Evaluating the Use of a Rain Gauge Mesonet to Increase the Spatial Coverage and Accuracy of Rainfall Measurements

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ABSTRACT

Measuring precipitation is a fundamental aspect of meteorology, but many flaws exist with the current way that precipitation is measured. For instance, some areas rely on a singular rain gauge to represent precipitation across their city or region, which can lead to mesoscale differences in precipitation not being detected. This experiment aimed to determine if multiple rain gauges are necessary to detect small-scale variances in precipitation within a specific region, instead of relying on only one official gauge. Twenty-nine rain gauges were placed in a mesonet across the State College, Pennsylvania area, ten of which were commercial-style rain gauges and nineteen of them were much smaller and less expensive garden-variety gauges. These rain gauges recorded precipitation for a 15-day observation period from 3-17 September 2020. Their measurements were compared to the official Walker Building cooperative observer program (COOP) rain gauge, which is located on the University Park Campus of Penn State University and currently represents the precipitation for the entire State College area. Three significant precipitation events during the observation period revealed that the commercial rain gauges are much more accurate than their garden-variety counterparts, with a 27% relative error between all the garden-variety gauges and the Walker Building COOP gauge compared to a 7% relative error between all the commercial gauges and the Walker Building COOP gauge. However, there were some random and systemic errors in this experiment, such as how close some rain gauges were placed to their surroundings and the fact that precipitation measurements varied greatly from one gauge to another, even between the same type of rain gauge. This further supports the fact that one rain gauge cannot be relied on to represent the precipitation across an entire region since it can lead to biased measurements. This could negatively impact people who depend on accurate precipitation values, such as farmers and municipal officials. Increasing the density of commercial rain gauges will help to better detect small-scale variances in precipitation leading to more accurate precipitation measurements and more accurate forecasts, since this data could be incorporated into weather models.

1. Introduction

Collecting accurate precipitation measurements has always proven to be both an important and challenging problem for meteorologists. Precipitation can vary greatly across a region, making the process of measuring how much precipitation actually fell across that area difficult due to the limited amount of observation sites currently available (Kidd et al. 2017). These variances in precipitation can be caused by small-scale, or mesoscale, phenomena during precipitation events or by other factors, such as topography (Briggs and Cogley 1996).

Variations in precipitation are important to understand because these differences can be cumulative and lead to developing regions of drought or help meteorologists understand why long-term precipitation trends are present (Dai et. al. 1997). For example, precipitation measurements are of great interest to those in the agriculture sector to monitor the health of their cops (Kidd et al. 2017). Accurate precipitation measurements are also important for watershed modeling to accurately simulate streamflow (Ercan and Goodall 2012). Flash flooding can also occur with very heavy rainfall over a short period of time and being able to accurately measure this intense rainfall is crucial (Kidd et al. 2017). Long-term precipitation measurements must also be accurate due to their importance for monitoring the changes to our climate (Kidd et al. 2017).

Despite all these important applications for precipitation measurements, problems arise when precipitation observing locations are very limited. With very few point measurements of precipitation relative to the size of our planet, the gaps are often filled using spatial interpolation techniques (Kidd et al. 2017). However, this method of estimating averaged precipitation across an area has proven to be inaccurate, especially when studying an area with nonuniform terrain (Grosiman and Easterling 1994). This is particularly true with summertime thunderstorms that are sometimes only a few miles across and can easily miss a rain gauge entirely, leading to a large underestimation of rainfall for the surrounding area (Brock and Richardson 2001). On the other hand, if a thunderstorm passes directly over a rain gauge, the gauge will overestimate the rainfall for the surrounding area that did not see as much precipitation (Brock and Richardson 2001).

Rain gauges can also malfunction or provide inaccurate data, leading to fewer reliable precipitation measurements. Wind can cause precipitation to be underestimated by deflecting smaller rain drops out of the rain gauge, while heavy dew formation can accumulate in a rain gauge leading to a slight overestimation of rainfall (Brock and Richardson 2001). Large water drops can also splash out of the rain gauge when they hit the top portion of the gauge leading to an underestimation of rainfall (Brock and Richardson 2001). Additionally, rain gauges cannot be placed too close to any obstructions such as trees and buildings which can cause turbulence and deflect precipitation (NWS 2017). Gauges should also not be in wide open spaces or on tops of buildings due to wind and turbulence impacts (NWS 2017). The ideal location for a rain gauge is where it is naturally shielded in all directions, however this is not the case for all rain gauges across the country leading to inconsistencies and errors with precipitation data (Sieck et. al. 2007).

One of the best ways to address these challenges with measuring precipitation and potential errors that can occur is to increase the spatial resolution of rain gauges (Gyasi-Agyei 2020). If only one rain gauge is present in a certain town or city, adding several more rain gauges in the surrounding area will not only provide a more accurate representation of the precipitation across the region, but also provide unique insights into the precipitation measurements, such as why one location is receiving more precipitation compared to another. This is the goal of this study, where 29 rain gauges were placed in the State College, Pennsylvania area to collect precipitation over a 15-day period. The precipitation measurements from all 29 individual locations will be compared to one another as well as to the measured precipitation at the Eric A. Walker Building on Penn State's University Park Campus, which is an established cooperative observing site. Spatial patterns in precipitation will be explored to potentially explain why one location received more precipitation than another. Differences in rainfall measurements may arise due to the different types of rain gauges used, if the gauges were sited correctly, and the spatial representativeness of the entire rain gauge mesonet. If data collection is successful, this experiment will provide an excellent framework for others to set up a highly concentrated rain gauge mesonet across a different town or city so that small-scale differences in precipitation can be better identified.

2. Experimental Methods

The rain gauge network for this experiment consisted of 29 rain gauges scattered around the State College, Pennsylvania area, with nine commercial rain gauges, one tipping bucket rain gauge, and 19 garden variety rain gauges (Figure 1). Additionally, the official COOP rain gauge at the Walker Building on Penn State's University Park campus, where daily observations are taken each morning, was used as a reference gauge for this experiment (Figure 1; green point). Twenty-two rain gauges were located within the 1.7-mile diameter circle encompassing downtown State College and the Penn State University Park campus, with fewer rain gauges scattered elsewhere but no farther than 4.25 miles from the Walker Building (Figure 1). This provided a good sampling of the State College area for mesoscale differences in precipitation to be assessed during the observation period.

