Comparison of Collocated Automated (NCECONet) and Manual (COOP) Climate Observations in North Carolina

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ABSTRACT

The National Weather Service's Cooperative Observer Program (COOP) is a valuable climate data resource that provides manually observed information on temperature and precipitation across the nation. These data are part of the climate dataset and continue to be used in evaluating weather and climate models. Increasingly, weather and climate information is also available from automated weather stations. A comparison between these two observing methods is performed in North Carolina, where 13 of these stations are collocated. Results indicate that, without correcting the data for differing observation times, daily temperature observations are generally in good agreement (0.96 Pearson product–moment correlation for minimum temperature, 0.89 for maximum temperature). Daily rainfall values recorded by the two different systems correlate poorly (0.44), but the correlations are improved (to 0.91) when corrections are made for the differences in observation times between the COOP and automated stations. Daily rainfall correlations especially improve with rainfall amounts less than 50 mm day^{-1}. Temperature and rainfall have high correlation (nearly 1.00 for maximum and minimum temperatures, 0.97 for rainfall) when monthly averages are used. Differences of the data between the two platforms consistently indicate that COOP instruments may be recording warmer maximum temperatures, cooler minimum temperatures, and larger amounts of rainfall, especially with higher rainfall rates. Root-mean-square errors are reduced by up to 71% with the day-shift and hourly corrections.

This study shows that COOP and automated data [such as from the North Carolina Environment and Climate Observing Network (NCECONet)] can, with simple corrections, be used in conjunction for various climate analysis applications such as climate change and site-to-site comparisons. This allows a higher spatial density of data and a larger density of environmental parameters, thus potentially improving the accuracy of the data that are relayed to the public and used in climate studies.

1. Introduction

Accurate and reliable weather and climate information are important in many areas of society—in government, economy, agriculture, tourism, water resources, and emergency response, to name a few. Climate observing stations such as the Cooperative Observer Program [(COOP): managed by the National Weather Service (NWS)] have been used for over a century to provide temperature and precipitation information to operational weather forecasters, researchers, and the public. The COOP stations are the backbone of climate change studies and have the advantage of long periods of record (with several providing over 100 years of data). The COOP data are thus well established and generally accepted as invaluable data sources in the climate community, often providing a good density of coverage.

Currently, there is a growing trend of state-based automated networks that report hourly observations for a wide range of parameters (e.g., Alabama, California, Colorado, Florida, Georgia, Illinois, Indiana, North Carolina, Oklahoma, Washington, etc.). One such system in North Carolina is the North Carolina Environment and Climate Observing Network (NCECONet), which is operated and maintained by the State Climate Office of North Carolina (SCO-NC; information available online at http://www.nc-climate.ncsu.edu). A num-

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ber of these automated sites are located at agricultural research stations, which also participate in the COOP network. These NCECONet stations provide hourly observations for atmospheric and soil parameters that COOP stations do not report, and they also help increase the density of observed data.

The automated networks continue to expand, and the COOP network itself is posed to become an automated platform [as part of the Near Real (Time) Observational Network (NERON)]. Therefore, assessing the compatibility of the automated data with long-term COOP data is an important issue in developing regional climate information and for data continuity. Various aspects of weather and climate operations and research, on the smaller individual researcher scale and on the larger climate policy scale, rely on these surface observations. Therefore, it is critical to understand how the recent automated observations (e.g., NCECONet) compare with the historical manual observations (COOP).

There is a relatively limited number of published studies that compare data from different instrument platforms that are in field, collocated, and not altered or moved for the purposes of research. Sun et al. (2005) compared data from the Automated Surface Observing System (ASOS: maintained by the NWS) to data from the U.S. Climate Reference Network (USCRN) at two locations—one was a facility designed for testing instruments under the same conditions and the other did not have the platforms collocated. Hubbard et al. (2004) compared air temperature observations from the COOP instrumentation with the USCRN instrumentation, with the instruments placed side by side for the purposes of the study. That study focused on the effects of solar radiation and winds on the two instrument designs.

Guttman and Baker (1996) developed one particular analysis for data from the ASOS and the COOP. They concluded that, even though differences in sensors and measurement approaches cause variability in the datasets, the most significant differences between the two datasets are caused by the distance separating the stations and from the differences in land usage and topography that are associated with the separation in the two measurements. The collocated NCECONet and COOP stations are therefore ideally suited to address the issue of how similar the COOP and automated data are in developing a climatology for rainfall and temperature information, and hence are considered in our analysis. The collocation of the station sites also helps to reduce siting errors, which are of critical importance in assessing regional changes in these parameters (Davey and Pielke 2005). Thus, the objective of this study is to compare the observations for maximum air temperature, minimum air temperature, and total rainfall amounts at daily and monthly periods for 13 different collocated COOP and automated NCECONet stations.

2. Methods

Daily weather observations at NCECONet stations are made available through the North Carolina Climate Retrieval and Observations Network of the Southeast (NC-CRONOS) database (available online at http://www.nc-climate.ncsu.edu/cronos). Data from COOP stations are available from the National Climatic Data Center (NCDC; available online at http://www.ncdc.noaa.gov). For the sites used in this study, both types of weather observing sites are collocated at the agricultural research stations, typically within 500 m of each other. Though the Guttman and Baker (1996) study found data inhomogeneities with stations separated by distances as small as 500 m, it found consistent data between two particular stations that were 0.25 miles ($\sim$400 m) from each other but had similar site characteristics, such as terrain and land use. Here, since each site is rural farmland covering at least 0.4 km^2, siting characteristics are a minimal issue for the purposes of this study. The locations of the paired NCECONet and COOP stations used for this study are shown in Fig. 1, spanning from Waynesville in mountainous western North Carolina, through the rolling hills of the more populous central Piedmont region, to Lewiston in the coastal plain of eastern North Carolina. Table 1 also gives the general climate region of each site. The variety of climates is chosen to broaden the scope of this research beyond a singular latitude, soil type, terrain, etc. More information on the many climates represented in North Carolina can be obtained from the SCO-NC.

Daily rainfall, maximum temperature, and minimum temperature data are compiled for August 2001 through January 2004. While automated data became available from some stations in the NCECONet in mid-1996, new stations have gradually been incorporated and data and instrumentation quality were significantly improved in the few years following the inception of the network. Specifically, a number of improvements related to consistent instrumentation and data collection were implemented in early 2001, so this study utilizes data beginning in mid-2001.

