Impacts of Homemade Rain Gauge Design and Micrometeorology on Precipitation Measurement Accuracy

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ABSTRACT

Accurate precipitation observations are essential in the verification of weather forecasts, the study of climate patterns, and the decision-making process across many industries. Here, we investigate the impacts of both rain gauge design and micrometeorological phenomena on precipitation measurement accuracy. To test inexpensive, nonstandard materials, a homemade rain gauge was built using a plastic funnel and glass jar for the collection container, a graduated cylinder for the measurement container, and plastic bucket for the wind shield. Precipitation was collected and measured daily from 14–27 September 2018 near Walker Building in University Park, Pennsylvania using three rain gauges—our homemade gauge, a commercial gauge, and the Myers Weather Center gauge. We found that the homemade gauge had maximum errors of 25% and 31% relative to the commercial and Weather Center gauges, respectively. Since the Weather Center gauge was sited closer to Walker Building and other obstructions, we hypothesize that reduced evaporation and increased turbulence likely occurred, resulting in some of the observed errors between each gauge. While the homemade gauge's wind shield might have aided in increased catch, the transfer of water between the separated collection and measurement containers was a major deficiency in its design. To improve the design for future studies, it is recommended that the two containers need to be physically integrated, comprised of durable plastic materials, and accompanied by a sturdier, more effective wind shield. This study suggests that a single rain gauge is not reasonably representative of an entire city or region.

1. Introduction

Daily precipitation measurements are valuable to atmospheric scientists, engineers, farmers, and anyone else seeking to understand weather and climate patterns. Rain gauges are meteorological instruments made in various shapes and sizes that have been used for hundreds of years to measure near-surface liquid precipitation amounts (Neff 1977). A simple rain gauge is an open-mouthed container with straight sides, consisting of collection and measurement parts (NWS 2014). With any rain gauge, precipitation readings are taken at a single point. However, since precipitation is spatially variable, these point measurements often do not represent broad areas; thus, multiple observational sites are required (Brock and Richardson 2001). Although random errors often occur when collecting precipitation data, a plethora of systematic errors exist that can be prevented through study and preparation. We are interested in determining the most important factors in the design and operation of rain gauges and why they are important.

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Previous studies have revealed that environmental factors can significantly influence the accuracy of rain gauges (Yang et al. 1998). In general, the windier the location, the less precipitation falls into the gauge (NWS 2014). Wind flow deflects smaller drops out of rain gauges, resulting in underestimation of precipitation (Brock and Richardson 2001). The wind speed at gauge height can be helpful for recognizing wind-induced errors (Yang et al. 1998). Gauges should not be sited in wide-open or elevated areas, such as on top of buildings, due to the wind (NWS 2014). Gauges also should be sited away from trees and buildings, which can lead to atmospheric turbulence and deflected precipitation (NWS 2014). Ideally, the distance to obstruction should be at least double the height of obstruction (NWS 2014).

In addition to wind-induced turbulences, wetting losses—water that can be evaporated from the gauge's internal walls after precipitation has fallen or the container has been emptied (Yang et al. 1998)—results in underestimated precipitation amounts (Groisman and Legates 1994). Evaporation errors, albeit typically negligible, can be significant if rain events are brief with small precipitation amounts (Brock and Richardson 2001). Furthermore, dew can result in measurable precipitation, which is an overestimation (Brock and Richardson 2001). Debris, such as leaves or twigs, can block the small end of the funnel (Brock and Richardson 2001); therefore, gauges should be maintained on a regular basis by removing debris (WMO 2008).

Rain gauges must be capable of measuring all types of precipitation, including snow and ice. Due to its light weight and tendency to blow around more, snow tends to undercatch, or not be accurately measured, more than rain (NWS 2014). Moreover, snow and ice may accumulate sufficiently to block the gauge (Brock and Richardson 2001). In heavy snowfall areas, gauges are mounted on towers above the maximum snow level to which snowfall accumulates (NWS 2014). The funnel and inner measuring tube should be taken out when a frozen precipitation event is expected, but left in place when freezing rain is anticipated (NWS 2014). Similar to snow, ice is difficult to measure precisely. For this reason, at most meteorological observation sites, ice observations tend to be more qualitative than quantitative (WMO 2008).

