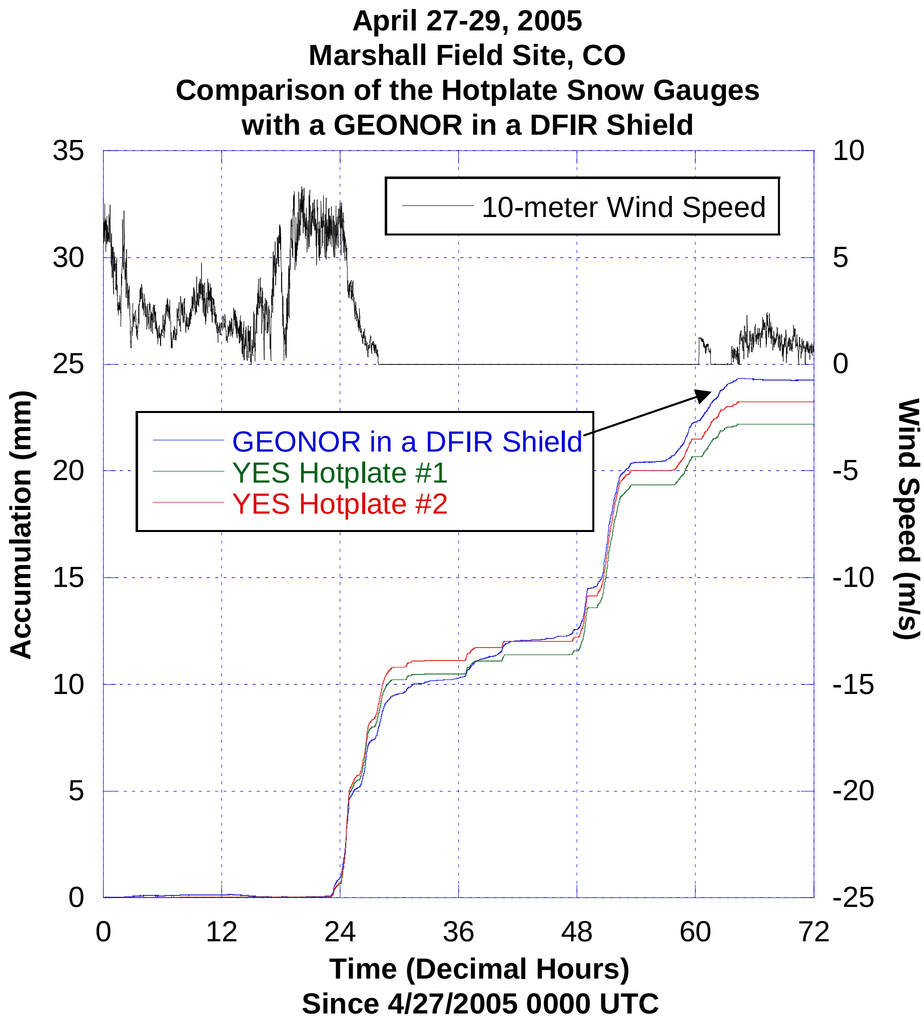


Figure 6. Comparison of the Hotplate Snow Gauges accumulation with a GEONOR in a DFIR Shield during a snow event at the NCAR test site near Boulder, Colorado; (the GEONOR data are shown in blue, Hotplate #1 in green and Hotplate #2 in red)

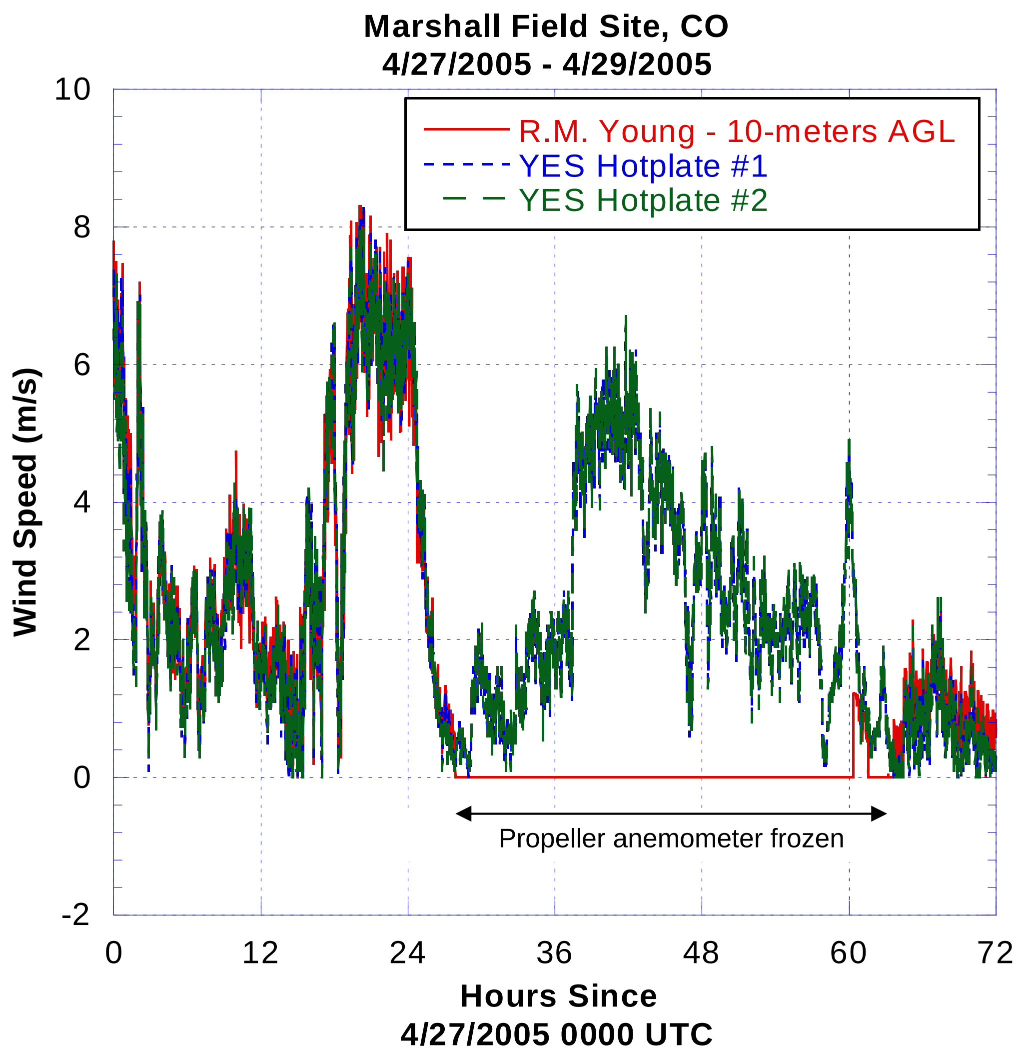


Figure 7. Wind Speed measurements made by the two Hotplate snow gauges during a period in which the propeller anemometer froze up

Performance results of other test cases at the NCAR Marshall test site and additional technical information on the Hotplate is provided in Appendix A.

9.2 Aurora Test Results

Two Hotplates were deployed during the winter of 2004-05 as part of this Aurora sponsored project. One gauge was deployed in Ames, Iowa at the Iowa DOT maintenance garage along with a GEONOR in a 2/3 DFIR wind shield (see Figure 4). The second Hotplate was deployed along with a GEONOR in a double Alter shield in Worthington, Minnesota (see Figure 5).

There were 18 precipitation events at the Ames, Iowa site and 15 events at the Worthington, Minnesota site. A listing of the precipitation cases at the two sites is provided in Tables 2 and 3.

Table 2. Listing of the Ames, Iowa precipitation events

Start Date/Time (UTC)	End Date/Time (UTC)	Reported Weather – Airport METARs Ames Airport	Total Liquid Equivalent Precipitation GEONOR (inches)
6 February 08:00	7 February 14:00	Rain 09:00-12:30; Rain 14:00-20:00; Snow/Mist 21:00-00:00; Snow/Mist 05:00-14:00	0.55
9 February 01:00	9 February 08:00	Snow/Mist 01:30-09:15; Mist 09:15-15:00	0.15
13 February 05:00	14 February 05:00	Rain/Mist 05:00-03:00	0.65
19 February 21:00	20 February 00:00	Snow/Mist 21:00-23:00	0.04
10 March 09:00	10 March 23:00	Snow/Mist 09:00-10:00; Freezing Rain 10:30-11:15; Rain 18:00	0.04
12 March 14:00	12 March 20:00	Snow 14:00-16:15; Snow 19:00-19:30	0.04
18 March 18:00	18 March 21:00	Rain 18:00-21:00	0.2
24 March 12:00	25 March 00:00	Unknown/Mist 11:00-13:00; Rain/Mist 13:00; Mist 14:00-19:00; Rain/Mist/Unknown 20:00-00:00	0.7
30 March 17:00	31 March 00:00	Thundershower/Rain 18:00-20:00	0.3
11 April 10:00	12 April 07:00	Rain/Mist 10:00-14:30; Rain/Mist 20:30-07:00	2.75
16 April 09:00	16 April 19:00	Rain 09:00-18:00	0.1
17 April 02:00	17 April 03:00	Mist 03:00	0.04
19 April 10:00	19 April 12:00	Thundershower/Rain 11:15	0.02
20 April 04:00	20 April 10:00	Thunderstorm in Vicinity/Rain/Mist 04:00-10:00	0.4
22 April 01:00 10:00	22 April 07:00 15:00	Thunderstorm in Vicinity/Rain 01:00-6:00 Rain 11:15-14:15	0.3 0.15
25 April 19:00	25 April 20:00	Rain 19:00	0.01
26 April 16:00	27 April 00:00	Rain 20:00; Rain 22:00-00:00	0.02

Table 3. Listing of the Worthington, Minnesota precipitation events

Start Date/Time (UTC)	End Date/Time (UTC)	Reported Weather – Airport METARs Jackson, Minnesota (MJQ) Luverne, Minnesota (LYV)	Total Liquid Equivalent Precipitation GEONOR (inches)
8 February 14:00	8 February 20:00	MJQ Snow 17:00-20:00 LYV Snow 14:00-00:00	0.06
9 February 00:00	9 February 13:00	MJQ Snow 00:00-13:00 LYV Snow 00:00-10:00	0.02
13 February 07:00	13 February 00:00	MJQ Rain/Drizzle 09:00-00:00 LYV Rain/Drizzle 07:00-23:30	0.6
19 February 17:00	19 February 23:00	MJQ Snow 21:00-23:00 LYV Snow 17:00-21:00	0.04
20 February 02:00	20 February 18:00	MJQ Mist/Snow/Unknown 00:00-18:00 LYV Mist/Unknown/Rain/Drizzle 00:00-17:30	0.06
24 February 01:00	24 February 10:00	MJQ Snow 02:20-09:00 LYV Snow 00:00-10:00	0.2
10 March 02:00	10 March 10:00	MJQ Snow 06:30-10:00 LYV Snow 06:30-09:30	0.02
12 March 05:00	12 March 17:00	MJQ Snow 13:00-14:30; Snow 17:00-23:30 LYV Snow 10:00-15:00; Snow 16:30-18:30	0.05
18 March 00:00	18 March 19:00	MJQ Snow/Mist 01:00-00:00 LYV Snow/Mist/Unknown 00:00-00:00 (24 hrs)	0.3
30 March 10:00	30 March 17:00	MJQ Rain/Drizzle 11:00-16:30 LYV Rain/Snow/Drizzle 10:00=17:00	0.1
6 April 10:00	6 April 14:00	MJQ Rain/Thundershower/Drizzle 10:00-15:00 LYV Thundershower 09:00-12:00	0.25
12 April 02:00	12 April 23:00	MJQ Rain/Mist/Drizzle 00:00-00:00 (24 hrs) LYV Rain/Drizzle 00:00-03:15; Rain 08:00-08:30; Rain/Drizzle 13:30-1630; Rain/Drizzle 19:30-21:15	0.4
16 April 02:00	16 April 13:00	MJQ Rain/Drizzle/Mist/Thundershower 01:00-16:30 LYV Drizzle 00:00-07:00; Rain 11:30-12:30	0.55
19 April	19 April	MJQ Rain/Drizzle 08:15-11:30	

09:00	13:00	LYV Drizzle 09:00-10:00	0.05
20 April 19:00	20 April 22:00	MJQ No reported precipitation LYV Rain/Drizzle 17:00-21:30	0.02
22 April 01:00	22 April 05:00	MJQ Rain/Drizzle 03:00-04:30 LYV Rain 01:15-05:30	0.45

This was not an overly active winter season for southwestern Minnesota as they had very few significant snow events.

