The Hotplate Precipitation Gauge

ROY M. RASMUSSEN
Research Applications Laboratory, National Center for Atmospheric Research, Boulder, Colorado

JOHN HALLET AND RICK PURCELL
Desert Research Institute, Reno, Nevada

SCOTT D. LANDOLT AND JEFF COLE
Research Applications Laboratory, National Center for Atmospheric Research, Boulder, Colorado

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ABSTRACT

A new instrument designed to measure precipitation, the “hotplate precipitation gauge,” is described. The instrument consists of a heated thin disk that provides a reliable, low-maintenance method to measure precipitation rate every minute without the use of a wind shield. The disk consists of two heated, thermally isolated identical aluminum plates—one facing upward and the other downward. The two plates are heated independently, and both are maintained at constant temperature above 75°C by electronic circuitry that heats the plates depending on the deviation from the set temperature. Precipitation rate is estimated by calculating the power required to either melt or evaporate snow or to evaporate rain on the upward-facing plate, compensated for wind effects by subtracting out the power on the lower, downward-facing plate. Data from the World Meteorological Organization reference standard for liquid-equivalent snowfall rate measurements, the Double Fence Intercomparison Reference (DFIR) shield system, were used as the truth to develop the hotplate algorithm. The hotplate measures the liquid-equivalent precipitation rate from 0.25 to 35 mm h⁻¹ within the National Weather Service standard for solid precipitation measurement. The hotplate was also shown to measure wind speed during severe icing conditions and during vibration. The high update rate (precipitation rate, wind speed, and temperature every 1 min), make this an ideal gauge for real-time applications, such as aircraft deicing and road weather conditions. It serves as an accumulation gauge by integrating the 1-min rates over time. It can also be used as a rain gauge for rainfall rates up to 35 mm h⁻¹.

1. Introduction

The estimation of snowfall rate remains one of the most challenging measurements to make because of the wide variety of snow types, shapes, size distributions, and particle densities. This is true for both radar estimates of snowfall rate (Rasmussen et al. 2003) and ground-based measurements using gauges (Golubev 1985a,b; Goodison et al. 1989; WMO/CIMO 1985; Rasmussen et al. 2000, 2001; Yang et al. 1998). Ground-based instruments have typically relied on tipping bucket, weighing, or optical gauges to estimate liquid-equivalent rates. Weighing gauges weigh the snow as it falls into a bucket, which is usually filled with a glycol-based solution and a thin layer of oil to prevent evaporation of water from the solution. This type of measurement is inherently an accumulation over time, and thus snowfall rates are typically estimated from the amount of accumulation over a period of 10 min or so. Weighing gauges are subject to frequent maintenance because of the use of glycol and oil, and they are also sensitive to vibration resulting from the weighing mechanism. The only direct rate gauges are the tipping bucket–type gauges, which have been widely shown to significantly underestimate snowfall rate because of heating and wind effects (Groisman and Legates 1994). Optical gauges (Gultepe and Milbrandt 2010) accurately measure particle volume, and as such perform well for rain. Optical gauges typically do not do a very good job in measuring snow because of their inability to measure snow density. The Vaisala FD12P,
however, has combined an optical sensor with a simple measure of snow-water content using a heated plate to provide improved snow estimates.

Another method to estimate snowfall rate is by visibility, which is used by the U.S. National Weather Service to estimate light, moderate, and heavy snowfall intensity (Office of the Federal Coordinator for Meteorological Services and Supporting Research 2005). Recent studies (Rasmussen et al. 1999, 2000), however, have shown that the use of visibility for estimating snowfall rate can be misleading in many instances because of the wide variety of snow crystal types. A particular hazard identified for aviation from these studies is the “high snowfall rate–high visibility” condition. Under this condition dense and compact snow crystals, such as rimed plates or isometric crystals, can have a moderate to heavy snowfall rate and yet a visibility-estimated intensity of only light precipitation resulting from the small cross-sectional area represented by such crystals. Such a misleading condition was found to occur during five of the major deicing accidents (Rasmussen et al. 2000).

To overcome this problem, real-time estimates of the liquid-equivalent snowfall rate updated once every minute are needed. For this reason, aviation real-time nowcasting systems, such as the Weather Support to Deicing Decision Making (WSDDM) system (Rasmussen et al. 2001), include real-time snowfall rate measurements as a key component.

A key issue with most snow gauges is the undercatch of snow resulting from wind effects (see, e.g., Jevons 1861; Yang et al. 1998, 2001). As airflow impacts a solid gauge, which is typically cylindrical in shape, the impact of the wind creates updrafts over the gauges that lead to the undercatch of snow resulting from the relatively low terminal velocity of snowflakes (~1 m s⁻¹). To reduce this effect, a variety of wind shields have been devised to slow and/or modify the airflow to allow snow to fall naturally without deviation, thus increasing the amount of precipitation collected by the gauge (Alter 1937; Nipher 1878; Goodison et al. 1989, 1998; Yang et al. 1998).

Snow can also accumulate on the gauge itself, blocking the collection orifice. During calm winds snow can accumulate on any surface tilted from the vertical and form a cap over the gauge, blocking any further snow from collecting in the gauge (Rasmussen et al. 2001). Winds can cause snow to preferentially accumulate on the upstream side of a gauge, leading to further blockage (Rasmussen et al. 2001). To reduce this effect, Rasmussen et al. (2001) added temperature-controlled heat tape on the collar of the gauge in order to prevent snow buildup on, and over the top of, the collar. This temperature-controlled heat tape maintains the orifice temperature near 2°C, which is warm enough to melt the snow and prevent capping without producing a heat plume over the top of the gauge.