The aforementioned and other sources of error need to be recognized when designing a rain gauge. Gauges should be strong and durable enough to function properly in various types of weather and be large enough to collect water during heavy precipitation events. Different materials used in rain gauge design can affect the performance of a time series (Groisman and Legates 1994). The National Oceanic and Atmospheric Administration (NOAA) runs the Cooperative Observer Program (COOP), for which rain gauges are either classified as recording or non-recording (NWS 2014). The standard 8-inch non-recording precipitation gauge has an overflow can and funnel top both 8 inches in diameter, a measuring tube 2.53 inches in diameter, and a calibrated measuring stick (NWS 2014). A wind shield can be quite beneficial, helping to protect the rain gauge from the wind. Yang et. al (1998) showed that an NWS standard 8-inch precipitation gauge caught 13% more precipitation with a wind shield than without it at the Valdai Hydrological Research Station in Russia.

In this experiment, we designed and constructed our own unique homemade rain gauge and tested it alongside a plastic commercial rain gauge for a 14-day period near Walker Building in University Park, PA. We compared these precipitation measurements and Myers Weather Center measurements with one another. Our main objectives were the following: 1) determine the types of impacts rain gauge design has on precipitation measurement accuracy and 2) identify the micrometeorological phenomena that affect precipitation measurement accuracy. Given the limited budget for purchasing supplies, we expected that the quality of materials used to construct our homemade rain gauge would be the primary reason for inaccurate measurements. Turbulence and evaporation were expected to likely distort measurements during windy and sunny days, in part due to the siting of the gauges. Through this experiment, we learn how homemade rain gauge performance can be improved to match or even surpass commercial rain gauge performance.

2. Experimental Methods

For the construction of our homemade rain gauge, commonly found materials were purchased for $30 USD. A 64-fl oz Mason jar was selected as the collection container because of its glass composition, adding weight and durability to the overall gauge. In addition, two plastic funnels, each with a 4-inch top diameter and 0.25-inch bottom diameter, were acquired. The 16-fl oz funnel was used to build the gauge, while the 4-fl oz funnel was used to pour water into the measurement container. A 1-inch circular hole was punctured in the jar's lid, allowing for the bottom of the 16-fl oz funnel to be placed through this opening, which was secured to the lid using duct tape. The gauge was placed inside a 12-inch-wide blue plastic bucket, as shown in Fig. 1. This bucket acted as an overflow container, stabilizer, and wind shield. Not physically connected to the collection container, a 100-mL cylinder was used as the measurement container. A Cole-Parmer plastic commercial gauge (Model 03319-00) and the Myers Weather Center gauge were co-located with the experimental gauge. Displayed in the center image in Fig. 2, the commercial gauge had a 10 to 1 ratio, meaning that 10 inches of rainfall in the measurement container would be equivalent to 1 inch of actual rainfall in the collection container. Since the inner tube was marked in inches of actual rainfall, no conversion of measurements was necessary.

The experimental and reference gauges were placed approximately 70 feet from the Myers Weather Center gauge on a relatively flat grass lawn near Walker Building in University Park, PA (Fig. 3). Most of the nearby major obstructions—including trees, walls, and buildings—were over 50 feet away. Although these obstructions could have influenced precipitation measurement accuracy, the Weather Center gauge, which is used for the NWS official measurements, was also affected by many of the same obstructions. The proximity of each gauge to a given obstruction varied, which allowed us to study micrometeorological phenomena. Furthermore, all gauges were sited near a paved path occasionally crowded by pedestrians and cyclists during weekdays; measures were taken to ensure the gauge would not be interfered with. The location of our gauges was also convenient for making daily measurements because of the proximity to Walker Building.

Precipitation was collected from 14-27 September 2018 and measured at 8 AM EDT (12Z) each day. The precipitation type, weather conditions, and any other observations were also noted daily. To measure precipitation, the lid of the homemade gauge was removed, and the liquid water from the jar was poured into the 4-fl oz funnel, emptying out into the 100-mL graduated cylinder. If excess water remained in the jar, the process of emptying the graduated cylinder and filling it with water repeated until the entire volume of water ($\pm$ 1 mL) was measured. All wet materials—namely the jar, funnels, and graduated cylinder—were wiped dry before resetting the rain gauge for the next day. For the commercial gauge, the height of water in the inner tube in inches of actual precipitation was recorded instead. Daily precipitation totals from the Weather Center gauge (http://www.meteo.psu.edu/ wjs1/wxstn/DATA/current.ht ml) were recorded as well.

