Rainfall Analysis for the Late April into Early May 2017 Flood Event in Southern Missouri and Northern Arkansas

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ABSTRACT

In late April 2017, a slow moving frontal system in the central U.S. was the focusing mechanism for widespread heavy showers and thunderstorms. Multiple waves of rainfall impacted portions of northeast Oklahoma, northern Arkansas, southern Missouri, and southern Illinois from 28 April 2017 to 1 May 2017. Traditional National Weather Service (NWS) rainfall estimation techniques use daily and multi-day rainfall reports only indirectly due to rainfall being analyzed on an hourly basis. Analyzing the event on a daily basis would allow for better usage of hourly, daily, and multi-day rainfall reports and increase the precision of subsequent storm total rainfall estimates.

This report presents an analysis of rainfall reports from the impacted areas and categorizes the rainfall rarity in terms of the area's rainfall climatology. NWS hydrologists collected additional reports of rainfall from private weather stations and social media. Radar-derived estimates of rainfall were bias corrected using techniques currently in use by NWS River Forecast Centers (RFCs), but adjusted slightly to use the kriging interpolation technique. A secondary interpolation using co-kriging with radar beam elevation height was also performed. Bias-corrected rainfall estimates were then analyzed to determine annual exceedance probability (AEP) values for each location. The area of heaviest storm total rainfall exceeded the 1-in-1000 annual chance event and multiple counties experienced rainfall greater than the 1-in-100 annual chance. The secondary interpolation technique utilizing co-kriging caused mostly minor changes to the rainfall analysis but did increase rainfall estimates in the hardest-hit areas due to the significant distance from radar sites.

1.0 Introduction

A slow-moving weather system produced heavy rainfall across portions of the central U.S. including parts of Missouri and Arkansas from April 29, 2017, through May 1, 2017. On the afternoon of April 28th, 2017, a stationary front that extended from southeast Missouri across west central Arkansas began moving slowly northward as a warm front. An upper level storm system moved east from the Rocky Mountains bringing moisture from the Gulf of Mexico northward. By April 29th, the warm front had moved into southern Missouri and became the focusing mechanism for multiple waves of slow-moving thunderstorms. Very high amounts of atmospheric moisture were available for these thunderstorms with precipitable water values observed at the National Weather Service (NWS) office in Springfield, Missouri above daily record values (Figure 1). Finally by May 1st a cold front moved east across the area bringing an end to the rainfall.

The heaviest rainfall occurred over an approximately 48-h period ending the morning of April 30. Storm total rainfall amounts of 3-6 inches were widespread across southern Missouri with isolated areas receiving more than 10 inches. For portions of northern and northeastern Arkansas, amounts of 2-3 inches were widespread with isolated amounts up to 9 inches. For the hardest hit areas, preliminary estimates suggested that rainfall of this magnitude was rare - having a less than 1% chance of occurring in a given year (also known as annual exceedance probability, or AEP). This rainfall led to widespread flooding across multiple NWS river forecast center (RFC) forecast areas. Although the most widespread flooding occurred within the area served by the Lower Mississippi River Forecast Center (LMRFC), record flooding was also observed in areas served by the Arkansas-Red Basin River Forecast Center (ABRFC), Missouri

Basin River Forecast Center (MBRFC), North Central River Forecast Center (NCRFC), and the Ohio River Forecast Center (OHRFC).

Over the following days, numerous river locations downstream of the heavy rainfall experienced flash flooding and river flooding. Flash flooding in some areas was particularly severe. Post-event flood surveys indicated that multiple bridges and structures were not only flooded but were completely destroyed. Additionally, several stream gauges were damaged with a few swept away. Numerous people were rescued from flooded areas (NWS Springfield, 2017). In the LMRFC area, preliminary stream gauge observations indicate that over 20 locations set new stage records (Figure 2). When adding in locations from neighboring RFCs, this number climbs to at least 30, with almost half of these locations having a period of record longer than 50 years. The extreme nature of this event necessitates the collection of as much data as possible to establish an accurate historical context of rainfall severity.