The collection of precipitation began on September 3, 2020 and continued until September 17, 2020. Observers placed their individual rain gauges at locations that would have the least obstructions to measuring the precipitation accurately (NWS 2017). Each observer selected a daily observation time their rain gauge would be checked, ranging from 12 UTC to 18 UTC, and, at this time, any rainfall from the previous 24-hour period was recorded. The commercial rain gauges had two tubes inside of them with the inner-most tube measuring precipitation to the nearest tenth of an inch, so measurements were able to be made to the nearest hundredth of an inch (Figure 2). A funnel with a four-inch diameter was affixed to the top of these commercial gauges to help avoid under-catch caused by the wind. In contrast, the official COOP gauge at the Walker Building had an eight-inch diameter funnel and a windshield to further prevent under-catch from occurring. Similar to the commercial gauges, the official COOP gauge had two tubes inside of it with rain being collected in the inner-most tube and measurements were made to the nearest hundredth of an inch. Rainfall observations were recorded automatically with the tipping bucket gauge every time the bucket tipped, which occurred after about every 0.01 inches of rainfall.

Examining rain gauge number six in closer detail, precipitation observations were made daily at 13 UTC throughout the 15-day observation period. This gauge was a garden variety rain gauge with a single tube and had tick marks to the nearest tenth of an inch, so precipitation measurements were made to the nearest hundredth of an inch, and it could measure rainfall up to five inches (Figure 3a). Any precipitation amount below a reading of 0.01 inches on the rain gauge was counted as a trace of precipitation (T), meaning that some precipitation fell, but not enough to be measured. Additionally, anomalies that impacted precipitation measurements were noted, such as tilting of the gauge or any dew formation impacting the precipitation measurements. Rain gauge number six was placed approximately six feet to the southwest of a two-story apartment building on a small patch of slightly sloped grass and approximately five feet to the northwest of a set of two concrete steps that followed this slope (Figure 3b). Additionally, the rain gauge was approximately two feet in front of a concrete slab that served as the porch of the apartment building (Figure 3c). This location was chosen to try to prevent any error that could have been introduced due to obstructions in the area.

Basic statistics were used to analyze the precipitation data across the 29-gauge network in the State College area. Individual mean and standard deviation, *SD*,

$$SD = \sqrt{\left(\frac{\sum|x-\bar{x}|^2}{n}\right)} \quad (1)$$

calculations were completed on the daily measurements for the commercial gauge network of ten gauges, which includes the one tipping bucket gauge, the 19 garden-variety gauge network, and the entire 29 commercial and garden gauge network. Additionally, daily values of absolute error, *AE*, and percent error, *PE*, were calculated for rain gauge number six relative to the Walker Building COOP gauge, relative to the entire 29 commercial and garden variety gauge network daily mean, and relative to the garden variety rain gauge network,

$$AE = |v_A - v_E| \quad (2)$$

$$PE = \left|\frac{v_A - v_E}{v_E}\right| * 100\% \quad (3)$$

where v_A is the approximate, or measured, value and v_B is the exact value.

Furthermore, daily absolute and percentage relative error values were calculated for the garden variety gauge network relative to the commercial gauge network and relative to the Walker Building COOP gauge. Finally, the daily absolute and percentage relative error values were calculated for the commercial gauge network relative to the Walker Building COOP gauge. All data was analyzed using Microsoft Excel.

3. Results

Six days from the 15-day observation period were identified to investigate further as days where at least one gauge in the mesonet recorded precipitation (Table 1). The most significant precipitation event occurred on the first day of the observation period, as the mean precipitation measurement for the commercial gauges was 0.44 inches and the mean precipitation measurement for the garden gauges was 0.29 inches. (Table 1). The measurements from the Walker Building COOP gauge and from rain gauge number six were much more centered on the distribution for the commercial gauge mesonet on this day (Figure 4b – blue box plot) than they were for the garden gauge mesonet (Figure 4c – blue box plot), where they were on the upper end of that distribution. Standard deviations values on this day were large, at 0.29 inches for the commercial gauges and 0.18 inches for the garden gauges, indicating that precipitation amounts varied greatly from one gauge to the next (Table 1). The range of precipitation measurements was much larger for the commercial gauges (Figure 4b – blue box plot) than it was for the garden gauges on this day (Figure 4c – blue box plot), with the 25th to 75th percentile range extending from 0.18 to 0.65 inches. The second day of the observation period, 4 September, also saw some precipitation, but it was much less than on 3 September and the precipitation totals did not vary as much with a standard deviation of 0.04 inches for the commercial gauge mesonet and 0.02 inches for the garden gauge mesonet (Table 1). On 5, 10, and 13 September, only one or two gauges in the mesonet recorded any precipitation, while no precipitation was measured in the Walker Building COOP gauge or in rain gauge number six. Finally, nearly all the gauges in the mesonet measured some precipitation on 14 September, with a mean of 0.06 inches for the commercial gauges and 0.03 inches for the garden gauges (Table 1). The Walker Building COOP gauge measurement from this day was centered on the distribution of commercial rain gauges (Figure 4b – green box plot) while the garden gauge distribution was lower than the measurement from the COOP gauge (Figure 4c – green box plot). Precipitation measurements were consistent from gauge to gauge for the majority of the full mesonet with the 25th to 75th percentile range extending from 0.02 to 0.08 inches (Figure 4c – green box plot), leading to a standard deviation of 0.02 inches for the garden gauge mesonet and a standard deviation of 0.03 inches for the commercial gauge mesonet. The cumulative mean precipitation from the 15-day observation period for the commercial gauge mesonet was 0.59 inches, almost double the 0.33 inches that the garden variety gauges measured, and much closer to the Walker Building COOP gauge, which had a cumulative total of 0.65 inches (Table 1).

Individual rain gauges, as well as the rain gauge mesonets, are compared to one another to assess their accuracy and to quantify their experimental error (Table 2 and Figure 4). Rainfall measurements from rain gauge number six were within 0.08 inches to those observed at the Walker Building COOP gauge, leading to a total error between these two gauges of 0.01 inches (Table 2). However, the full rain gauge mesonet, the commercial gauge mesonet, and garden-variety gauge mesonet had larger mean errors of when compared to the Walker Building COOP gauge, as precipitation measurements with these mesonets deviated as much as 0.26 inches from the COOP gauge (Table 2). The largest daily absolute errors were found between rain gauge number six and the full mesonet (Figure 5a – orange line) as well as between rain gauge number six and the garden mesonet (Figure 5a – grey line), especially for the first precipitation day when the absolute errors for both these comparisons were around 0.3 inches. The largest daily percent relative errors, as high as 100%, were also found between rain gauge number six and the full mesonet (Figure 5b –

orange line) as well as between rain gauge number six and the garden mesonet (Figure 5b – grey line).

