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Evaporation from weighing precipitation gauges: impacts on automated gauge measurements and quality assurance methods

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Abstract

The effects of evaporation on precipitation measurements have been understood to bias total precipitation lower. For automated weighing-bucket gauges, the World Meteorological Organization (WMO) suggests the use of evaporative suppressants with frequent observations. However, the use of evaporation suppressants is not always feasible due to environmental hazards and the added cost of maintenance, transport, and disposal of the gauge additive. In addition, research has suggested that evaporation prior to precipitation may affect precipitation measurements from auto-recording gauges operating at sub-hourly frequencies. For further evaluation, a field campaign was conducted to monitor evaporation and its impacts on the quality of precipitation measurements from gauges used at US Climate Reference Network (USCRN) stations. Collocated Geonor gauges with (nonEvap) and without (evap) an evaporative suppressant were compared to evaluate evaporative losses and evaporation biases on precipitation measurements. From June to August, evaporative losses from the evap gauge exceeded accumulated precipitation, with an average loss of $0.12\,\mathrm{mm\,h^{-1}}$. However, the impact of evaporation on precipitation measurements was sensitive to calculation methods. In general, methods that utilized a longer time series to smooth out sensor noise were more sensitive to gauge (−4.6 % bias with respect to control) evaporation than methods computing depth change without smoothing (< +1 % bias). These results indicate that while climate and gauge design affect gauge evaporation rates computational methods can influence the magnitude of evaporation bias on precipitation measurements. It is hoped this study will advance QA techniques that mitigate the impact of evaporation biases on precipitation measurements from other automated networks.

1 Introduction

In situ observations of precipitation are an integral component of hydrological studies (drought, flooding, etc.), and are often used to correct and validate radar, satellite, and modeled estimates of precipitation (Wang and Wolff, 2010). However, point measurements of precipitation have well known biases (Sevruk and Hamon, 1984; Goodison et al., 1981; Lanza et al., 2005; Sieck et al., 2007) (e.g. wind, gauge evaporation, wetting factor, and observer errors) that impact the quality of precipitation measurements. International studies organized by the World Meteorological Organization (WMO) have fostered partnerships and collaborations since the 1990s focused on these sources of error in an effort to improve precipitation measurements (Sevruk et al., 2009). A majority of these investigations have concentrated on wind-induced under-catch and the development of methods to correct for such errors (Survek et al., 2009). However, for automated networks with well-shielded precipitation gauges, such as the US Climate Reference Network (USCRN), gauge evaporation is also an important source of observational error (WMO, 2008).

Yang et al. (1998) defines gauge evaporation errors as the amount of precipitation loss prior to observation, which suggests that the effects of gauge evaporation can be mitigated with frequent observations (WMO, 2008). The magnitude of evaporative loss from precipitation gauges vary by season (Dunne and Leapold, 1978; Aaltonen et al., 1993; Strangways, 2004) and are more pronounced in warm-dry climates (WMO, 2008), due to greater evaporative demand. Gauge design has also been found to effect evaporation rates (Survek, 1974; Golubev et al., 1992). Gauges with an open, more exposed (no-funnel) reservoir had higher evaporation rates as more of the internal moisture (internal reservoir and walls) are exposed to the atmosphere. Golubev et al. (1992) noted the non-funnel capped Tretyakov gauge had evaporation rates ($1.15\,\mathrm{mm\,day^{-1}}$) six times greater than the funnel-capped standard 8″ gauge ($0.19\,\mathrm{mm\,day^{-1}}$) used at Cooperative Observer (COOP) stations. Precipitation biases due to gauge evaporation can be up to 4 % (WMO, 2008), which is nearly equivalent to the 5 % annual average change in precipitation reported in the most recent National assessment (Walsh et al., 2014). To improve the quality of precipitation measurements, the WMO (2008) suggest taking observations frequently to reduce the magnitude of evaporation per observation cycle and making use of evaporative suppressants.