A precise comparison of the Hotplate to a “ground truth” gauge could not be performed at these sites because no GEONOR in a full-scale DFIR shield was deployed, but the 2/3 DFIR shield at the Ames site was sufficient for performing comparisons.

Hotplate performance problems arose shortly after the deployment at each site due to the siting of the Hotplate as discussed in Section 0. Terrain features at the Worthington site and obstacles at the Ames site initially resulted in several false precipitation reports and a slight reduction in the precipitation capture efficiency.

To correct for these siting deficiencies, a correction algorithm was created specific to each site. The signal coming from the Hotplate was transformed into a precipitation rate based on the wind speed as well as the wind direction. This stabilized the baseline measurements for the Hotplates during the test deployment period. Correction algorithms such as those implemented for this test are not required for operational systems that are sited properly (away from obstructions and well above sloping terrain features).

Figures 8 and 9 show the accumulation from the Hotplate compared against the corresponding GEONOR at each site after these correction algorithms were implemented.

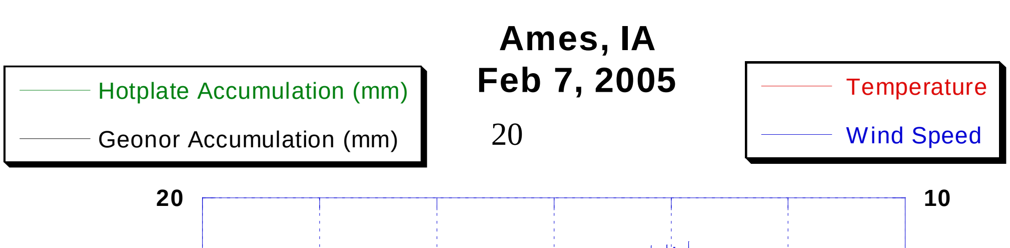


Figure 8. Accumulation comparison between a Hotplate snow gauge and a GEONOR during a light snow event in Ames, Iowa on February 7, 2005

Figure 8 shows a light snow event in Ames, Iowa on Feb. 7, 2005. The total liquid equivalent precipitation amount was approximately 6 mm (0.25 inches). The Hotplate was in good agreement with the GEONOR in the 2/3 DFIR shield which is comparable to the full-scale DFIR shield for the relatively low wind conditions of approximately 5 m/s (10 mph). The difference between the GEONOR and the Hotplate was less than 1 mm (0.04 inches). The Hotplate also recorded some very light intermittent precipitation about 2 hours before the GEONOR first recorded the event.

A comparison of liquid equivalent precipitation amounts between the Hotplate and the GEONOR gauge for a very light snow event on February 9, 2005 at Ames, Iowa is shown in Figure 9. In this case, the wind speeds were light at less than 4 m/s (8 mph) and the air temperatures were between -4^{o}C (26^{o}F) and -8^{o}C (18^{o}F). The Hotplate reported a higher accumulation than the GEONOR by 1 mm (0.04 inches), a difference of about 12%. The total liquid equivalent precipitation amount for this event was only 3.8 mm (0.15 inches) over a 5 hour period. In this case it is not clear if the GEONOR slightly under reported precipitation or if the Hotplate over reported the precipitation. The difference between the two sensors over this long time period is still within NWS guidelines.

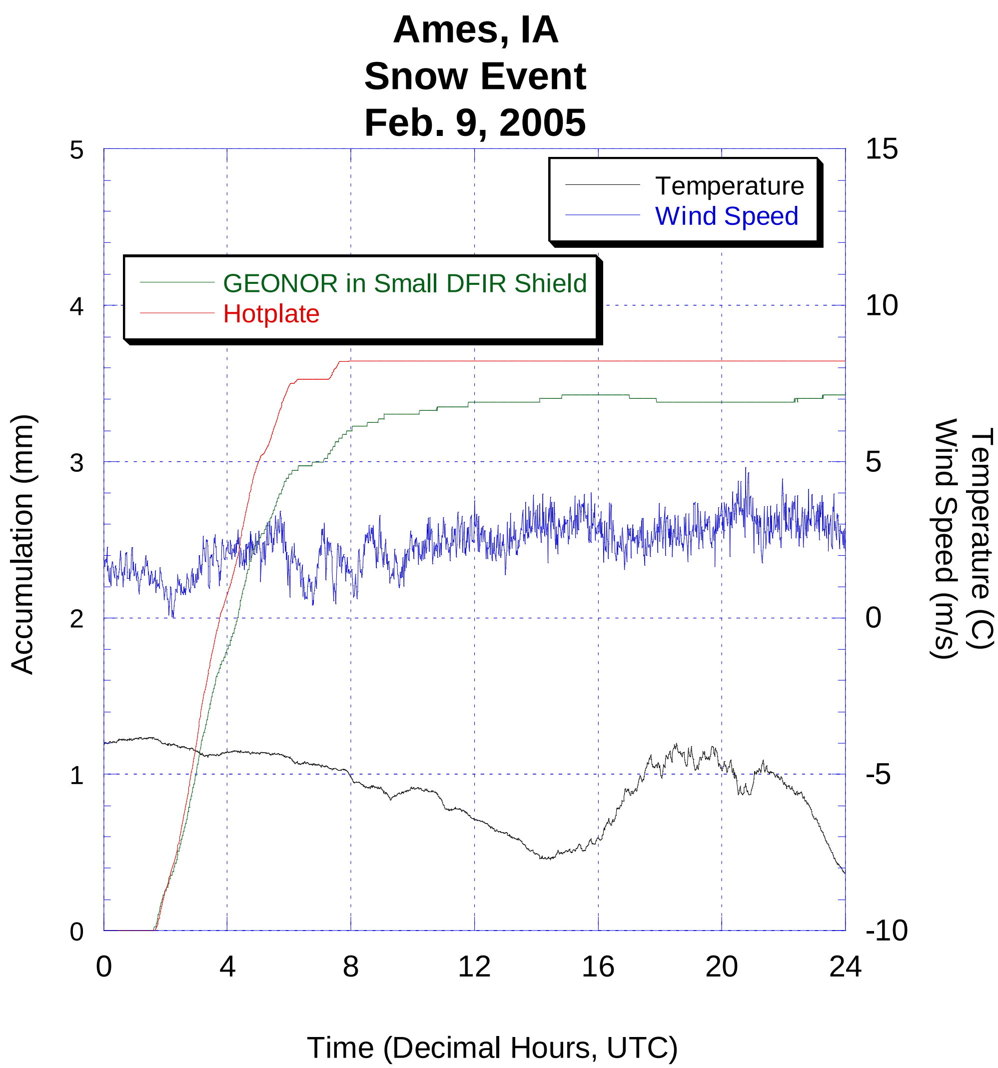


Figure 9. Accumulation comparison between a Hotplate snow gauge and a GEONOR during a very light snow event in Ames, Iowa on February 9, 2005

A comparison of liquid equivalent precipitation amounts between the Hotplate and the GEONOR gauge for an event that had a mix of snow and rain, then all rain on February 13, 2005 at Ames, Iowa is shown in Figure 10. In this case, the wind speeds were generally light at less than 5 m/s (10 mph) and the air temperatures were between +3^{o}C (37^{o}F) and +6^{o}C (43^{o}F). The Hotplate reported a higher accumulation than the GEONOR by about 10%.

The two precipitation rate curves shown in Figure 10 have similar slopes throughout the event suggesting the difference was likely due to the assumption by the Hotplate that the precipitation was primarily rain when the air temperature was near +3°C (38°F). It is likely that snow was mixed with rain from time to time during this event resulting in the measurement differences. The total liquid equivalent precipitation amount for this event at Ames was 19 mm (0.7 inches) over 18 hours, but most of the precipitation fell in the first 10 hours.

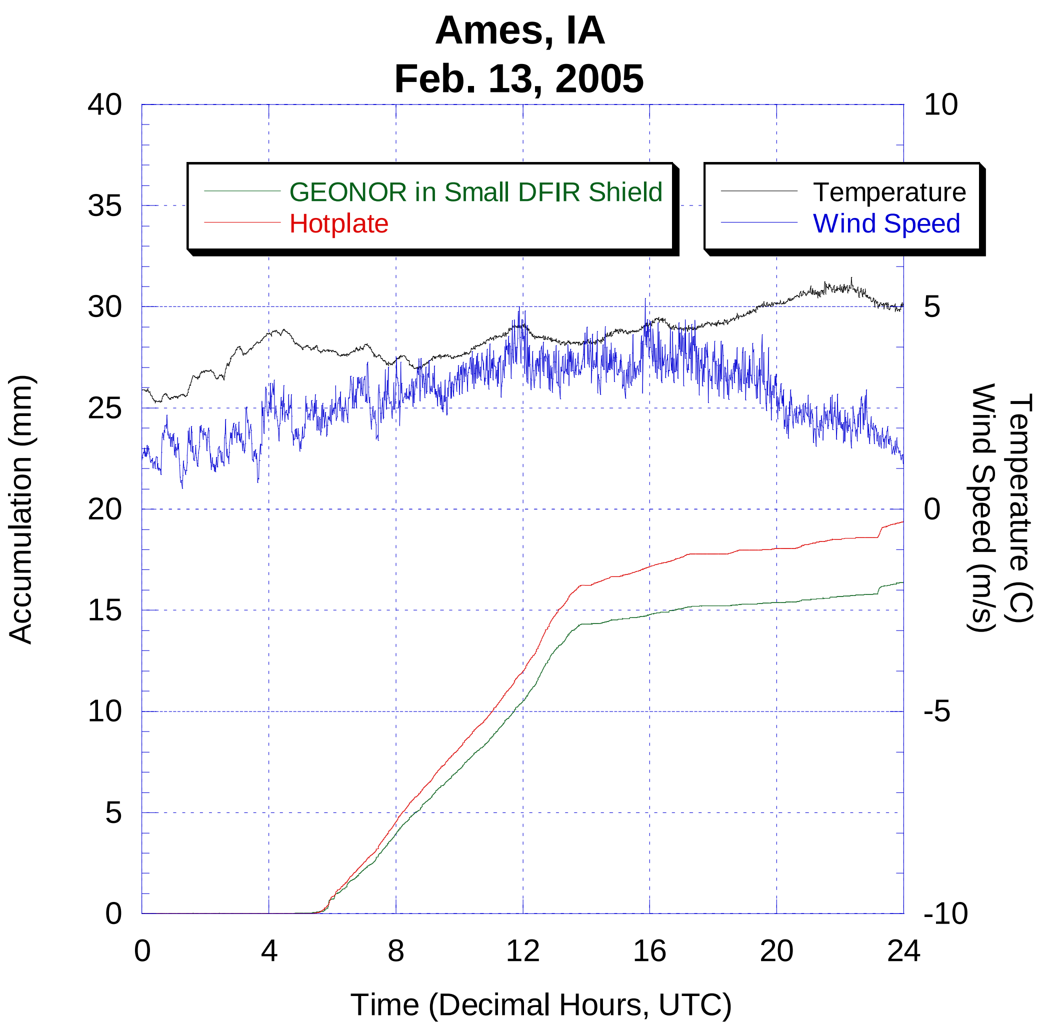


Figure 10. Accumulation comparison between a Hotplate snow gauge and a GEONOR during a mixed precipitation type (mix of rain/snow changing to rain) event in Ames, Iowa on February 13, 2005

Figure 11 shows the 13 February 2005 event at the Worthington, Minnesota site. In this case the wind reached 7 m/s (15 mph) and the air temperature dropped from +3°C (38°F) at the beginning of the precipitation event to +°1C (34°F) toward the end. The total precipitation measured by the GEONOR was 15 mm (0.6 inches) while the Hotplate recorded 18 mm (0.7 inches). As in the previous example from Ames, the difference is likely due to the assumption by the Hotplate that the precipitation was primarily rain when the air temperature was near +3°C (38°F) and primarily snow when the air temperature dropped to near +°1C (34°F). It is likely that snow was mixed with rain from time to time during this event resulting in the measurement differences. The difference between the two sensors for this mixed precipitation case was approximately 20%.