The total precipitation observations from all gauges in the mesonet and the Walker Building COOP gauge are interpolated to create a regional precipitation map for the entire observation period (Figure 6). Specific maxima and minima in the total precipitation amounts can easily be identified and the rain gauges that correspond to those higher or lower precipitation values can be referenced since the latitude and longitude of each gauge is known. A clear rainfall maximum can be identified in the southwestern part of the study area where rain gauge number nine recorded 1.09 inches of precipitation, the most of any gauge in the mesonet. Generally, higher precipitation amounts were recorded in the southern half of the study area, including in parts of Western State College and Boalsburg (Figure 6). On the other hand, lower precipitation amounts were observed in the northern half of the study area, in places such as Toftrees and Innovation Park, but also on parts of Penn State's University Park campus.

4. Discussion

The 15-day precipitation observation period featured six days of measurable precipitation where at least one of the rain gauges in the 29-gauge mesonet recorded rainfall. During the 24-hour period ending on the morning of 3 September, some showers passed through Central Pennsylvania associated with a cold front (Figures 7b and 7c). Precipitation totals varied widely across the state, including within the rain gauge mesonet, with a minimum of zero inches and a maximum of an inch of rainfall measured (Figures 7a and 4a – blue box plot). The Walker Building COOP gauge recorded at 0.54 inches on this day and the mean of the commercial gauges was 0.44 inches, while the mean of the garden-variety gauges was much less at 0.28 inches (Table 1). An area of low pressure passed to the south of Pennsylvania during the next 24-hour period, resulting in scattered showers throughout the state, but precipitation totals were more uniform and not as high as the previous day across the State College area (Figures 7d, 7e, and 7f). The Walker Building COOP gauge measured 0.05 inches on this day, the garden gauge mean was 0.02 inches, and the commercial gauge mean was 0.06 inches, demonstrating the lighter and more consistent precipitation measurements (Table 1).

The next three precipitation days featured very light precipitation across parts of the State College area since precipitation was reported in only one or two of the gauges of the mesonet each of these days. Scattered cloud cover and a few isolated showers could have moved through the State College area with areas of low pressure close by (Figures 8a and 8b). On the fifth precipitation day, 13 September, only two rain gauges reported rainfall, and one of them took their precipitation measurements at 18z allowing for the approaching storm system to produce precipitation in the area before their observation was taken (Figure 8c). Finally, a line of scattered showers passed through Pennsylvania associated with a cold front during the 24-hour period ending on the morning of 14 September, leading to light precipitation totals in Central Pennsylvania as no rain gauge in the mesonet measured more than 0.09 inches of rain (Figures 7g, 7h, and 7i; Table 1).

Precipitation measurements for rain gauge number six were close to the amounts recorded at the Walker Building COOP site with an 11% total mean relative error between the two (Table 2). However, this accuracy was an anomaly compared to the rest of the garden-variety gauge mesonet and the full mesonet. The total mean relative error was 77% between gauge six and the garden gauge mesonet as well as between gauge six and the full mesonet (Table 2). This indicates that gauge six had rainfall measurements that were much closer to the Walker COOP site than most of the other gauges in the mesonet (Figure 4a). The entire garden-variety gauge mesonet had a total mean relative error of 27% when it was compared to the Walker Building COOP site, more than twice the amount of error as rain gauge number six alone (Table 2). The commercial gauge mesonet was much more accurate when compared to the Walker Building COOP gauge measurements, with a total mean relative error of only 7% (Table 2).

All six precipitation days during the observation period showed a similar trend, with rain gauge number six and the entire commercial gauge mesonet recording measurements that were the closest to the Walker Building COOP gauge. On the other hand, the relative errors for the garden-variety gauge mesonet and the full mesonet were consistently the highest throughout the experiment, with a 49% relative error for the garden-variety gauge mesonet and a 40% relative error for the full mesonet (Table 2). Systematic and random sources of error were most likely much more common with the garden-variety rain gauges when compared to the commercial gauges, possibly leading to the higher relative error percentages. For instance, rain gauge number six, a garden variety gauge, got tilted slightly during one of the precipitation days possibly causing it to catch less precipitation than what actually fell. Gauge six was also placed too close to a two-story apartment building, as a rain gauge should be positioned away from an obstruction a distance that is equivalent to at least twice the height of the obstruction (NWS 2017). The apartment building close to rain gauge number six was about 20 feet tall, so the gauge should have been placed at least 40 feet away from this obstruction. The gauge, however, was only placed six feet from the building, possibly creating a bias in the amount of precipitation that was observed due to turbulence and deflection likely caused by the nearby building (NWS 2017) (Figure 3b). Some of these systematic and random errors for rain gauge number six likely are true for other garden-variety gauges in the mesonet, possibly providing an explanation as to why the total relative error between the garden gauges and the Walker Building COOP gauge was 27% (Table 2). The garden variety gauges were very easy to tilt which likely impacted their performance, as multiple garden variety gauges noted having this issue during the observation period, whereas the commercial gauge had a much sturdier base. Additionally, the opening of the commercial gauge was much wider than that for the garden gauge, allowing for a more accurate measurement of the precipitation.

Over 0.75 inches of cumulative precipitation was observed in the southwest part of the study area, with a maximum of 1.09 inches, while less than 0.30 inches of precipitation was measured in the northernmost part of the study area (Figure 6). This demonstrates that picking any one rain gauge in the network, or even using the Walker Building COOP gauge alone as a representation of precipitation throughout the entire State College region, results in some important information being lost to the assumption that all precipitation across the study area is uniform. Precipitation varies widely across small distances, causing locations just a few miles apart to receive drastically different amounts of rainfall, so it is best to use multiple accurate rain gauges to represent precipitation across a region (Figure 6). This would be best achieved by using commercial rain gauges as their accuracy was displayed to be far superior to the accuracy of the garden variety rain gauges. Despite the commercial gauge costing much more than the garden variety gauges, smaller error scores were consistently observed with the commercial gauge mesonet when compared to the official Walker Building COOP site.