The automated stations in NCECONet use a Vaisala HMP45C probe for measuring temperature and relative humidity at 1-min intervals. Daily (from midnight to midnight) temperature maxima and minima are ob-

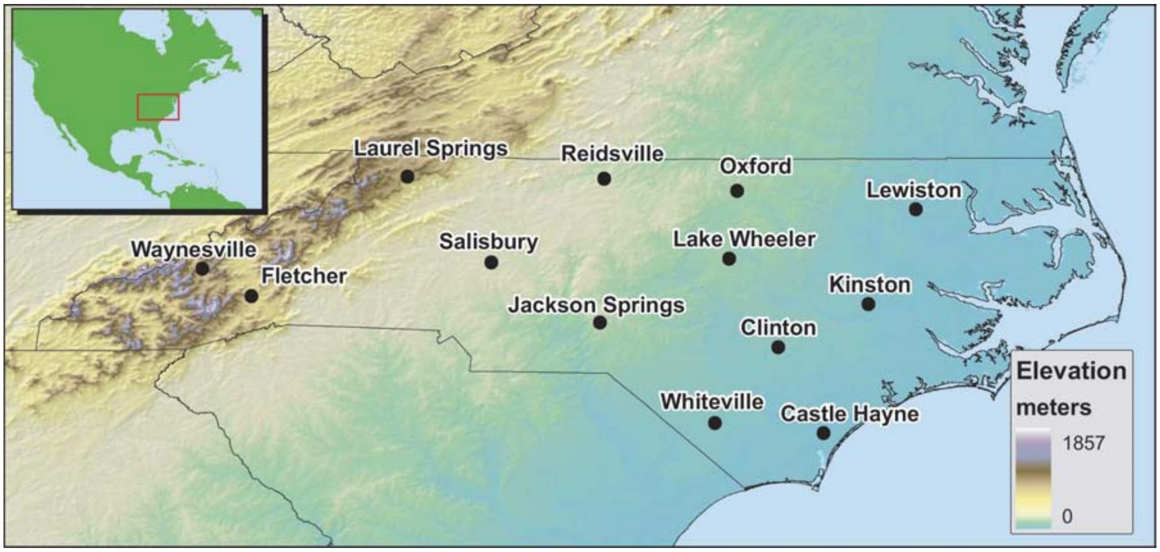

FIG. 1. Locations for each NCECONet and corresponding COOP observing station that was used in the comparison study. The time period that was the main focus in the study was from August 2001 through January 2004. Elevations are shown (m), and latitude and longitude are labeled (°).

tained from these 1-min samples. For rainfall measurements, NCECONet stations use Texas Engineering 525 tipping buckets. This sensor counts the number of times the funnel tips over, and each tip constitutes 0.01 in. (0.254 mm). COOP stations use maximum/minimum temperature sensors (MMTS) for temperature and 8-in. (203.2 mm) standard gauges for rainfall. Daily observation times at COOP stations vary from station to station, but they usually report a sunrise-to-sunrise or sunset-to-sunset day, with daily temperature extremes based on observations taken every 2 s. Information on the temperature and rainfall sensors used by these two platforms, and on sampling intervals, is provided in Table 2. NCECONet stations conform to World Meteorological Organization instrumentation standards, and COOP stations are generally in open, well-sited areas.

Table 1 shows the latitude–longitude, COOP observation time, and general climate of the region within the state for these stations. A majority of the COOP stations record observations for a particular calendar date at 0800 or 1700 LT rather than at midnight; that is, for example, the data recorded for a certain date would be the precipitation totals and temperature extremes for the 24-h period beginning at 0800 LT the previous day and ending at 0800 LT on the current date. Thus, the high and low temperatures that they record may not actually be for the date on which they were recorded—they can be off by a day. Such an overlap between the days is also seen in the daily rainfall totals.

TABLE 1. Details for the 13 locations used in this study. The measurements are made at agricultural research stations.

Station	Latitude (°)	Longitude (°)	Region	Elevation (m)	COOP observation time (LT)
Castle Hayne	34.32	−77.92	Coastal plain	11.9	0900
Clinton	35.02	−78.28	Coastal plain	47.9	0800
Fletcher	35.43	−82.56	Mountains	630.6	0800
Jackson Springs	35.22	−79.73	Piedmont	222.8	0800
Kinston	35.37	−77.55	Coastal plain	18.0	1700
Lake Wheeler	35.73	−78.65	Piedmont	128.0	1700
Laurel Springs	36.40	−81.30	Mountains	875.4	0800
Lewiston	36.13	−77.17	Coastal plain	14.9	2400
Oxford	36.28	−78.62	Piedmont	151.8	0700
Reidsville	36.35	−79.70	Foothills	271.3	0800
Salisbury	35.70	−80.62	Foothills	250.9	0800
Waynesville	35.65	−82.97	Mountains	834.2	0800
Whiteville	34.40	−78.80	Coastal plain	27.1	0800

TABLE 2. Information on instrumentation and sampling intervals.

	Rain gauge	Temperature sensor	Determination of daily temperature extremes
COOP	8-in. (203 mm) standard collection gauge	Minimum/maximum sensor	From observations taken every two seconds
NCECONet	Texas Engineering 525 tipping bucket	Vaisala HMP45C probe	From observations taken every minute

Therefore, the time of observation needs to be accounted for in comparing the two datasets.

This need for a correction for the time of observation has been well documented (e.g., Baker 1975; Blackburn 1983; Karl et al. 1986; Mitchell 1958; Schaal and Dale 1977). Biases resulting from changing observation time at a particular COOP station could be as large as 5.4°C under extreme conditions (Mitchell 1958) with a significant change, such as from a morning observation time to an evening observation time, creating up to a 1.4°C annual bias (Baker 1975). A study by Wu et al. (2005) investigated temperature and precipitation discrepancies between geographically close (<10 km separation) COOP stations and used similarly close hourly observing Automated Weather Data Network (AWDN) stations to recreate daily data for the 24-h days that the nearby COOP station uses. This latter study found that data from most paired AWDN–COOP stations had daily root-mean-square errors of about 6°C for maximum temperature, 3°C for minimum temperature, and 5 mm for precipitation.

Here, observation time for a specific site is obtained from the COOP station logs. For a 1700 LT observation, it is assumed that the station will correctly record the high and low temperatures for that calendar day because both parameters tend to fall between early morning and late afternoon. For 0800 LT observations, however, the recorded maximum temperature is likely that of the previous calendar day, while the minimum temperature is assumed to be correct because it was likely reached before 0800 LT. Accordingly, observations of maximum temperature at stations with morning times of observation are moved back one calendar day.

