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RESEARCH ARTICLE

The importance of choosing precipitation datasets

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Abstract

Precipitation data are important for hydrometeorological analyses, yet there are many ways to measure precipitation. The impact of station density analysed by the current study by comparing measurements from the Missouri Mesonet available via the Missouri Climate Center and Community Collaborative Rain, Hail, and Snow (CoCoRaHS) measurements archived at the program website. The CoCoRaHS data utilize citizen scientists to report precipitation data providing for much denser data resolution than available through the Mesonet. Although previous research has shown the reliability of CoCoRaHS data, the results here demonstrate important differences in details of the spatial and temporal distribution of annual precipitation across the state of Missouri using the two data sets. Furthermore, differences in the warm and cold season distributions are presented, some of which may be related to interannual variability such as that associated with the El Niño and Southern Oscillation. The contradictory results from two widely-used datasets display the importance in properly choosing precipitation data that have vastly differing temporal and spatial resolutions. With significantly different yearly aggregated precipitation values, the authors stress caution in selecting 1 particular rainfall dataset as conclusions drawn could be unrepresentative of the actual values. This issue may be remediated by increased spatiotemporal coverage of precipitation data.

KEYWORDS

CoCoRaHS, Mesonet, precipitation, rain gauge, rainfall heterogeneity

1 | INTRODUCTION

Precipitation data are some of the most fundamental parameters necessary for hydrometeorological analyses. In spite of this need, the majority of data are, typically, recorded automatically via rain-gauge networks. The Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) is one network that is maintained by thousands of public volunteers (Cifelli et al., 2005; Kelsch, 1998; Moon, Guinan, Snider, & Lupo, 2009; Reges & Doelsken, 2011; Reges et al., 2016). Originating at Colorado State University as the result of the flash flood of 1997 (Petersen et al., 1999; Weaver, Gruntfest, & Levy, 2000), CoCoRaHS is a grassroots volunteer network of daily precipitation observations within the United States, the Canadian Provinces, the U.S. Virgin Islands, the Commonwealth of Puerto Rico, and the Bahamas. Through implementation of low-cost measurement tools, volunteers of all ages and backgrounds collect precipitation data, often daily, between 6 and 10 a.m. local time. Observations are uploaded to the CoCoRaHS website (https://cocorahs.org) or through a variety of apps, which are immediately available to the public.

To aid in the calibration and validation of National Aeronautics and Space Administration's Soil Moisture Active/Passive satellite, volunteers are also able to take routine measurements of soil moisture and report to the CoCoRaHS website via 0–2″ soil samples. Furthermore, community efforts to collect and disseminate information regarding soil moisture aids in the United States Department of Agriculture's drought monitoring process via 7–9″ soil samples. Volunteers are also capable of measuring evapotranspiration (ET) through a gauge (ETgauge) that simulates crop reference ET. The ETgauge is a modified evaporimeter (atmometer) such that crop albedo and vapour diffusion resistance parameters (i.e., leaf properties) are simulated via a ceramic evaporating cup covered with a green-coloured canvas. Due to the setup of the device, the ceramic evaporator at the top of the ETgauge more closely simulates grass references ET (ET_o).

In addition to being a community effort, many organizations utilize the data that are generated from the CoCoRaHS network including, but not limited to, the National Oceanic and Atmospheric Administration and the National Hydrologic Warning Council. Furthermore, several peer-reviewed publications utilize the data ranging from hydrologic analyses (e.g., Bunkers, Smith, Driscoll, & Hoogestraat, 2015; Grant et al., 2013; Smith, Smith, Baeck, & Miller, 2015), atmospheric aerosol analyses (e.g., Fang & Yongmei, 2012; Kelleners & Verma, 2012; Kelly et al., 2012), and verification of precipitation estimations from radar (e.g., Moon et al., 2009; Kluver et al., 2016; Martinaitis et al., 2014; Smith et al., 2015; Wolfe & Snider, 2012; Zhang, Qi, Langston, Kaney, & Howard, 2014). Therefore, the applications of the data generated from the CoCoRaHS network are very broad and impactful in several different fields of science.

Utilizing citizens to collect precipitation data has several advantages over traditional automatic electrical devices. For example, local random errors (Ciach & Krajewski, 1999a; Habib, Krajewski, & Kruger, 2001; Kitchen & Blackall, 1992), effects of turbulence (Habib, Krajewski, Nespor, & Kruger, 1999), and underperformance of gauges, particularly during instances of convective precipitation (Ciach, 2002; Ciach & Krajewski, 1999b) can result in errors of up to 20% (Frankhauser, 1997) for automated instrumentation. Similarly, many errors have been documented through the implementation of radar to estimate precipitation (Berne & Krajewski, 2013), despite its superior spatial and temporal coverage (Simpson, Hubbart, & Fox, 2016). These errors include degraded performance as the range from the radar increases (Seo, Breidenbach, Fulton, Miller, & O'Bannon, 2000; Smith, Seo, Baeck, & Hudlow, 1996; Ryzhkov, Giangrande, & Schurr, 2003), errors in estimating the drop size distribution (Bringi et al., 2003; Zhang, Vivekanandan, & Brandes, 2001), and inaccurate representations of precipitation shape (Beard & Chuang, 1987; Gorgucci, Baldini, & Chandrasekar, 2006; Gorgucci, Scarchilli, Chandrasekar, & Bringi, 2000).

In Missouri, the collection of CoCoRaHs data began in March 2012. Moon et al. (2009) detailed the establishment of CoCoRaHs observations in the state, examining the distribution of CoCoRaHs instruments during the first 4 years and then comparing the quality of CoCoRaHS reports to the National Weather Service (NWS), Cooperative Observer Program, and radar-derived measurements during the remnants of hurricanes Gustav and Ike (September 2008). Moon et al. (2009) concluded that the CoCoRaHs observations were consistent with NWS Cooperative Observer Program and radar-derived estimates of precipitation for these two events. Occasionally, errant data are found, and the local NWS offices (and KY3 TV in Springfield) are instrumental in helping the Missouri Climate Center quality control the data.

One of the multiple advantages CoCoRaHS data provides over automated rain gauges and radar is the quality control associated with the data. For example, tipping buckets can become clogged, resulting in erroneous collection of precipitation (Ciach, 2002), whereas radars may suffer from erroneous rain rate calculations from radome wetting (Kurri & Huuskonen, 2008) and bright-band contamination (Cunha, Smith, Baeck, & Krajewski, 2013; Kumjian, 2013; Ryzhkov et al., 2003). Albeit, collection of data is once daily, resulting in a loss of temporal resolution; CoCoRaHS has the benefit of daily inspection, which allows for superior quality control of data. However, few reports have detailed the findings from the CoCoRaHS network.

The overarching objective of the current study was to analyse the performance of 10 years of CoCoRaHS data within the state of Missouri, from 2007 to 2016. Due to the daily resolution of the data, aggregation to yearly analyses were conducted to produce an understanding of the spatial heterogeneity of precipitation in the state of Missouri. Additionally, data were separated into warm and cool seasons to determine any seasonal impacts on precipitation trends. Results will be compared with the Missouri Mesonet's tipping-bucket rain gauge network to determine accuracy and overall agreement. Therefore, the current study will analyse the performance of a densely populated gauge network operated by multiple individual citizens compared to several automated tipping-bucket rain gauges. Results will further our understanding as to the reliability of the public for documenting rainfall data in comparison to automated devices, which are more sparsely located in terms of yearly and seasonal resolutions. Furthermore, any differences between the two precipitation sources would highlight the need for increased spatiotemporal precipitation coverage, as these sources typically serve as ground truth for radar quantitative precipitation estimate studies (e.g., Ryzhkov et al., 2003; Simpson et al., 2016).