5. Conclusion

One of the primary goals of this study was to analyze the differences between the garden-variety rain gauges, the commercial rain gauges, and the official Walker Building COOP gauge. Another goal was to determine if a rain gauge mesonet was needed to detect small-scale variances in precipitation instead of relying on one rain gauge to represent an entire area. These goals were achieved by setting up a rain gauge mesonet of 29 gauges in the State College area and recording precipitation over a 15-day observation period, which revealed several important takeaways:

1. The commercial rain gauge mesonet was more accurate than the garden gauge mesonet when compared to the Walker Building COOP gauge, with much a 7% total relative error versus the 27% total relative error for the garden gauge mesonet which consistently recorded less rainfall than the Walker Building COOP gauge.
2. Precipitation measurements varied greatly from one gauge to another, even between the same type of rain gauge, indicating that one gauge cannot be relied on to represent the precipitation across an entire region.
3. Many sources of error were present with this study from random, meteorological factors, and due to systematic, human errors, such as the placement of the rain gauges in relation to nearby obstructions, all of which need to be taken into consideration.
4. Gauges were not distributed uniformly throughout the State College area, with many gauges clustered in Downtown State College. A more uniform distribution of the garden-variety and commercial gauges throughout the study area would have produced different results that might have represented the area's precipitation better.

One of the goals of this research project was to determine if one rain gauge can accurately and reliably represent the precipitation that falls across an entire city or region. The results imply that this is not a reasonable presumption as precipitation can vary drastically across small distances, as cumulative precipitation totals varied from less than 0.30 inches to more than an inch over the State College area in this study. If many rain gauges were not scattered across the region during our observation period, these variances in precipitation would not have been detected and recorded. More specifically, on precipitation days four and five, the Walker Building COOP gauge did not record any precipitation, whereas a couple of rain gauges in the commercial gauge mesonet recorded a small amount of precipitation. If the Walker Building COOP gauge was the singular gauge representing the State College area, these small precipitation accumulations would have been missed that the other rain gauges in the surrounding areas recorded. Therefore, using a single rain gauge to represent the precipitation across an entire region will lead to biased precipitation measurements, which could adversely impact people who depend on accurate precipitation values, such as farmers and municipal officials. For example, mesoscale factors could contribute to the formation a small region of intense rainfall over a farmer's fields, but if this intense region of precipitation does not pass over the closest official rain gauge, then the precipitation accumulations at the two locations would differ. Precipitation statistics from the official rain gauge would underestimate the rainfall that fell on the farmer’s fields, and over time this error could add up to create large discrepancies between the rainfall recorded at official rain gauges and the rainfall that fell across the surrounding areas.

To improve the way that precipitation is measured across the country so that it is more accurately calculated, and so that differences across relatively small distances are not left out, more rain gauges are needed. However, it is important to place these rain gauges strategically across the country so that this solution is feasible and so that the greatest resolution of precipitation measurements is achieved. Equally spacing rain gauges in a one-mile by one-mile grid pattern across a populated region, and using a coarser resolution in more rural areas, would address these problems. These added rain gauges would more accurately represent the precipitation that falls across a specific region, and the grid-like pattern will help with interpolation of the data as well as ensuring that all areas are accounted for. Using commercial rain gauges would be the best idea, since they proved to be much more accurate than their garden-variety counterparts in this experiment. This increase in accuracy would justify the higher price tag for the commercial gauges versus the garden-variety gauges.

Several improvements could be made for a future study that would be conducted in a similar vein to this one, such as extending the length of the observation period so that the conclusions from this study could be reinforced or new conclusions might be formed. Additionally, conducting a study with just commercial rain gauges could investigate the performance of these gauges in more detail and further prove the point that commercial rain gauges should be the primary choice when selecting the type of gauge to use on a larger scale across the country.

With improvements to the way that local, mesoscale precipitation extremes are measured and, therefore, accounted for in the future, weather forecasts will be improved, which will benefit a broad range of people, including the public that rely on these forecasts daily. But it is important to understand that the accuracy of precipitation measurements across the country needs to improve first, and the best way to do that is to increase the spatial coverage of reliable rain gauges. Once this goal is achieved, only then can the more accurate precipitation data be incorporated into weather models and forecasts.

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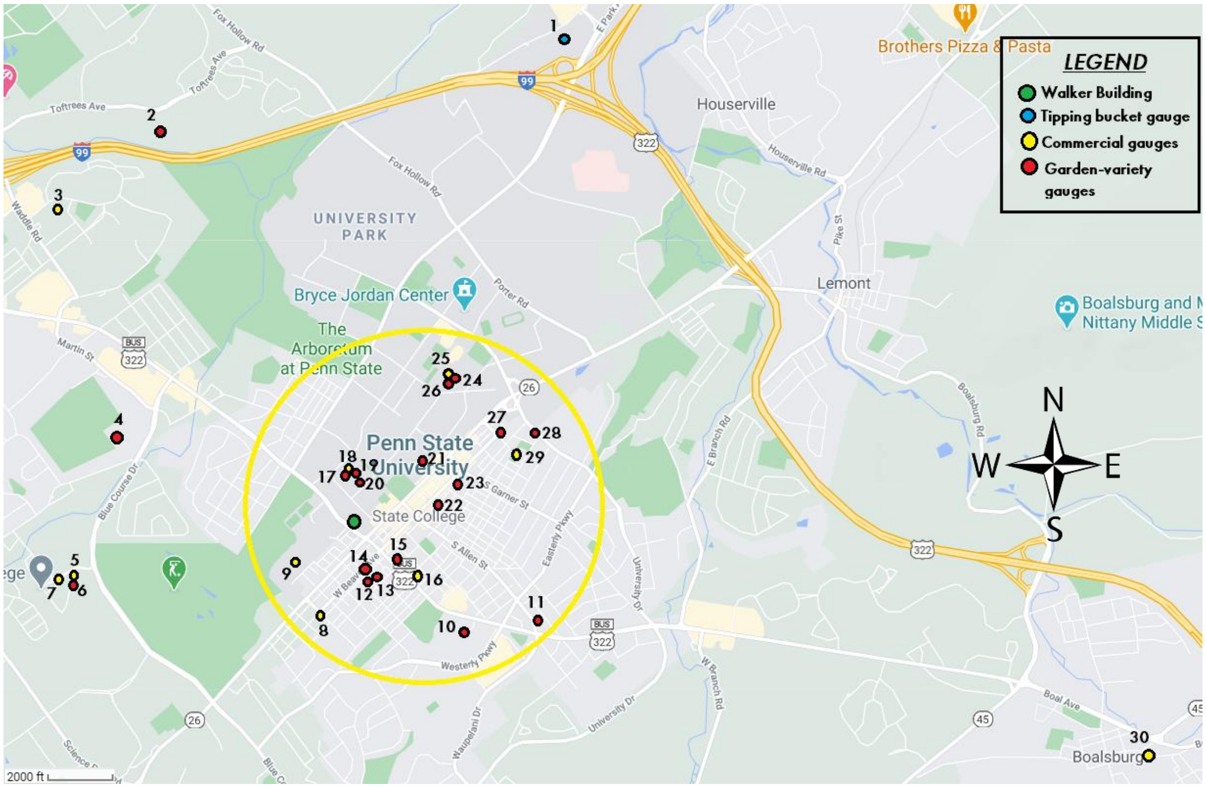