Rainfall totals are also significantly affected by differences in observation time. For morning observation times, rainfall totals can be generally improved by shifting daily rainfall totals back one calendar day. To correct rainfall for observation time, however, hourly rainfall records are used from NCECONet stations. If, for example, a COOP station records its data at 1700 LT, hourly records for the corresponding NCECONet station are used to obtain the 1700 to 1700 LT rainfall totals. If any hour of data is missing from a NCECONet station, that 24-h period is not used in order to ensure accurate comparison.

Note that daily COOP observations may be read at a time other than the official observation time, but are nonetheless recorded for the official time. The impact on the data depends on how far from the official time of observation that the observation was made and whether the reading was before or after the official time. For example, if a reading is made at 0600 LT but recorded for 0800 LT, the minimum temperature may not have been reached for that calendar day and, instead, the minimum temperature recorded is for the previous calendar day. Because these variations in read time are not documented, they are not accounted for here. Note that it is also possible, though infrequent, that the maximum temperature for a calendar day may occur later than 1700 LT. No special correction was employed for such occurrences. This should be kept in mind when considering the results of this procedure.

Because the 1-min observations, from which daily temperature extremes are compiled, are not currently archived in a useable format for later analysis, the correction procedure for rainfall cannot be reasonably applied to temperature. Differences in sample intervals between measuring networks can be a source of bias in data comparison and should be accounted for, when reasonable. For example, daily temperature maxima and minima from the ASOS stations are determined from 5-min running averages of 10-s sample intervals, calculated at every minute. Concerning the NCECONet, the SCO has plans to make the 1-min observations available for usage later in 2006.

Another manipulation adopted for the data analysis is a monthly average for temperature and monthly sum for rainfall. Over a monthly scale, discrepancies from differences in observation times and instrumentation are masked to a certain degree. Monthly averages and sums are often used in seasonal trend analyses and other longer-term studies.

The measurements are quality assured for missing values, range checks, and consistency checks. Additionally, if either the COOP or the NCECONet data point is missing data for a particular calendar day, the entire calendar day is omitted. Once the data corrections and quality control checks are performed, data points from corresponding days are compared using mean (NCECONet − COOP) error (ME), mean absolute

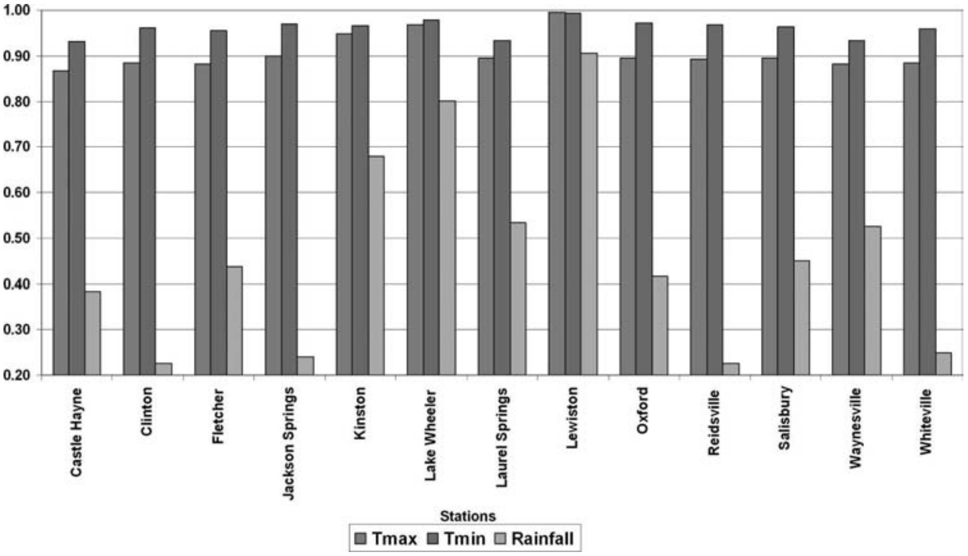

FIG. 2. Temperature and precipitation R before any time of observation corrections. Temperatures correlate fairly well, with minimum temperature consistently showing better correlation than maximum temperature. Precipitation R on the whole is poor.

(NCECONet − COOP) error (MAE), and root-mean-square error (rmse) (see Wu et al. 2005), as well as Pearson product–moment correlation (R).

3. Discussion of results

a. Unadjusted observations

Without any adjustments for time of observation, temperature records correlate fairly well between the automated and COOP stations (Fig. 2). Figure 3 shows box plots of temperature and rainfall with median, upper and lower quartiles [i.e., the distance between which is the interquartile distance (IQD)], range from (upper quartile + 1.5IQD) to (lower quartile − 1.5IQD), and outliers (beyond the range) given. The median R for $T_{\max}$ is 0.89 and for $T_{\min}$ is 0.96 (Fig. 3a), indicating that temperature records between the different platforms are already in fairly good agreement despite differences in time of observation. The higher R for $T_{\min}$ compared to $T_{\max}$ suggests that $T_{\max}$ is more affected than $T_{\min}$ by differing times of observation. Further, the median $T_{\max}$ R at morning stations, which should be more affected by observation time than evening stations and, thus, undergo a day-shift adjustment, is 0.08 higher than at evening stations.

Unadjusted rainfall correlations are relatively poor with a median of 0.44, with a range extending from 0.22 at Reidsville to 0.91 at the midnight-observing Lewiston station (Fig. 3b). The effect of time of observation is also seen in rainfall records with the median correlation at evening stations 0.40 higher than at morning stations.

The MEs between the collocated stations indicate that COOP stations tend to record warmer $T_{\max}$ observations than NCECONet, and vice versa for $T_{\min}$ (Fig. 4a). The median $T_{\max}$ ME is −0.38°C, while the median $T_{\min}$ ME is 0.26°C. For rainfall, the COOP gauge tends to record greater amounts than the automated network, with a median ME of −0.48 mm (Fig. 4b). These biases between the two platforms may merely be instrumentation issues, but little can be concluded from bias until adjustments are made.

Similar to correlation, MAE and rmse also indicate that $T_{\min}$ observations are more consistent than for $T_{\max}$. The median MAE (rmse) for $T_{\max}$ is 3.06°C (4.12°C), while those for $T_{\min}$ are much lower at 1.45°C (2.49°C) (Figs. 5a and 6a, respectively). The median MAE of rainfall is 3.75 mm and the median rmse is 9.58 mm, reflecting the large range in calculated R (Figs. 5b and 6b, respectively).

b. Day-shift adjusted observations

Table 1 contains observation times for the 13 stations used in this study. One adjustment used in this study is a day-shift adjustment, which involves moving $T_{\max}$ and rainfall data back one calendar day at morning observation COOP stations.