The homemade gauge's collection and measurement containers had different radii; thus, volume of water in the graduated cylinder was converted to height of water in the hypothetical funnel region. Knowing that the volume of water was constant when transferring it from the collection to measurement container, this height was calculated using

$$V_C = \pi {r_F}^2 h_F. \quad (1)$$

where V_C is the volume of the graduated cylinder (mL), r_F is the funnel's radius (in), and h_F is the height of water in the hypothetical funnel region (in). For example, a measurement of 10 mL of precipitation in the graduated cylinder would correspond to h_F equaling 0.05 in. In order to assess the performance of the homemade gauge, we treated the measurements from the commercial gauge and Weather Center gauge as accepted values and calculated percent error with the formula

$$PE = \left| \frac{P_M - P_A}{P_A} \right| \cdot 100 \quad (2)$$

where PE is percent error, P_M is the measured precipitation value, and P_A is the accepted precipitation value. For example, if the homemade gauge collected 0.3 in. of precipitation and the commercial gauge collected 0.4 inches of precipitation, then the PE between the two measurements would equal 25%. All calculations and data analyses were performed in Python, which produced the tables, graphs, and figures shown in the Results section.

3. Results

Rain was the only form of precipitation that fell during the 14-day observation period (Table 1) which was measured on eight days throughout the period (Table 2). The most observed weather condition was cloudy (six times), and most mornings were humid (> 80% relative humidity). Severe weather activity, such as thunderstorms, did not occur at 12 UTC on any day, but could have occurred between measurement times. For example, the remnants of Hurricane Florence brought moderate to heavy rain during the afternoon of 17 September. On most mornings, we noticed condensation of water vapor onto the funnel, as well as dew on the grass surrounding the homemade and commercial gauges. We accidentally spilled water out of the graduated cylinder on 25 September, the only time it rained while measuring precipitation. Throughout the period, no conspicuous debris was noted, and all the gauges appeared to stay in place between measurement times.

All quantitative observations appear in Table 2. The homemade and commercial gauges had measurable precipitation on five days during the measurement period—18, 22, 25, 26, and 27 September. However, the Weather Center gauge had measurable precipitation on 14 September as well. We observed a trace of precipitation, or unmeasurable precipitation (< 0.01 in), three times with the homemade and commercial gauges and four times with the Weather Center gauge. The homemade gauge's measurable precipitation values ranged from 8-235 mL, or 0.04-1.14 inches (derived using Eq. 1). As for the commercial gauge and Weather Center gauge, the measurable values ranged from 0.04-0.93 inches and 0.01-0.94 inches, respectively. For visualization of the data, we plotted daily precipitation measurements in Fig. 4. Note that each trace of precipitation was set to zero; therefore, the plot only depicts measurable precipitation. We recorded the greatest amount of precipitation on 18 September, although the values for the commercial and Weather Center Gauge are closer to each other and lower than the value for the homemade gauge. These comparisons are true for 26 September as well, but the magnitudes of precipitation were lower. For 25 and 27 September, the commercial gauge value was slightly less than the other two, but all values were relatively close to one another. We recorded the least amount of measurable precipitation for all gauges on 22 September, with the homemade gauge and commercial gauge having the same value and the Weather Center gauge having a slightly lower value.

Percent errors of the homemade gauge relative to the commercial gauge and Weather Center gauge are shown in the two rightmost columns of Table 2. For 14 and 22 September, the homemade gauge relative to the commercial gauge had 0% errors, and the homemade gauge relative to the Weather Center gauge had 100% errors, the largest out of all calculated errors. We did not find any measurable liquid in the homemade and commercial gauges on 14 September, but noticed relatively low precipitation amounts on 22 September. The other errors, for 18, 25, 26, and 27 September, ranged from 1-31%—with 25% as the highest error relative to the commercial gauge and 31% as the highest error relative to the Weather Center gauge. Fig. 5 shows the percent errors for each day on a bar graph. Out of the four days with percent errors between 0% and 100%, the red bar is higher than the green bar on three of those days, more so on 27 September. Only on 25 September is the red bar higher than the green bar. Similar to Fig. 4, there are more zero values than nonzero values in Fig. 5 because there were more days without measurable precipitation than days with measurable precipitation.