The above problems with current snow gauges are mostly due to the large, solid obstacle that weighing gauges typically present to the flow. In this paper we present a new precipitation gauge, called the “hotplate precipitation gauge.” This gauge uses a heated thin disk to provide a reliable, low-maintenance method to measure precipitation rate every minute without the use of a wind shield. The operating principle is based on a simple physical concept that the measurement of latent heat required to evaporate falling snow, rain, or supercooled rain (or a mix thereof) provides high-resolution information on precipitation rate. Heated wires and rods have been used for many years in instruments measuring water and ice content of clouds from aircraft (Hallett 1980; Korolev et al. 1998; King et al. 1978; King and Turvey 1986). What is new is the application of this concept to the ground-based measurement of precipitation in the form of a heated flat plate, with real-time wind correction, and the utilization of a resolution such that the rates are only limited by the inherent statistical properties of the precipitation itself (Hallett and Rasmussen 2006). The guiding design principle has been the minimization of the complexity of the sensor, incorporating thermal, mechanical, and electrical simplicity. The system can accurately measure rainfall rates up to 35 mm h⁻¹.

2. Description of the hotplate precipitation gauge

The hotplate precipitation gauge (shown in Figs. 1 and 2) consists of two identical, heated aluminum plates: one facing upward and exposed to precipitation (Fig. 1a) and the other facing downward mounted underneath the top plate (Fig. 1b). 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 ambient temperature and not by precipitation. The two plates are heated to nearly identical constant temperatures (above 75°C), which is hot enough to melt and evaporate small snow particles striking the plate in less than a second and large snowflakes within a few seconds. The plates are maintained at a constant temperature during wind and precipitation conditions by either increasing or decreasing the electrical current to the plate heaters. During normal windy conditions without precipitation, the plates cool nearly identically because of their similar size and shape. During precipitation conditions, the top plate cools because of the melting and evaporation of the precipitation and wind, while the bottom plate is only affected by the wind. The difference between the power required to heat the top plate compared to the bottom plate is then proportional to the precipitation rate. A typical surface
installation of the hot plate has the head located at a height of 2 m above ground. Further technical details of the hotplate are given in appendix A.

Three uniformly spaced concentric rings are placed orthogonal to each plate in order to prevent snow/rain particles from sliding off the top plate during high wind conditions (Fig. 1). Because of its disk shape, the hotplate has minimal effect on the airflow around it and thus does not require a wind shield. In addition, because all of the snow melts and evaporates, it does not require any glycol or oil, making it low maintenance. It does, however, require deployment at a flat and level site. The hotplate precipitation gauge has undergone 7 yr of testing at the National Center for Atmospheric Research (NCAR) Marshall Field Site (a site near Boulder, Colorado) as well as testing under more extreme conditions at Mount Washington, New Hampshire. In the next section we describe the hotplate algorithm, and in section 4 compare its performance to standard weighing precipitation gauges. In section 5, an evaluation of the commercial version of the hotplate manufactured by Yankee Environmental Systems, Inc., is discussed. Concluding remarks are made in section 6. More detailed technical information about the design and calibration of the hotplate is found in appendixes A and B.

3. Algorithm

a. Calculation of precipitation rate

The raw output of the hotplate system is the difference in power that is used to maintain the top and bottom plates at constant temperature. To convert this power difference to liquid-equivalent rate, a theoretical conversion factor was calculated, assuming that 100% of the heat of vaporization/sublimation from the precipitation is transferred to the hotplate. The conversion factor is based on the area of the hotplate ($A_h$), the heat capacity of water ($C_p$), the density of water ($\rho_w$), and the latent heat of sublimation ($L_s$) and evaporation ($L_e$). The resulting equations for the conversion factor are given by

$$
\text{Conversion factor} = \frac{A_h \cdot C_p \cdot \rho_w}{L_s + L_e}
$$
f_{\text{snow}} = \frac{1}{A_{\text{h}}(C_p + L_s) \rho_\text{w}} \times 1000 \text{ mm m}^{-1} \text{ 3600 s h}^{-1}, \\
(1)

f_{\text{rain}} = \frac{1}{A_{\text{h}}(C_p + L_s) \rho_\text{w}} \times 1000 \text{ mm m}^{-1} \text{ 3600 s h}^{-1}. \\
(2)

Using values of the latent heat of sublimation at 0°C = 2.834 × 10^6 J kg^{-1}, the heat capacity of water at 0°C = 4.218 × 10^3 J C^{-1} kg^{-1}, the density of water = 1 × 10^3 kg m^{-3}, and hotplate area of 8.844 × 10^{-3} m^2, the value of f_{\text{snow}} = 0.144. The value for f_{\text{rain}}, using a latent heat of vaporization at 0°C of 2.5 × 10^6 is 0.1628. In practice, this conversion factor was ~20% lower because of the imperfect heat transfer from the precipitation to the hot plate (losses to the air, e.g.). The actual conversion rates were determined by comparing the predicted precipitation rate from the hotplate to the measured rates from a GEONOR precipitation gauge in the Double-Fence Intercomparison Reference (DFIR) shield (see discussion below). The resulting value of the conversion factor f (mm W^{-1} h^{-1}) is given by the following:

1) for ambient temperatures greater than or equal to T_{\text{rain}} = 4°C, f = f_{\text{rain}} = 0.1219;
2) for ambient temperature less than or equal to 0°C, f = f_{\text{snow}} = 0.1118; and
3) for ambient temperatures between 0°C and T_{\text{rain}}, f = \text{linear combination of } f_{\text{snow}} \text{ and } f_{\text{rain}}.

The different conversion factors for rain and snow reflect the use of the latent heat of sublimation for snow and the latent heat of evaporation for rain.