Shifting $T_{\max}$ and rainfall data back one calendar day

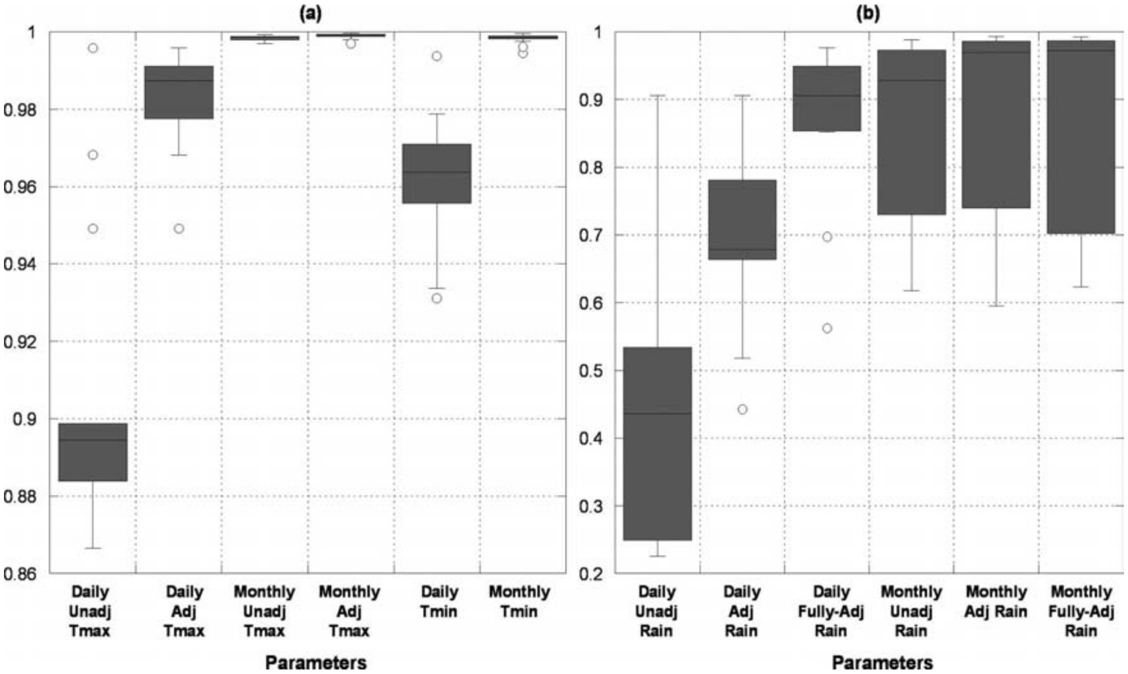

FIG. 3. Box plots of R of (a) temperature and (b) rainfall at the different adjustment levels. The $T_{\max}$ and rainfall R improve significantly with the day-shift adjustment, and a full hourly adjustment further improves rainfall R. Monthly averaging/summing also greatly increases R values.

at morning stations improves the median correlations among those stations by 0.10 and 0.28 (to 0.99 and 0.68), respectively (Figs. 3a and 3b, respectively). The day-shift adjustment brings the overall (morning and evening stations) median $T_{\max}$ correlation to 0.02 higher than the $T_{\min}$ correlation, which remains unadjusted at 0.96 because $T_{\min}$ is here assumed to be correct for reasons stated in section 2.

Conversely, MEs remain nearly unchanged with the day-shift adjustment (Fig. 4). The median $T_{\max}$ ME improves by 0.03°C at morning stations to −0.34°C, improving the overall median ME to −0.36°C (Fig. 4a). Rainfall MEs do not change with this adjustment, remaining at a median of −0.34 mm for morning stations (Fig. 4b). The existence of these temperature biases before and after adjustments indicates that they are likely due to differences in instrumentation between COOP and NCECONet (the COOP MMTS versus the NCECONet probe). This applies also to rainfall whose MEs indicate that COOP stations record higher rainfall amounts on average than NCECONet stations. The persistent presence of these rainfall biases through adjustments may be due to the tendency of tipping buckets, which are used at the automated stations, to clog and accumulate errors during heavy downpours (Molini et al. 2005), rather than due to micrometeorology or observation time differences. Through site visits the clogging biases have been noted, and the frequency of clogging varies widely depending on weather and siting.

As expected, the corrections show that the MAEs and rmse improve significantly. For the morning stations, the median $T_{\max}$ MAE (rmse) improves by 2.21°C (2.60°C) to 0.09°C (1.55°C), improving the overall median MAE (rmse) to 0.93°C (1.58°C) (Figs. 5a and 6a, respectively). For rainfall, the average MAE (rmse) at morning stations reduces by 1.73 mm (3.24 mm) to 2.33 mm (7.16 mm), reducing the overall median MAE (rmse) to 2.29 mm (6.99 mm) (Figs. 5b and 6b, respectively).

c. *Fully adjusted rainfall observations*

Full adjustment involves a complete correction for time of observation by obtaining hourly automated rainfall data and calculating 24-h totals based on the respective COOP station's observation time. Temperature data are not adjusted this way for reasons stated in the previous section.

These adjustments using hourly observations also include eliminating calendar days with any missing hours of data. The average number of days deleted per station is 47 out of 914, or 5%. Though Lewiston COOP has a midnight time of observation (as do all the NCECONet