2 | DATA AND METHODOLOGY

2.1 | CoCoRaHS data

The CoCoRaHS data were retrieved from the domain http://cocorahs.org, particularly from the state of Missouri for the current analyses. Since the beginning of CoCoRaHS data in Missouri (2006; Table 1), over 1,648 separate locations have been established to record precipitation. However, because CoCoRaHS is a community-driven organization, individuals will move or cease precipitation collection for personal matters. Subtracting these stations results in, as of July 2017, 1,186 current stations (Figure 1). As outlined in Moon et al. (2009), many stations are associated with major urban centres (e.g., Columbia, Kansas City, Springfield, and St. Louis) in addition to some smaller towns (e.g., Rolla). In order to analyse a decade's worth of data, the stations that have been collecting precipitation data since the admission of Missouri into the CoCoRaHS network to 2016 were included for this study, totaling 75 stations (Figure 2).

Precipitation data were collected at the 75 separate stations and were recorded in inches by individuals who are admitted to the program contingent upon the use of a standard 4-inch (10.16 cm) overflow tube, whereby the funnel directs precipitation into the measuring tube, magnifying the amount of precipitation by an order of magnitude. This allows the resolution of rainfall to be measured to the nearest 0.254 mm. If 25.4 mm of precipitation is recorded within a day, the excess rainfall is collected in the overflow tube. If users observe less than 0.254 but more than zero millimetre within a 24-hr period, the result is recorded as trace ("T"). Furthermore, the individual operators are instructed to not report morning dew that may form on the gauge. If individuals miss a 24-hr period, but return several days later with precipitation within their gauge, they are instructed to submit a "multiple day accumulation form," in which data is entered as an asterisk (*) for the time period to operator was absent from the device. The total amount of accumulated rainfall over the time period is reported after the last asterisk has been recorded. From the data retrieved, no instances of multi-day reports occurred from the 75

TABLE 1 List of areas in addition to year admitted to the Community Collaborative Rain, Hail, and Snow Network

Year	Regions admitted to the CoCoRaHS network
1998	Colorado
2003	Wyoming
2004	Kansas
2005	New Mexico, Texas, Maryland, Virginia, District of Columbia, Pennsylvania, Indiana
2006	Missouri, Oklahoma, Montana, Illinois, and Alaska
2007	Nevada, Wisconsin, Tennessee, South Dakota, Iowa, North Carolina, New York, Florida, Alabama, Kentucky, and Oregon
2008	Louisiana, New Jersey, South Carolina, Rhode Island, Georgia, Washington, Utah, Michigan, Mississippi, California, and North Dakota
2009	Idaho, Ohio, Massachusetts, Vermont, Arkansas, West Virginia, Hawaii, Connecticut, New Hampshire, Maine, Arizona, Delaware, and Minnesota
2012	Canada
2013	Nebraska
2014	Puerto Rico
2015	U.S. Virgin Islands
2016	Bahamas

Note. CoCoRaHS = Community Collaborative Rain, Hail, and Snow Network.

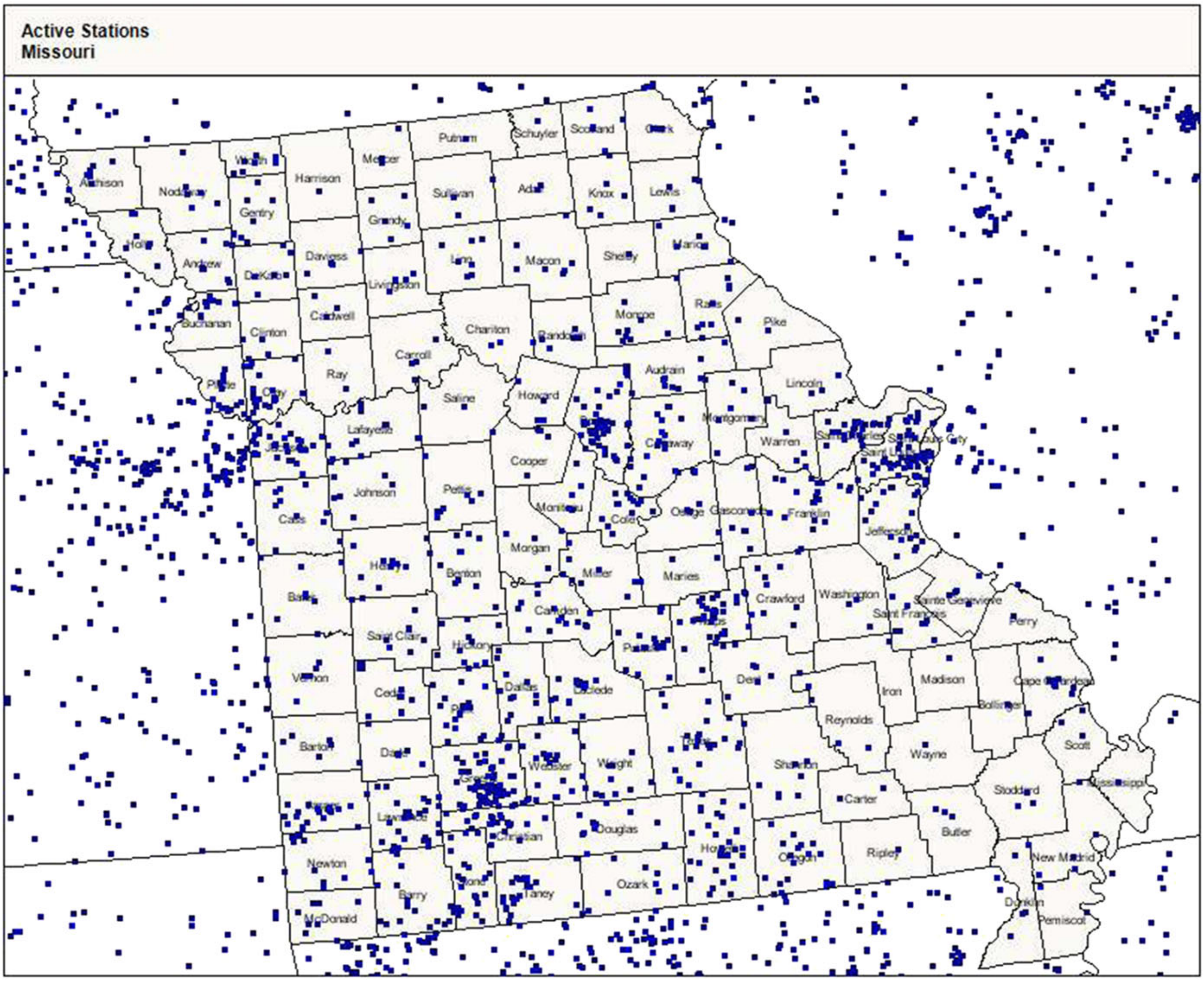

FIGURE 1 Community Collaborative Rain, Hail, and Snow Network stations in the state of Missouri with overlay of counties as of July 2017

stations utilized between December and January (i.e., intra-annually; https://www.cocorahs.org/State.aspx?state=MO).

Methods for measuring snowfall are different from measuring rain. For example, the inner measuring cylinder and funnel are