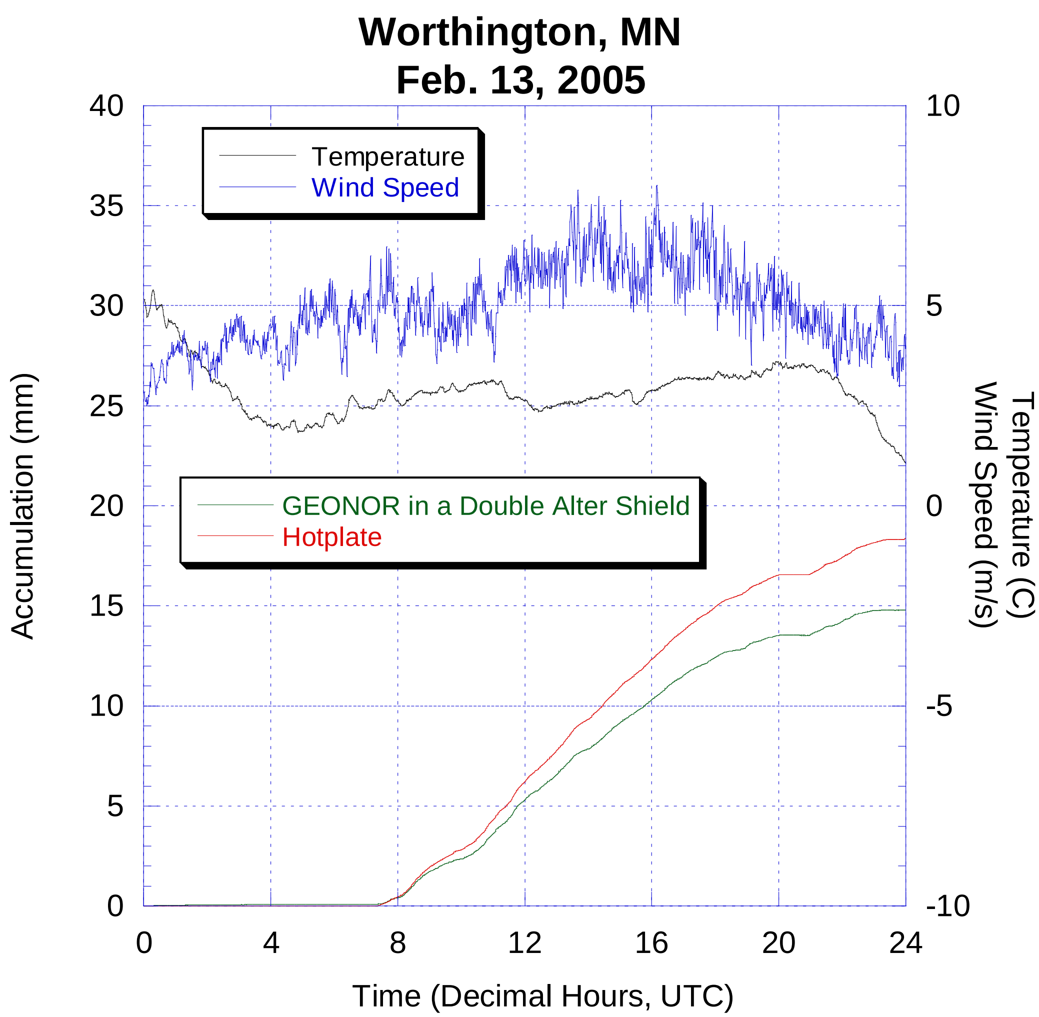


Figure 11. Accumulation comparison between a Hotplate snow gauge and a GEONOR during a mixed precipitation event in Worthington, Minnesota on February 13, 2005

Figure 12 shows a comparison of liquid equivalent accumulation between the Hotplate and a GEONOR in the double Alter shield during a rain event in Worthington, Minnesota on April 12, 2005. This plot shows that the Hotplate can easily measure light rain as well as snow events. The GEONOR measured about 0.5 mm (0.02 inches) more total liquid than the Hotplate. The two sensors were within 5% of each other, which is excellent agreement.

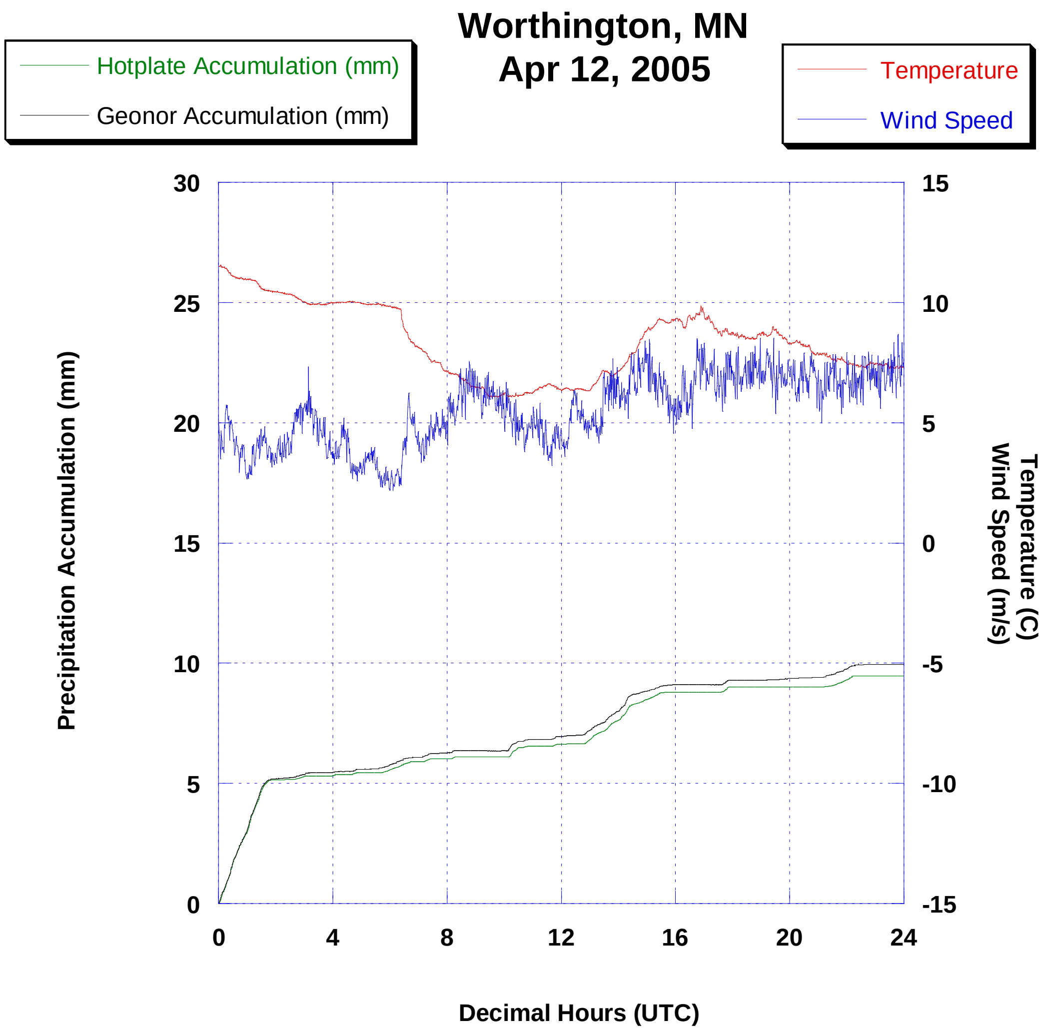


Figure 12. Accumulation comparison between a Hotplate snow gauge and a GEONOR during a rain event in Worthington, Minnesota

9.3 Summary Results

In this section, a summary comparison of all the cases from the Ames, Iowa site is presented. The data from the Ames site were chosen for this comparison because they were configured with the GEONOR in the 2/3 DFIR wind shield, which provides a better representation of "truth" than the sensor site in Worthington, Minnesota, which had the GEONOR in the double Alter wind shield. The precipitation cases used to generate the results shown in this summary analysis are listed in Table 2.

Figure 13 shows a daily (24 hour period) comparison between the GEONOR and the Hotplate liquid equivalent precipitation for the Ames, Iowa site and Figure 14 shows an hourly comparison of the same.

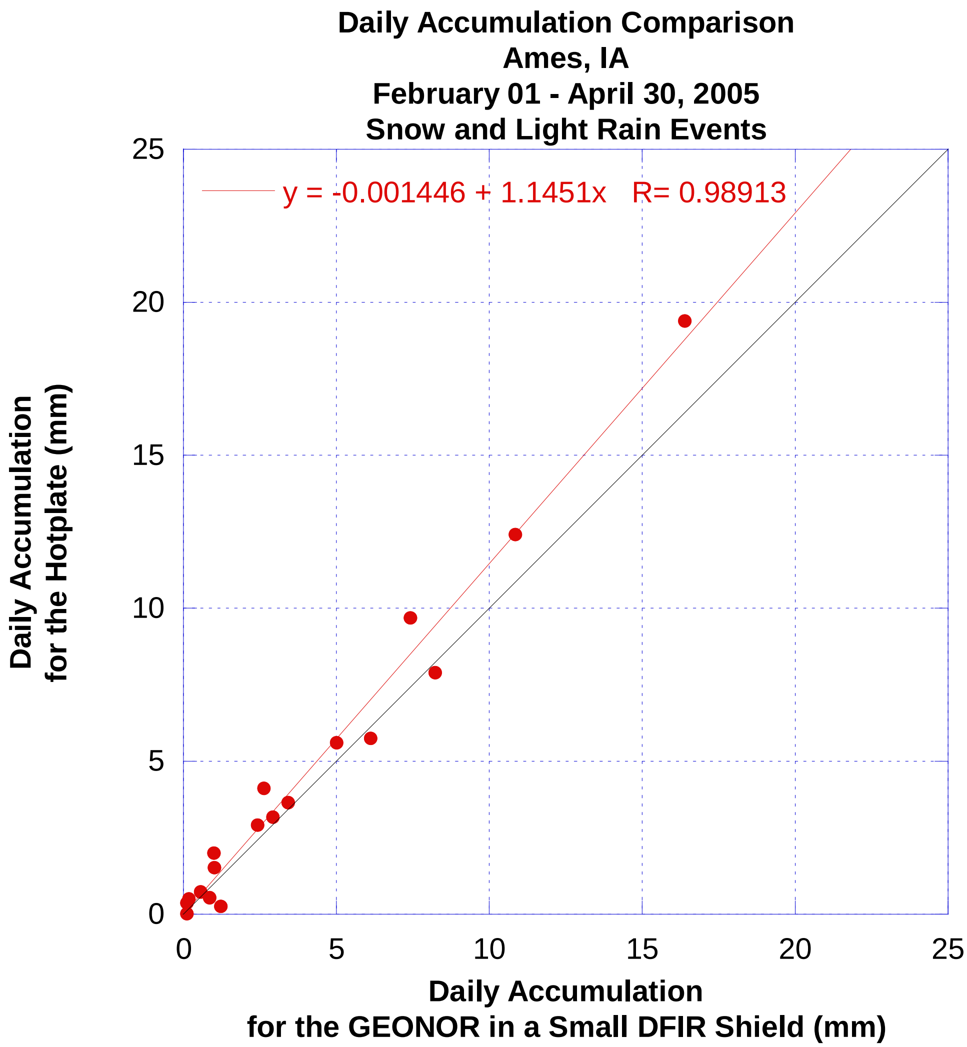


Figure 13. Daily (24 hour period) comparison between the GEONOR and the Hotplate liquid equivalent precipitation for the Ames, Iowa site