The value of 4°C for the distinction between rain and snow was based on experience in Denver, Colorado. In actuality, the wet-bulb temperature of 0°C should be used to make this distinction because it accounts for the cooling of the particles resulting from sublimation. Future versions of the hotplate may include a sensor for relative humidity allowing this improvement to be made.

The sensor and reference plate temperatures are set such that the power difference (ΔP) in watts; the power of the sensor plate minus the power of the reference plate, (P_\text{w} - P_\text{r}) averages 0 W in the absence of precipitation. The top and bottom plates and heaters were made as identical as possible 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. It was found in practice, however, that ΔP often had a small dependence on wind speed during nonprecipitation conditions that needed to be accounted for. Thus, the equation to calculate precipitation rate can be given as

\[ \text{precipitation rate (mm h}^{-1}) = [\Delta P - (a + bU + cU^2)] f, \]

where f is the calibration factor, U is the wind speed (m s^{-1}), and a, b, and c are coefficients of the curve fit between ΔP and U during nonprecipitation conditions. One-minute average values of wind speed are calculated directly from the hotplate using a curve fit between the power of the lower plate power P_\text{r} and a measured 10-m wind speed as a function of temperature. The currently used equation is given below:

\[ U = \left[ \frac{(P_\text{w} - c_1)}{c_2(c_3 - T_a)} + c_5 \right]^{c_4}, \]

where c_1, c_2, c_3, c_4, and c_5 are constants determined by calibration and T_a is the ambient temperature (°C). Typical values of the constants are c_1 = 15, c_2 = 0.205, c_3 = 72, and c_4 = 1.25.

The output wind speed is representative of a 2-m wind speed (level of the hotplate). The commercial version of the hotplate provided by Yankee Environmental Systems (YES) has this 2-m wind speed calculation included in the factory calibration. It should be noted that the wind speed calibration was conducted in a flat environment, so estimates obtained in complex terrain should be used with caution.

Using Eq. (3), the precipitation rate is calculated every minute, and then a 5-min running average formed. If this 5-min average precipitation rate does not exceed a threshold of 2 W, it is assumed that it is not precipitating. A 2-W threshold is used to account for wind variations on the top and bottom plates and also the diurnal shortwave (SW)/IR heating–cooling of the hotplate. Further discussion of factors leading to the 2-W threshold is given in appendix A. Once the 5-min precipitation rate is greater than the threshold, precipitation is assumed to have started. During precipitation, rates are calculated every minute until the rate drops to zero.

A 2-h time series of the sensor power, reference power, and the power difference is given in Fig. 3. During the first 20 min of the time series, no snow is falling and the sensor and reference power traces are nearly equal, as expected. After 20 min, snow commences and the traces separate, with the sensor power being larger than the reference power. The delta power trace shows a power difference of approximately 10–20 W during this period.

Applying the conversion factors discussed above, the delta power trace shown in Fig. 3 can be converted to a snowfall rate trace and accumulation trace, as shown in Fig. 4. Note the highly variable snowfall rate observed by the hotplate at the 1-min time scale. This type of variability is observed in most snowstorms and indicates

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a finescale storm structure that is often smoothed out by accumulation gauges, which typically require a 10-min accumulation time period to calculate rate.

To verify the algorithm, a World Meteorological Organization (WMO) reference standard for liquid-equivalent snowfall rate measurements was deployed at the Marshall Field Site. This standard, the DFIR shield system (Golubev 1985a,b; Goodison et al. 1989; Fig. 5 herein), consists of two vertical double fences of 40- and 15-ft diameter with a GEONOR weighing gauge inside, which is also surrounded by a smaller, Alter shield. This reference also works extremely well for rain.

b. Accounting for snow undercatch resulting from wind effects

Comparison of the Desert Research Institute (DRI)/NCAR hotplate prototype 010 (hereafter called “original hotplate”) snow accumulation with snow accumulation from the DFIR (Fig. 5) revealed that the hotplate underestimated snow accumulations when the winds were above 1 m s⁻¹.

One of the first cases of this was evident on 10–11 April 2001, during which a snow event occurred with gradually increasing wind (Fig. 6). Note that a peak wind speed of 14.0 m s⁻¹ is reached at 1120 UTC.

During this event the difference between the hotplate accumulation and the GEONOR increased with increasing wind speed, as shown in Fig. 7, indicating a large undercatch by the hotplate. To further quantify this result, a ratio of the hourly hotplate accumulation to the hourly DFIR accumulation was formed. If the ratio is 1.0, then the hotplate is estimating the same accumulation as that of the

GEONOR in the DFIR shield. The results of plotting this ratio versus wind speed are shown in Fig. 8. Note that the catch efficiency decreases linearly with increasing wind speed. Thus, the catch of the hotplate is reduced by 50% for a wind speed of 5 m s⁻¹, and by 80% for a wind speed of 10 m s⁻¹. We speculate that wind effects maintain the collection efficiency near 0.2 at winds higher than 10 m s⁻¹ (as observed in the Denver blizzard cases discussed below and discussed further in appendix A). The new precipitation rate equation is then given as

\[ R_{\text{actual}} = R/E, \]  

where \( R \) is the uncorrected precipitation rate and \( R_{\text{actual}} \) is the corrected precipitation rate. The collection efficiency \( E \) is given from Fig. 8 using the hotplate wind speed \( U \) at 2 m adjusted to the 10-m level as

\[ E = 1.0 - 0.08U \quad \text{for} \quad U < 10 \text{ m s}^{-1} \]
\[ = 0.2 \quad \text{for} \quad U > 10 \text{ m s}^{-1}. \]  

The cause for the wind undercatch is not the formation of an updraft at the leading edge of the hotplate as in the weighing gauges discussed above, although this may be a factor at wind speeds greater than 10 m s⁻¹ (appendix A). The main cause for the undercatch is due to snow particles bouncing and/or sliding off the hotplate surface. As the winds increase, the particles have more momentum and a greater likelihood of bouncing or sliding off. An important feature of the hotplate designed to minimize this effect is the short concentric circular ridges on the top and bottom of the hotplate (Fig. 1). Another important consideration is that the surface of the hotplate needs to be hydrophilic rather than hydrophobic. This
allows the meltwater from any impacting particle to spread out on the surface rapidly and essentially “grab” the surface before sliding or bouncing off. The normal weathering of aluminum results in a hydrophilic rather than hydrophobic surface; thus, all of the hotplates are provided without any coating or anodization.