However, recent research comparing USCRN with COOP stations indicate gauge evaporation can bias observations taken at a sub-hourly frequency (Leeper et al., 2014a). Despite COOP gauges monitoring precipitation from an unshielded gauge, USCRN observations of liquid precipitation (from a well-shielded gauge) were slightly less than COOP. These results are contrary to other studies comparing shielded and unshielded gauges (Groisman et al., 1991; Golubev et al., 1992; Duchon and Essenburg, 2001). A portion of this dry bias, among others, was attributed to computational methods within the quality assurance (QA) system that were sensitive to sensor noise and gauge evaporation (Leeper et al., 2014a). Addition analysis, using a precipitation generator that included sensor noise and gauge evaporation signals, revealed that calculations of depth change was sensitivity to gauge evaporation (Leeper et al., 2014b). For instance, evaporative decreases in gauge depth occurring immediately prior to a precipitation event lead to overestimates of the initial gauge depth, which resulted in an underestimate of total precipitation (Leeper et al., 2014b). These results ultimately lead to the development of a new QA system that was less sensitive to sensor noise and gauge evaporation in artificial tests (Leeper et al., 2014b). These studies suggest that while evaporative demand of a station's location and design of the precipitation gauge influence gauge evaporation rates, the techniques or QA methods used to evaluate depth change (quantify precipitation) may impact the magnitude of gauge evaporation bias on precipitation measurements.

To evaluate the impact of gauge evaporation on QA processes, a field experiment was conducted over the summer of 2013 using two Geonor T-200B all-weather precipitation gauges initialized with and without an evaporative suppressant. The purpose of this study is to quantify evaporative losses from the Geonor gauge used at USCRN stations and evaluate the effectiveness of calculation methods to monitor precipitation at sub-hourly frequency without the use of evaporative suppressants. To the authors' knowledge, this is the first study to quantify evaporative losses from the Geonor T-200B gauge. Given that the impacts of gauge evaporation on precipitation measurements extends to other networks beyond the USCRN, this study may provide valuable insights to the development of QA methods resistant to evaporative biases. This is particularly true of networks operating gauges with an exposed reservoir and no evaporative suppressants.

2 Methodology

To observe precipitation, the USCRN uses the all-weather Geonor T-200B gauge equipped with redundant load sensors shown in Fig. 1a. In addition, the Geonor has a similar design to the Russian Tretyakov gauge, with an open vertical shaft and exposed internal reservoir (Fig. 1b). The Geonor gauge can detect changes in gauge depth of up to one hundredth of a millimeter and from field tests reliably report precipitation to an accuracy of 0.2 mm (Baker et al., 2005).

To quantify evaporation rates from the Geonor gauge and evaluate QA performance, a field experiment was performed over the 2013 summer (June to August) at the NOAA/FAA/NCAR Winter Precipitation Test Bed in Marshall, CO (described in Rasmussen et al., 2012). The campaign consisted of two identical Geonor T-200B gauges collocated within 10 m as shown in Fig. 2. The northern gauge (evap) was not setup with an evaporative suppressant and was compared against the southernmost gauge (nonEvap) that had a suppressant added, which served as a control. Using an independent rain detector (Vaisala DRD11A, Helsinki, Finland) to differentiate between wet and dry periods, changes in gauge depth from the paired gauges were used to quantify evaporative loss (during dry periods) and evaluate evaporation biases on precipitation measurements during rainy conditions.

The most direct approach to quantify evaporative loss from the Geonor gauge is to compare depth changes between evap and nonEvap gauges over dry periods. Changes in depth were evaluated hourly from one-minute observations by subtracting the last minute depth from the first, and then averaging over the redundant sensors in each gauge. To evaluate the sensitivity of gauge evaporation to atmospheric conditions, air temperature (Thermometrics 1000 Ω Platinum Resistance Thermometer, Northridge, CA, USA, housed in a MetOne 0766B Fan Aspirated Radiation Shield, Grants Pass, OR, USA), humidity (Vaisala HMT337, Helsinki, Finland), and wind speed (MetOne 014A Wind Speed Sensor) were monitored throughout the study period. In addition, a USB temperature logger (EL-USB-1 USB temperature logger, Lascar Electronics, Salisbury, UK) was submerged within the reservoir of the evap gauge to observe internal water temperature and estimate evaporative demand from within the gauge.