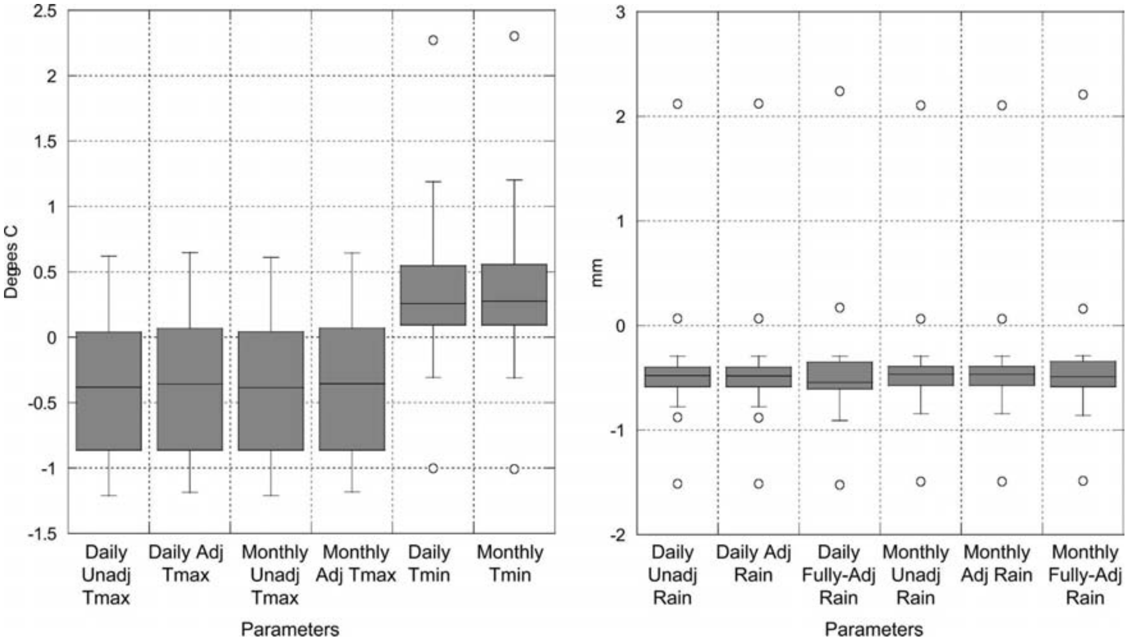

FIG. 4. Box plots of (NCECONet − COOP) daily and monthly MEs for (a) temperature and (b) rainfall at the various levels of adjustment. In general, COOP stations tend to record warmer maximum temperatures and NCECONet stations tend to record warmer minimum temperatures. COOP stations, on average, record greater rainfall amounts than NCECONet; ME remains nearly unchanged through adjustments, possibly indicating an instrumentation bias.

stations), it is still subject to the deletion of days with missing data.

The full hourly adjustment improves correlations over unadjusted and day-shift adjusted rainfall correlations. Fully adjusted rainfall records increase the median correlation by 0.23 over day-shift adjusted and by 0.47 over unadjusted R, to 0.91 (Fig. 3b). Correlations at evening stations improve 0.10 over the day-shift method, while the correlations at morning stations are 0.23 greater than day-shift adjusted observations and 0.51 greater than unadjusted observations, further indicating that morning observation times have a greater negative effect on data consistency than evening times. An update of Fig. 2 is shown in Fig. 7, with day-shift adjustments shown for $T_{\max}$ and this full hourly adjustment for rainfall.

The full adjustment does not improve the overall median ME upon the day-shift adjustment, decreasing by 0.06 to −0.54 mm, with morning stations decreasing by 0.03 to −0.48 mm and one of the three evening stations increasing slightly, one decreasing, and one remaining unchanged (Fig. 4b). The median MAE (rmse) continues to improve from the day-shift adjustment with the full adjustment, decreasing by 1.14 mm (3.08 mm) to 1.15 mm (3.91 mm). Morning stations improve more than evening stations, decreasing by 1.17 (2.81 mm) to 1.16 mm (4.34 mm) at morning stations, compared to decreasing at evening stations by 1.10 mm (1.70 mm) to 1.07 mm (3.91 mm) (Figs. 5b and 6b, respectively).

d. Monthly observations

Another manipulation, the monthly average/sum of daily unadjusted, day-shift adjusted, and fully adjusted observations, improves $T_{\max}$ and $T_{\min}$ correlations (both unadjusted and day-shift adjusted) at every station to nearly 1.00 (Fig. 3a). Monthly summation also improves unadjusted, day-shift adjusted, and fully adjusted rainfall correlations to 0.93 for unadjusted observations and 0.97 for day-shift and fully adjusted observations (Fig. 3b).

The median monthly unadjusted and adjusted $T_{\max}$ and $T_{\min}$ MEs are nearly identical to daily MEs (Fig. 4a). Monthly averaging improves the median $T_{\max}$ unadjusted and adjusted MAEs to 0.64°C and for $T_{\min}$ decreases to 0.4°C (Fig. 5a). The $T_{\max}$ unadjusted (adjusted) rmse improves to 0.71°C (0.67°C) and for $T_{\min}$ decreases to 0.60°C (Fig. 6a).

The monthly manipulation for rainfall is a summation; therefore the differences and rmses are quite large and are divided by the average number of days in a month (30.42) so that the monthly data can be compared with daily data. Monthly MEs for rainfall improve slightly upon daily MEs with monthly unadjusted, day-shift adjusted, and fully adjusted MEs

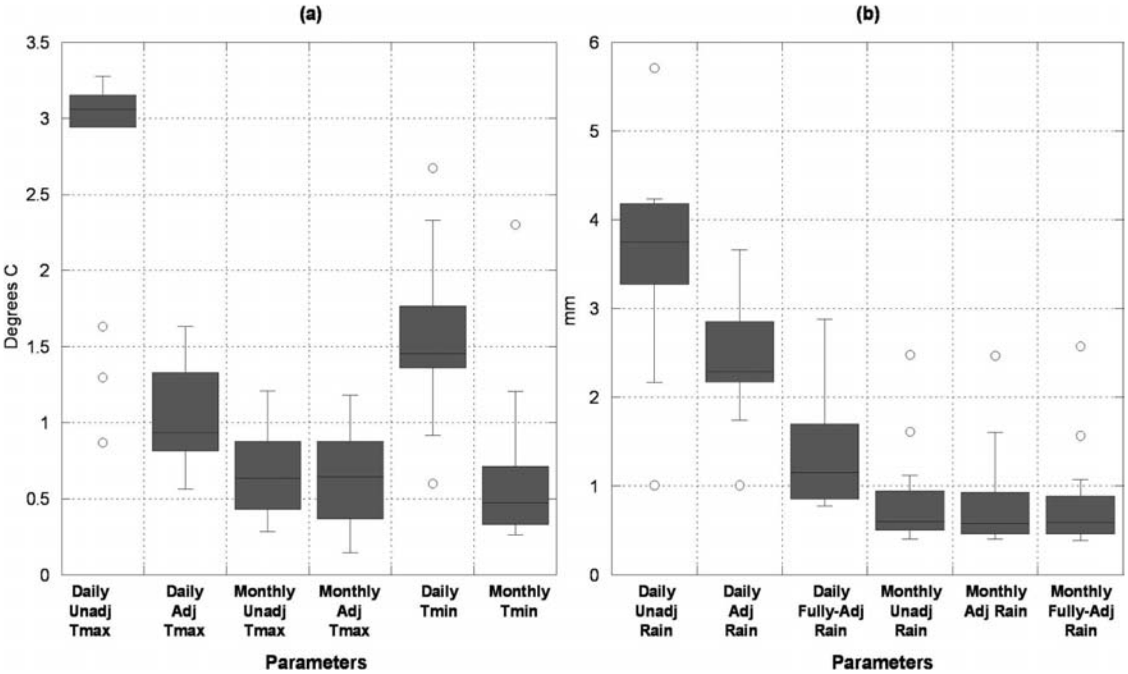

FIG. 5. Box plots of (NCECONet − COOP) daily and monthly MAEs for (a) temperature and (b) rainfall with various adjustments. MAEs decrease significantly with day-shift and full adjustments, indicating an increasing data linearity.

improving to −0.47, −0.47, and −0. 49 mm, respectively (compared to −0.48, −0.48, and −0.54 mm, Fig. 4).