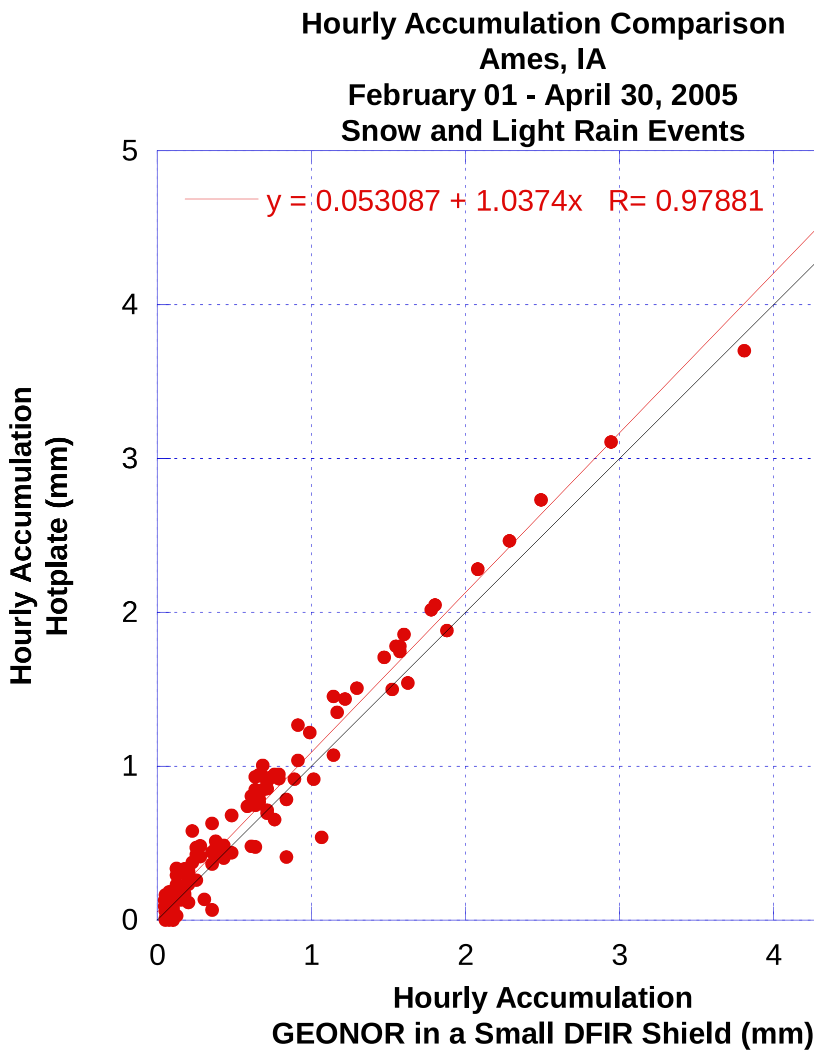


Figure 14. Hourly comparison between the GEONOR and the Hotplate liquid equivalent precipitation for the Ames, Iowa site

These summary results show excellent agreement between the GEONOR and the Hotplate. The one-to-one (perfect) fit line is shown and the data fall very close to this line. The R value is a measure of correlation where zero means no correlation and one is a perfect match. In the hourly accumulation plot shown in Figure 14 an R value 0.978, which indicates a very high correlation or excellent agreement between the GEONOR and the Hotplate.

10. OPERATIONAL CONCEPT FOR LIQUID EQUIVALENT DATA

The dilution rate of anti- and deicing chemicals is proportional to the amount of water in the precipitation. Knowledge of the liquid equivalent precipitation rate is necessary to properly calculate the effective period of anti- and deicing chemicals. Visibility has often been used to estimate snowfall intensity, but studies by Rasmussen et al. (1999 and 2000), indicated that visibility is a poor measure of snowfall intensity when one is concerned with liquid equivalent amounts.

Personnel responsible for snow and ice control could optimize operations if the amount of water in the snow were known in real time. Knowledge of liquid equivalent rates can be used to estimate chemical failure times. If snow and ice control practitioners know whether the falling snow is dry, wet or in between, then the amount of chemicals and the timing of subsequent treatments could be calculated to optimize operations by reducing the amount of chemicals used and the number of plow runs.

The Weather Support for [Aircraft] Deicing Decision Making System (WSDDM) utilizes real- time liquid equivalent information and informs aircraft deicing personnel and pilots about the amount of time that is available before anti- and deicing chemicals will fail. The information is based on precipitation rate measurements from snow gauges including Hotplate gauges.
If the same type of information were provided to snow and ice control personnel, they could better estimate the time of failure of the last treatment and plan for additional treatments. Users could be provided with general information about the amount of water in the snow in real time. This could be as simple as indicators of “wet”, “dry”, or “average” or “heavy”, “light” or “average” water content, or provided as an index from 1 to 5.

In addition, users could also be provided with dilution time information indicating an estimate of the amount of time remaining before another anti-icing treatment is required based on the amount and type of chemical put down during the last treatment. Figure 15 provides a conceptual illustration of what the described product might look like if it were configured for Iowa DOT. These concepts have not been tested or demonstrated for roadway snow and ice control, but have been proven successful for airport snow and ice control.

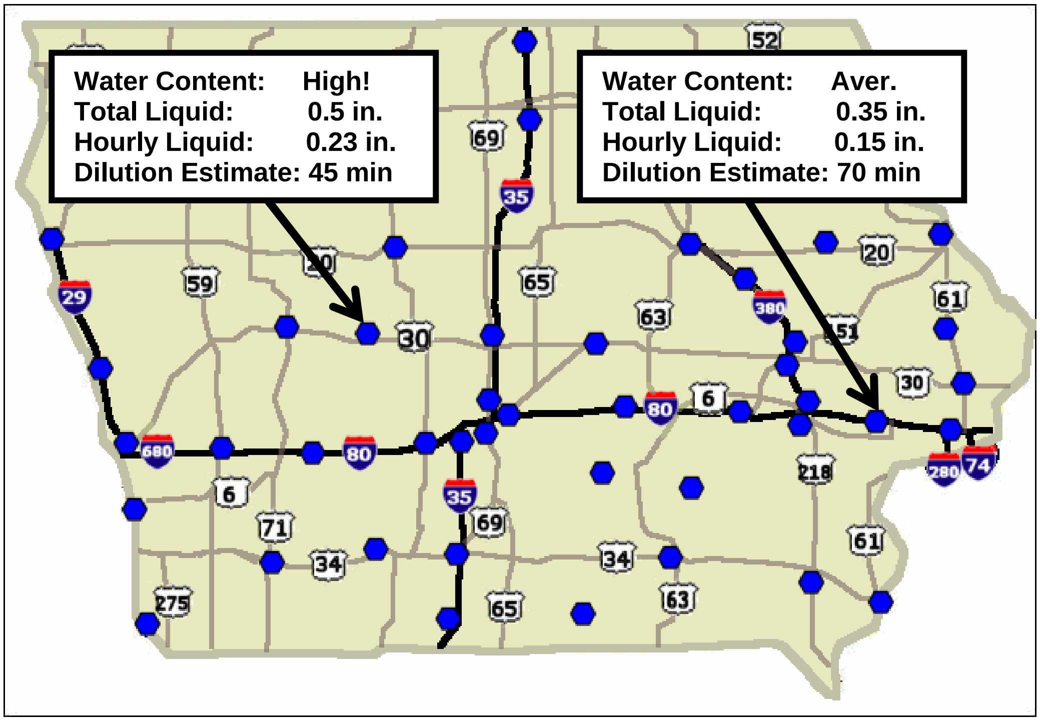


Figure 15. Conceptual illustration of a tactical snow and ice decision product designed to provide snow and ice control personnel information about liquid equivalent snowfall rate and estimates of when anti-icing chemicals will fail due to dilution; the information would be calculated using real-time snow gauges or snow gauges combined with weather radar data. Iowa RWIS sites are shown as the blue dots

11. GENERAL CONSIDERATIONS

11.1 Siting Recommendations

For proper deployment of the Hotplate. a relatively flat, open area without large obstructions near the instrument is required A 25 ft. radius flat area with no obstructions is desirable. It is also important that the Hotplate itself be level. The standard system provided by Yankee Environmental Systems is fully self-contained, complete with the sensor head, pedestal, and electronics box. A photo of the Yankee TPS-3100 is shown in Figure 16.

Another alternative, and one that may be more appropriate to roadside installations, would to be to mount the gauge on the ESS wind sensor tower. The sensor height should be chosen to be above local obstructions by approximately 1 m (3 feet) and the length of the extension arm should be long enough to minimize the effect of the tower itself. It must also be securely mounted so that it does not bounce or vibrate during high winds. Two photos of Hotplate gauges installed on a weather sensor tower at the NCAR test site are shown in Figure 17.

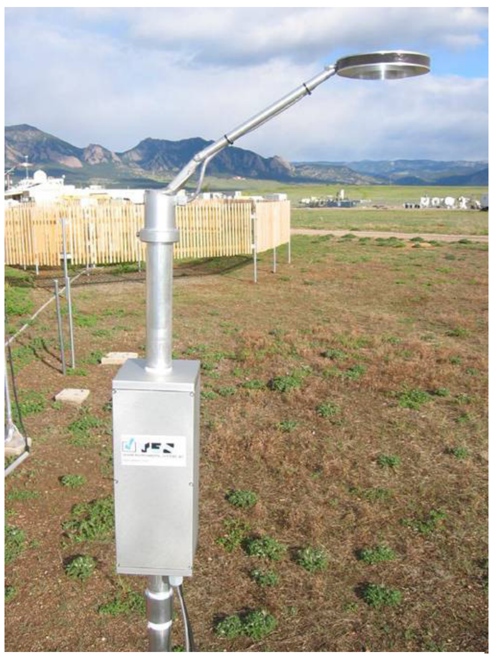


Figure 16. Photo of the Yankee Environmental Systems, TPS-3100 at the NCAR test site near Boulder, Colorado

Figure 17. Hotplate snow gauge installed on a weather sensor tower at NCAR's test site near Boulder, Colorado

11.2 Energy Requirements

The Hotplate can be operated using either 110 or 220 Volts AC (this is set during manufacturing). The power consumption is dependent on wind speed. The amount of power required during non-precipitation events ranges from 50 to 150 watts, depending on the ambient temperature. During precipitation events, the power required increases to range closer to 100 – 250 watts with a maximum power consumption of 600 watts.

11.3 Maintenance Requirements

The Hotplate is a major improvement over traditional weighing snow gauges with regard to maintenance requirements. The Hotplate does not have any moving parts and does not require any glycol or other fluids. Because the Hotplate operates around 80°C, the plates naturally stay free of cobwebs, beehives, ice, etc. This allows the Hotplate to be virtually maintenance free.

11.4 Calibration Requirements

The Hotplate snow gauge should come from the manufacturer fully calibrated and no additional calibration should be necessary once the instrument is deployed. All wind correction algorithms are loaded in the systems firmware. If the sensor is not activated (heated) throughout the year then it should be checked to ensure no objects (e.g., birds) have nested on it and that its surfaces are clear of contaminants.

11.5 Products Generated

The Yankee TPS-3100 has an output string that consists of the 1-minute liquid equivalent snowfall rate (mm/hr), accumulation (mm), outdoor ambient temperature (^{o}C), control box temperature (^{o}C), the wind speed (m/s), and system status messages.

11.6 System Limitations

The Hotplate is able to measure liquid equivalent precipitation rates between 0.01 inches/hour (0.25 mm per hour) and 0.5 inches/hour (12 mm/hour) within 10% of the WMO standard. The upper measurement limit of 0.5 inches/hour (12 mm/hour) is well above the normal liquid equivalent precipitation rate for snow events. Total liquid precipitation accumulation is calculated by integrating its one-minute precipitation rates over time. Since some precipitation types (hail, graupel, ice pellets) can bounce off the top surface of the Hotplate, these types of precipitation may go unreported or be under reported. The Hotplate gauge performs very well for precipitation rates normally associate with snow.

11.7 Current Cost

The current cost of a Yankee TPS-3100 is $10,000. The future price of the instrument is anticipated to be lower if sufficient demand of the product results in lower production costs.

11.8 Data Integration

The Hotplate can be used as a stand alone instrument or could be integrated into a system such as an ESS or RWIS. There are no technical reasons why the Hotplate could not become an optional sensor for RWIS or ESS systems. Since the Hotplate can report ambient temperature, wind speed, accumulation and precipitation rates, it can easily be used as a stand alone system.

11.9 System Footprint

The footprint of the standalone Hotplate is rather small, requiring a simple 8” x 8” concrete pad. With the Hotplate arm extended for operations, the footprint for the entire instrument is only 8”W; 22”D; 72”H. The footprint would be different if the sensor was mounted on an instrument tower and decoupled from its electronic box.

12. TACTICAL WINTER WEATHER PRODUCT USER NEEDS ASSESSMENT

12.1 Background

NCAR researchers used the Hotplate evaluation project as an opportunity to gather some limited user needs information related to tactical snow and ice control operations. During the course of the FHWA's Maintenance Decision Support System (MDSS) project, winter maintenance personnel indicated that they needed improved short term (0-3 hour) weather information to support winter maintenance operations during winter storm events. The MDSS was designed to focus on strategic decisions generally made 24-48 hours prior to the onset of winter storms. Because of this requirement, prototype MDSS products were based on weather and road condition forecast models and, with the exception of surface observations, did not incorporate radar based products and short-term forecast methods and techniques to extrapolate radar echoes.