In Lincoln et al (2017), it was suggested that an increased density of rainfall observations and reports of flooding could improve the estimation of event magnitude (including rainfall AEP). For the event studied in Lincoln et al, the addition of rainfall reports obtained through crowd-sourcing (public reports, posts to social media, private data collection networks) decreased rainfall totals in some areas and increased rainfall totals in other areas, although the hardest-hit areas generally were increased.

The purpose of this report is to re-evaluate the rainfall estimates for the late April/early May rainfall event using additional data obtained by following the methodology of Lincoln et al (2017). The collection of additional point rainfall data will be discussed along with the updating of gridded rainfall estimates based upon this data. Multiple rainfall interpolation techniques will be presented and discussed.

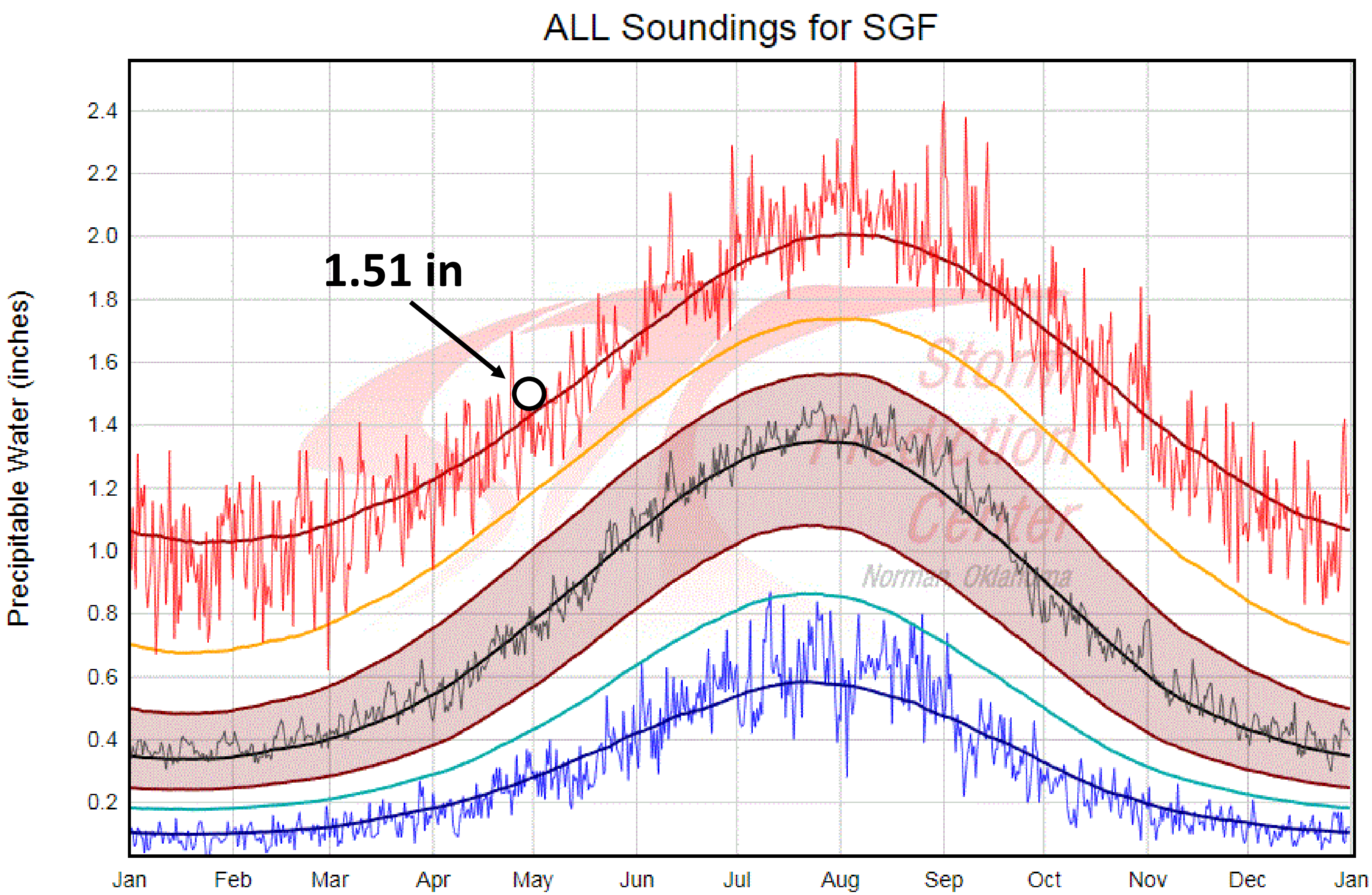

Figure 1. Precipitable water climatology values from soundings at NWS WFO Springfield, Missouri. Observed precipitable water value for 1200 UTC 29 April 2017 is indicated by the white circle; values remained at approximately this level through 1200 UTC 30 April 2017. This precipitable water value was above the daily record for that time of year and was among the highest ever recorded for the month of April at Springfield.