4. Discussion

Throughout the 14-day period, the precipitation type in the homemade and commercial gauges was rain. Moderate to heavy rain from the remnants of Hurricane Florence during the afternoon of 17 September led to the highest 24-hour rainfall during this period, measured on 18 September. The sustained winds associated with this storm were not particularly strong, reaching 12 mph, as shown on the Weather Underground History page (https://www.wunderground.com/history/monthly/us/pa/state-college/KUNV/date/2018-9). Maximum sustained winds were equally strong on 18, 25, and 26 September and slightly stronger on 21 September with 14 mph winds. Fig. 4 shows that all the gauges had measurable precipitation on 22, 25, 26, and 27 September, but the intensity of rain varied. While a brief drizzle episode likely led to measurable precipitation on 22 September, heavier and long-lived showers were likely responsible for the higher totals measured on 25-27 September. Only the Weather Center gauge had measurable precipitation on 14 September, but brief drizzle probably did occur prior to making measurements. Light showers might have also occurred prior to 15, 16, 19, and 21 September when a trace was recorded in at least one of the gauges, as displayed in Table 2. However, we noted in Table 1 that there was dew on the funnel and the grass surrounding the gauges on those days. This suggests that dew, rather than light showers, caused a trace of precipitation on each of these days.

In Fig. 5, the percent errors of the homemade gauge relative to the commercial gauge are 25% or less, which are quite low compared to the higher percent errors of the homemade gauge relative to the Weather Center gauge. Thus, the homemade gauge was mostly accurate compared to the commercial gauge and not as accurate compared to the Weather Center gauge. Regarding the collection of precipitation, the primary source of error for the homemade and commercial gauges was likely due to the evaporation of water from the gauges during the daytime. Since the homemade and commercial gauges were farther away from Walker Building and trees, they were more prone to be exposed to sunlight, which increased the rate of evaporation. These two gauges were also close to sidewalks and streets, which may have contributed to local warming and, therefore, greater evaporation. This may explain why these two gauges both had 0.00 inches of precipitation on 14 and 16 September, while the Weather Center gauge had 0.01 inches on 14 September and a trace on 16 September. However, on days with significant rainfall, the bucket might have shielded the homemade gauge from the wind and sun more, leading to higher precipitation totals. Due to its glass composition, the homemade gauge was more susceptible to condensation of water vapor during heavier, daytime rainfall events. Although the Weather Center gauge was more shaded by trees, its proximity to Walker Building and trees was also a likely source of error. On days when there was more rainfall and wind, these obstructions might have caused less precipitation to reach the gauge. The Weather Center gauge recorded less precipitation than the other two gauges on 22 and 26 September, possibly due to its proximity to obstructions. These obstructions may have also caused more mechanically-driven turbulence around the Weather Center gauge through the interaction of air flows with these surfaces, leading to undercatch.

Unlike the commercial and Weather Center gauges, which had connected collection and measurement containers, the homemade rain gauge had separated containers. The transfer of water from the Mason jar to graduated cylinder via the 4-fl-oz funnel was a major source of measurement error. Systematic errors included not pouring all the water from the Mason jar to graduated cylinder and accidentally spilling water during the process. As noted in Table 1, water was spilled out of the graduated cylinder due to overflow on 25 September. On days with higher amounts of precipitation, there was residual water in the graduated cylinder each time we poured the water out of it. On 25 September, it was raining when we made our measurements, which was another major source of error because more rain could have fallen into the jar, funnel, and graduated cylinder during the process. We also did not make these measurements exactly at the same time, which allowed the rain to accumulate in one gauge more than in another. For all gauges, we encountered parallax errors because of the slight and different angles at which we viewed the markings. On 14 and 16 September, the inconsistency in the definition of a trace and in rounding may have justified why precipitation amounts differed between the Weather Center gauge and the other gauges. We recorded a trace if water was visible on the bottom of the homemade and commercial gauges, but even a single raindrop in the Weather Center gauge would qualify as a trace.