Figure 1. *Map showing all thirty rain gauge locations in State College (yellow dots for commercial gauges, red dots for garden-variety gauges, and a blue dot for the tipping bucket gauge) and location of the Walker Building, where official daily rainfall observations are made (green dot). The region defined as downtown State College and on-campus at Penn State's University Park Campus is shown as the area within the yellow circle. This circle has an approximate diameter of 1.7 miles. (Map credit: Google Maps)*

Figure 2. *Picture of a commercial style rain gauge used in this experiment.*

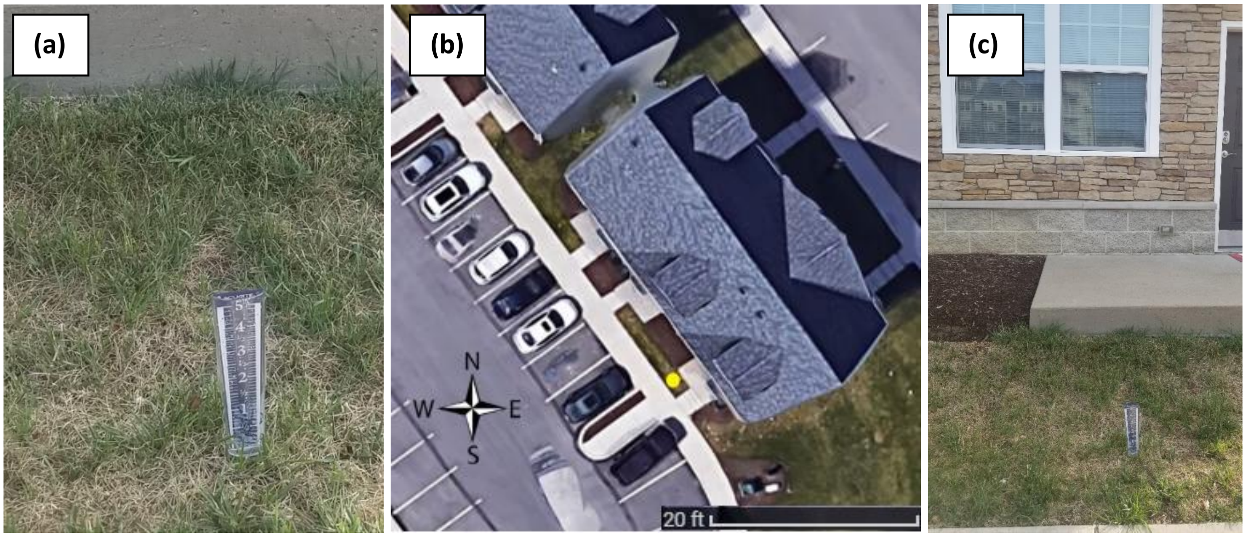

Figure 3. *Picture of rain gauge number six (panel a), aerial view of the area around rain gauge number six with the gauge's location represented by the yellow dot (panel b), and picture of where rain gauge number six was sited in relation to the front of the apartment building (panel c).*