Returning to the 10–11 April 2001 snow event, the application of the wind correction yields a close match of the hotplate accumulation as compared to that of the GEONOR in the DFIR accumulation (Fig. 9). Other cases show a similar close correlation of the hotplate to the GEONOR in the DFIR accumulation when the wind speed correction is applied to the hotplate (Fig. 10). Additional testing during snowstorms since 2001 has shown that this correction curve applies for wind speeds up to 15 m s\(^{-1}\).

Applying both the wind catch correction and the wind correction from Eq. (3), false precipitation during nonprecipitation days have been reduced to less than 0.01 in. h\(^{-1}\) (0.25 mm h\(^{-1}\)). Based on these results the algorithm sets to 0 all of the precipitation rates less than 0.01 in. h\(^{-1}\) (0.25 mm h\(^{-1}\)), and thus requires a threshold of 0.01 in. h\(^{-1}\) (0.25 mm h\(^{-1}\)) before precipitation is recorded.

c. Accounting for solar and IR radiation

Both the sensor and reference plates are thermally influenced by their radiation environment. Direct sunlight on the sensor plate supplies energy-supplementing electrical power and is equivalent to a negative precipitation, which is obviously not recorded. In the occasional situation of precipitation from individually passing showers, this could result in an underestimate of actual precipitation. A more serious concern is that of radiation loss to a nocturnal cold sky, which is radiatively colder than the surface below the instrument, leading to an apparent continuous small precipitation rate. Such situations are taken into account by the 2-W threshold before indicating precipitation onset. The main impact of this effect

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5}
\caption{The DFIR shield with a GEONOR weighing gauge in the center at the NCAR Marshall Field Site. Diameter of the outer fence is 40 ft and the inner fence is 15 ft.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6}
\caption{A 10-m wind speed (m s\(^{-1}\)) and accumulation (in.) from the GEONOR in the DFIR shield for 11 Apr 2001.}
\end{figure}
is a higher threshold for the onset of precipitation (by ~0.1 mm h⁻¹) than otherwise would be possible (the current threshold is 0.25 mm h⁻¹). It should be noted that 0.25 mm h⁻¹ is equal to 0.04 mm min⁻¹, so the amount of water needed to be measured is quite small, and as a result quite challenging. See appendix A for more discussion of this issue.

d. Impacts of wind speed on the onset threshold of the hotplate

Another factor impacting the onset threshold of the hotplate and other gauges is the wind speed. As shown in Fig. 8, the collection efficiency of the hotplate is reduced at higher wind speeds. For a wind speed of 5 m s⁻¹ at hotplate level, the collection efficiency is 50%. At 8 m s⁻¹, the collection efficiency is 35%. In order for the hotplate to exceed the 2-W threshold, the precipitation during a wind of 5 m s⁻¹ needs to be two times higher than at 0 m s⁻¹, and at 8 m s⁻¹, it needs to be a factor of 2.85 higher, resulting in onset thresholds of 0.5 mm h⁻¹ at 5 m s⁻¹ and 0.7 mm h⁻¹ at 8 m s⁻¹. Because the wind correction factor for an Alter-shielded gauge is similar to that in Fig. 8, gauges using an Alter shield will also have the same increasing threshold with increasing wind speed. In the case of weighing gauges, the main impact will be a longer time for the threshold of precipitation to be reached. If the threshold is 0.2 mm, then a rate of 0.25 mm h⁻¹ during a wind of 5 m s⁻¹ would take over 1 h to be reached, while a rate of 0.5 mm h⁻¹ would reach the threshold in 30 min or so.

e. Need for a mean vertical velocity of close to zero over the plate

Because the hotplate precipitation signal is the difference between the top and bottom plate power, the hotplate needs to be sited on a flat and level site in order for the mean airflow to impact the horizontal plane of the hotplate at an angle of 0°. If there is a mean downdraft present, the hotplate will exhibit a false precipitation rate proportional to the mean vertical downdraft speed. If there is an updraft, the extra cooling of the bottom plate delays the onset of precipitation until a sufficiently high rate is achieved. Thus, deployment of the system in complex terrain, for instance, needs to account for mean vertical velocities associated with the siting of the sensor. A recent deployment of hotplates during the Vancouver, British Columbia, Canada winter Olympics required an increase of 0.25 mm h⁻¹ to the onset threshold to eliminate noise generated by the complex terrain.
4. Full winter season performance evaluation

In this section we evaluate the performance of the hot-plate for two winter seasons using the algorithm described above. The reference for snow measurement is a GEONOR gauge located in a DFIR shield at the Marshall Field Site as discussed in the previous section. Our previous studies have shown that the GEONOR in the DFIR shield meets or exceeds the National Weather Service (NWS) 8-in. can with a single Alter shield in all cases (Rasmussen et al. 2001, 1999). It also compares well with manual measurements made with a 30 cm x 50 cm flat pan every 10 min. This technique is the current standard for snowfall rate used by the SAE ground-deicing community [SAE Aerospace Recommended Practices (ARP) 5485]. In the following the hotplate is compared to the U.S. National Weather Service criteria for weighing snow gauge performance as used by the NWS Automated Surface Observing System (ASOS) program office (Greeney et al. 2007).