To evaluate QA performance, gauge data from the collocated evap and nonEvap gauges were processed through the two USCRN QA systems. The one-minute observations of gauge depths were aggregated to five-minute periods by simply taking the minute observation corresponding to each fifth minute period within the hour (5, 10, 15, . . . ,55). The initial QA methodology uses a pairwise approach to combine redundant observations of depth change and will be referred to as pairwise. The newer methodology assigns weights to the redundant measures of gauge depth (wAvg) to compute a weighted average. These two QA systems also differ on how depth change is computed. The pairwise method averages gauge depth data from the previous two hours to smooth sensor noise and establish a reference depth from which to evaluate depth change. This differs from the wAvg method, which sets the reference depth to the previous gauge depth without any smoothing. The magnitude of observation biases and sensitivity of QA approaches to gauge evaporation will be evaluated by comparing QA calculated precipitation measurements from evap and nonEvap gauges. More information including detailed descriptions of the two QA methods is available in Leeper et al. (2014b).

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

3 Results

3.1 Study period conditions

Over the three-month study period, air temperature and total precipitation were typical of Boulder Colorado summers that have an average (1893–2013) temperature and precipitation total of 21.2 °C and 131.3 mm respectively (COOP 050848; http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?co0848). Air temperature ranged from 34.3 to 5.7 °C with a slightly warmer mean (21.3 °C) than the gauge evaporation study conducted in Valdai Russia by Golubev et al. (1992). The atmosphere was also drier with mean relative humidity and dew point temperatures of 44.6 % and 7.6 °C respectively. These conditions were ideal for a gauge evaporation field study, which was reflected in large vapor pressure deficits of 2.6 kPa on average. Vapor pressure deficit, the difference between vapor pressure of saturated air and current atmosphere conditions, is directly proportional to evaporation rates (Dunne and Leopold, 1978). From June to August, there were a total of 29 precipitation events (continuous precipitation with two or more hours of no precipitation between events), totaling 244 h of atmospheric wetness as observed from the collocated rain detector. The results include two subsections: dry conditions to quantify evaporative losses from the Geonor gauge, and wet conditions to evaluate the impact of gauge evaporation on reported precipitation.

3.2 Dry conditions

Comparisons of depth change between gauges clearly reveal an evaporation signal (Fig. 3). Over the three-month study period, evaporative losses from the evap gauge totaled 228.5 mm over dry non-rainy hours. Similar losses in gauge depth were not found from the nonEvap gauge (2.6 mm). Average hourly losses from evap and nonEvap gauges over the dry period were 0.122 (±0.07) and 0.001 (±0.02) mm h^{-1} respectively. Reductions in depth from the nonEvap gauge were of similar magnitude to the NWS standard 8″ gauge reported in the Golubev et al. (1992) study. Given average losses were well below the accuracy and near the precision of the instrument, depth changes over the dry period from the nonEvap gauge were considered negligible.

Evaporative losses from the evap gauge were well correlated with atmospheric conditions conducive for evaporation. Average gauge losses were generally greatest during warm (Fig. 4a) and dry (Fig. 4b and c) conditions when evaporative demand was highest. However, surface winds seemed to have somewhat less impact on gauge evaporation, with reductions in gauge depth observed regardless of wind speed (Fig. 4d). The increase in gauge depth at lower winds speeds (between 0 and 2 $\mathrm{m\,s^{-1}}$) may be related to condensation buildup on the gauge reservoir during the early morning hours when surface winds were generally calm. Regardless of atmospheric conditions, changes in nonEvap gauge depth over dry hours were negligible compared to the evap gauge.

Similarly, diurnal variations in gauge depth were larger for the evap than nonEvap gauge (Fig. 5a). Over the diurnal cycle, evap depth change was mostly negative with the largest average reduction of 0.24 $\mathrm{mm\,h^{-1}}$ at 18:00 LT when reservoir (water) temperatures were warmest (Fig. 5b). A diurnal signal was also detected from the nonEvap gauge, albeit over a much smaller range that was not as systematically negative. The largest average increase (0.03 $\mathrm{mm\,h^{-1}}$) and decrease (0.04 $\mathrm{mm\,h^{-1}}$) over the diurnal scale from the control (nonEvap) gauge were considered negligible. However, it is interesting to note that both evap and nonEvap gauges had small rises in gauge depth near 06:00 LT, which may indicate condensation buildup on the reservoir bucket as noted previously.