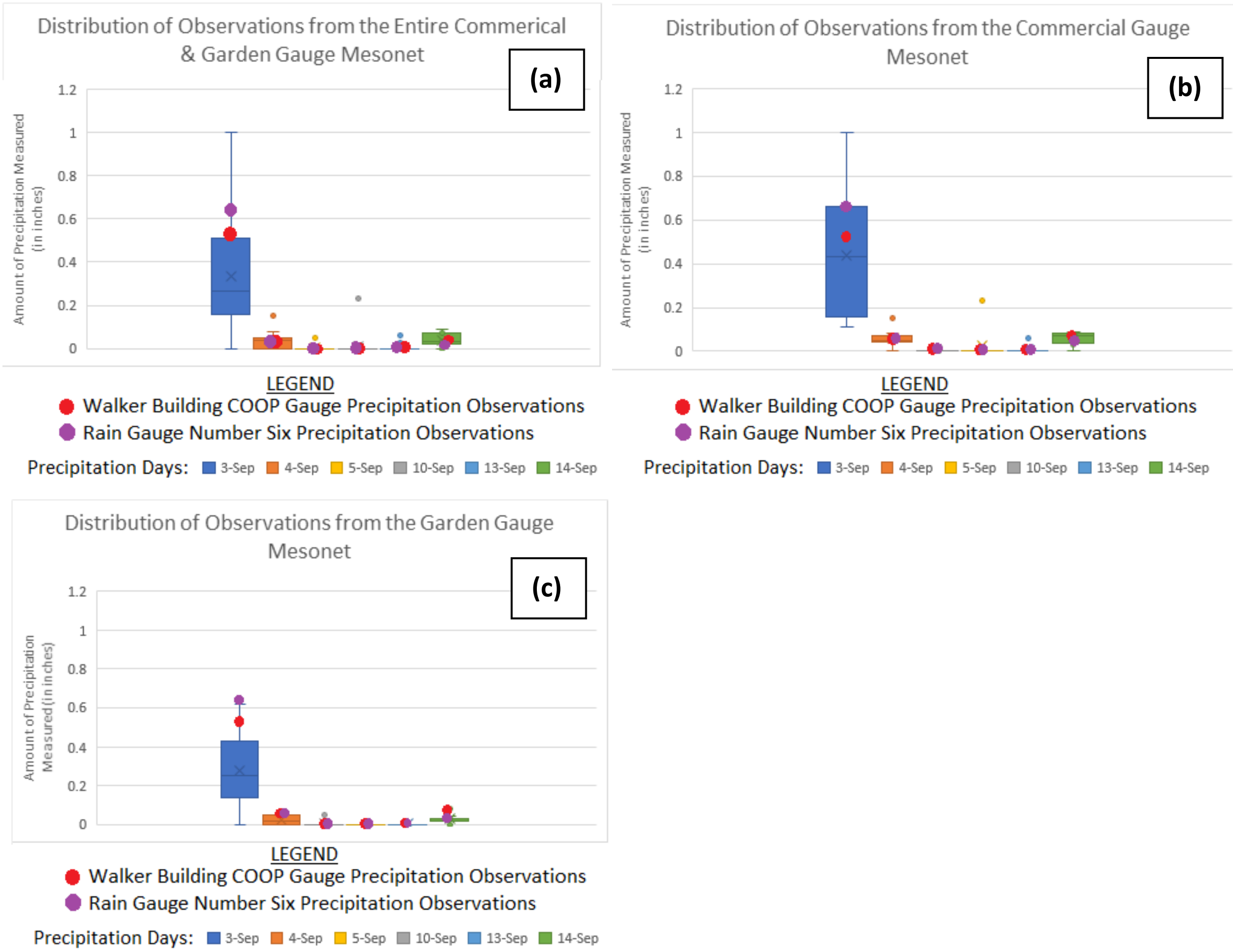

Figure 4. *Box and whisker plots of daily precipitation observations from the full mesonet (panel a), the commercial gauge mesonet (panel b), and the garden variety gauge mesonet (panel c) for each of the six precipitation days. Precipitation on 3 September is represented by the dark blue box plot, precipitation on 4 September is represented by the orange box plot, precipitation on 5 September is represented by the yellow box plot, precipitation on 10 September is represented by the grey box plot, precipitation on 13 September is represented by the light blue box plot, and precipitation on 14 September is represented by the green box plot. 25th, 50th, and 75th percentiles of the distribution are represented by the top and bottom extent of the boxes and the 5th and 95th percentiles are represented by the whiskers above and below the boxes. Outliers below the 5th percentile or above the 95th percentile are shown as small dots with the same color as the box plots that they are associated with. Points are plotted for each of the precipitation days for the precipitation observations from rain gauge number six (purple dots) and the Walker Building COOP gauge (red dots).*

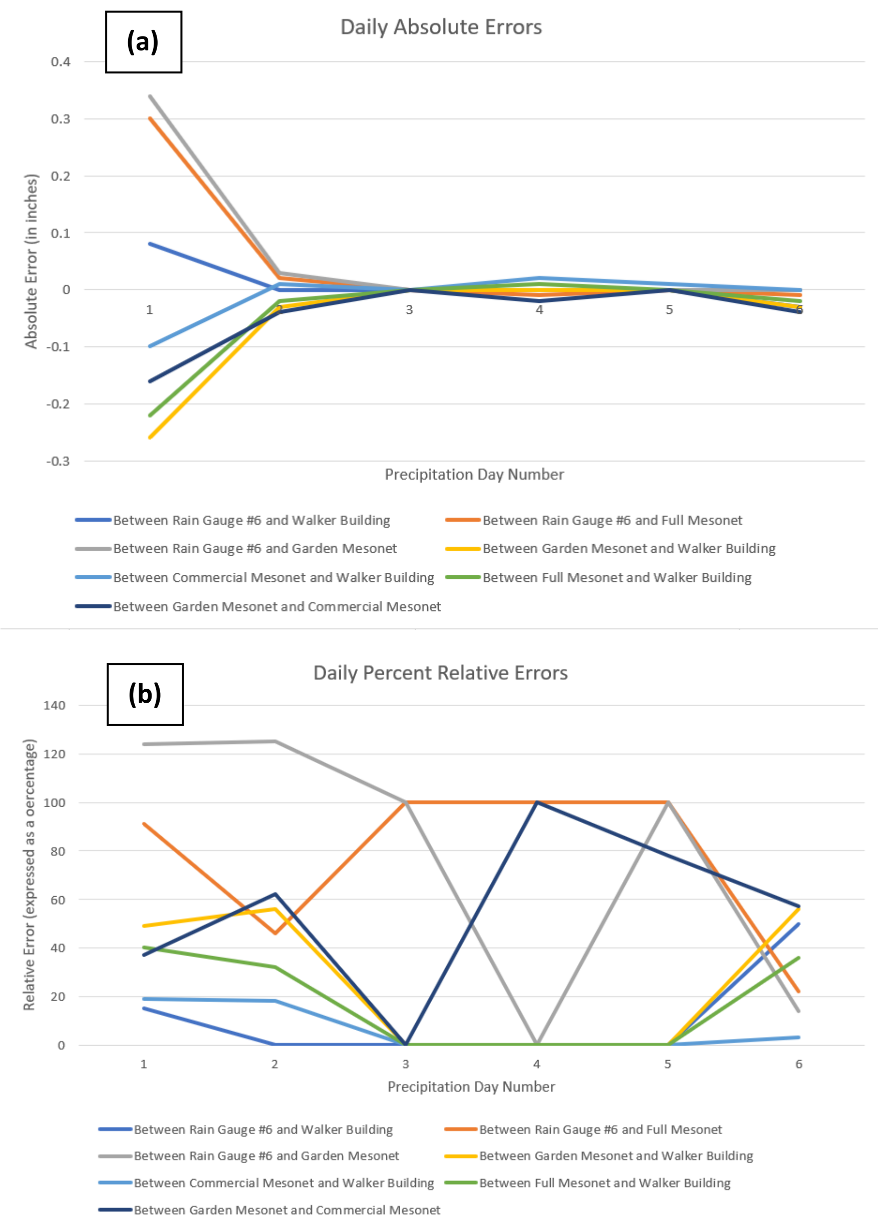

Figure 5. *Summary of daily absolute error (panel a – inches) and percent relative error (%) for all six precipitation days. The blue line shows the comparison between rain gauge number six and the Walker Building COOP gauge. The grey line shows the comparison between rain gauge number six and the garden gauge mesonet. The light blue line shows the comparison between the commercial gauge mesonet and the Walker Building COOP gauge. The dark blue line shows the comparison between the garden gauge mesonet and the commercial gauge mesonet. The orange line shows the comparison between rain gauge number six and the full mesonet. The yellow line shows the comparison between the garden gauge mesonet and the Walker Building COOP gauge. The green line shows the comparison between the full mesonet and the Walker Building COOP gauge.*