NWS criteria

1) The absolute value of the difference between the GEONOR in the DFIR hourly accumulation and the hotplate hourly accumulation is less than or equal to 0.02 in. (0.5 mm), or 4% of the hourly total, whichever is greater, and;
2) there is no measurable precipitation during non-precipitating conditions (<0.12 mm in an hour) (Greeney et al. 2007).

EVALUATION OF SNOW EVENTS AT MARSHALL USING THE NWS CRITERIA

Snow storms from 2001 and 2002 observed at the Marshall Field Site were analyzed, consisting of 137 h of snowfall in 2001 and 138 h in 2002 (Table 1). Days without precipitation were also analyzed. All 137 h with precipitation in 2001 passed the above criteria. A histogram of the hourly accumulation errors for both seasons is given in Fig. 11, showing that the error has a Gaussian distribution with a mean of zero, and that only 1 h exceeded the NWS criteria. A scatterplot of the accumulation from the hotplate and the GEONOR in the DFIR is shown in Fig. 12, with the outlier point indicated. This point occurred for the highest wind speed observed (10 m s⁻¹; see Fig. 13), and the hotplate algorithm overestimated the accumulation by a small amount over the specification. The correlation coefficient between the hotplate and the GEONOR in the DFIR is 0.98, indicating a very high correlation between the two with the bias close to 0. The error also shows very little bias with wind speed, as shown in Fig. 13.
The 1838 h of nonprecipitation from the same period passed the above criteria 82.6% of the time (Table 1). Individual hours of hotplate data were also analyzed to determine the bias in accumulation based on precipitation type. The results (Fig. 14) show that unrimed snow had the highest collection efficiency, while rimed and heavily rimed particles had the lowest. This trend follows the expected behavior of rimed particles to bounce off the hotplate more than unrimed snow particles. Note that snow pellets–graupel still have a collection efficiency of 0.6, despite their tendency to bounce off solid surfaces because of their nearly spherical shape and relatively high density.

The nonprecipitation days during this period had false reports of accumulations no greater than 0.005 in. h\(^{-1}\) (0.125 mm h\(^{-1}\)) 99.9% of the time (Fig. 15), indicating good performance of the algorithm during nonprecipitation events as well.

5. Case study evaluation of commercial hotplate manufactured by Yankee Environmental Systems, Inc.

In the following, cases comparing two commercial versions of the hotplate described above are evaluated using a variety of snow and rain events. The commercial hotplate is based on the original hotplate but includes a circuit board heater instead of the thin film heater on the original unit. Other improvements include a more compact electronics box that is mounted on the hotplate pole below the head and the ability to measure precipitation rates up to 35 mm h\(^{-1}\) through the use of a higher voltage supply.

a. 10–11 April 2005 rain/snow event

A rain event started just before 0530 UTC 10 April 2005. Around 1000 UTC the rain transitioned to snow and ice pellets and continued on and off until 1130 UTC 11 April. Observations from a Light Emitting Diode Weather Identifier (LEDWI) were used along with a collocated Weather Identifier and Visibility Sensor (WIVIS) to determine the precipitation type. The WIVIS
is a recently updated version of the LEDWI manufactured by ScTI. 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 GEONOR weighing snow gauge in a WMO standard DFIR shield (Fig. 16).

The accumulation from each hotplate is nearly identical to the DFIR accumulation during the rain period from 0600 to 1000 UTC. The accumulation of the hotplates during the first half of the snow period between 1000 and 1600 UTC is within 5% of the DFIR. Between 1600 and 2200 UTC, the accumulation of all three hotplates is ~1 mm, while the DFIR accumulation is close to 3 mm. This period featured winds between 5 and 10 m s\(^{-1}\), which results in a hotplate collection efficiency between 0.5 and 0.25. The observed DFIR rate during this period was ~0.75 mm h\(^{-1}\); thus, the rate that the hotplate experienced a wind undercatch ranges from 0.35 to 0.18 mm h\(^{-1}\). Because the threshold rate for the hotplate is 0.25 mm h\(^{-1}\), much of this period was below detectable, resulting in the observed undercatch.

The wind speed derived from the hotplate reference plate power and ambient temperature adjusted to a 10-m level using a standard logarithmic relation was compared with an R.M. Young propeller anemometer mounted at 10-m AGL (Fig. 17). Both YES hotplates show agreement within ±1 m s\(^{-1}\) to the propeller anemometer. The one-to-one comparison shows a correlation of 0.98 between the hotplate and anemometer wind speeds.

b. 27–29 April rain–snow 2005 event

A rain event started at 2300 UTC 27 April 2005. Around 0030 UTC 28 April, the rain transitioned to snow and continued through 1730 UTC 29 April. The two YES hotplates accumulations were within 5% of the DFIR for the event (Fig. 18).
During this storm the propeller anemometer iced up and stopped reporting at 0400 UTC 28 April. Because the hotplate measures the wind speed using the bottom plate, a reliable wind speed measurement was maintained by both hotplates for the entire event despite the severe icing (Fig. 19).

c. Two Denver blizzards: 20–21 and 28–29 December 2006

A significant test of the hotplates occurred during two blizzards that severely impacted Denver and the Colorado Front Range during December 2006. Both events were characterized by winds over 15 m s\(^{-1}\) and snowfall rates over 8 mm h\(^{-1}\) liquid equivalent. The first blizzard occurred on 20–21 December 2006 and the second on 28–29 December 2006. These two unprecedented events provided a rigorous test of the Yankee hotplate under severe wind and high rate conditions.