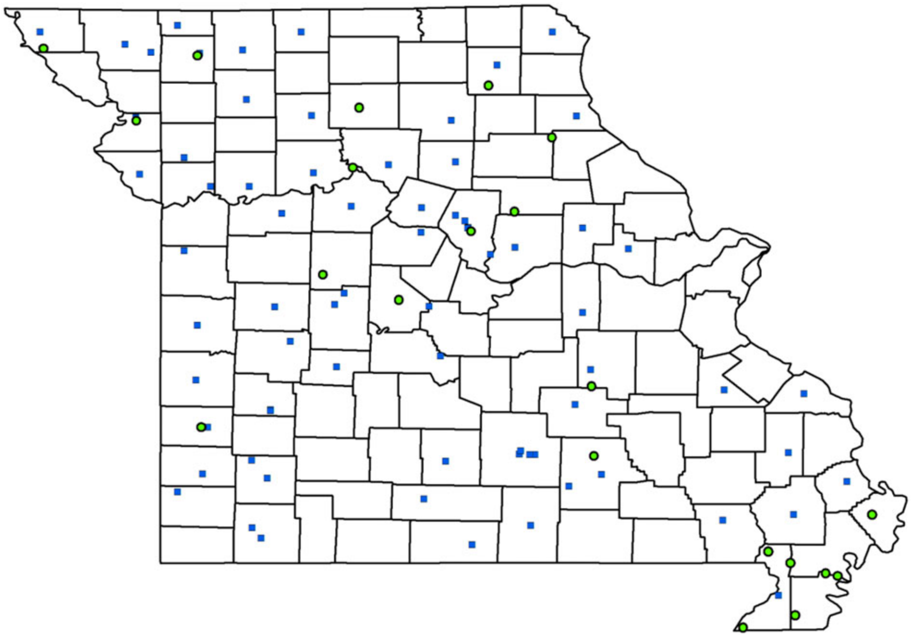

FIGURE 2 The 75 Missouri Community Collaborative Rain, Hail, and Snow Network stations (blue squares) and 22 Missouri Mesonet stations (green circles) utilized for the current study

recommended to be removed for measurements of snow water content and other frozen precipitation, such that snowfall accumulates in the outer (i.e., overflow) cylinder. The observer is instructed to pour *X* amount of warm water into the detached inner cylinder and introduce that to the snow in the outer cylinder. After all of the snow has melted, the water with the newly melted snow amount is re-introduced to the inner cylinder for a total amount. The difference between *X* amount of warm water and the new total amount of water is the reported daily precipitation amount the observer records. Alternatively, the snowfall can be melted down and then be measured by pouring the melted liquid into the inner cylinder.

Although errors associated with CoCoRaHS measurements are not well documented, it has been observed that typical errors include, but are not limited to imprecise readings from the meniscus of precipitation measurements, evaporation from strong solar radiation in the afternoon, wind effects (i.e., turbulence), and inaccuracies in snow melting and snow measuring techniques.

2.2 | Missouri Mesonet data

The Missouri Mesonet is comprised of several fully equipped weather stations that record air temperature, relative humidity, wind direction and speed, precipitation, barometric pressure, solar radiation, and soil temperature at a depth of 2 and 4 inches. For the purpose of this study, precipitation will be analysed as compared against the results of that obtained from CoCoRaHS measurements. From the 35 stations that are operational as of July 2017, only 22 have historical data dating back to 2006 (Figure 2).

Precipitation data from the Missouri Mesonet are recorded via a Campbell Scientific TE525 tipping bucket. Each rain gauge has a 15.24 cm orifice that introduces up to 0.254 mm of precipitation to a fulcrum device, which causes a tip to be registered. Gauge errors range from −1% to 1%, −3% to 0%, and −5% to 0% for precipitation up to 25.4 mm hr^{-1}, 25.4 to 50.8 mm hr^{-1}, and 50.8 to 76.2 mm hr^{-1}, respectively. To mitigate the errors associated with the rain gauges, each device is located, approximately, 1 m above the ground with properly maintained vegetation height to decrease effects from turbulence. Furthermore, all stations are located at a minimum of twice the distance of the height of the nearest building.

The tipping buckets also have a limit as to their performance during extreme temperatures. For example, the manufacturer states the optimal performance of the TE525 tipping bucket series is between 0 and 50 °C. For all stations, no daily maximum temperature exceeded 50 °C, whereas 2% of the days had a minimum temperature below 0 °C. Due to the relatively low number of days below the manufacturer-recommended temperature, these were included in the analyses to determine whether any significant ($p < .05$) differences exist between the tipping bucket reports and the CoCoRaHS data during the cool season.

2.3 | Warm and cool season definition

Due to its inland location and lack of proximity to large bodies of water, Missouri is subject to frequent changes in temperature. Consequently, Missouri has a continental type of climate that is characterized by strong seasonality (Ahrens & Henson, 2014). The summer months typically exhibit warm, moist air masses that produce convective (i.e., heavy) precipitation over relatively short-time periods. Mesoscale convective complexes are frequent, which provide a mix of convective and stratiform precipitation to the Midwest during the evening hours. Additionally, stratiform precipitation is frequent following the convective leading edge of cold frontal passages, which typically occur bi-weekly. Conversely, during El Niño conditions, the Midwest is susceptible to prolonged high pressures, primarily through blocking patterns, which produce prolonged drought periods.

Winter months are typically characterized as cool and humid, in which snowfall and rainfall events are frequently observed. All of

Missouri experiences freezing temperatures every year. Furthermore, there are an average of 110 days with temperatures below 0 °C for the northern half of the state, whereas the number of freezing days reduce to approximately 70 in the bootheel (i.e., south-east) region. The warm and cool seasons are defined such that an agronomic perspective is invoked, whereby freeze probabilities are considered over a climatological (i.e., 30 years) period. From 1986 to 2016, the only month with a mean average temperature below 0 °C was January, whereas February and December averages 0.83 and 0.55 °C, respectively. Furthermore, March and November registered average temperatures of 6.5 °C. Therefore, November to March were designated as the "cool" season, whereas April to October are referred to as the "warm" season. Therefore, the warm and cool seasons have 7 and 5 months, respectively (Lebedeva et al., 2017).

2.4 | Data processing

The aggregated summation values were ingested into ArcGIS Desktop 10.5, in which Kriging interpolations were conducted between each of the 75 CoCoRaHS locations and the 22 Missouri mesonet stations. From the diverse literature of regarding the use of spline or inverse distance weighting being the superior technique (e.g., Declercq, 1996; Gallichand & Marcotte, 1993; Weber & Englund, 1992) to the Kriging procedure (e.g., Creutin & Obled, 1982; Laslett & McBratney, 1990; Rouhani, 1986; Weber & Englund, 1994), Zimmerman, Pavlik, Ruggles, and Armstrong (1999) provides evidence that the Kriging method is significantly superior to the inverse distance weighting method in terms of sampling pattern, noise, and correlation. Therefore, the interpolation scheme invoked for the current study was the spherical Kriging method, using 12-point interpolations.

Differences between the Missouri Mesonet and CoCoRaHS data are, primarily, due to the aforementioned errors for each method of precipitation collection. In general, most Mesonet stations are in the vicinity of a CoCoRaHS location and, therefore, can assume to experience the same amount of precipitation; External forcing (e.g., El Niño or La Niña) of precipitation does not impact the overall differences in rainfall observed for the current study.

3 | RESULTS AND DISCUSSION

3.1 | Yearly Results

In order to determine whether the accumulation of data represents a normal distribution, normal probability plots were constructed for each year (Figure 3). Seven of the 10 years (2009, 2010, 2012, 2013, 2014, 2015, and 2016) produced statistically significantly ($p < .05$) evidence that the precipitation data follow a normal distribution using the Anderson–Darling test (Stephens, 1976). Years 2009, 2010, and 2013 exhibit data that is right skewed, indicating that the majority of stations recording yearly precipitation lie below the mean (1,288.3, 1,140.8, and 1,150.5 mm respectively), overall. Conversely, years 2012, 2015, and 2016 exhibit left-skewed precipitation data. Two thousand and seven and 2011 rainfall amounts show high variance, with regionally large precipitation amounts in the south-west and south-east, respectively.

In addition to determining the normality of the spatial distribution of precipitation, boxplots were constructed also to visualize mean, quartiles, and outliers of each of the 10 years of data (Figure 4). From the aforementioned probability results, the years that rejected the null hypothesis of normality under the Anderson–Darling test (e.g., 2007, 2008, and 2011) either resulted in a relatively large number of outliers (e.g., 2007 and 2011) in addition to a large range of yearly accumulated precipitation. Years 2012, 2013, and 2014 were neutral El Niño and Southern Oscillation (ENSO) phases (Newberry, Lupo, Jensen, & Rodriges-Zalipynis, 2016), which also resulted in the most evenly distributed rainfall amounts for the state of Missouri. This is evidenced by the near-symmetrical quartiles between the mean values in addition to the symmetry of the variability outside of the upper and lower quartiles.