3.3 Wet conditions

The impact of gauge evaporation on calculated precipitation was discernable, but dependent on the QA method. Precipitation differences between evap and nonEvap gauges were generally larger when using the pairwise algorithm (Fig. 6). Overall, the pairwise method reported 3.0 mm (4.9 %) more precipitation from the nonEvap than evap gauge, with the nonEvap gauge reporting 0.1 mm more precipitation per event

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

(see Table 1). The wAvg algorithm reported 0.2 mm (−0.3 %) less precipitation from the nonEvap gauge for a negligible average event difference of +0.01 mm event^{-1}. Time series of the accumulated precipitation difference between gauges (nonEvap minus evap) reveal that the pairwise method consistently reported more precipitation from the nonEvap gauge. Conversely, wAvg differences were variable in sign, which likely reflects natural variations in the spatial distribution of precipitation over the three month study period.

Examination of QA processes revealed that methods used to determine depth change within the algorithms impacted their sensitivity to gauge evaporation. To compute depth change, both QA methods compare current gauge depth with a reference depth (currentDepth – referenceDepth). Pairwise, which calculates a reference depth at the beginning of an event as the average of previous depths (two hours), tended to report negative depth changes prior to precipitation events (Fig. 7a–f). In other words, the time-averaged (two-hour) reference depth was greater than the current depth, as result of gauge evaporation. This biases total precipitation since positive increases in gauge depth must surpass the evaporative deficit and exceed 0.2 mm to be detected. In event 18, the over estimation of reference depths using the pairwise method resulted in missed precipitation. For the same event, precipitation was calculated by pairwise from the nonEvap (control) gauge with little or no negative depth change reported prior to precipitation (not shown). For the wAvg method, the same total precipitation (0.3 mm) were reported from both evap and nonEvap gauges. In addition to under-reporting total precipitation, poor evaluations of reference depths due to gauge evaporation caused the pairwise algorithm to report precipitation later in time for event 25 (Fig. 7c and d) and with different sub-hourly intensities for event 16 (Fig. 7e and f) relative to wAvg.

4 Conclusions

The gauge evaporation field campaign revealed that evaporation from the Geonor T200B all-weather precipitation gauge, used by the USCRN network, was extensive. Evaporative losses from the evap gauge over the three month study period exceeded total precipitation reported from both QA methods. In line with previously studies, evaporative losses were more pronounced during dry conditions when evaporative demand was greater (dry and warm conditions during the afternoon hours). In addition, the evap gauge had a much larger diurnal variation in gauge depth over dry periods than the evaporation suppressed gauge, which likely challenge QA processes distinguishing between noise and precipitation. The largest hourly average loss from the evap gauge of 0.24 mm was considerably larger than control (0.04 mm). Evaporation rates from the evap gauge were on average slightly higher than the Golubev et al. (1992) study using the Treykov gauge. However, these results are likely due to the greater evaporative potential (warmer, dryer conditions) of Colorado summers compared to Polygon, Russia.

The impacts of gauge evaporation on precipitation measurements were similar to WMO studies with losses from the evap gauge ranging between 0 to 4.9 % with respect to control. However, these results varied by calculation algorithm. The algorithm averaging past gauge data to minimize the effects of wire noise (pairwise) and evaluate depth change had larger differences between the evap and nonEvap (control) gauges compared to the wAvg approach. The pairwise algorithm underestimated total precipitation by 3.0 mm (4.9 %) over the three-month campaign. In addition to underestimating total precipitation, evaporative biases often shifted the timing of precipitation start times and impacted sub-hourly precipitation intensities. Conversely, the wAvg approach was less sensitive to gauge evaporation, reporting similar precipitation totals between evap and nonEvap gauges with differences of 0.2 mm or 0.3 %. Furthermore, differences between evap and nonEvap gauges varied in sign suggesting that dissimilarities may be related to the spatial distribution of precipitation rather than near systematic (evap < nonEvap) differences reported from the pairwise method.