The snowfall rates and winds, as measured by the TIP7 hotplate (a Yankee hotplate manufactured after the two Yankee hotplates mentioned above) at the Marshall Field Site for the 20–21 December 2006 blizzard, are shown in Fig. 20. Note that the winds were between 6 and 12 m s\(^{-1}\) during the event, and that rates as high as 7 mm h\(^{-1}\) occurred for a short time period. Rates varied between 2.0 and 6 mm h\(^{-1}\) in the time range of a few minutes, showing the highly variable nature of this snow event and also the ability of the hotplate to measure changes on the scale of minutes. The comparison of the hotplate accumulation to the GEONOR in the DFIR accumulation during this event is shown in Fig. 21. Note that the hotplate accumulation was within 1% of the GEONOR in the DFIR accumulation for the first 16 h of the event. During the last 16 h the hotplate slightly overestimated the accumulation, ending up with hotplate accumulation that was 3% more than the DFIR accumulation by the end of the 27-h event.

As mentioned above, a second blizzard occurred on 28–29 December 2006, and the comparison of the hotplate to the GEONOR in the DFIR is shown in Fig. 22. As was the
case on 20 December, the agreement is very good throughout the significant accumulation period of the event (within 5% of the DFIR accumulation for the first 12 h). At the end, the hotplate underestimated the accumulation, ending up with a 7% undercatch for the entire event. Overall, the hotplate performed extremely well during both of these blizzards, indicating that the wind correction given in Fig. 8 is robust for both low and high wind events.

6. Error analysis

To quantify the error structure between the hotplate and the GEONOR, we calculated the nondimensional error for the two blizzard cases and a few other smaller storms during November 2006 and January 2007 at the Marshall Field Site. The nondimensional error is defined as the 10-min smoothed hotplate rate minus the 10-min average rate from the GEONOR in the DFIR divided by the same. This provides an estimate of typical deviations of the hotplate from the GEONOR in the DFIR over 10-min periods. Errors are calculated every minute using the 10-min averages. The results are shown in Fig. 23, indicating a Gaussian structure to the errors and a mean bias of only 0.05 (the hotplate slightly overestimates). Considering that this is a Gaussian distribution with standard deviation of 0.25, this indicates that 69% of the hotplate rates are within 25% of the DFIR 10 min rate, and that 95% of the hotplate rates are within 50% of the DFIR 10-min rate.

7. Discussion

The hotplate snow/precipitation gauge represents a new concept in precipitation measurement that takes advantage of the high latent heat of melting and evaporation of water to diagnose the 1-min liquid-equivalent snowfall/precipitation rate. The advantage of this device over traditional weighing gauges (such as the GEONOR, Vaisala VRG, and OTT) is the high resolution (1-min rates versus 10-min average rates in weighing-type gauges); the complete evaporation of the precipitation, which removes the need to empty the bucket or to use glycol and oil in the weighing buckets; and the small footprint, eliminating the need for a shield to increase catch efficiency. The onset threshold is similar to current weighing gauges (near 0.25 mm h\(^{-1}\)). Performance of the hotplate is similar to an Alter-shielded GEONOR gauge.

The other categories of precipitation sensor involves optical or radar devices such as the FD12P, HSS (optical), or Precipitation Occurrence Sensor System [POSS; short-range FMCW radar (Sheppard and Joe 2008)]. The main shortcoming of optical and radar devices is the lack of information on the snow density. Because optical devices and radar mainly measure particle volume, the lack of information on snow density prevents accurate estimation of liquid-equivalent snowfall rate. These devices, however, have an advantage over the hotplate and other...
weighing devices at low snowfall rates and high wind conditions because they are quite sensitive to low rates and relatively insensitive to wind speed (Sheppard and Joe 2008). A system consisting of a hotplate combined with an optical–radar device provides a potential method to accurately cover liquid-equivalent snowfall rates at nearly all rates and at high wind speeds. We are currently testing such a system and the results show promise and will be reported on in a future publication.

While not extensively discussed in this paper, the hotplate performs well in rainfall rates up to 35 mm h\(^{-1}\), after which it saturates. Considering that the vast majority of rainfall falls at rates less than this, the hotplate can provide reasonable coverage in rain as well.

8. Conclusions

A hotplate precipitation gauge has been described consisting of two heated plates used to estimate precipitation mass by measuring the power required to melt and evaporate precipitation on the upward-facing sensor plate. The power is converted to a precipitation rate using the appropriate latent heat of sublimation or evaporation depending on precipitation type. The current version of the hotplate makes the inference of precipitation type based on temperature.

The system has no moving parts and no fluids to change and does not require a wind shield. The hotplate has elegance and uniqueness in that the precipitation sensor (the top) is essentially collocated with the wind speed sensor (the bottom), with the identical size, shape, and temperature of each ensuring an identical averaging area and response time. Of equal importance is that the two are separated by a mere 1.5 cm so that the differential velocity (and air temperature) between airflow over the top and bottom is minimal.

The hotplate performs best under relatively low wind conditions. As with most gauges, low rates during high wind conditions are a challenge.

The hotplate was extensively evaluated for snow conditions and found to meet National Weather Service and WMO standards as follows:

1) The hotplate system measures liquid-equivalent snowfall rates every minute from 0.25 to 35 mm h\(^{-1}\) within National Weather Service standards for solid precipitation measurements and to within 25% of the WMO standard snow-measuring wind-shielded (Double Fence Intercomparison Reference shield) gauge 69% of the time.

2) The hotplate is able to measure wind speed even during severe icing conditions.

The hotplate also performs well for drizzle and rainfall rates up to 35 mm h\(^{-1}\) (Gultepe 2008).