In order to maximize accuracy in collection and measurement of precipitation, a rain gauge should have an effective wind shield and a measurement container physically integrated with the gauge. The results of this experiment suggest that a rain gauge should be far enough from obstructions to increase the catch of precipitation. This is consistent with the National Weather Service's guidelines, which state that gauges should be sited away from trees and buildings (NWS 2014). Furthermore, our experiment showed that evaporation errors can be significant during brief rain events with small precipitation amounts (Brock and Richardson 2001). Ideally, an official rain gauge with an effective windshield should be located on a roof of a building or in an open area, without obstructions. Overall, we achieved our objectives of determining the impacts gauge design and micrometeorological phenomena have on a gauge's accuracy.

5. Conclusions

The primary objectives in this experiment were to determine how both rain gauge design and micrometeorological phenomena could affect precipitation measurement accuracy. To accomplish this goal, we tested the performance of our own homemade rain gauge and compared it with the performances of two distinct reference gauges. The results suggest that the quality of materials used to construct a homemade gauge is the primary factor impacting precipitation measurement accuracy, thus confirming our hypothesis. It is paramount for both engineers designing a commercial gauge and people creating a homemade gauge to invest wisely in the materials that comprise the gauge. To build an improved homemade gauge, we would physically integrate the collection and measurement containers to avoid spillage. If designing a commercial gauge, we would use durable plastic containers with lower specific heat capacities in comparison with the Mason jar to potentially reduce condensation on the gauge during heavier precipitation events. This gauge would appear similar to the commercial and Weather Center gauges, but would also have an effective wind shield to prevent undercatch. The wind shield should surround the rain gauge symmetrically and, unlike the bucket in this experiment, be composed of metal strong and heavy enough to withstand higher gusts.

As expected, turbulence and evaporation are significant micrometeorological phenomena that affect precipitation measurement accuracy. However, we found that dew also impacts precipitation measurement accuracy. This experiment demonstrated the importance of choosing a proper location for a rain gauge—even a deviation of 70 feet resulted in differences in precipitation measurements of 0.01 inches or greater. It is not reasonable to use one gauge in one location to measure precipitation amounts for an entire city or region because of microclimatic variation. The variation in precipitation across a given city or region may be minimal, but obstructions and surface types can play major roles in the amount of precipitation a gauge actually collects and measures. A better method for measuring precipitation for an entire city or region would be to create a grid of automated gauges and take averages of the values. This would be costly to implement for numerous cities or regions, but the improvement in precipitation measurement accuracy would be marked. When choosing a location for a gauge, the distances from and heights of obstructions should be taken into careful consideration. Future investigations are needed to better understand how wind direction, frozen precipitation, and various types of severe weather affect the accuracy of a rain gauge.