The performance of the wAvg algorithm to account for gauge evaporation in field tests is in line with an earlier study using synthetic precipitation events with simulated gauge evaporation rates. These combined studies demonstrate that the wAvg approach to calculating precipitation is less sensitivity to gauge evaporation than the pairwise algorithm and a more suitable method to monitor USCRN station precipitation and National trends. Additionally, these studies also suggest that, while gauge design and atmospheric conditions affect gauge evaporation rates, algorithms used to evaluate depth change can influence the magnitude of evaporation biases on precipitation measurements, as suggested by Sevruk et al. (2009). Moreover, suppressants and evaporative adjustments to precipitation records may not be required to estimate a "true" precipitation signal provided a reasonable algorithm is applied to process gauge data. This is important for networks wanting to monitor precipitation from protected wildness areas where the use of evaporative suppressants may be restricted or where the additional maintenance and disposal of the additive is too costly. In addition, the success of the algorithm in reducing evaporative bias on precipitation measurements improves the utility of the record by limiting the need for scientists to correct datasets to account for gauge evaporation. It is hoped that the calculation techniques explored in this study and described in detail by Leeper et al. (2014b) can provide an outline to QA technicians of other networks wanting to develop and revise precipitation algorithms for gauges without the use of evaporative suppressants in addition to evaluating current methods. To foster additional studies and collaboration, the one-minute field campaign gauge dataset is available as an online supplement to allow QA technicians of other networks to evaluate the sensitivity of their methods to gauge evaporation.

The Supplement related to this article is available online at doi:10.5194/amtd-7-12851-2014-supplement.

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Table 1. Reported precipitation event totals from the evap and nonEvap gauges and gauge differences (evap – nonEvap) using pairwise and wAvg algorithms.

	evapGauge		nonEvapGauge		Gauge Difference	
EventID	Pairwise (mm)	wAvg (mm)	Pairwise (mm)	wAvg (mm)	Pairwise (mm)	wAvg (mm)
1	2.2	2.3	2.1	2.0	0.1	0.3
2	0.0	0.3	0.0	0.2	0.0	0.1
3	0.0	0.0	0.3	0.3	−0.3	−0.3
4	5.1	5.5	5.6	5.4	−0.5	0.1
5	3.3	3.7	3.7	3.7	−0.4	0.0
6	1.5	1.6	1.4	1.5	0.1	0.1
7	0.6	0.6	0.6	0.6	0.0	0.0
8	0.8	0.9	0.8	0.9	0.0	0.0
9	0.3	0.2	0.0	0.3	0.3	−0.1
10	0.0	0.2	0.2	0.3	−0.2	−0.1
11	0.0	0.0	0.2	0.2	−0.2	−0.2
12	0.2	0.0	0.2	0.2	0.0	−0.2
13	6.7	7.0	6.6	6.8	0.1	0.2
14	3.8	3.9	3.6	3.6	0.2	0.3
15	0.7	0.8	0.5	0.7	0.2	0.1
16	0.6	0.6	0.5	0.5	0.1	0.1
17	0.3	0.5	0.3	0.3	0.0	0.2
18	0.0	0.3	0.3	0.3	−0.3	0.0
19	16.7	17.2	16.9	16.8	−0.2	0.4
20	0.3	0.4	0.5	0.7	−0.3	−0.3
21	3.5	3.7	3.4	3.6	0.1	0.1
22	0.0	0.3	0.3	0.3	−0.3	0.0
23	5.2	5.3	5.2	5.2	0.0	0.1
24	0.0	0.2	0.3	0.3	−0.3	−0.1
25	4.4	4.7	4.7	4.8	−0.3	−0.1
26	1.4	1.6	1.8	1.7	−0.4	−0.1
27	0.0	0.3	0.6	0.4	−0.6	−0.1
28	0.0	0.0	0.0	0.2	0.0	−0.2
29	0.0	0.2	0.0	0.3	0.0	−0.1
Total	57.6	62.3	60.6	62.1	−3.0	0.2