It is likely and desirable that operational versions of the MDSS will include both tactical and strategic weather and road condition products; therefore road weather researchers wanted to explore some advanced capabilities that may, if developed further and tailored for road weather users, have the potential for supporting tactical winter maintenance operations. It is anticipated that a combination of WSDDM and MDSS capabilities would provide a more complete decision support system than either of the two systems individually.

This component of the Aurora project was quite small and very few resources were applied as the primary objective of the project was to evaluate the Hotplate system. Nevertheless, some useful information was gathered and is provided herein.

12.2 Evaluation Process

NCAR chose to use the WSDDM system as the demonstration vehicle for this evaluation. This was done because the WSDDM system was readily available and easily configurable for the Iowa and Minnesota users. It was recognized that the WSDDM system was designed and tailored for aircraft deicing operations and that the utility of the system for this evaluation was limited. A photograph of the WSDDM display hardware is shown in Figure 18.

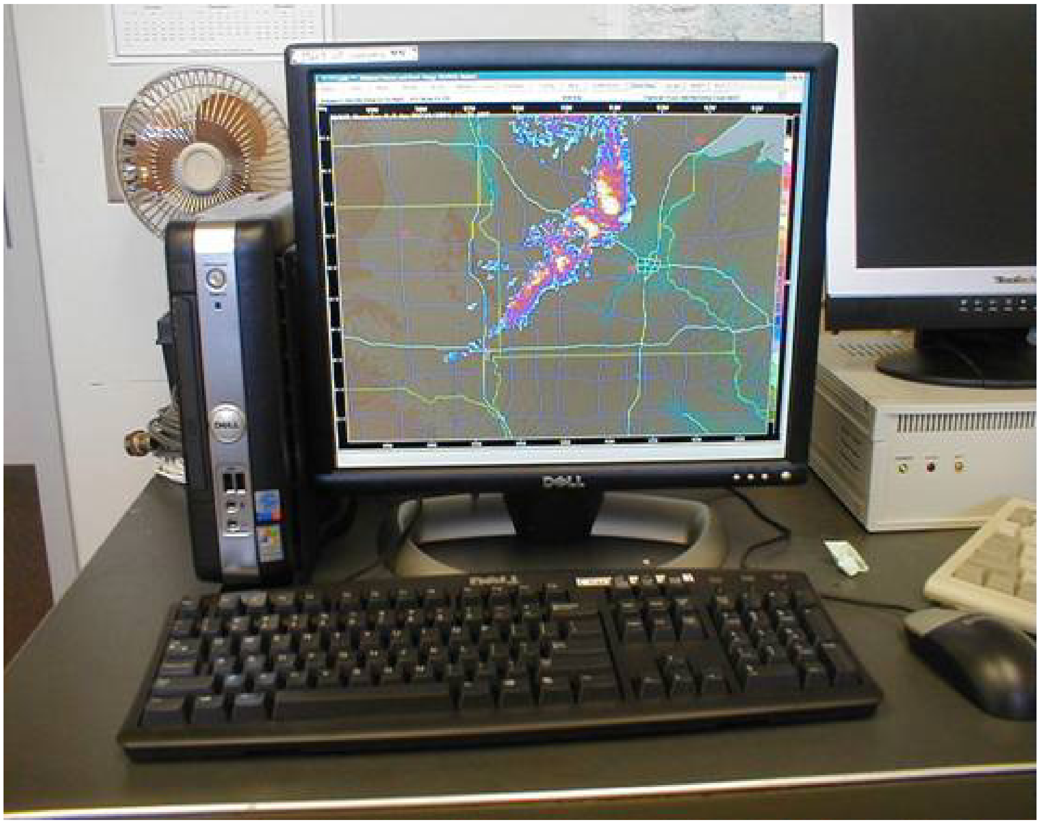


Figure 18. Photograph of the WSDDM display hardware

The WSDDM system is designed as a winter weather nowcasting[1] tool that provides real-time liquid equivalent snowfall information for the management of aircraft deicing/anti-icing and snow removal. Inputs to the system include data from Doppler weather radar such as NEXRAD, real-time snow gauge data, and surface observations. Algorithms are used to calculate the motion of the precipitation field and the radar snow intensities are dynamically calibrated using data from the real-time snow gauges. The WSDDM products include:

Measurements of liquid equivalent snowfall rate updated every minute
One-hour nowcast of snowfall/rain rate and the location of snow/rain bands updated every five minutes
High resolution depiction of radar reflectivity (intensity) and surface weather observations
High resolution depiction of precipitation type based on radar intensities and reported precipitation type
Time series of temperature, wind speed and direction, humidity, snowfall rates, liquid equivalent precipitation rates, and barometric pressure updated every minute

WSDDM displays were installed at both the Ames and Worthington DOT garages for this evaluation. An example of the WSDDM screen centered on Des Moines, Iowa is shown in Figure 19.

[1] Nowcasting generally refers to a weather prediction of 0 to 3 hours into the future.

The WSDDM system software operates under the Linux operating system, so Linux PCs were used to host the display software. Training was performed at the time of installation and once again in January 2005 when the Hotplate sensors were installed at the two sites.

As noted previously, the WSDDM display was not tailored for roadway winter maintenance users, which made it a bit complicated as many of the product and button labels were not intuitive. There was a concern by the evaluation team that the lack of tailoring and the limited training that was conducted would reduce its effectiveness as a demonstration vehicle and this was confirmed when the end of season user interviews were conducted. Even with these caveats, meaningful information was gleaned from the process.

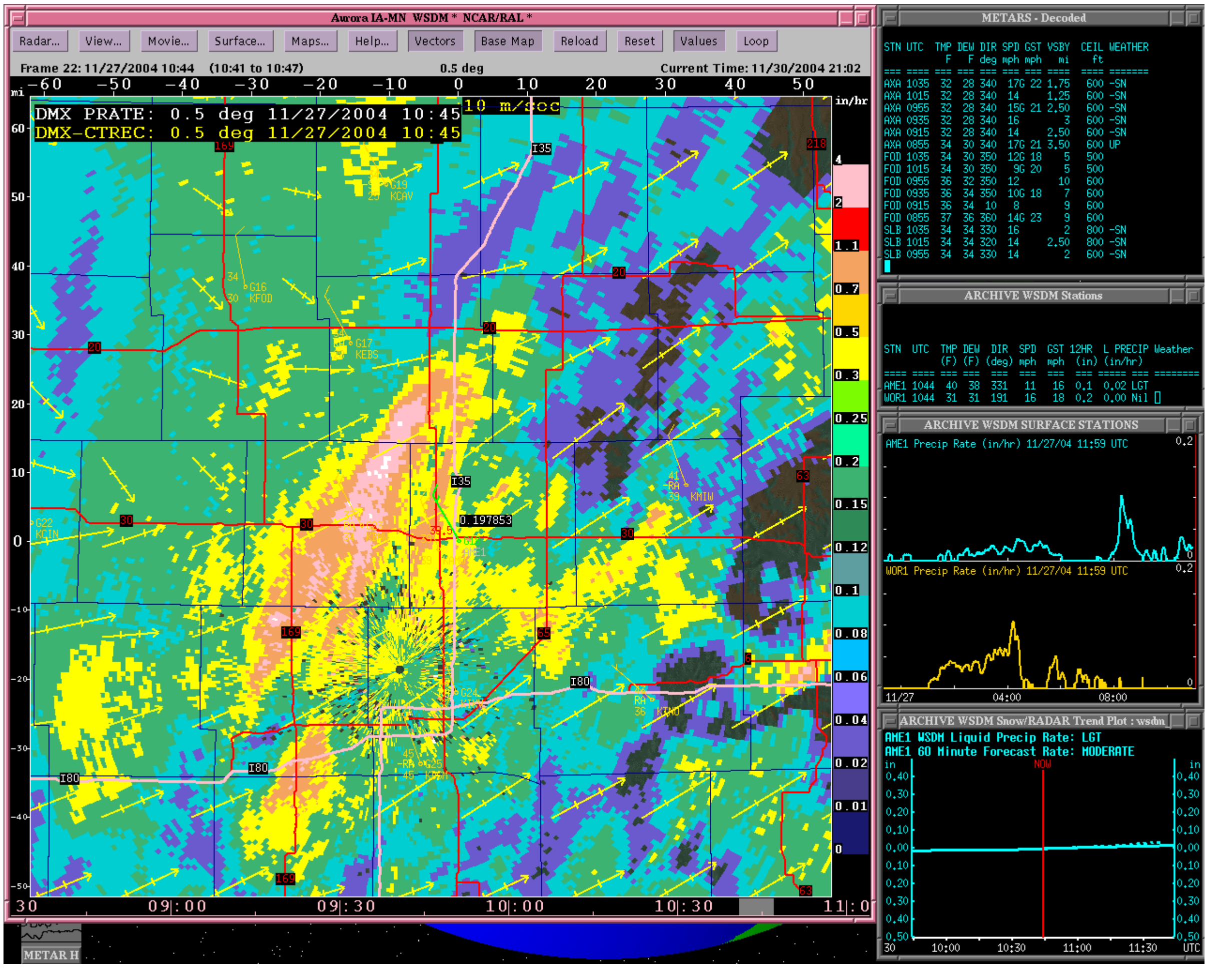


Figure 19. Photograph of the WSDDM display screen centered on Des Moines, Iowa showing calibrated precipitation rate and echo motion vectors (main screen) and surface observation listing (METARS and Ames and Worthington weather sites), surface observation time series, precipitation rates measured by the GEONOR gauges, and 60 minute extrapolated liquid equivalent precipitation rates (right panels)

12.3 Findings

At the conclusion of the Hotplate evaluation period, a short questionnaire was distributed to the WSDDM users at both the Ames, Iowa and Worthington, Minnesota DOT maintenance garages. The questionnaire, which is provided in Appendix C, asked the users to rate the weather products that they felt were most important for tactical snow fighting operations. They were also asked to provide feedback on specific WSDDM products. One DOT staff member from each garage completed the questionnaire and participated in the follow-on interview. Because of the very limited sample, the results should be used with caution.

12.3.1 Ratings for Weather and Road Condition Parameters

Most Important Information

- Pavement temperature
- Air temperature
- Wind speed and direction
- Radar echo motion
- Precipitation type
- Precipitation start and end times
- Hourly precipitation accumulation

WDDM Product Use

- Primarily for general guidance on precipitation type, rate, start time, and motion
- System was too complicated (not tailored) for routine use, more training was desired
- The products would be very useful if tailored for DOT maintenance operations (summer and winter)

Desired Features

- Snow depth information
- Overlays of radar with surface data (METAR and RWIS)
- Detailed map overlays with radar products
- Blend of current and forecasted weather and road conditions
- Freezing drizzle information
- Ability to view graphical weather information on hand-held devices

The users indicated that although they generally liked the products and capabilities of the WSDDM system, its interface was complex and it was not located in an area that made it readily accessible. In the interviews the users indicated that they would like to see a merging of MDSS and WSDDM capabilities (e.g. product, features, and functions) into a single operational system tailored for their operation. They also indicated a desire for additional visibility and video sensors at their ESS/RWIS sites, and snow drift information.

Freezing drizzle was also mentioned as a phenomenon that caused them major problems and that is not well predicted by forecasters or detected by radars. They indicated that a better indicator of freezing drizzle is needed in future decision support systems.

REFERENCES

Goodison, B.E., P.Y.T. Louie, and D. Yang, 1998: WMO solid precipitation measurement intercomparison, final report. WMO/TD-No.872, WMO, Geneva, 212pp.

Mahoney, W.P., and W. L. Myers, 2003: Predicting Weather and Road Conditions: An Integrated Decision Support Tool for Winter Road Maintenance Operations. Transportation Research Record: Journal of the Transportation Research Board, 1824, 98-105.

Middleton, W.E.K, 1969: Invention of the Meteorological Instruments. John Hopkins Press, 362 pp.

National Center for Atmospheric Research (NCAR), 2004: The Maintenance Decision Support System Project, Technical Performance Assessment Report, Iowa Field Demonstration, Winter 2003, http://www.rap.ucar.edu/projects/rdwx_mdss/documents/index.html.

Rasmussen, R.M., J. Vivekanandan, J. Cole, B. Myers, and C. Masters, 1999: The Estimation of Snowfall Rate Using Visibility. J. Appl. Met., 38, 1542 – 1563.

Rasmussen, R.M., J. Cole, K. R.K. Moore, and M. Kuperman, 2000: Common Snowfall Conditions Associated with Aircraft Takeoff Accidents. J. of Aircraft, 37, 110 – 116.