To achieve the above performance for both precipitation rate and wind speed, the hotplate needs to be deployed in a level configuration at flat and level sites in order to avoid mean vertical motions that can bias the precipitation and wind estimates. While deployments of the system have been made in complex terrain, the siting in this case should be in a forest clearing and precipitation onset thresholds may need to be increased slightly.

To improve the system performance during high winds and low rates, the hotplate could be combined with an optical sensor that is able to measure precipitation under these conditions. One of the authors of this paper has created such an integrated system under Federal Aviation Administration (FAA) funding for ground deicing purposes using the Vaisala PWD-22 as the optical sensor and the hotplate as the liquid water equivalent sensor.

The high update rate of the hotplate (precipitation rate, wind speed, and air temperature every minute) provides an ideal gauge for real-time applications, such as aircraft deicing and road weather. Its measurement of precipitation rate every minute provides the potential for long-term monitoring of precipitation characteristics in the context of climate change (Hallett and Rasmussen 2006) if combined with optical sensors to account for low precipitation rates occurring during high winds. It can also be used as an accumulation gauge by integrating the 1-min rates over time.

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APPENDIX A

Design and Theoretical Considerations

Design considerations

1) Principle of operation

The hotplate measures the amount of power needed to keep the top and bottom hotplates at the preset temperature (typically >70°C) while the hotplate is experiencing cooling resulting from forced convection, radiation, and latent heat release of precipitation.

(i) Forced convection from a flat disk

Forced convection from a flat disk (Kobus and Wedekind 1995) can be written as

\[ Q_c = \frac{k_c X (T_a - T_p)}{\text{Nu}} \]  
(A1)

\[ \text{Nu} = 0.356(\text{Re})^{0.6}(\text{Pr})^{1/3} \]  
(A2)

where Nu is the Nusselt number, Re the Reynolds number, and Pr the Prandtl number (see Pruppacher and Klett (1997) for the definition of the nondimensional numbers]. \( T_a \) the ambient air temperature (°C), \( T_p \) the plate temperature (°C), \( k_c \) the thermal conductivity, \( X \) a constant depending on the geometry, and \( Q_c \) the heat transfer (cal s⁻¹) from the disk. This equation set will likely be modified from a flat disk resulting from the presence of the concentric rings; however, we do not expect the fundamental form of the equations to change. When no precipitation is falling and radiative effects are small (see next section), the rate of cooling resulting from wind on the top and bottom plates is nearly identical, and thus the subtraction of the top plate power from the bottom plate power results in a near-zero value. In practice, however, radiative effects cause the difference to vary from zero.

(ii) Radiative cooling/heating effects

Both the top and bottom plates will emit radiation at the emissivity of aluminum at the temperature of the plates, which is significantly less than that of a blackbody. They will also absorb radiation from the environment at both short and long wavelengths. At night, the top plate will typically cool more than the bottom plate resulting from the bottom plate receiving emission from the relatively warm ground, while the top plate receives emission from the colder sky. The presence of clouds can make the downwelling sky radiation larger than but typically not as large as the radiation from the ground. During the day, direct solar heating on the top plate is typically larger than the reflected solar intercepted by the bottom plate; thus, an imbalance is present. In practice, the magnitude of these radiation effects is on the order of 1–2 W of heating–cooling per hour, which leads to a power consumption that is not due to precipitation and therefore noise to the system. To prevent this noise from causing false precipitation accumulations, a noise threshold of 1–2 W h⁻¹ is included in the hotplate algorithm. This is the equivalent of requiring a threshold rate of 0.25 mm h⁻¹ before natural precipitation can be declared to be present. Future improvements to the hotplate will include a direct measurement of the radiation to help eliminate this noise source.

(iii) Latent heat release

When frozen precipitation impacts the hotplate, it first melts, releasing the latent heat of melting, and then evaporates, releasing the latent heat of evaporation. The rate of release depends on the temperature of the plate, with higher temperatures obviously causing faster melting and evaporation. Laboratory testing by the authors has shown that snowflakes melt and evaporate within a minute for plate temperatures >70°C. The above factors were taken into account in order to come up with the proper design of the hotplate resulting in the following design goals:

Design goal 1: Heat loss from the top and bottom plates should be as similar as possible during conditions with no precipitation in order for the baseline value of \( \Delta P \) to be as close to zero as possible.

Design goal 2: Precipitation impacts the top plate only, with little or no impaction on the bottom plate. This allows subtraction of the power of the top plate from the bottom plate to obtain the power associated with only the precipitation that melts and evaporates on the top plate.

Design goal 3: Most precipitation melts and evaporates within a minute. This allows us to use 1 min as the fundamental resolution of the instrument.

Design goal 4: The temperature of the two plates will be set to be equal to each other as much as possible in order for the heat transfer from the top and bottom plates to be as equal as possible. The temperature of the plates is determined by the heater resistance. The
resistance of the heat varies with temperature and therefore it can be used as a mechanism to set the hotplate at a specific temperature. The software sets a resistance set point to which the system is driven. Power usage is determined by measuring volts and amps.

2) HOTPLATE SITING CONSIDERATIONS

In order for the heat transfer on the top and bottom plates to be nearly equal, the winds need to impact the hotplate nearly parallel to the orientation of the plate. If the winds impact the hotplate at an angle, the plate receiving the direct force of the wind will cool more than the more shielded plate, resulting in a bias due to the wind impact angle. Thus, this type of sensor is most effective at an airport or other flat site where winds parallel to the hotplate can be ensured. This also means that a key-mounting and maintenance issue for the hotplate is to ensure that the plates are within $1^\circ$–$2^\circ$ of level.