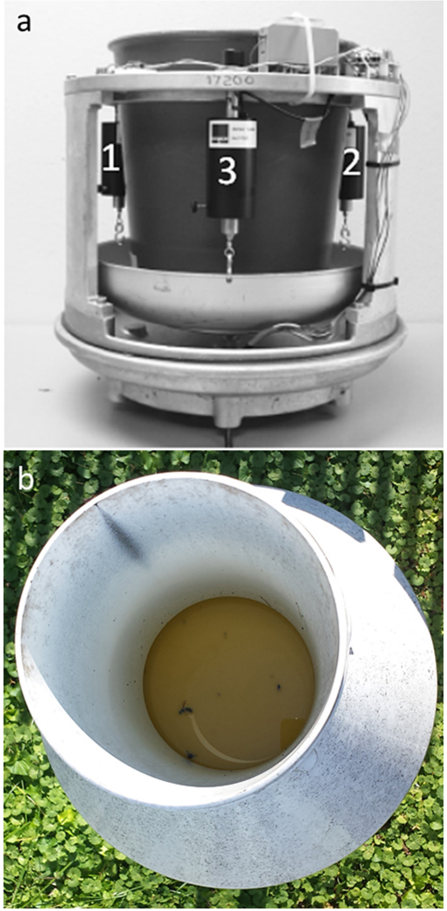

Figure 1. Photographs of the Geonor T200B gauge **(a)** interior outfitted with redundant sensors and **(b)** looking through the gauge opening to the exposed interior reservoir.

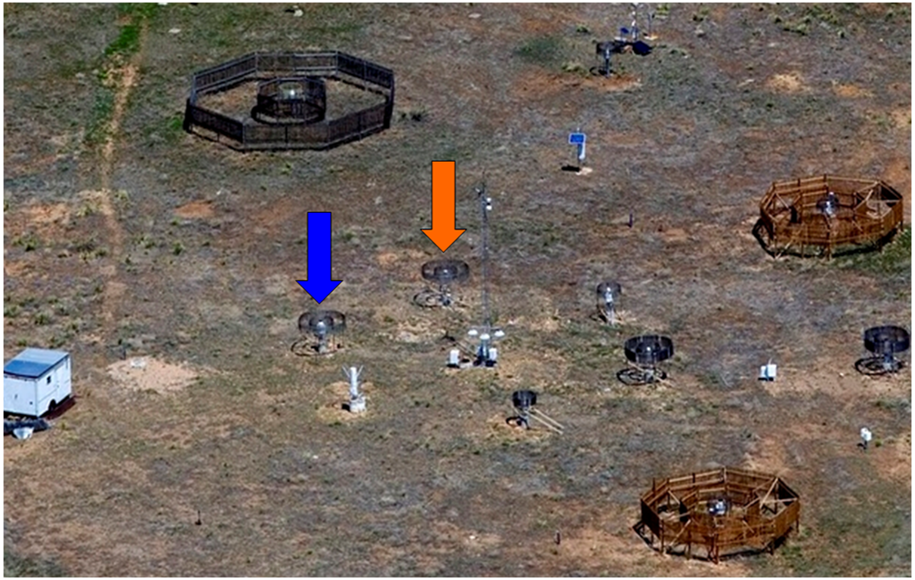

Figure 2. Image of evap (under orange arrow) and nonEvap (under blue arrow) Geonor T200B gauges used in this experiment.

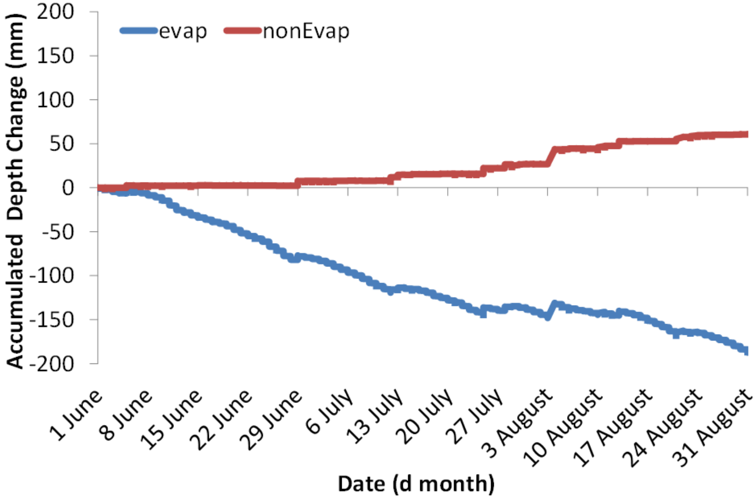

Figure 3. Hourly three wire mean depth change over the three-month study period in 2013.