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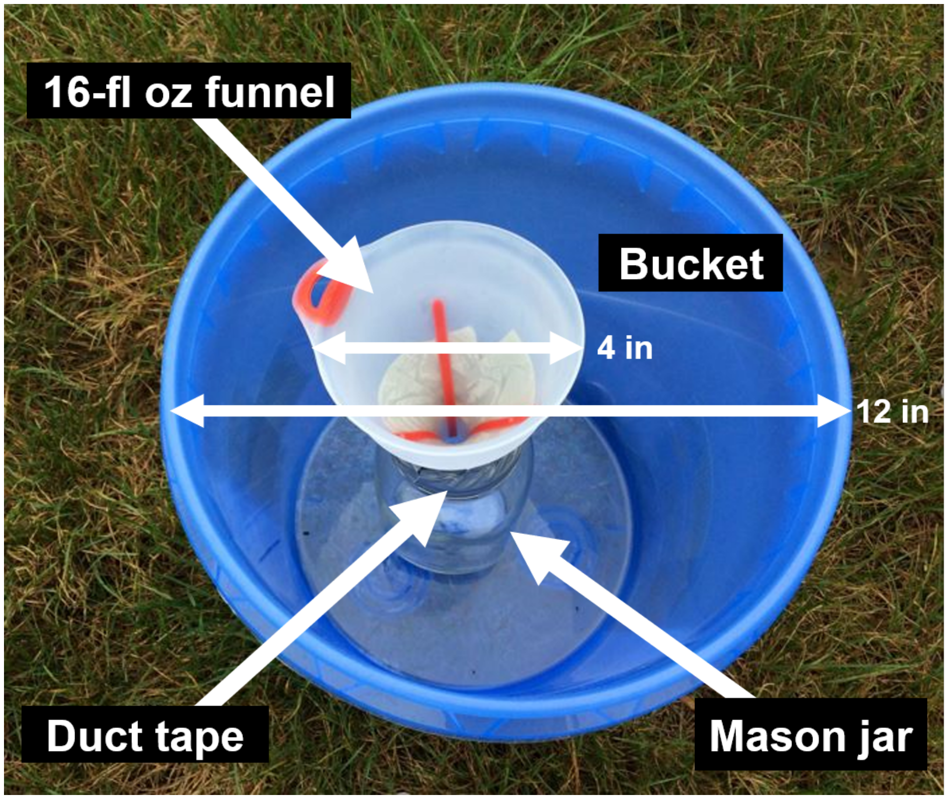

FIG. 1. Photo of our homemade rain gauge, as viewed from the top. The Mason jar, 16-fl oz funnel, duct tape, and bucket are displayed.

FIG. 2. Photos of the Weather Center gauge (left), commercial gauge (center), and grass lawn with all three gauges in sight (right). Some of the major obstructions are shown—including Walker Building, a stone wall, and several trees.

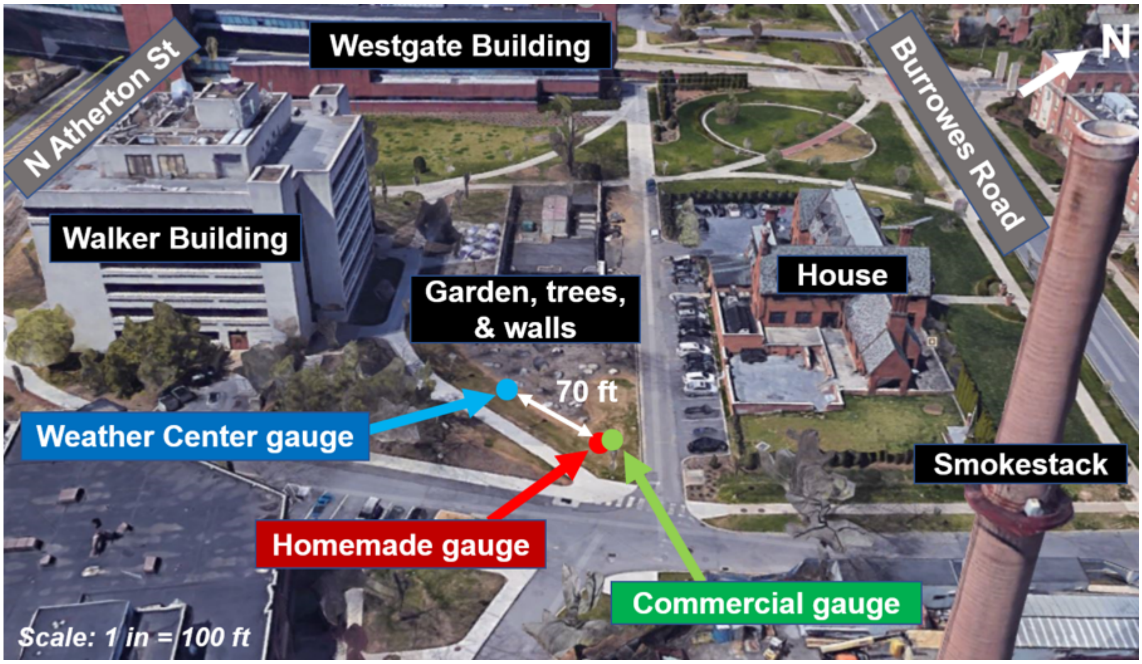

FIG. 3. Map of the measurement site and surrounding area. The homemade gauge (red), commercial gauge (green), and Weather Center gauge (blue) are indicated by dots. Various obstructions (black) and major roads (grey) are labeled. (Image from Google Earth)

TABLE 1. Qualitative data for each day at 8 AM EDT (12 UTC). Precipitation type (third column), meteorological observations (fourth column), and additional notes (fifth column) are included. Precipitation type indicates the predominant form of precipitation that fell in the preceding 24 hours but does not indicate that it was precipitating at the time of measurement. In contrast, meteorological observations were the weather conditions at the time of measurement.