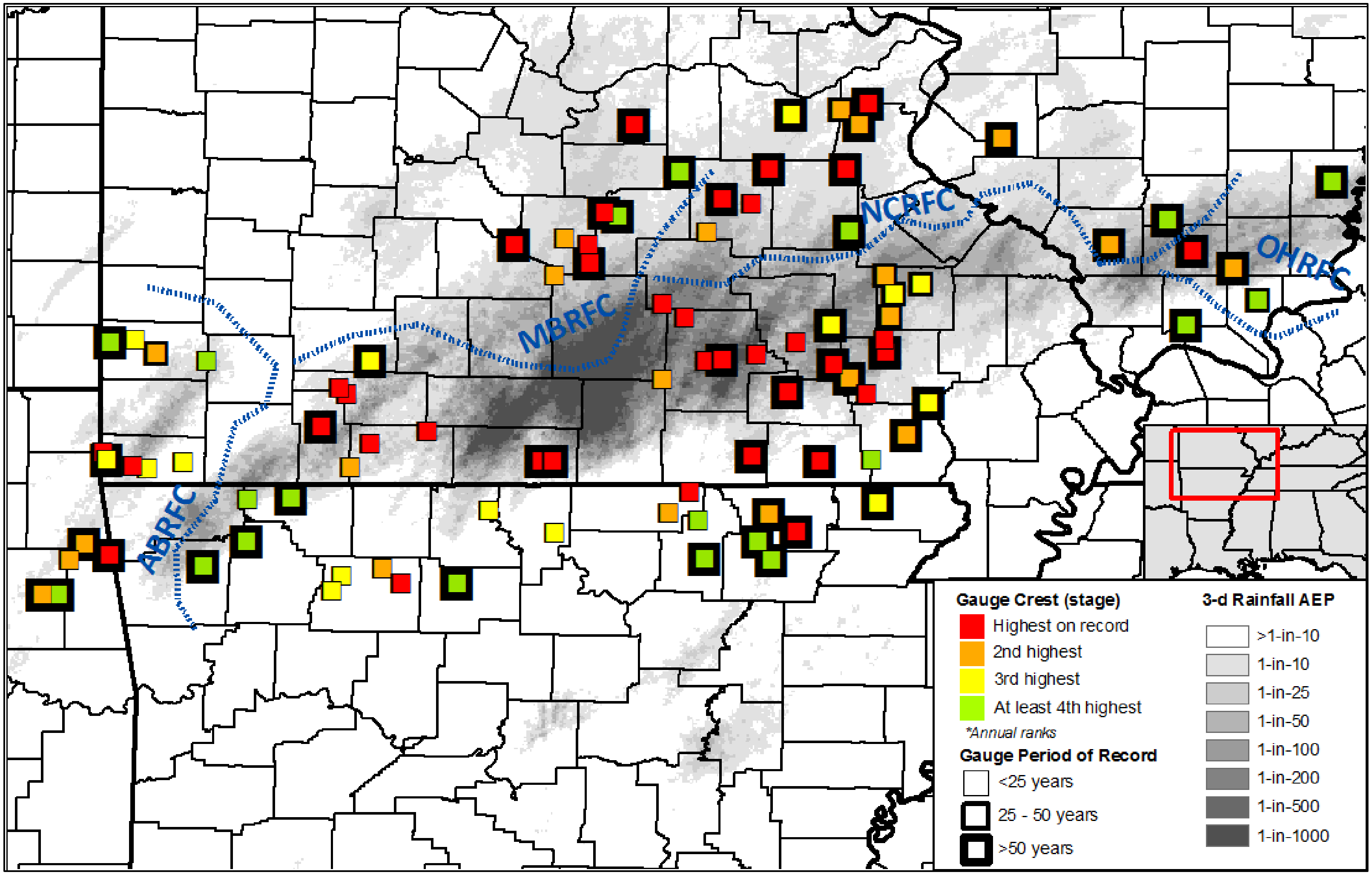

Figure 2. Stream gauge crests in southern Missouri, northern Arkansas, far northeast Oklahoma, and far southern Illinois from the late April into early May 2017 flood event. Stream gauges which recorded a top 3 crest during the event are shaded yellow, orange, or red. Relative storm total rainfall (3-d ending 1200 UTC May 1) magnitude is indicated by gray shading. Blue lines delineate the approximate boundaries of NWS RFC forecast areas. For areas outside of the LMRFC forecast area, stream gauge locations were added for general information and may not be comprehensive. Crest ranking is based upon *annual* statistics. All crest data preliminary.

1.1. Discussion of previous rainfall analyses for this event

The official gridded rainfall data of the NWS is produced hourly from remotely-sensed radar estimates bias-corrected using point rain gauge observations. The base gridded radar rainfall estimate used at the LMRFC comes from Multi-Radar Multi-Sensor (MRMS) data. Hourly rain gauge data from multiple sources – the Automated Surface Observing Systems (ASOS; automated stations located at airports), United States Geological Survey (USGS; automated stations co-located with stream gauges), and the United States Forest Service (USFS; automated stations) – are then compared to the base gridded radar rainfall estimate, MRMS, to calculate a bias correction factor for each point. These bias correction factor values are then interpolated to a grid via the inverse distance weighted method and multiplied by the raw rainfall estimates to create the bias-corrected RFC best-estimate rainfall. Hydrometeorologists at the RFCs can also make manual edits to the RFC best-estimate rainfall to further improve the data. It is important to note that daily and multi-day rainfall reports are not automatically utilized by this process to create the RFC best-estimate rainfall; RFC hydrometeorologists must make manual edits to reconcile the hourly and daily data.

Based upon the RFC best-estimate rainfall data, a preliminary analysis of rainfall severity was completed by the NWS Hydrologic Design Studies Center (HDSC). HDSC looked at the maximum value from running 48-h rainfall accumulations between April 28th and May 2nd (the so-called “worst case 48-h rainfall) to determine the severity of the rainfall event. Maximum 48-h rainfall totals across southern Missouri (approximately 3-6 inches with isolated 10 inch observations) were relatively rare. Portions of several counties received rainfall with only a 1-in-10 chance of occurring in a given year, with the rainfall maximum near Cabool, Missouri, having only a 1-in-1000 AEP (Figure 3).