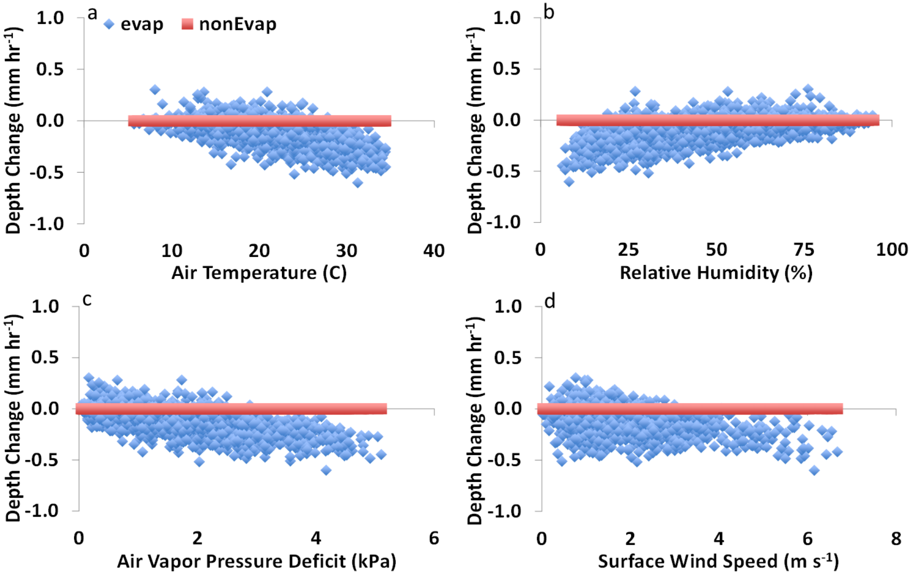

Figure 4. Hourly three wire mean depth change over dry periods by **(a)** air temperature, **(b)** relative humidity, **(c)** air-vapor pressure deficit, and **(d)** surface wind speed.

AMTD
7, 12851–12871, 2014

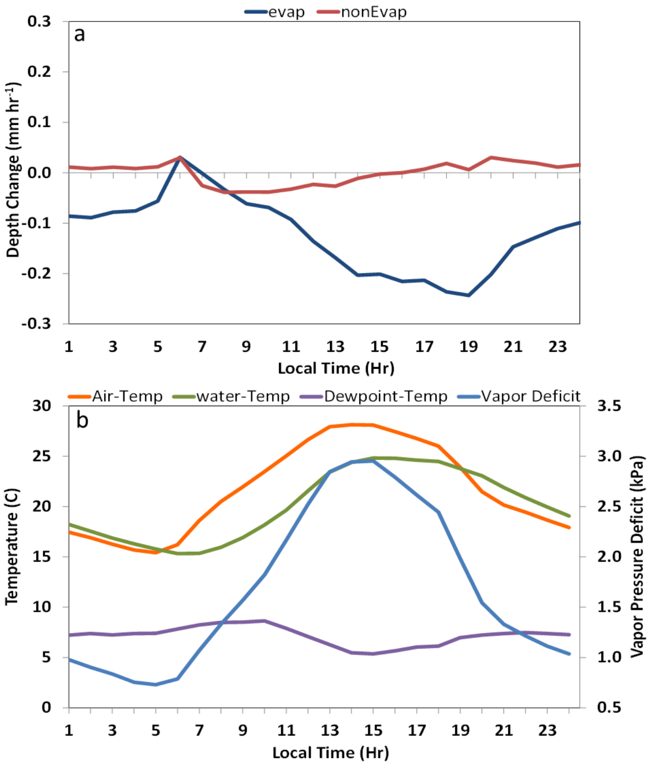

Figure 5. Hourly mean **(a)** three wire depth change for evap and nonEvap gauges and **(b)** air and water temperatures and air-vapor pressure deficit over the diurnal cycle.