Monthly MAEs for rainfall decrease significantly compared to their respective daily MAEs, with monthly unadjusted, day-shift-adjusted, and fully adjusted MAEs averaging 0.60, 0.58, and 0.59 mm, respectively (3.79, 2.29, and 1.15 mm for daily MAEs, see Fig. 5b). Similarly, monthly unadjusted, day-shift-adjusted, and fully adjusted monthly rmse decrease to 0.98, 0.78, and

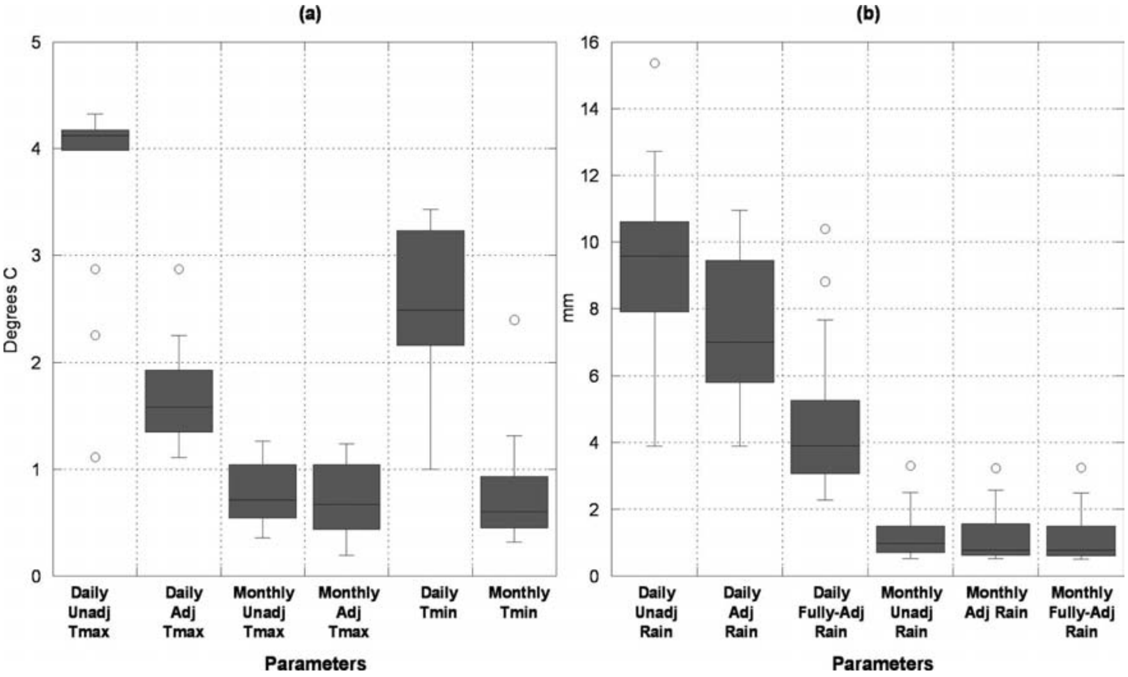

FIG. 6. Box plots of daily and monthly rmse for (a) temperature and (b) rainfall with different levels of adjustment. As with MAE (Fig. 5), data variance decreases significantly as adjustments are applied.

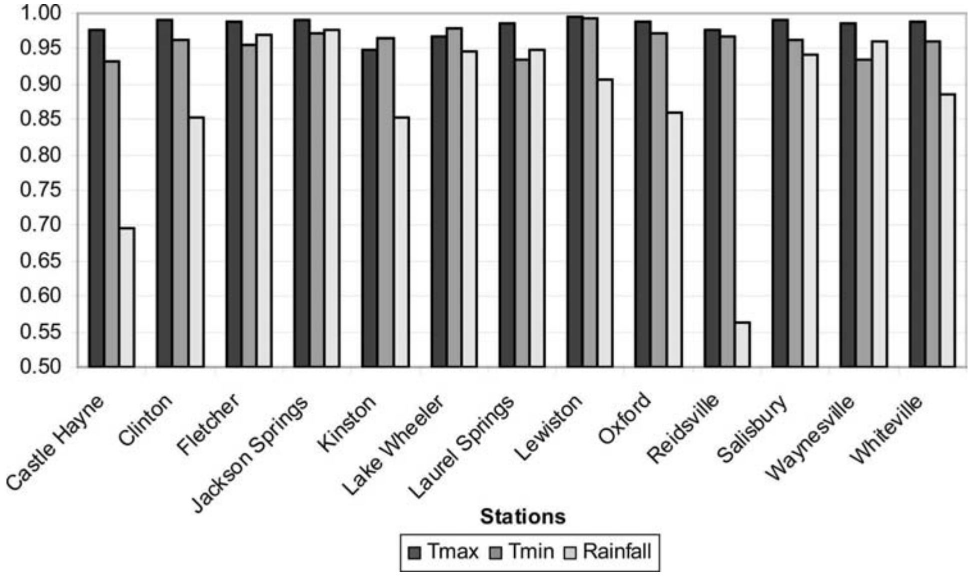

FIG. 7. Shown are the R of adjusted $T_{\max}$, $T_{\min}$, and rainfall. The $T_{\max}$ R is after day-shift adjustments, while rainfall R is after full hourly adjustments. The $T_{\min}$ does not undergo an adjustment, but is shown for completeness.