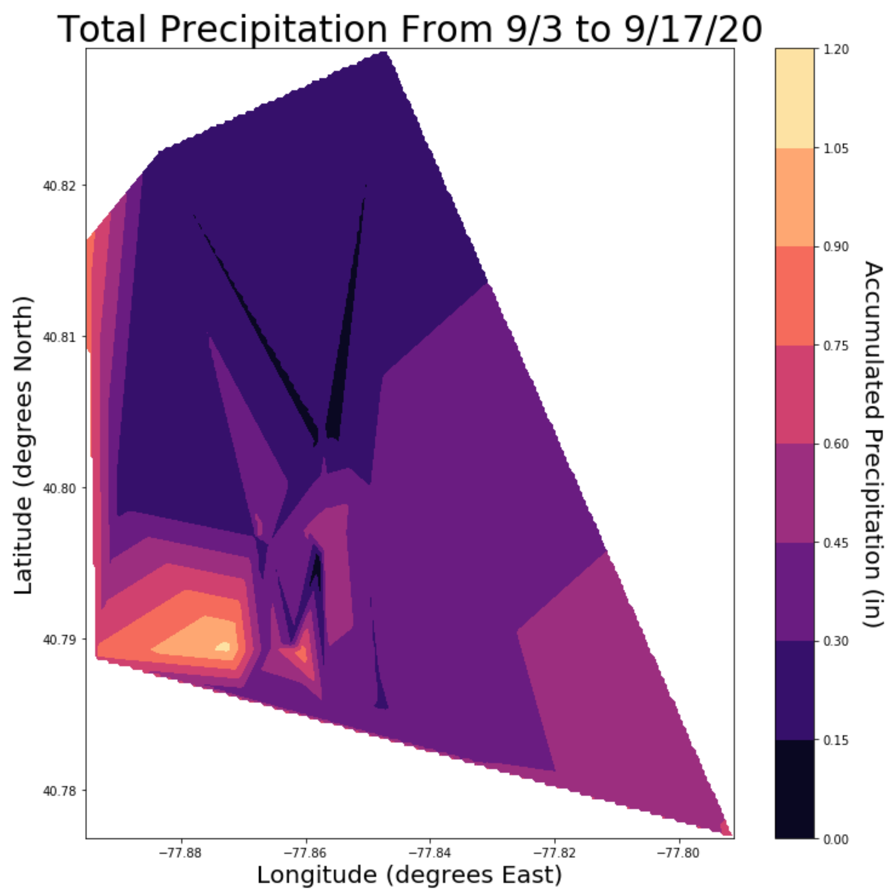

Figure 6. *An interpolated total precipitation (inches) map from the entire observation period for all gauges in the mesonet as well as the Walker Building COOP precipitation observations. The total precipitation values at each gauge location are interpolated using Python across the area to produce this map.*

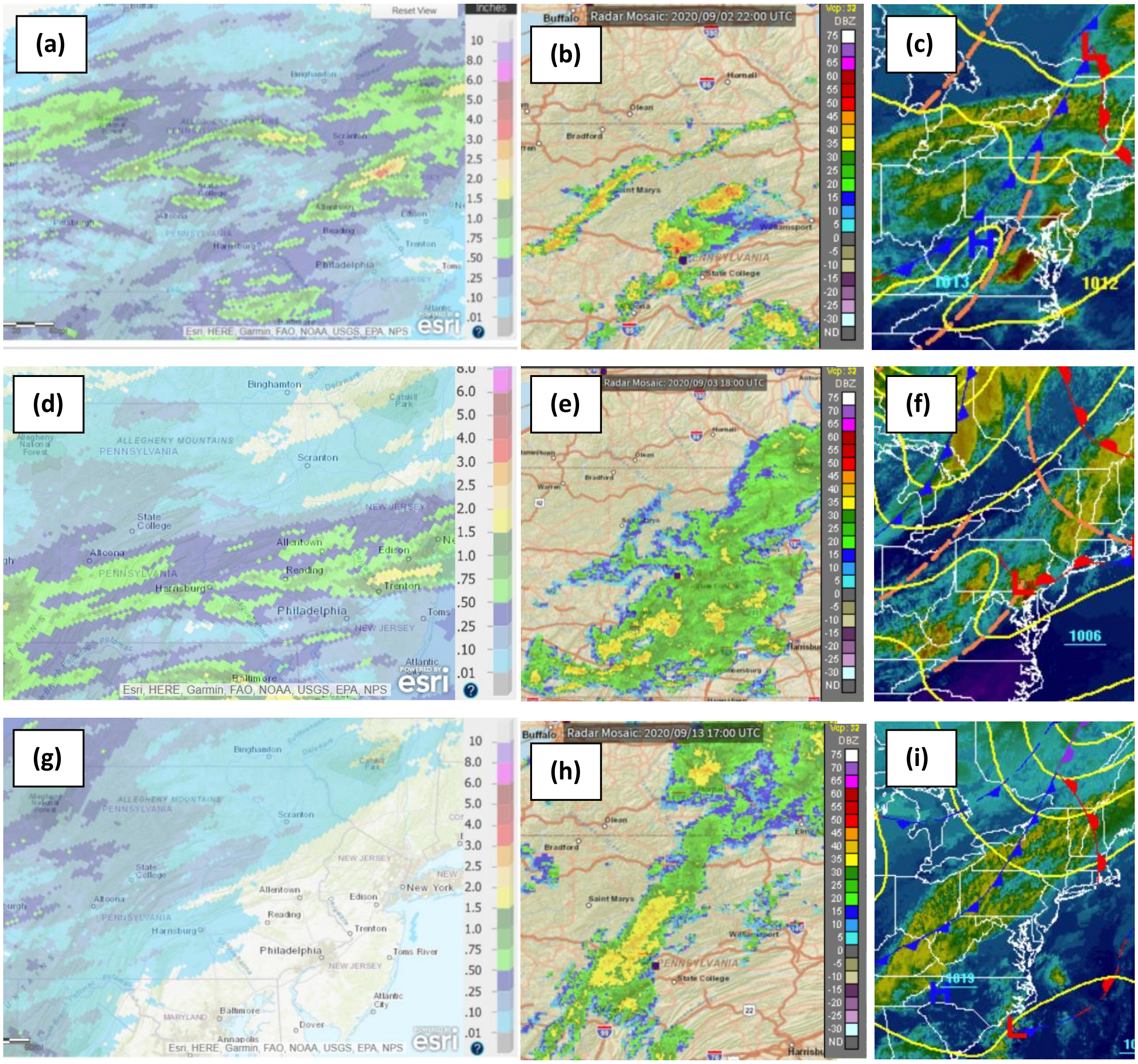

Figure 7. *Radar estimated precipitation (colored; inches) across Pennsylvania from 12z 9/2/20 through 12z 9/3/20 (panel a), 12z 9/3/20 through 12z 9/4/20 (panel d), and 12z 9/13/20 through 12z 9/14/20 (panel g).Credit: National Oceanic and Atmospheric Administration (NOAA) Advanced Hydrologic Prediction Service (AHPS). Radar reflectivity (dBZ) capture across Central Pennsylvania from 22z 9/2/20 (panel b), 18z 9/3/20 (panel e), and 17z 9/13/20 (panel h). Credit: NOAA National Centers for Environmental Information (NCEI). Surface analysis across the Eastern United States for 00z 9/2/20 (panel c), 21z 9/3/20 (panel f), and 00z 9/14/20 (panel i) with fronts (cold fronts in blue and warm fronts in red), troughs (orange dashed lines), centers of low (L) and high (H) pressure, and isobars (yellow lines; every four mb) plotted over infrared satellite imagery. Credit: NOAA Weather Prediction Center (WPC).*