Rasmussen, R., M. Dixon, F. Hage, J. Cole, C. Wade, J. Tuttle, S. McGettigan, T. Carty, L. Stevenson, W. Fellner, S. Knight, E. Karplus, and N. Rehak, 2001: Weather Support to Deicing Decision Making (WSDDM): A Winter Weather Nowcasting System. Bull. Amer. Soc., 82, 579-595.

Rasmussen, R., J. Hallet, M. Tryhane, S. Landolt, R. Purcell, M. Beuabien, W. Jeffries, F. Hage, and J. Cole, 2005: The Hotplate Snowgauge. Proceedings, 13th Symposium on Meteorological Observations and Instrumentation, Savannah, GA, 20-24 June, 2005, American Meteorological Society.

APPENDIX A

The Hotplate Snow Gauge

Roy M. Rasmussen[1], NCAR, Boulder, CO; and J. Hallett[2], M. L. Tryhane[1], S. D. Landolt[1], R. Purcell[2], M. C. Beaubien[3], W. Q. Jeffries[3], F. Hage[1], and J. Cole[1]

[1]National Center for Atmospheric Research
Research Applications Laboratory
Boulder, CO 80307
[2]Desert Research Institute
Reno, NV

1. INTRODUCTION

Recent studies (Rasmussen et al. 1999, Rasmussen et al. 2000) have shown that the use of visibility to estimate snowfall rate can be misleading in many instances due to the wide variety of snow crystal types. The hazard identified for aviation is the "high snowfall rate – high visibility" condition. Under this condition, the liquid equivalent snowfall rate can exceed 2.5 mm/hr, the rate at which five of the major deicing accidents occurred (Rasmussen et al. 2000), while the visibility based snow intensity can be light. This is in fact the condition that occurred during the LaGuardia deicing accident on March 22, 1992 (Rasmussen et al. 2000). In order to overcome this problem, real-time estimates of the liquid equivalent snowfall rate updated every one minute are needed. The current ASOS systems provide hourly snowfall intensities based on visibility, which is clearly inadequate for aircraft ground deicing needs. A winter weather nowcasting system called the Weather Support to Deicing Decision Making (WSDDM) system (Rasmussen et al. 2001) has recently been developed that includes real-time weighing snowgauges as a key component. These types of gauges essentially weigh the snow as it falls into a bucket filled with a glycol based chemical and a thin layer of oil to prevent evaporation. Wind shields are also required to be used with these snow gauges in order to prevent undercatch of snowfall due to wind impacting the gauge itself. In order to adapt this gauge for real-time use, Rasmussen et al. (2001) added a temperature controlled heat tape on the collar of the gauge in order to prevent snow build up on the collar. While effective, these gauges typically require a wind shield to increase the catch, a regular re-charge of the collection bucket with fresh glycol and oil, and report snowfall rates that are averages over 5-10 minutes due to the accumulation nature of the gauge. In this paper we present a new snowgauge, called the "hotplate snowgauge" which provides a reliable, low maintenance method to measure snowfall rate every minute without the use of a wind shield.

2. Description of the Hotplate Snowgauge

The hotplate snowgauge (shown in Figures 1,2 and 3) consists of two identical heated plates, one facing upwards and exposed to precipitation (Fig. 1) and the other facing downwards just below the top plate (Fig. 2). The lower plate is insulated from the top plate and is designed to serve as a reference plate that is only affected by wind and not by precipitation. The two plates are heated to nearly identical constant temperatures (~ 70 °C), which is hot enough to melt and evaporate small snow particles striking the plate in less than a second and large snowflakes in a

* Corresponding author address: Matthew L. Tryhane, NCAR, P.O. Box 3000, Boulder, CO 80307; Email: mtryhane@ucar.edu

few seconds. The plates are maintained at constant temperature during wind and precipitation conditions by increasing or decreasing the current to the plate heaters. During normal windy conditions without precipitation, the plates cool nearly identically due to their identical size and shape. During precipitation conditions, the top plate cools due to the melting and evaporation of precipitation while the bottom plate is only affected by the wind.

Figure 1. Top view of hotplate. Diameter of plate is 13.0 cm.

The difference between the power required to cool the top plate compared to the bottom plate is then proportional to the precipitation rate. Three concentric rings are placed orthogonal to each plate in order to prevent snow particles from sliding off the top hotplate during high wind conditions. Due to its aerodynamic shape, the hotplate has minimal effect on the airflow around it, and thus does not require a wind shield. In addition, since all the snow melts and evaporates, it does not require any glycol or oil, making is very low maintenance. The hotplate snowgauge has undergone five years of testing at Marshall (a site near Boulder) and two years of testing at Mt. Washington, NH. In the next section we describe the hotplate snowgauge algorithm and in Section 4 compare its performance to standard weighing snowgauges during a winter season. In Section 6 an evaluation of the commercial version of the hotplate manufactured by Yankee Environmental is discussed. Concluding remarks are made in Section 5.

Figure 2. View of lower plate. Diameter of plate is 13.0 cm.

3. Algorithm

3.1 *Calculation of precipitation rate*

The raw output of the hotplate system is the difference in power used to maintain the top and bottom plates at constant temperature. In order to convert this power difference to liquid equivalent rate, a theoretical calibration factor was developed based on the area of the hot plate, the heat capacity and density of water, and the latent heat of melting and evaporation. The value of the calibration factor, f, for a hotplate system with upper plate maintained at 75 °C is 0.0039 inches/hour liquid equivalent per power difference in Watts. In practice, this value was increased slightly depending on the hot plate to account for heat transfer losses.

The sensor and reference plate temperatures are set such that the power difference (ΔP in Watts, power of the sensor plate minus the power of the reference plate, Ps-Pr) is about 0 Watts when there is no precipitation falling. The top and bottom plates were made identical in order to minimize any wind speed dependence on the power consumed by either plate, thus making ΔP independent of wind speed as much as possible.

Figure 3. Commercial version of the hotplate snow gauge deployed at the NCAR Marshall Field Site just south of Boulder, CO.

However, it was found in practice that ΔP still had a small dependence on wind speed that needed to be taken into account. Thus, the equation to calculate precipitation rate can be given as:

$$\text{Rate (mm/hr)} = (\Delta P - (a + b*w + cw^2))*f \qquad (1)$$

where w is the wind speed in m/s and a, b, and c are coefficients of the curve fit between ΔP and w during non-precipitation conditions.

Using equation (1), the rate is calculated every minute, and then a five minute running average formed. If this five minute average rate does not exceed a threshold of 2 Watts, it is assumed that it is not precipitating. A 2 Watt threshold is used to account for wind variations on the top and bottom plates and also the diurnal solar heating of the hotplate. Once the five minute rate is greater than the threshold, precipitation is assumed to have started. During precipitation, rates are calculated every minute until the rate drops below zero.

A two hour time series of the sensor power, reference power, and the power difference is given in Figure 4. During the first 20 minutes of the time series no snow is falling, and the sensor and reference power traces are nearly equal as expected. After 20 minutes, snow commences and the traces separate, with the sensor power being larger than the reference power as expected. The delta power trace shows a power difference of approximately 10 -20 Watts during this period.

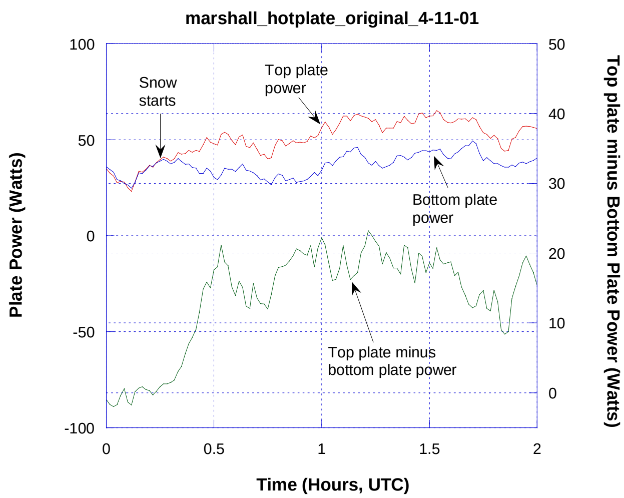


Figure 4. Two hour sensor, reference, and delta power time series from the hotplate during a snow event.

Applying the conversion factor discussed above, the delta power trace shown in Figure 4 can be converted to a snowfall rate trace and accumulation trace as shown in Figure 5.

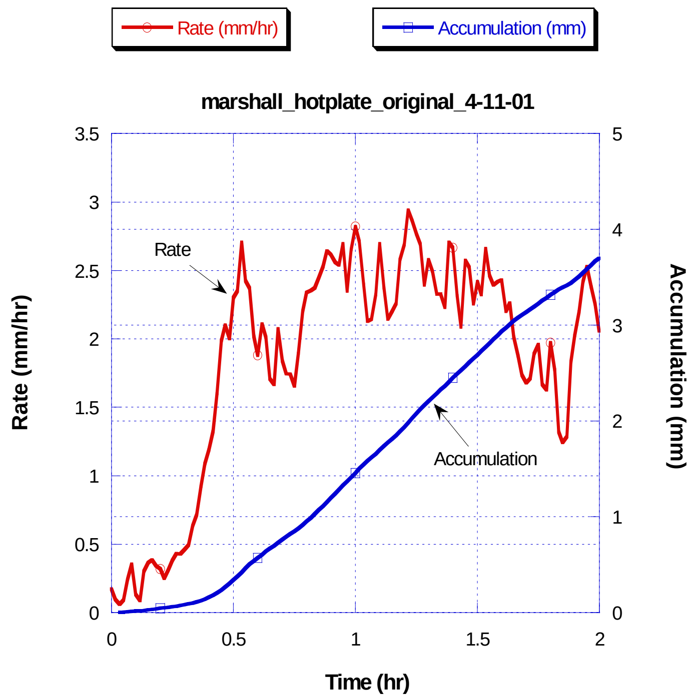


Figure 5. Two hour time series of snowfall rate and accumulation derived from the power time series in Figure 4.

3.2 Accounting for undercatch due to wind effects

Comparison of the hotplate accumulation with a weighing snowgauge in a WMO standard Double Fence Intercomparison Reference (DFIR) shield revealed that the hotplate under-estimated snow accumulations when the winds were above 3 m/s. On April 10-11, 2001, a snow event occurred in which the wind speed gradually increased during the event, as shown in Fig. 6. Note that a peak wind speed of 11.5 m/s is reached at 1120 UTC.

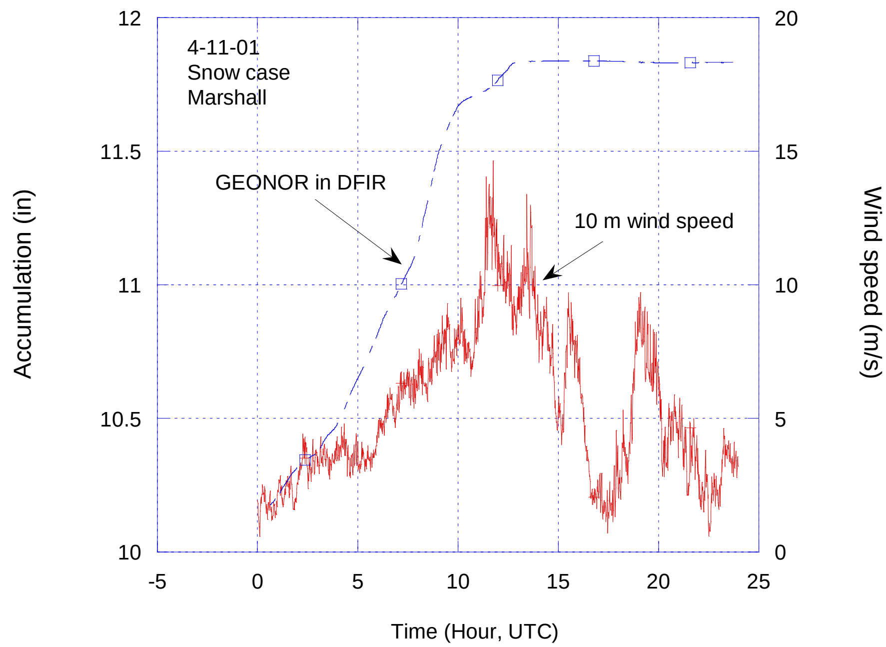


Figure 6. Ten meter wind speed and GEONOR in the DFIR shield accumulation for April 11, 2001.