0.77 mm, respectively (9.58, 6.99, 3.91 mm for daily rmse, Fig. 6b).

e. Additional discussion

The effect of different corrections and adjustments to the temperature and rainfall data for a typical site (Clinton, North Carolina) is presented in Fig. 8, which contains scatterplots that compare COOP data with corresponding automated NCECONet data. This location is selected as an example because its (absolute) biases, rmse, and correlations are closest of the 13 stations to the 13-station average. Large differences in temperature and rainfall observations between COOP and NCECONet are present before any adjustments (Figs. 8a,c,d). Before adjustments, $T_{\min}$ data (Fig. 8c) show highest colinearity, while $T_{\max}$ (Fig. 8a) and rainfall (Fig. 8d) are widely scattered. There is a marked increase in the linearization of $T_{\max}$ data when day-shift adjustments are performed, improving the rmse from 4.12° to 1.18°C (Figs. 8a,b). The $T_{\max}$ correlations tend to improve with warmer temperatures, especially with values greater than 20°C, while $T_{\min}$ correlations, with rmse of 2.45°C, vary more than adjusted $T_{\max}$ correlations. The day-shift adjustment for rainfall also greatly improves the linearization of the rainfall data, with the rmse improving at Clinton from 10.82 to 7.12 mm (Figs. 8d,e). The final adjustment of rainfall provides a nearly linear relationship between COOP and NCECONet rainfall measurements with an rmse of 5.27 mm (Fig. 8f).

Figure 9 contains cumulative relative frequency plots comparing NCECONet and COOP daily rainfalls at Clinton and Lewiston before and after full adjustments. These plots indicate that COOP gauges measure greater amounts of rainfall than those measured by the NCECONet. They also show that, with greater rates of rainfall, the difference increases at some stations and actually inverts (the automated station begins recording more than COOP) at others. In addition to their tendency to clog, errors of up to 1% can also accumulate with tipping buckets at higher rainfall rates ($\geq$50 mm h^{-1}) because some water is lost in the fraction of a second it takes for the measuring lever to tip over (Molini et al. 2005).

4. Conclusions

Automated stations present a significant augmentation to established manual stations, and many fields of meteorology can benefit from the integration of measurements from the two station types. In North Carolina, for example, incorporating data from the 27 established NCECONet stations with data from the 179 currently active COOP stations creates a 13% more dense network of data and provides valuable hourly data to supplement daily data. Indeed, the inclusion of the 20 ASOS and 47 AWOS stations in the state further increases station density by 25%. Similar advantages are expected in other states where the data from the COOP and available automated stations can be integrated after appropriate quality checks.

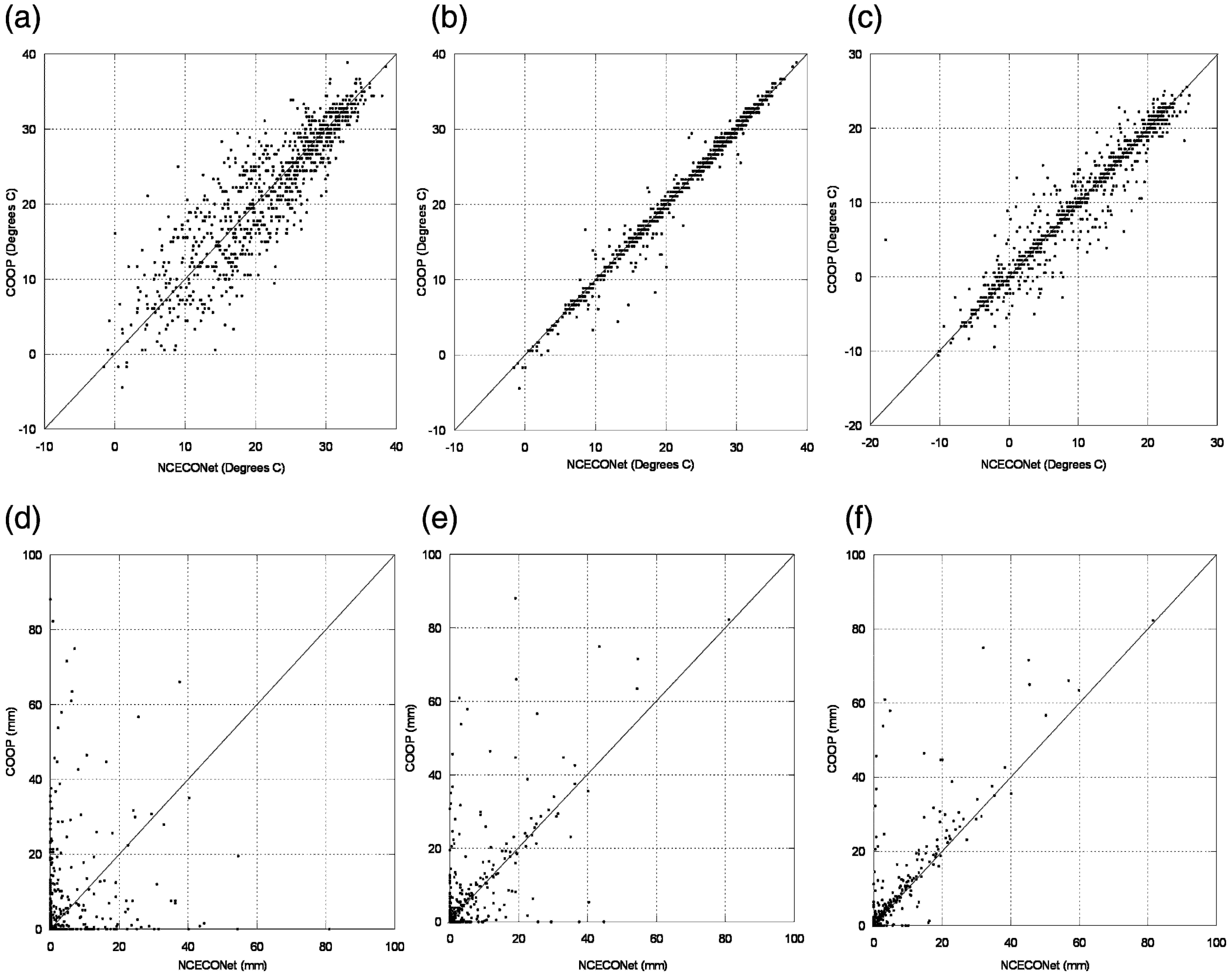

FIG. 8. Scatterplots showing daily NCECONet and COOP data for Clinton: (a) unadjusted T_{max}, (b) day-shift-adjusted T_{max}, (c) T_{min}, (d) unadjusted rainfall, (e) day-shift-adjusted rainfall, and (f) fully adjusted rainfall. Lines of equivalence are shown. The more the scatter points fall along this line, the more colinear the COOP and NCECONet data are. Warmer (spring and summer) temperatures have smaller variances than cooler (autumn and winter) temperatures. Data linearity increases significantly with T_{max} and rainfall day-shift adjustment, and with the full adjustment for rainfall.