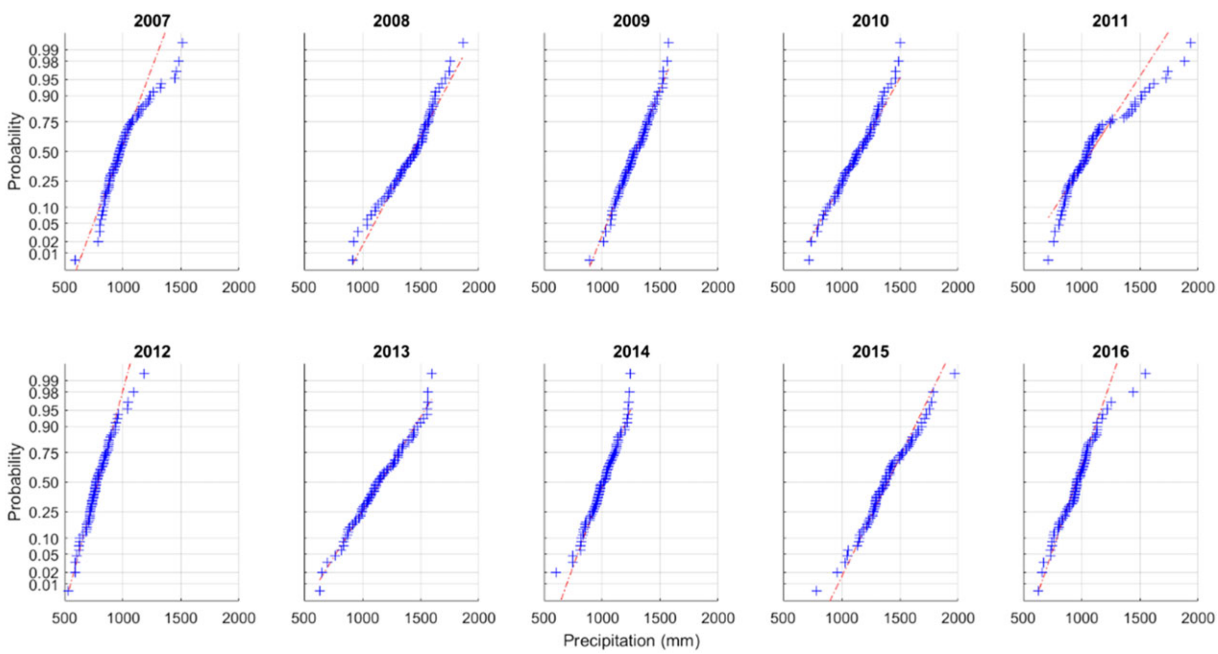

FIGURE 3 Normal probability plots for the 75 Missouri Community Collaborative Rain, Hail, and Snow Network stations

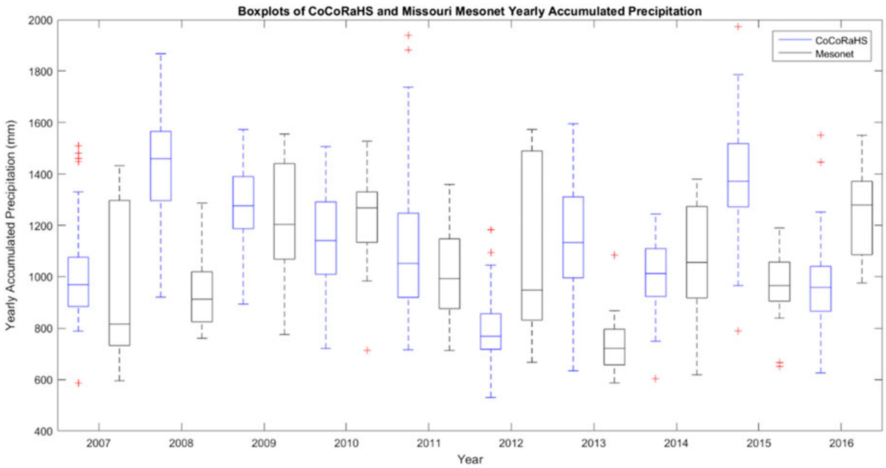

FIGURE 4 Boxplots displaying the yearly accumulation of precipitation (in millimetre) recorded by the 75 Missouri Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) stations (blue) and the 22 Missouri Mesonet stations (black) for the current study with outliers (red)

The range in the Missouri Mesonet data were larger than for the CoCoRaHS results (Figure 5). However, only two of the Missouri Mesonet stations rejected the null hypothesis of normally distributed precipitation throughout the state: 2007 and 2012, via the Anderson–Darling test. These two particular years exhibited pronounced variability marked by the long tails via their normal probability plots (Figure 5). In spite of most other years (with the exception of 2013) displaying the same pattern, the results were such that the test statistic fell below the Anderson–Darling critical values (Stephens, 1976). This may be due, at least in part, to the fact that the Anderson–Darling test tends to weigh the tails of the distribution more than the Kolmogorov–Smirnov test, which is only valid for continuous distributions (Stephens, 1977).

The overall yearly average precipitation recorded by the CoCoRaHS locations was 1,126.6 mm, whereas the average rainfall registered from the Missouri Mesonet stations was 1,050.6 mm. This resulted in the Missouri Mesonet and the CoCoRaHS being significantly different ($p < .01$) with a confidence interval between 36.1 and 115.9 mm, a t-statistic value of 3.7472 with 346.15 degrees of freedom. Furthermore, years 2007, 2009, 2010, 2011, and 2014 were the only years where the means of precipitation were significantly ($p < .05$) similar. The Missouri Mesonet locations tended to produce fewer outliers than the CoCoRaHS sites, which may be due partly to increased spatial resolution of the CoCoRaHS stations (Figure 2), indicating that the heterogeneity of precipitation is enough to produce significantly different rainfall totals over the course of a year, similar to the findings of Hubbart et al. (2014).

From the CoCoRaHS data in Missouri, there were no years in the 2007–2016 period that exhibited a maximum amount of precipitation below 1,000 mm (Figure 6). In general, the majority of rainfall was recorded in the southern region (particularly the south-east) with the exception of 2010, where the bulk of precipitation was measured in the northern portion of Missouri. The largest amount of rainfall recorded by CoCoRaHS locations was in 2011 (1,932.7 mm), followed by 2015 (1,868.7 mm). Evidence also suggest that when the largest amount of precipitation occurs in the south-east region, there is, typically, a north-west to south-east gradient of precipitation values, typical