During this event the difference between the hotplate accumulation and the GEONOR increased with increasing wind speed. In order to further quantify this result, we examined the hourly GEONOR and hotplate accumulations and formed the hourly accumulation ratio. If the ratio is 1.0, then the hotplate is estimating the same accumulation as the GEONOR in the DFIR shield. The results are shown in Figure 7. Note that the catch efficiency decreases linearly with increasing wind speed. Thus, the catch of both hotplates is reduced to 50% for a wind speed of 5 m/s, and by 80% for a wind speed of 10 m/s. Beyond 10 m/s the catch efficiency is set to 0.2. Thus, the effect of the wind needs to be taken into account in the hotplate algorithm to prevent under-catch.

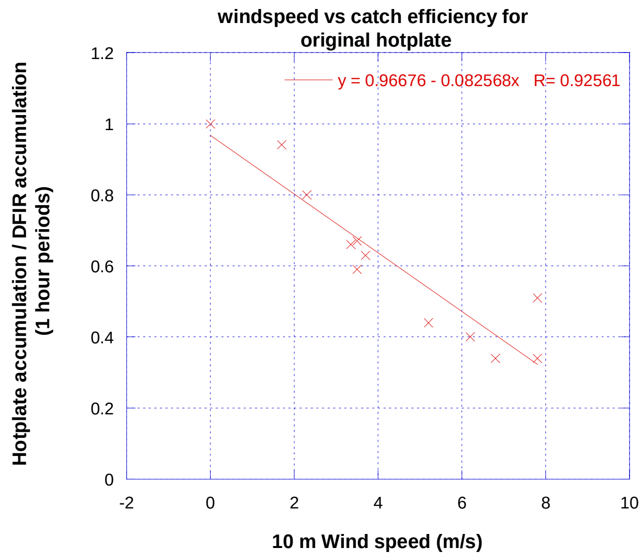


Figure 7. Catch efficiency for the hotplate as a function of wind speed using data from April 11, 2001.

Applying both the wind catch correction algorithm and the baseline wind correction described above, false precipitation during non-precipitation days have been reduced to less than 0.01 in/hr

Based on these results the algorithm sets to zero all precipitation rates less than 0.01 in/hr, and thus requires a threshold of 0.01”/hr before precipitation is recorded. An example of the performance of the hotplate for a high wind case is shown in Figure 8.

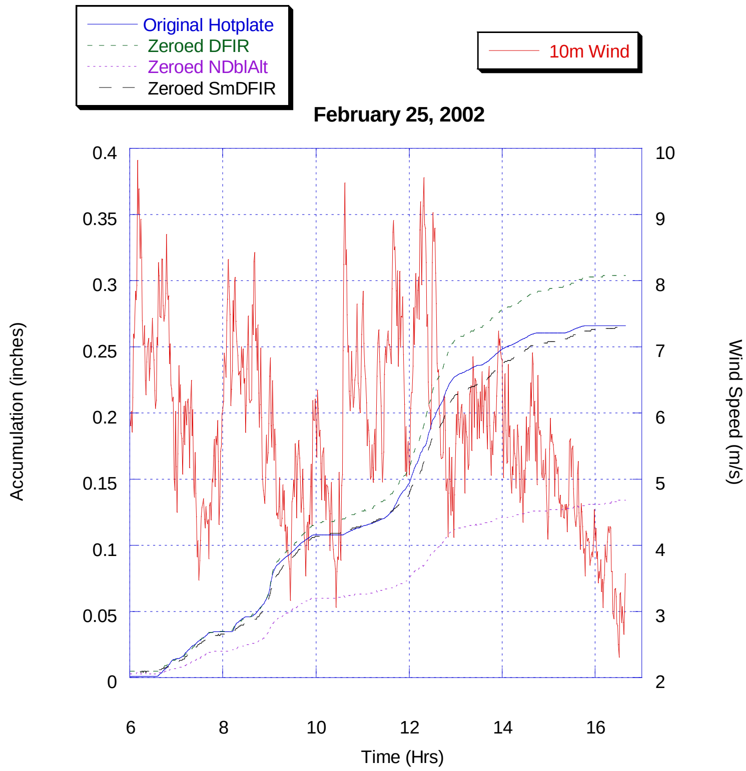


Figure 8. Hot plate accumulation compared to GEONOR snowgauge in DFIR shield, GEONOR in a small DFIR shield, and GEONOR in a double Alter shield.

The results show excellent performance of the hotplate for winds up to 9 m/s. Additional testing has shown that this correction curve applies up to 15 m/s. This algorithm has been tested on a variety of snowstorms since 2001 and proven to be robust. Thus, taking into account wind effects is crucial to the proper performance of the hotplate.

4. Full Winter Season Performance Evaluation

In this section we evaluate the performance of the hotplate using the above described algorithms. The reference snow measurement is a GEONOR snowgauge located in a DFIR shield at the Marshall test site. The DFIR is the WMO standard snow shield for use with weighing gauges. In our previous studies, we have shown that the GEONOR in the DFIR shield meets or exceeds the NWS 8" can with a single Alter shield in all cases. The criteria for the intercomparison were:

1) The absolute value of the difference between the Geonor in the DFIR hourly accumulation and the original hotplate hourly accumulation was less than or equal to 0.02 inches, or 4% of the hourly total, whichever is greater, and;
2) No measurable precipitation during non-precipitation events (less than 0.12 mm in an hour).

The above criteria are used by the National Weather Service ASOS Program Office to evaluate the performance of weighing snow gauges.

Seven storms have been analyzed from 2001, as shown in Table 1, consisting of 137 hours of precipitation. In addition, three days without precipitation have also been analyzed (March 13, 14, and 15, 2001).

Table 1. Precipitation events at Marshall test site evaluated

Date (2001)	Depth	Type	Liquid
1. 7-9 Feb	5”	snow	0.33”
2. 14 Feb	3.5”	snow	0.29”
3. 10-12 March	8”	snow	0.75”
4. 17 March	1.5”	snow	0.19”
5. 25-26 March	7”	snow	0.56”
6. 31 March	0.5”	snow	0.09”
	-------		---------
Total	25”		2.11”

All 137 hours with precipitation passed the above criteria, as well as the 66 non-precipitation hours. The non-precipitation days had false reports of accumulations no greater than 0.004 inches per hour and maximum false reports of 0.001- 0.002 inches in an hour.

5. Case Study Evaluation of Commercial Hotplate Manufactured by Yankee Environmental

In the following two cases comparing two commercial versions of the hotplate described above are evaluated using two recent snow events.

5.1 April 10-11, 2005 Event

A rain event started just before 0530 UTC on April 10, 2005. Around 1000 UTC the rain transitioned to snow and ice pellets and continued on and off until 1130 UTC on the 11^{th}. Observations from a Light Emitting Diode Weather Identifier (LEDWI) were used along with a collocated Weather Identifier & Visibility Sensor (WIVIS) to determine the precipitation type. Three hotplates were available for evaluation during this event, two Hotplates built by YES, Inc. (YES Hotplate #1 and YES Hotplate #2) and the original hotplate, whose results were described above. The accumulation from each hotplate was compared with a weighing snowgauge in a WMO standard Double Fenced Intercomparison Reference (DFIR) Shield (Fig. 9). The accumulation from each hotplate is in excellent agreement with the truth gauge throughout the rain portion of the event. Wind speeds from 0.5 to 10 m/s had no effect on the collection efficiency of the gauge. Once the precipitation transitioned to snow and ice pellets, the hotplates slightly underestimated the precipitation rates as compared with the truth gauge. Since no human observer was present, it is assumed that some type of solid precipitation (ice pellets or graupel) was present. Winds varied throughout the event from 0 to 14 m/s. The hotplates underestimated the total accumulation for the event due to the precipitation rates dropping below 0.25 mm/hr or 0.01”//hr (minimum detectable rate) for portions of the event. The average rate for the event from all of the gauges differed by less than 0.25 mm/hr. Accumulation measurements from YES Hotplate #1 and #2 resulted in a difference of less than 1.5 mm for the entire event.

The wind speed derived from the reference plate power and ambient temperature was compared with a propeller anemometer mounted 10-meters AGL (Fig. 10). Both YES Hotplates show very good agreement with the propeller anemometer. A one-to-one comparison (Fig. 9) shows excellent correlation between the hotplate’s wind speed measurement and the true wind speed.

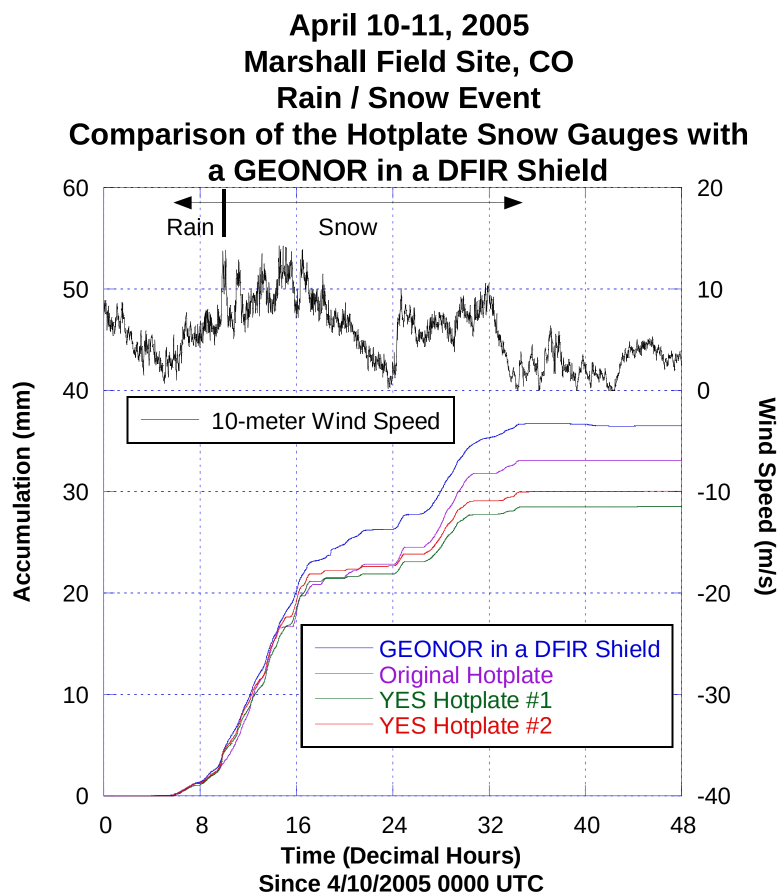


Figure 9. Liquid equivalent precipitation comparison of two Yankee Environmental System (YES) Hotplates, an original prototype Hotplate and the Geonor gauge. Wind speed is also shown.

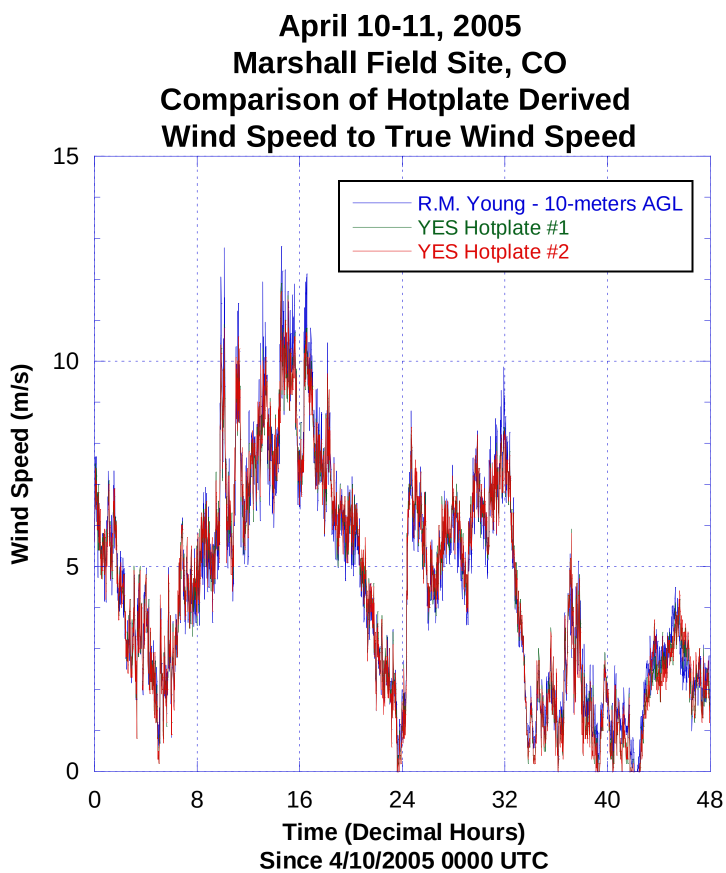


Figure 10. A comparison of the wind speed derived from the two Yankee Environmental System (YES) Hotplates and a standard anemometer.