Caution is needed when combining datasets from different instrumentation platforms and observation methods since not all data are homogenous. The estimates in this study suggest that data from heterogeneous measurement networks could have significant inconsistencies and should not be combined into a unified dataset without quality control and adjustments that account for inherent system biases. Such adjustments include, at minimum, consideration for differences in data observation time, location, and sensor characteristics.

This study concentrates on one of the more obvious biases—time of observation. Maximum temperature, minimum temperature, and rainfall records are compared for several years and basic corrections are performed for COOP station times of observation. The correlation statistics presented here indicate about an 11% uncertainty in combining maximum temperature records from automated stations and COOP stations, a 4% uncertainty with minimum temperature records, and a 56% uncertainty in rainfall records. Day-shift corrections on maximum temperatures and rainfall records improve median R at the adjusted stations by 0.10 and 0.28, respectively, and improve rmse by 2.06°C and 3.24 mm. An additional hourly correction applied to rainfall records further improves the overall median R by 0.23 and rmse by 3.08 mm upon the day-shift adjustment. Monthly averaging of daily observations improves correlation to nearly 1.00 for maximum and minimum temperatures and to 0.94 for unadjusted rainfall and 0.97 for both adjustments of rainfall. These adjustments have little to no effect on temperature and

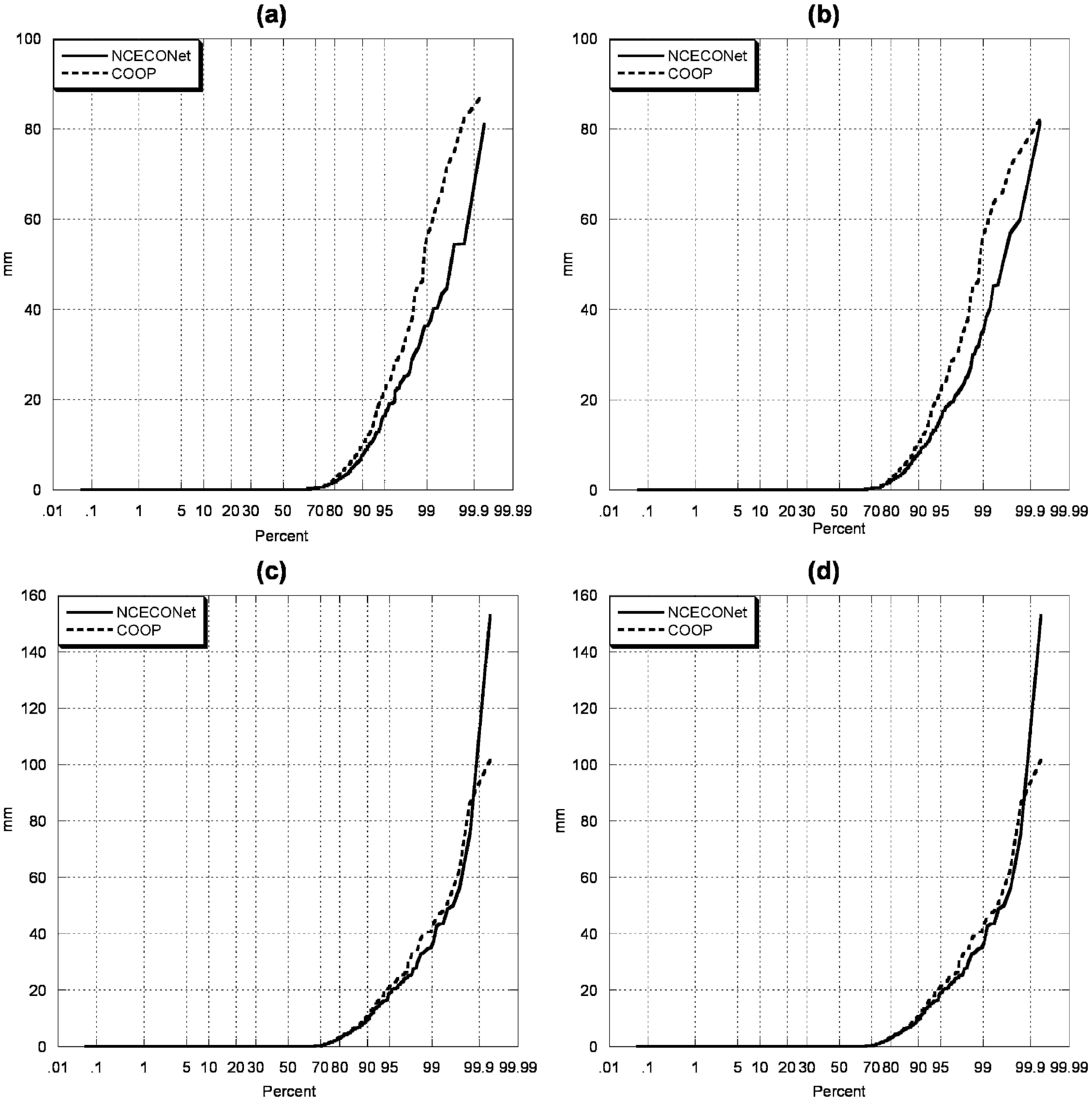

FIG. 9. Cumulative relative frequency plots of unadjusted and fully adjusted rainfall at (a), (b) Clinton and (c), (d) Lewiston. NCECONet stations generally measure lesser rainfall amounts than their COOP counterpart, especially with heavier rainfalls. All stations, except Whiteville and Reidsville, show this positive NCECONet − COOP difference. At Lewiston, NCECONet buckets measure lesser amounts than COOP gauges at heavier amounts of rainfall. Two other stations (Castle Hayne and Reidsville) show this as well, but at different thresholds (70 and 45 mm, respectively). Some stations also show a widening of the distribution variance with higher rainfall amounts.

rainfall measurement MEs between the platforms; COOP stations tend to record warmer $T_{\max}$ observations, cooler $T_{\min}$ observations, and greater rainfall amounts, especially with heavier rainfall rates.

Further investigations into monthly and seasonal biases can improve the understanding of the compatibility of different observing networks. Considering land use patterns and topography as well as changes in instrumentation, network density, and instrument sampling intervals can further heighten this understanding and improve the ability of meteorologists and climatologists to more accurately measure climate change. Because this study spans different terrains and climate regions, we believe the implications of this study reach beyond the state of North Carolina and are applicable across the United States.

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