Date	Time (UTC)	Precipitation Type	Meteorological Observations	Additional Notes
9/14/18	12:00	None	Cloudy; humid; light winds	None
9/15/18	12:00	Rain	Cloudy; humid; calm winds	Condensation on funnel; dew on grass
9/16/18	12:00	None	Fog; humid; calm winds	Condensation on funnel; dew on grass
9/17/18	12:00	None	Cloudy; humid; calm winds	None
9/18/18	12:00	Rain	Mostly cloudy; humid; calm winds	Condensation on funnel; dew on grass
9/19/18	12:00	Rain	Partly cloudy; humid; light winds	Condensation on funnel; dew on grass
9/20/18	12:00	None	Partly cloudy; humid; calm winds	Condensation on funnel; dew on grass
9/21/18	12:00	Rain	Cloudy; humid; light winds	Condensation on funnel; dew on grass
9/22/18	12:00	Rain	Fair; light winds	Condensation on funnel
9/23/18	12:00	None	Partly cloudy; humid; calm winds	None
9/24/18	12:00	None	Cloudy; humid; light winds	None
9/25/18	12:00	Rain	Light rain; humid; light winds	Water spillage
9/26/18	12:00	Rain	Cloudy; humid; light winds	None
9/27/18	12:00	Rain	Partly cloudy; humid; light winds	Condensation on funnel; dew on grass

TABLE 2. Precipitation measurements (inches) recorded daily at 8 AM EDT (12 UTC) near Walker Building in University Park, PA and percent relative errors (%). For the homemade gauge, measured values (third column) and values derived using Eq. 1 (fourth column) are displayed. Commercial gauge values and Weather Center gauge values occupy the fifth and sixth columns, respectively. A trace of precipitation means that precipitation fell, but was not measurable (< 0.01 in). Percent errors for both of these gauges, calculated using Eq. 2, are reported in the two rightmost columns.

Date	Time (UTC)	Homemade Gauge Value (mL)	Derived Homemade Gauge Value (in)	Commercial Gauge Value (in)	Weather Center Gauge Value (in)	Homemade Gauge / Commercial Gauge Error (%)	Homemade Gauge / Weather Center Gauge Error (%)
9/14/18	12:00	0	0.00	0.00	0.01	0	100
9/15/18	12:00	Trace	Trace	Trace	Trace	0	0
9/16/18	12:00	0	0.00	0.00	Trace	0	100
9/17/18	12:00	0	0.00	0.00	0.00	0	0
9/18/18	12:00	235	1.14	0.93	0.94	23	21
9/19/18	12:00	Trace	Trace	Trace	Trace	0	0
9/20/18	12:00	0	0	0.00	0.00	0	0
9/21/18	12:00	Trace	Trace	Trace	Trace	0	0
9/22/18	12:00	8	0.04	0.04	0.02	0	100
9/23/18	12:00	0	0.00	0.00	0.00	0	0
9/24/18	12:00	0	0.00	0.00	0.00	0	0
9/25/18	12:00	140	0.68	0.65	0.67	5	1
9/26/18	12:00	114	0.55	0.44	0.42	25	31
9/27/18	12:00	31	0.15	0.12	0.14	25	7