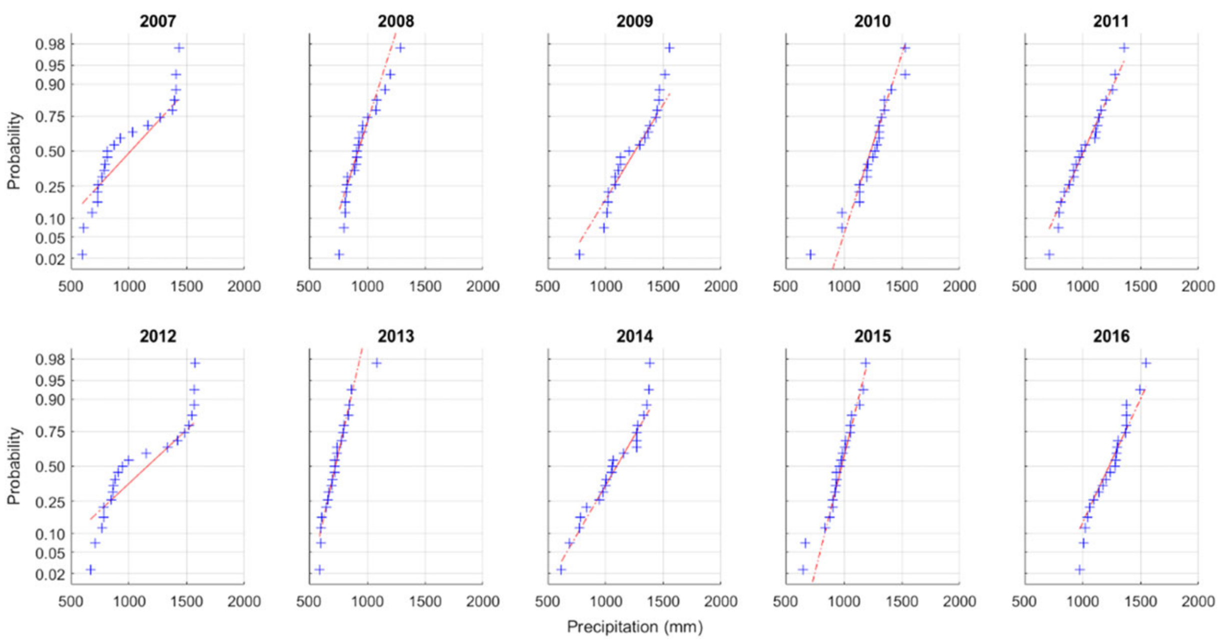

FIGURE 5 Normal probability plots for the 22 Missouri Mesonet stations

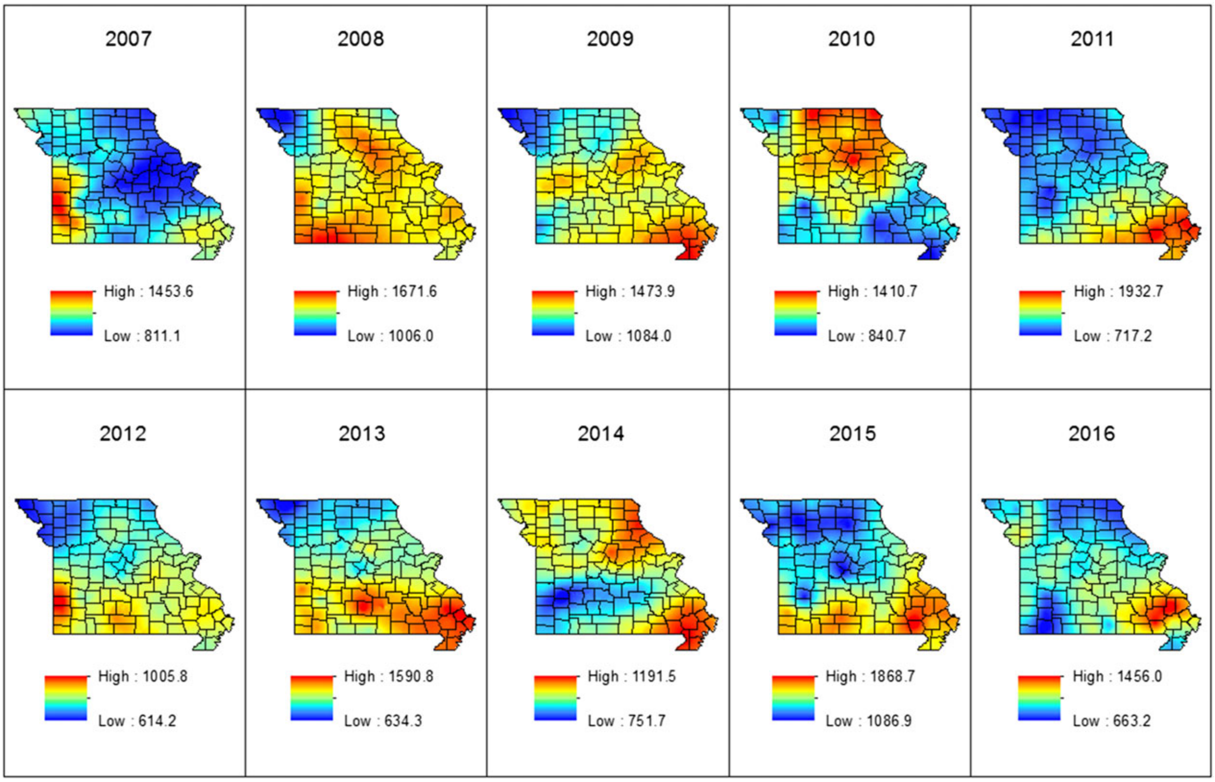

FIGURE 6 Yearly cumulative precipitation totals for Missouri from 2007 to 2016 in millimetre using the Community Collaborative Rain, Hail, and Snow Network stations

of precipitation patterns in the Midwest (Birk, Lupo, Guinan, & Barbieri, 2010). For several of the years (e.g., 2011, 2014, and 2016), when the maximum precipitation is located in the bootheel (i.e., south-eastern) region, the minimum is, typically, located in the south-west. This could be due, at least in part, to mesoscale and/or synoptic events associated with the impact the Ozark Plateau has on precipitation regimes. However, this conjecture would need further study.

For Boone County, Missouri (centre of Missouri), which contains the City of Columbia, one of the largest cities in the state, the effects of an urban heat island effect on precipitation amount is evident (Akyuz et al., 2004). For example, all stations located within Boone County recorded larger cumulative precipitation amounts than any other station within a 50-km radius for all years except 2009 and 2012. These results are consistent with those found in Hubbart et al. (2014), indicating that localized urban regions exhibit larger precipitation amounts than surrounding rural areas.

The years of 2012 and 2016 registered the least amount of rainfall (614.2 and 663.2 mm, respectively) since 2007. For 2012, the largest amount of precipitation occurred in the south-west (near Joplin, MO) with a minimum to the north, whereas the opposite was true for the year of 2016, such that the minimum amount of precipitation was to the south-west (and north-east), but the maximum was located in the south-east. As stated above, most years exhibited a north-west-south-east precipitation gradient with noticeable exceptions of 2007 and 2010, both of which were characterized by relatively strong El Niño during the warm season.

The Missouri Mesonet displayed less heterogeneity of precipitation, in spite of the data being relatively more evenly spaced than the CoCoRaHS stations (Figure 2). However, the general pattern of annual precipitation totals increasing to the south was evident with the Mesonet, similar to the CoCoRaHS results (Figure 7). In spite of this similarity, for the majority of Missouri Mesonet stations, the precipitation patterns were nearly opposite to what was reported from CoCoRaHS. For example, for 2007, the largest annual precipitation amount as measured by CoCoRaHS was in the south-west (1,435.6 mm), whereas the largest annual precipitation amount recorded by the Mesonet was in the south-east (1,431.8 mm). Furthermore, the range of minimum precipitation for 2007 was over 200 mm less for the Mesonet. Similar patterns of opposing maximum and minimum of precipitation were observed for all years with the exception of 2008, 2014, 2015, and 2016.

The largest values of precipitation recorded by the Mesonet were found in 2012 (1,574 mm), which happened to be the lowest recorded maximum for the CoCoRaHS data (1,005.8 mm), with the maximum being in the south-east and south-west regions of the state, respectively. The highest precipitation values for the majority of the state of Missouri were recorded in 2009, the only year that both methods of rainfall collection displayed a consistently large precipitation amount.

3.2 | Seasonal results

The warm season precipitation totals, typically, exhibited the same spatial pattern as the yearly accumulation of rainfall for the CoCoRaHS data (Figure 8), which is to be expected as convective precipitation dominates during the warm season, yielding larger rainfall amounts in comparison to relatively shallow storm systems during the cool season, which generates lower liquid precipitation (Birk et al., 2010).