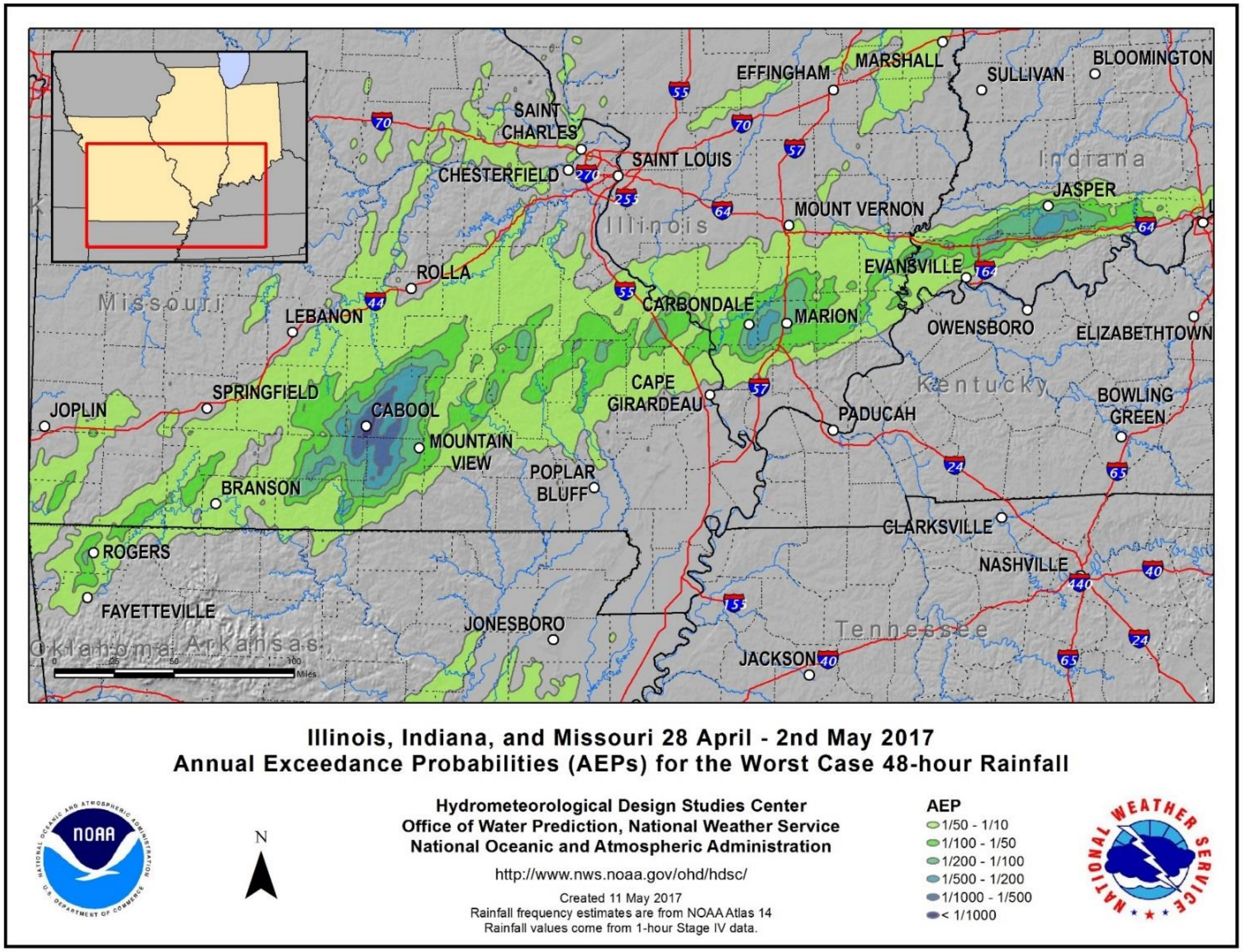

Figure 3. Map of relative rainfall magnitude (as defined by the annual chance of occurrence, or AEP) produced by the NWS Hydrologic Design Studies Center. Source rainfall used in the analysis was the RFC best-estimate bias-corrected based upon hourly rainfall gauges. Storm total rainfall reports collected post-event were not included.

2.0 Methodology

2.1 Rainfall estimation

In order to refine the rainfall analysis, additional point rainfall data was collected from multiple sources. Once compiled, the rainfall observations were put through a simple QC technique to remove obviously bad data. Next, the point rainfall data was used to bias-correct radar-only rainfall estimates.