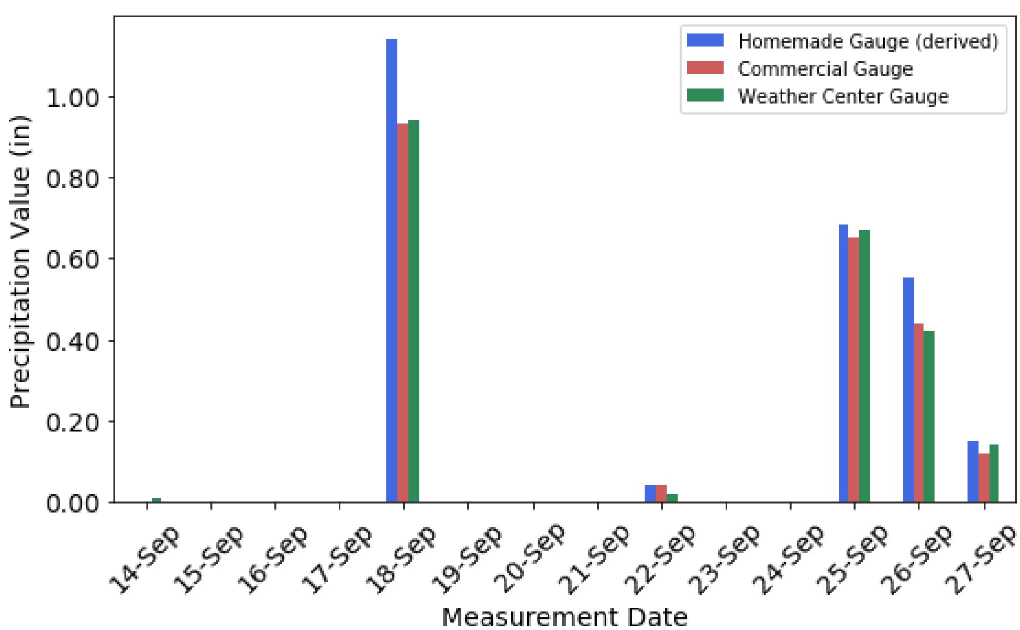

FIG. 4. Comparison between the homemade gauge derived (blue), commercial gauge (red), and Weather Center gauge (green) daily precipitation measurements (inches). Trace amounts of precipitation (< 0.01 in) were set to 0.00 in.

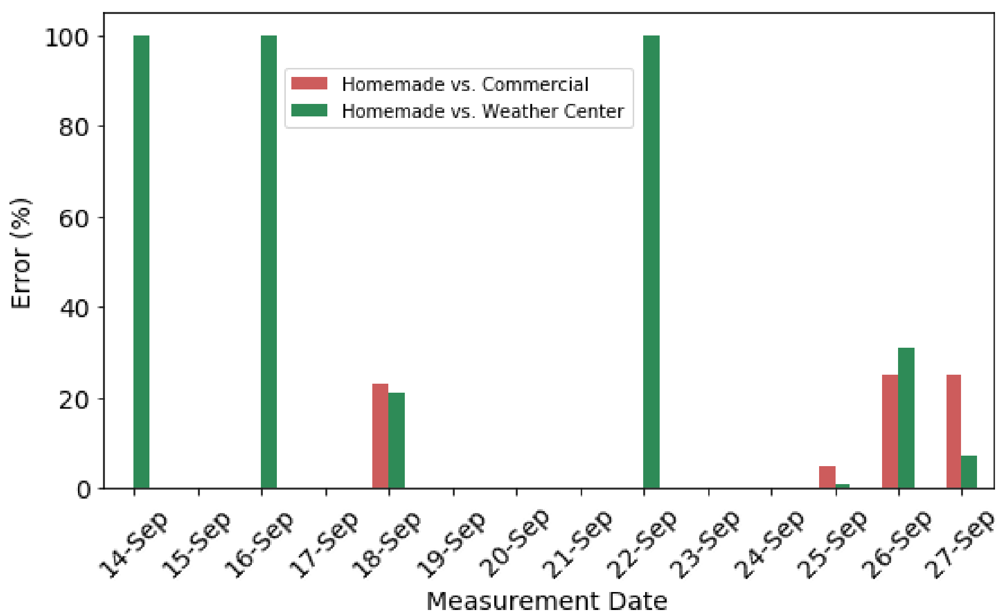

FIG. 5. Percent relative errors (%) of the homemade gauge relative to the commercial gauge (red) and the homemade gauge relative to the Weather Center gauge (green). For trace amounts of precipitation, percent errors were set to 0%.