The largest contribution of the warm season precipitation to the yearly total were in (92.5%) and 2007 (83.1%), both weaker El Niño

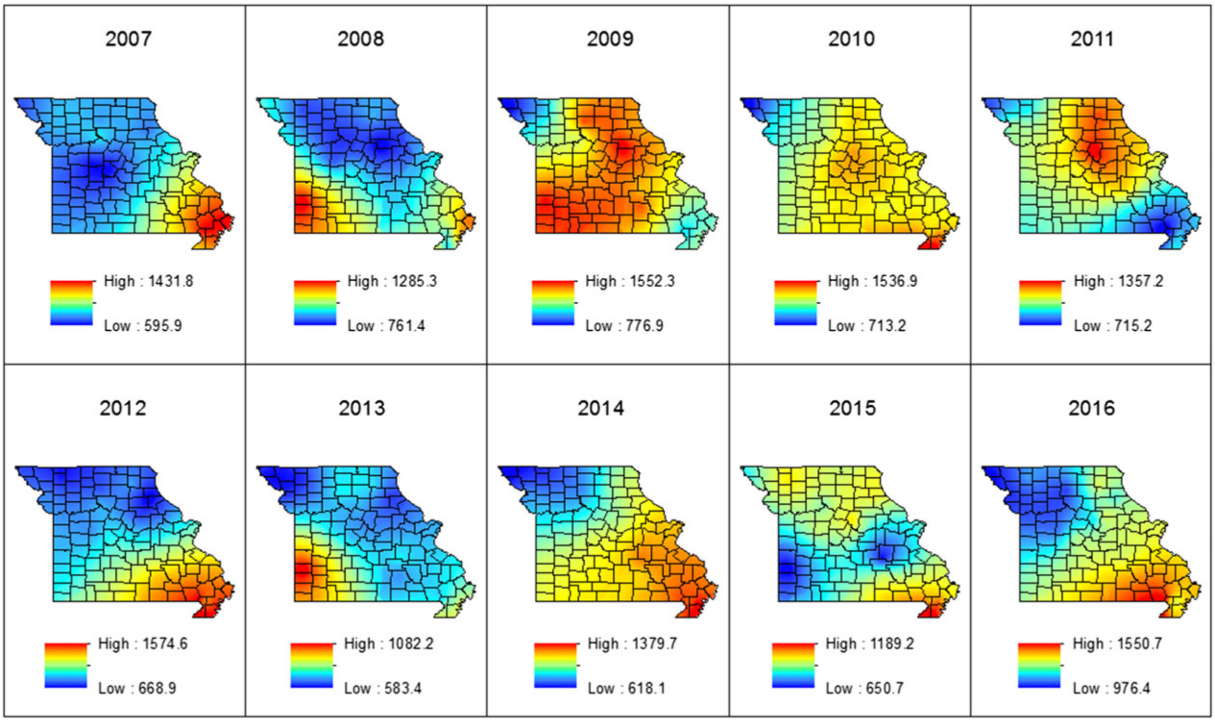

FIGURE 7 Yearly cumulative precipitation totals for Missouri from 2007 to 2016 in mm using the Missouri Mesonet stations

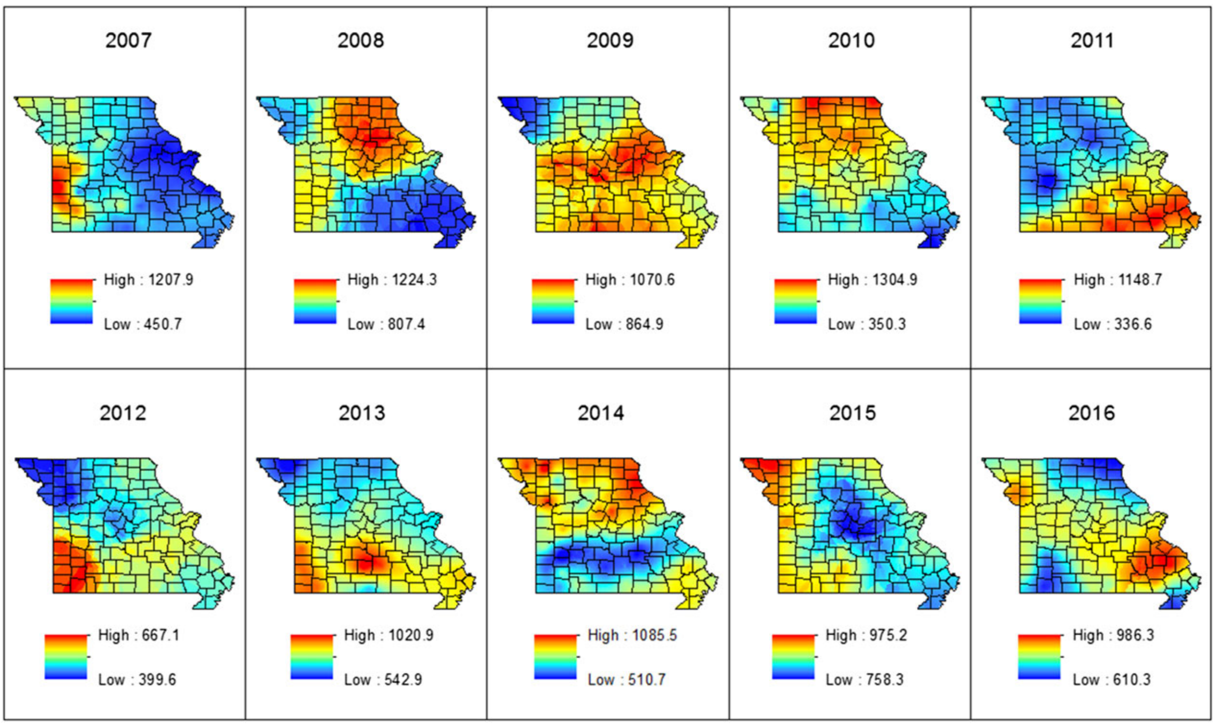

FIGURE 8 Warm season cumulative precipitation totals for Missouri from 2007 to 2016 in millimetre using the Community Collaborative Rain, Hail, and Snow Network stations

years during the warm season (see Center of Ocean and Atmosphere Prediction Studies: http://www.coaps.fsu.edu/pub/JMA_SST_Index/). The absolute largest warm season precipitation amounts were 2010 (1,304.9 mm) and 2008 (1,224.3 mm), and 2007 was the third largest (1,207.9 mm). Conversely, 2012 yielded the smallest contribution by warm season precipitation (667.1 mm), which comprised 66.3% of the total annual precipitation for the year. Both 2015 and 2016 also had warm season precipitation amounts below 1,000 mm (975.2 and 986.3 mm, respectively), which are characterized as relatively strong El Niño summers. Therefore, it may be summarized that during weak El Niño years, the south-east is primarily associated with low precipitation amounts during the warm season (i.e., drought conditions) with large precipitation amounts elsewhere (primarily to the west and north), whereas strong El Niño years are characterized by overall drier than normal summers where the bulk of precipitation is localized to the south-eastern portion of Missouri. However, this is a limited sample and studies such as Birk et al. (2010) show that ENSO behaviour in Missouri can change over time as related to interdecadal variability such as that associated with the Pacific Decadal Oscillation.

The overall minimum in warm season CoCoRaHS precipitation amount for the current 10-year study were for years 2011 (336.6 mm), 2010 (350.3 mm), and 2012 (399.6 mm), which may be due, at least in part, to the dominant neutral phase during this time period. However, the regions of largest recorded rainfalls were different for each years, ranging from the south-east, south-west, and overall north of Missouri. Conversely, the largest values of the minimum amount of precipitation for the warm season were for years 2009 (864.9 mm), 2008 (807.4 mm), and 2015 (758.3 mm). Unlike the maximum precipitation amounts, the minimum precipitation values were not attributed to a single ENSO phase nor a transition of phases (Newberry et al., 2016). Interestingly, with the exception of 2007–2008 and 2013–2014, the warm season precipitation amount in the south-eastern region displays a nearly oscillatory pattern of maximum/minimum precipitation amount for the state of Missouri.

In general, rainfall patterns for the cool season were maximum in the south-eastern region of Missouri for each of the 10 years of the current study (Figure 9). Furthermore, CoCoRaHS recorded precipitation patterns of the cool season match especially well for annual precipitation totals for 2007, 2010, 2011, 2012, and 2016. However, for 2008 and 2012, the cool season rainfall amount contributed to an extended portion of the south.

The evidence of the urban heat island effect in Boone County (Central Missouri) is prevalent through many of the years, especially 2007 and 2015. For example, the stations in Central Missouri for the cool season of 2007 registered an average precipitation total of, approximately, 350 mm, whereas the surrounding areas, up to 150 km from Central Missouri, registered below 200 mm of precipitation. The same general magnitudes were recorded for 2014, but the areal extent of rainfall totals were larger to the south-east.