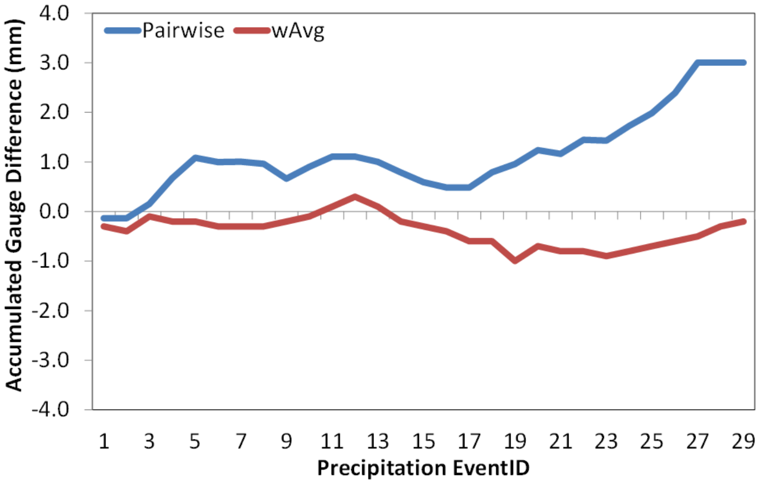

Figure 6. Evap and nonEvap accumulated precipitation differences between pairwise and wAvg calculation methods.

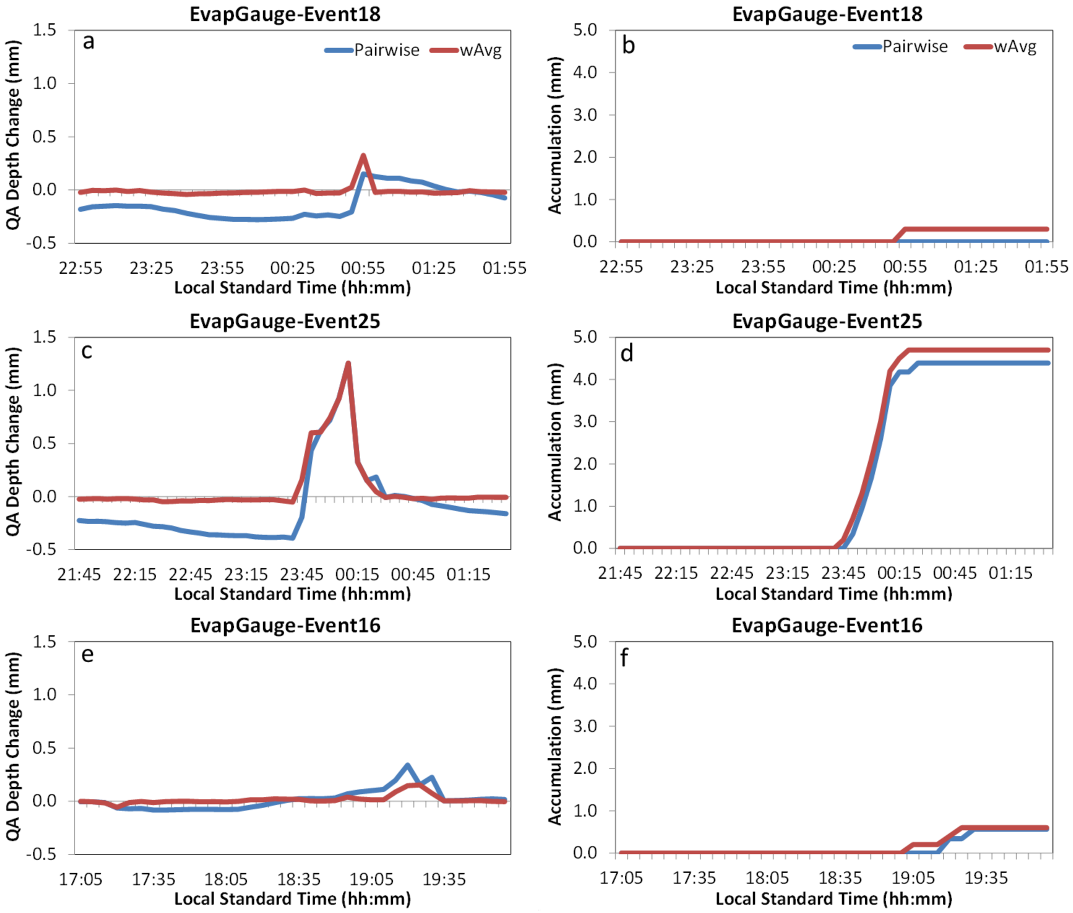

Figure 7. Left: sub-hourly computed depth changes from pairwise and wAvg algorithms and (right) reported sub-hourly precipitation from the evap gauge for precipitation events 18 (**a** and **b**), 25 (**c** and **d**), and 16 (**e** and **f**).