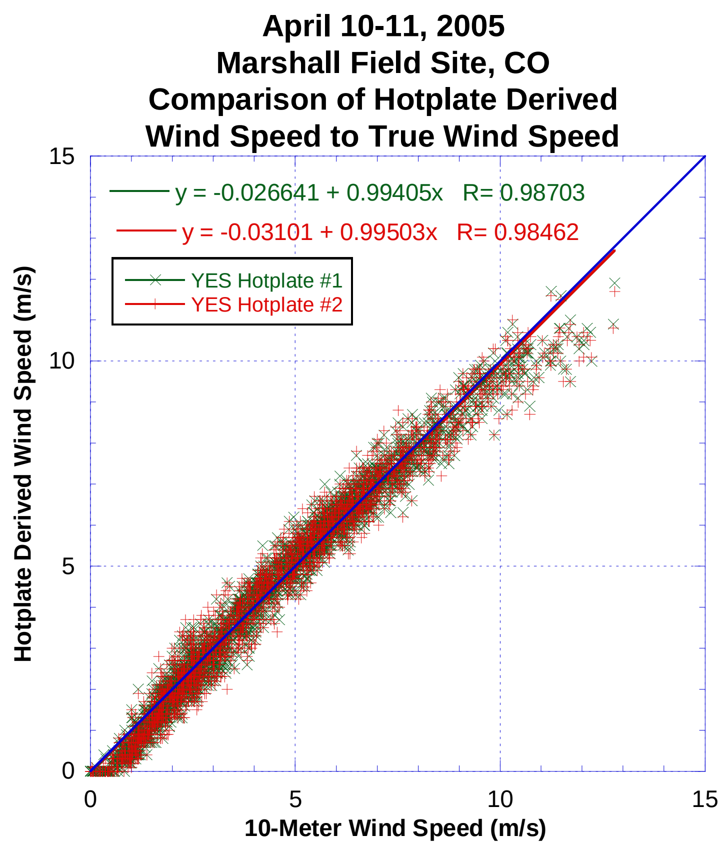


Figure 11. Comparison of the Hotplate derived wind speed and the true wind speed from 10 to 11 April 2005.

5.2 April 27-29, 2005 Event

A rain event started at 2300 UTC on April 27, 2005. Around 0030 UTC on the 28th, the rain transitioned to snow and continued through 1730 UTC on the 29th. The two YES Hotplates performed well during this event (Fig. 12). Table 1 shows that both the total accumulation and average rates during the event agreed well.

During this event the propeller anemometer froze up and stopped reported at 0400 UTC on the 28th. Since the hotplate measures the wind speed using the bottom plate, a reliable wind speed measurement was maintained by both hotplates for the entire event (Fig. 13). Thus, the hotplate can be used to measure wind speed during severe icing conditions.

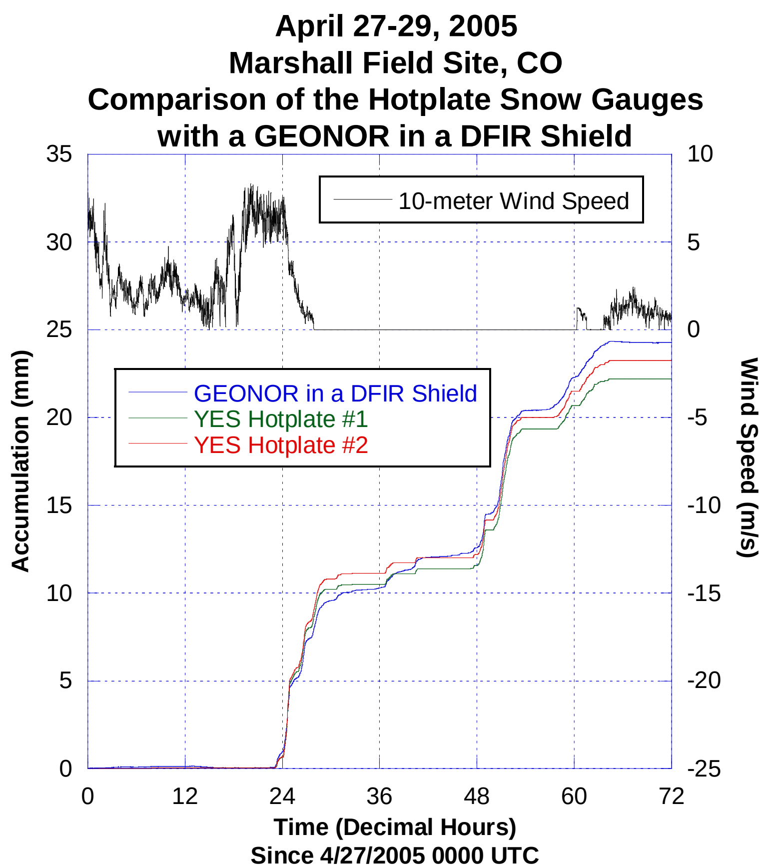


Figure 12. *Liquid equivalent precipitation comparison of two Yankee Environmental System (YES) Hotplates and the GEONOR gauge. The propeller anemometer froze during this event.*

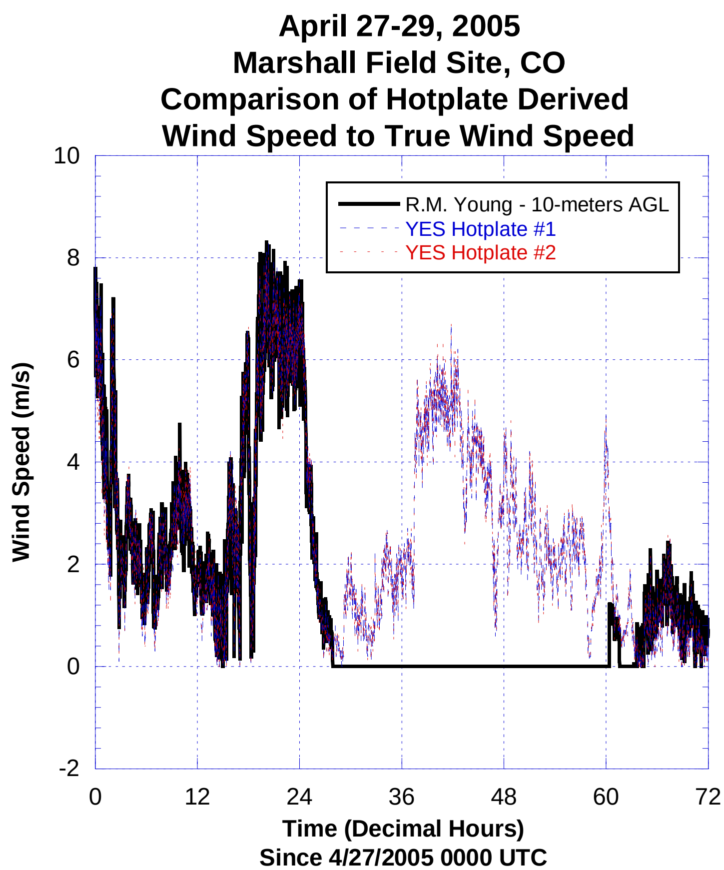


Figure 13. Comparison of the wind speed derived from the two Yankee Environmental Systems (YES) Hotplates and a propeller anemometer.

Table 2. Comparison of the total liquid equivalent precipitation accumulation and precipitation rates for the two Yankee Environmental System (YES) Hotplates and the GEONOR gauge.

	Total Accumulation (mm)	Avg. Rate (mm/hr)
GEONOR	24.25	0.64
YES #1	22.21	0.53
YES #2	23.23	0.56

6. Summary

A new hotplate snowgauge has been described consisting of two heated plates used to estimate snowfall mass by measuring the power to melt and evaporate snow on the upward facing sensor plate, compensated for wind effects by subtracting out the power on the lower plate facing downwards. The system measures liquid equivalent snowfall rate from 0.25 mm/hr to 25 mm/hr to within 10% of the WMO standard snow measuring wind shield/gauge setup. The hotplate was also shown to accurately measure wind speed even during severe icing conditions. The high update rate (precipitation rates, winds and temperatures every one minute), make this an ideal gauge for real-time applications such as aircraft deicing which requires update rates every minute. It can also be used as an accumulation gauge by integrating the one minute rates over time.

7. Acknowledgements

This research was sponsored by the National Science Foundation through an interagency agreement in response to requirements and funding by the Federal Aviation Administration's Aviation Weather Research Program. The views expressed are those of the authors and do not necessarily represent the official policy or position of the U.S. Government.

8. References

Rasmussen, R.M., M. Dixon, F. Hage, J. Cole, C. Wade, J. Tuttle, S. McGettigan, T. Carty, L. Stevenson, W. Fellner, S. Knight, E. Karplus, and N. Rehak, 2001: Weather Support to Deicing Decision Making (WSDDM): A Winter Weather Nowcasting System. *Bulletin of the American Meteorological Society*, **82**, 579 – 595.

Rasmussen, R.M., J. Cole, K. R.K. Moore, and M. Kuperman, 2000: Common Snowfall Conditions Associated with Aircraft Takeoff Accidents. *J. of Aircraft*, **37**, 110 – 116.

Rasmussen, R.M., J. Vivekanandan, J. Cole, B. Myers, and C. Masters, 1999: The Estimation of Snowfall Rate Using Visibility. *J. Appl. Met*.,**38**, 1542 – 1563

APPENDIX B

Yankee Environmental Systems Advertisement

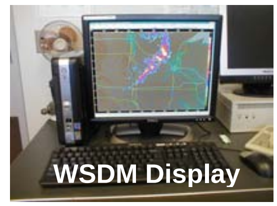
33498 11/7/03 7:48 PM Page 1

APPENDIX C

WSDDM Product User Questions
May 2005

Aurora Project

WSDDM Product User Questions



Primary Overall Project Objective: To test the performance of the *Hot Plate* snow gauge and assess its utility for supporting snow and ice control operations. If successful, it may become an optional sensor on future RWIS systems.

Project Objective (WSDDM Component): To explore the utility of new products that have the potential to aid tactical snow and ice control operations.

Caveat: Due to resource constraints, the WSDDM display, which was designed for airline deicing operations, was not tailored for winter maintenance operations. The project team was hoping that it could be used as a demonstration vehicle to introduce new capabilities to winter maintenance practitioners.

User Questions:

Q1. Rate the following weather and road condition information for its usefulness for tactical (snow event in progress) snow and ice control? Use 0= not important and 10=critical.

- Air temperature
- Road temperature
- Wind speed and direction
- Radar intensity
- Radar echo motion
- Snowfall rates (inches per hour)
- Precipitation type
- Visibility
- Snow depth
- Solar radiation intensity

Q2. How were the WSDM products used?

- Pre-planning events?
- During events?
- For general guidance?

Q3. Indicate answers as: 0 = Completely Disagree, 5 = Completely Agree

- The radar image showed weather where there was none
- The display was too complicated to operate
- The products were too complicated to understand
- I didn't receive enough training
- The products weren't reliable enough to trust
- It was hard to find the product I needed
- It was hard to find and zoom in on places of interest
- The product color scales were a problem
- The product legends were a problem
- The time zones/time formats were a problem
- I'd find it more useful if I had more training
- I'd find it more useful if I had a better user manual
- I'd find it more useful if it were available on the Web
- The display needs better maps
- The routes/zones need to be better identified
- The routes/zones need to be change color according to condition

Q4. Please prioritize the usefulness/importance of the following products. 1 = highest priority:

- Radar intensity
- Precipitation type
- Precipitation rate
- Echo motion vectors (yellow vectors with tick marks)
- Clickable decoded surface observation METAR/RWIS table
- METAR/RWIS station time series plot
- 1-minute RWIS station data table
- Forecasted precipitation accumulation plot

Q5. You have $100 dollars to spend on the following. How would you divide the funds?

- Improved maps
- Migrate to web browser based delivery
- Integrate time-to-failure estimates for anti-icing chemicals
- Add weather forecast products
- Integrate satellite imagery
- Add roadside weather sensors
- Install snow depth sensors
- Add NWS watches, warnings and advisories

Q6. What products or additional capabilities are desired for a tactical winter maintenance decision support system?

Q7. Do you see any utility in using such a system to support summer operations?