For all years with the exception of 2015, the overall warm season precipitation maximums were larger than the cool season maximums. Although designated a relatively strong El Niño, the 2015–2016 cool season registered 987.5 mm of precipitation in the south-east, compared to maximum of 975.2 mm in the north-west during the warm season. This could be due, at least in part, to the relatively warmer than average winter that occurred during 2015–2016, resulting in an unseasonably large amount of severe weather reports during December.

From a regional perspective, the maximum amount of cool season precipitation in the south-east of Missouri was more than the maximum amount of warm season rainfall for 2007 (634.8 mm compared to 500 mm), 2010 (453.9 mm compared to 350.3 mm), and 2015 (987.5 mm compared to 800 mm), all characteristically warm season El Niño events. Therefore, it is possible that during El Niño events, the majority of precipitation in the south-eastern portion of Missouri occurs during the cool season.

The Missouri Mesonet warm season accumulation of precipitation least closely matched the CoCoRaHS pattern of precipitation than the yearly data (Figure 10). For example, the maximum of warm season precipitation for the CoCoRaHS and Mesonet data were in the south-west and south-east for 2007, respectively, whereas the maximum for 2008, 2009, 2011, and 2014 for in the north-east and south-west, central and south-west/north-east, south-east and north-east, and north and south-east, respectively. Furthermore, the

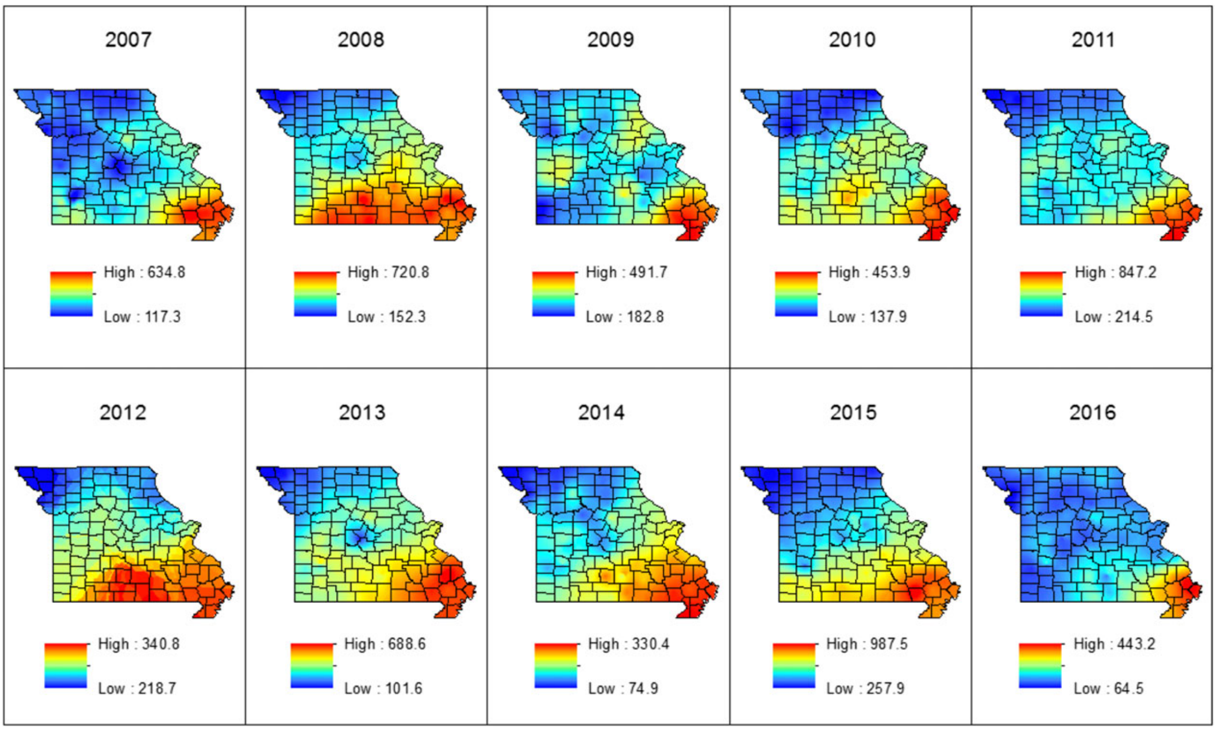

FIGURE 9 Cool season cumulative precipitation totals for Missouri from 2007 to 2016 in millimetre using the Community Collaborative Rain, Hail, and Snow Network stations

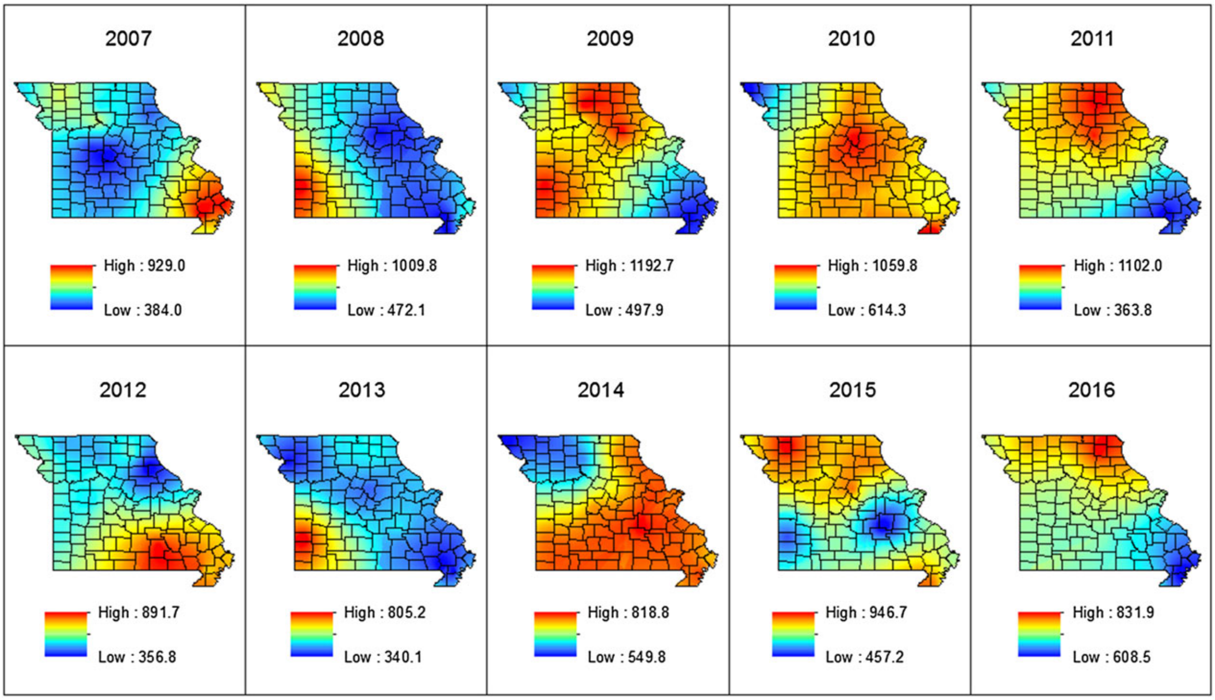

FIGURE 10 Warm season cumulative precipitation totals for Missouri from 2007 to 2016 in millimetre using the Missouri Mesonet stations

only year that showed any correlation between warm season and annual total precipitation patterns was for 2013 and 2015.

Overall, the absolute maximum warm season Missouri Mesonet rainfall amount was for 2009 (1,192.7 mm), with 2011 not far behind (1,102.0 mm). Additionally, 2010 and 2008 also registered over 1,000 mm of precipitation for the warm season (1,059.8 and 1,009.8 mm, respectively). The lowest warm season maximum precipitation values were 2013 (805.2 mm) and 2016 (831.9 mm). The extreme minimum values of precipitation were for years 2010 (614.3 mm) and 2016 (608.5 mm), whereas the lowest values of warm season precipitation, overall, were recorded during the years of 2013 (340.1 mm) and 2012 (356.8 mm), and both years were classified as ENSO neutral.