3) DESIGN, CONSTRUCTION, AND OPERATING CRITERIA

(i) Physical design considerations

The size of the plates was selected as 13-cm diameter, which is large enough to permit collection of falling rain or snow particles such that reasonable statistics may be expected over a 1-min period, yet small enough that power demands during heavy precipitation events and high wind speeds are not unrealistic. Sufficient power for the signal-to-noise ratio must allow detection of the 0.25 mm h$^{-1}$ precipitation rate.

The thickness of the dual-plate sensor assembly is determined by 1) the thickness of the thermal insulation that is used to inhibit crosstalk between the plates (about 5 mm), 2) the plate heaters, 3) the adhesive thickness, and 4) an aluminum plate of sufficient thickness for mechanical rigidity but maximizing thermal conduction, ~1 mm. With concentric ridges to inhibit particle loss during splash and sliding of wind-borne precipitation, a total thickness of about 15 mm is practical.

An edge mount attached to a metal ring that passes through the center of the sensor assembly with insulation on both sides supports the system. Center-mounted configurations were tried in early versions of the hotplate and found to bias the lower plate heat transfer because of the generation of eddies by the mounting pole.

(ii) Temperature control considerations

The temperature control system senses the total resistance of the heater, related by the resistance temperature of the heater material (copper is convenient) at 0.1-s intervals. This is chosen as the thermal time constant of a step change of ambient temperature to penetrate to the heater from precipitation impacting the metal plate. The plate resistance temperature is selected to be between 75$^\circ$ and 110$^\circ$C to maintain the particle evaporation on impact without flooding to the maximum rate to be measured, for precipitation, this is about 35 mm h$^{-1}$ based on measurements from rain events. Power is measured (voltage and current) and recorded or averaged from 0.1-s intervals. Control is achieved through a standard equation related to the resistance offset, with three variables, through a variable duty cycle. Data output is at either 1-s or 1-min intervals. A change of 0.5$^\circ$C causes the duty cycle to be activated. Field and laboratory calibration is necessary for wind speed and precipitation collection efficiency.

(iii) Considerations on the choice of the plate heaters

The heater on each plate is controlled to be near isothermal by choice of an average resistance of about 5 ohms, the set point, in increments of 0.01 ohms, which is equivalent to 0.02$^\circ$C. The selected temperature is determined by a combination of likely precipitation rate, wind speed, and ambient temperature to be consistent with complete evaporation without flooding of the top plate and minimum power consumption under quiescent conditions. Temperatures ranging from $+70^\circ$C to $+110^\circ$C are convenient. An approximation of the heat flow regime is the assumption that heat from each plate heater is negligible through the insulated layer between the top and bottom plates, and also negligible through the sides of the system. Thus, heat flows from the heater through the film and adhesive directly to the aluminum plate, which then is conducted to the plate surface to be lost by latent heat of evaporation of collected particles, surface airflow, and radiation. In practice the major heat resistance (and thermal gradient) lies in the heater and its adhesive.

(iv) Thermal regimes

Several thermal regimes occur. With zero wind speed (less than a few centimeters per second), both plates lose heat by natural convection, with a closed eddy above the upper plate, which is liable to shed, and airflow upward around the lower plate, which tends to stabilize the upper eddy. With modest horizontal airflow $>50$ cm s$^{-1}$ the heat transfer changes to a sloping flow, and increasing heat loss. With further increase of airflow (to less than several meters per second) flow over the two plates becomes less influenced by convection and a similarity develops between the top and bottom. This leads to a near-linear relationship between the top and bottom power requirements with increasing wind speed.

With a further increase of wind speed in excess of 10 m s$^{-1}$, a regime is entered where particle fall velocity no
longer exceeds the upward flow over the plate. At the same time, increasing turbulence occurs for plate flow, (characterized by Re) leading to an increasing particle capture. The measured turbulence of the plate flow power over a longer time scale (10 min) provides a measure of this effect.

At higher wind speeds, >15–20 m s\(^{-1}\), the turbulence increases providing an increasing capture of snow on the top plate providing opportunity for empirical correction for lowered collection with increasing wind speed.

### APPENDIX B

#### Calibration Procedures

This appendix describes calibration procedures for the hotplate. The following are useful to confirm functionality as necessary; the initial factory calibration and heater resistances should normally remain unchanged.

a. **Confirming the estimation of precipitation rate**

Use a syringe producing 1–3-mm diameter drops; from a height of about 10 cm distribute drops over an operating plate. Use a known volume of water over a fixed time, as 2.8 ml over 1 min, with 10 sequential tests to take start up and stop conditions into consideration. (This simulates \(\frac{1}{2}\) in. h\(^{-1}\).) Choose near-calm conditions, with temperatures from 0\(^{\circ}\)C to 10\(^{\circ}\)C for convenience. (The heat content of the water may be neglected with respect to latent heat effects; a correction for snow in relation to rain as ice–water vaporization latent heat is required, as 620–540.) Repeat for a variety of precipitation rates.

b. **Sensor resistance as an indication of temperature**

Place the entire sensor head in one end of a sealed plastic sleeve, immerse it in a bath or another controlled temperature environment, such as a freezer, and give it time to equilibrate. Measure each heater resistance over a range of temperatures from \(<-20^\circ\)C to \(>+50^\circ\)C.

c. **Wind tunnel calibration for wind and variation of sensor and reference power over likely wind speeds**

Should a wind tunnel be available, power requirements for the top and bottom plates may be measured as wind speed is increased. It is to be remembered that in the open, an approximate log wind vertical profile, modified by stability, is to be expected, whereas in a wind tunnel, the sensing head needs to be located about \(\frac{1}{2}\) up from the bottom of the tunnel to approximate such horizontal shear. Field data may be more useful, but may also be subject to changing stability. Uncertainties of the wind speed calibration derive from these considerations.

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