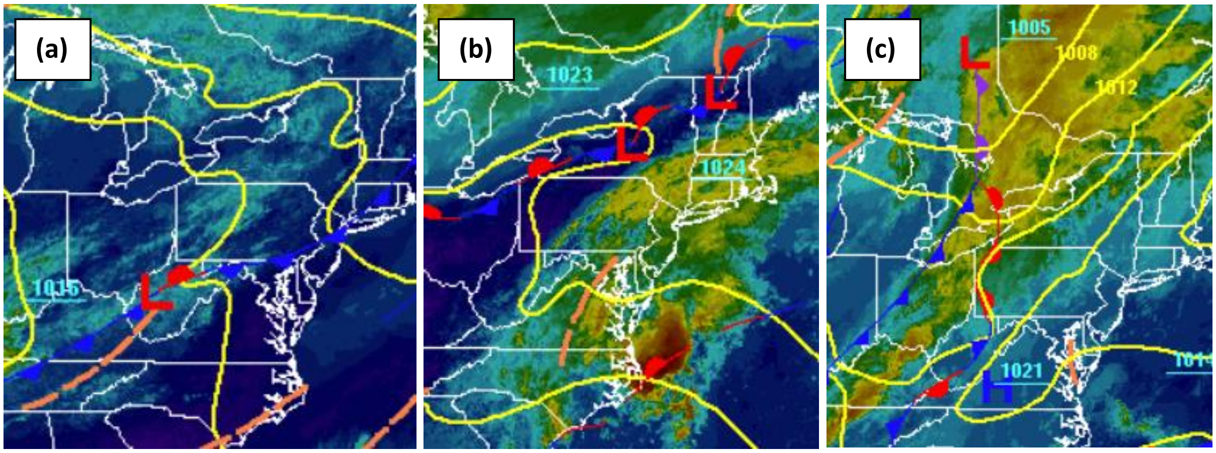

Figure 8. *Surface analysis across the Eastern United States for 15z 9/4/20 (panel a), 18z 9/9/20 (panel b), and 12z 9/13/20 (panel c) with fronts (cold fronts in blue and warm fronts in red), troughs (orange dashed lines), centers of low (L) and high (H) pressure, and isobars (yellow lines; every four mb) plotted over infrared satellite imagery. Credit: NOAA WPC.*

Table 1. *Precipitation totals and calculations for each of the six precipitation days during the observation period. The date of each precipitation day, the time that measurements for rain gauge number six were taken, and precipitation measurements on each of the precipitation days for rain gauge number six and for the Walker Building COOP gauge are all listed. The mean and standard deviation precipitation amounts for the commercial gauge mesonet and the garden variety gauge mesonet were also calculated. Finally, the experiment total accumulated precipitation and standard deviation were also included.*

		Time of Day Rain Gauge #6	Rain Guage #6	Commercial Gauge Mesonet (10 Gauges)		Garden Gauge Mesonet (19 Gauges)		12Z Walker Building
Precipitation Day	Date	Measurment Was Taken	Measurements (in.)	Mean (in.)	Standard Deviation (in.)	Mean (in.)	Standard Deviation (in.)	Measurments (in.)
1	9/3/2020	13Z	0.62	0.44	0.29	0.28	0.18	0.54
2	9/4/2020	13Z	0.05	0.06	0.04	0.02	0.02	0.05
3	9/5/2020	13Z	0	0.00	0.00	0.00	0.01	0
4	9/10/2020	13Z	0	0.02	0.07	0.00	0.00	0
5	9/13/2020	13Z	0	0.01	0.02	0.00	0.01	0
6	9/14/2020	13Z	0.03	0.06	0.03	0.03	0.02	0.06
Experiment Totals for Accum. Precipitation (in.)			0.70	0.59	--	0.33	--	0.65
Standard Deviation (in.)			0.25	0.17	--	0.11	--	0.21

Table 2. *Absolute error (inches) and relative error (%) between gauge types and mesonets for each precipitation day. These included rain gauge number six versus the Walker Building COOP gauge, the full mesonet, and the garden variety gauge mesonet; the Walker Building COOP gauge versus the garden variety gauge mesonet, the commercial gauge mesonet, and the full mesonet; and the garden variety gauge mesonet versus the commercial gauge mesonet.*

	Precipitation Day	1	2	3	4	5	6	Total Error Mean	Total Error Standard Deviation
Between Rain Gauge #6 and the Walker Building	Absolute Error	0.08	0	0	0	0	-0.03	0.01	0.04
	Relative Error	15%	0%	0%	0%	0%	50%	11%	0.20
Between Rain Gauge #6 and Full Mesonet	Absolute Error	0.30	0.02	0.00	-0.01	0.00	-0.01	0.05	0.12
	Relative Error	91%	46%	100%	100%	100%	22%	77%	0.34
Between Rain Gauge #6 and Garden Mesonet	Absolute Error	0.34	0.03	0.00	0.00	0.00	0.00	0.06	0.14
	Relative Error	124%	125%	100%	0%	100%	14%	77%	0.56
Between Garden Mesonet and the Walker Building	Absolute Error	-0.26	-0.03	0.00	0.00	0.00	-0.03	-0.05	0.10
	Relative Error	49%	56%	0%	0%	0%	56%	27%	0.29
Between Commercial Mesonet and the Walker Building	Absolute Error	-0.10	0.01	0.00	0.02	0.01	0.00	-0.01	0.04
	Relative Error	19%	18%	0%	0%	0%	3%	7%	0.09
Between Full Mesonet and the Walker Building	Absolute Error	-0.22	-0.02	0.00	0.01	0.00	-0.02	-0.04	0.09
	Relative Error	40%	32%	0%	0%	0%	36%	18%	0.20
Between Garden Mesonet and Commercial Mesonet	Absolute Error	-0.16	-0.04	0.00	-0.02	0.00	-0.04	-0.04	0.06
	Relative Error	37%	62%	0%	100%	78%	57%	56%	0.35