For all 10 years of the current study, the Missouri Mesonet recorded the maximum amount of cool season precipitation in the south-east (Figure 11), similar to the results presented by the cool

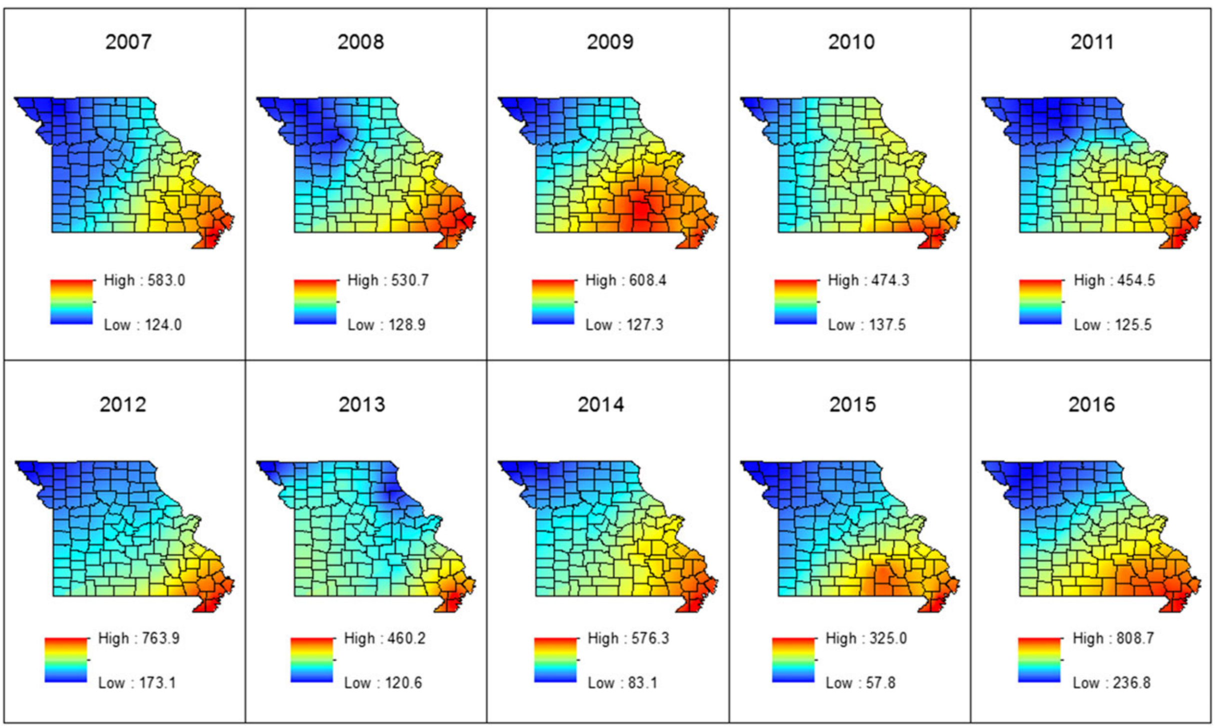

FIGURE 11 Cool season cumulative precipitation totals for Missouri from 2007 to 2016 in millimetre using the Missouri Mesonet stations

season CoCoRaHS sites. Conversely, all of the minimum amount of rainfall for the cool season were located in the north, primarily to the north-west. Years 2011, 2012, 2015, and 2016 registered, overall, lowest precipitation amounts along the northern border of Missouri, whereas 2007, 2010, 2012, and 2015 all recorded their lowest precipitation amounts along the western edge of the state.

4 | CONCLUSIONS

Multiple methods for collecting precipitation data at a point location exist, but the means of how the rainfall is collected varies. Typically, automated rain gauges in the form of tipping buckets collect precipitation data to ameliorate the attention necessary for the precipitation collection process. However, Colorado State initiated the CoCoRaHS network, which implements the general public to record daily precipitation values in order to increase the spatial resolution of rainfall collection, as automated rain gauges become relatively expensive over time. Since the CoCoRaHS program was implemented in 1998, the United States, U.S. Virgin Islands, Canada, Puerto Rico, and the Bahamas have joined to aid in the rainfall collection. Even though data have been collected, results from studies using these data are relatively few in the literature. Therefore, the current study analyzes 10 years of 75 separate CoCoRaHS precipitation data and compares the results to 22 Missouri Mesonet sites.

Seven out of the 10 years used in the current study reported a normal distribution of rainfall across the state of Missouri as recorded by the CoCoRaHS sites, whereas 8 of the 10 Missouri Mesonet stations were normally distributed. This may be due, at least in part, to the fact that there were more CoCoRaHS site locations in comparison to the Missouri Mesonet. This resulted in, overall, there being a significant ($p < .01$) difference between the CoCoRaHS and Missouri Mesonet yearly precipitation totals. When the entire 10-year dataset was divided into yearly accumulations, half of the years of precipitation were significantly different between CoCoRaHS and the Missouri Mesonet. Furthermore, it was shown that the most spatially even distribution of rainfall were, primarily, during ENSO neutral years (i.e., years 2012, 2013, and 2014).

The urban heat island effect (Hubbart et al., 2014) was evident, but mostly for the CoCoRaHS data, primarily due to the increase spatial resolution of rainfall. It was noticed that during weak El Niño years, the south-east is primarily associated with low precipitation amounts during the warm season (i.e., drought conditions) with large precipitation amounts elsewhere (primarily to the west and north). Conversely, strong El Niño years are characterized by overall drier than normal summers where the bulk of precipitation is localized to the south-eastern portion of Missouri. For all years with the exception of 2015, the overall warm season precipitation maximums were larger than the cool season maximums.

There were many instances in which the precipitation regimes were opposite in the two precipitation datasets. For example, the maximum of warm season precipitation for the CoCoRaHS and Mesonet data were in the south-west and south-east for 2007, respectively, whereas the maximum for 2008, 2009, 2011, and 2014 for in the north-east and south-west, central and south-west/north-east, south-east and north-east, and north and south-east, respectively. Furthermore, only 2 years showed any correlation between precipitation patterns, 2013 and 2015.

The results presented improve our understanding of the impacts of different methods of collecting precipitation. In this case, the CoCoRaHS network is a much denser precipitation network than the Missouri Mesonet and has been shown to more reliable than tipping-bucket measurements (Moon et al., 2009). For example, unpublished comparisons exhibited that tipping-bucket rain gauges used by the Fort Collins, Colorado storm-water utility were 10–20% lower than CoCoRaHS gauges (Reges et al., 2016). Research conducted by the West Texas Mesonet (www.mesonet.ttu.edu/) noted systematic low bias on the order of 5–10% over varying precipitation regimes. Depending on the precipitation data used, such as the current study, significantly ($p < .01$) different results may occur, especially when aggregated over yearly time scales. This may, in turn, yield in some cases opposite results for the spatial and temporal resolution of rainfall over regions as large as Missouri.

Furthermore, the quality control that is implicit with the CoCoRaHs data exceeds that of many different Mesonets within the contiguous United States (Reges et al., 2016). Specific examples include manual measurements of snowpack being combined with snow water equivalent reported by citizens that are utilized by the Snow Telemetry system (Pagano, Garen, & Sorooshian, 2004), in addition to the Airborne Gamma Radiation Snow Survey Program (Carroll, 2001). The combination of these validations enhances the National Operational Hydrologic Remote Sensing Center's remote sensing, snow modelling, and spatial analysis programs (Clow, Nanus, Verdin, & Schmidt, 2012).

With limited studies comparing the performance of CoCoRaHS to other sources of precipitation data, the current study presents a novel discussion comparing the results of 10 years' worth of rainfall data. With statistically significant ($p < .05$) differences for most years, results indicate the importance in carefully choosing a source of rainfall data. Furthermore, the results point towards the importance of the public in the collection and dissemination of rainfall data, which may yield more accurate calibrations of radar rainfall estimates and hydrologic modelling.

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