2.1.1 POINT RAINFALL DATA

The largest single source for additional data was the Community Collaborative Rain Hail and Snow network (CoCoRaHS; manual-reporting stations monitored by a volunteer observer network). Data was also obtained from the public via storm spotter reports (LSR; manually-estimated observations collected in rain gauges with a wide range of quality) and from social media requests (bucket survey; manually-estimated water depths collected in rain gauges and empty containers by the public with a wide range of quality). Although in Lincoln et al (2017) data was also collected from Weather Underground Personal Weather Stations and Davis Instruments, no private weather stations of adequate quality were found in the area of heaviest rainfall and collecting private weather station data for the entire study area was deemed too cumbersome and unnecessary for this report.

2.1.2 QUALITY CONTROL OF POINT RAINFALL DATA

The gauge QC technique utilized by Lincoln et al (2017) was used for this analysis. The technique involves a three-tier scale of “fail,” “questionable,” or “pass” based upon comparison of individual gauges against the official NWS bias-corrected, best-estimate rainfall data. Gauges “fail” if they record less than 50%, or greater than 200%, of the bias-corrected radar estimates. Gauges are “questionable” if they record less than 75%, or greater than 150%, but not less than 50% or greater than 200%. Gauges “pass” if they record rainfall between 75% and 150% of the bias-corrected radar estimates. Gauges marked as “fail” were omitted from further analysis.

2.1.3 GRIDDED RAINFALL DATA

The raw gridded rainfall estimates were the radar-only estimates obtained from the MRMS system. Hourly MRMS data was retrieved from the Iowa Environmental Mesonet’s rainfall archive (www.mesnet.argron.iastate.edu/rainfall) and then accumulated from 1200 UTC 28 April through 1200 UTC 01 May to provide a 3-d storm total. The MRMS radar rainfall estimates were bias corrected against the point rainfall data that did not fail the QC technique using two different interpolation techniques.

The first bias correction technique (method 1) was straight-forward and very similar to the process utilized operationally by the NWS RFCs. The bias correction factor (gauge value divided by raw radar rainfall estimate) was calculated for each gauge location. The bias correction factor point values are then interpolated to a bias correction grid using the kriging method. The kriging method assumed an exponential relationship between distance from observation and bias correction factor. The radar rainfall estimate is then multiplied by the bias correction grid to produce a bias-corrected rainfall estimate.

The second bias correction technique (method 2) was similar to the first method - kriging was used to interpolate point bias correction values into a bias correction grid. This second technique differed, however, by utilizing co-kriging (kriging interpolation that involves more than the one variable, distance from point value). The areas of heaviest rainfall occurred at distance from radar locations where the radar beam is sampling thousands of feet above ground level (Figure 4). During some heavy rainfall events with particularly high low-level moisture, radar rainfall estimates can be too low due to the radar beam "overshooting" much of the rainfall. To correct for this, co-kriging was used with the second variable being estimated radar beam height above ground level.

2.2 Rainfall frequency analysis

The bias-corrected rainfall analyses were then compared to rainfall frequency data from NOAA Atlas 14 (National Weather Service, 2013) to determine the storm total rainfall AEP. Selecting the proper rainfall duration to use for calculating the AEP was somewhat difficult, however. Daily rainfall reports used by the NWS span 1200 UTC to 1200 UTC, which makes this rainfall event span three "observation days." For virtually every location in the study area, however, the rainfall event did not exceed an approximately 48-h duration. Although the start and end times were not exactly the same for each point location, rainfall spanned from roughly 2300 UTC 28 April to 2300 UTC 30 April (Figure 5). Thus, although the storm total rainfall would be a 3-d total ending at 1200 UTC on 1 May, rainfall values were compared to rainfall frequency data for the 2-d (48-h) duration to provide the best estimate of event AEP because using the 3-d (72-h) duration would underestimate rainfall severity.

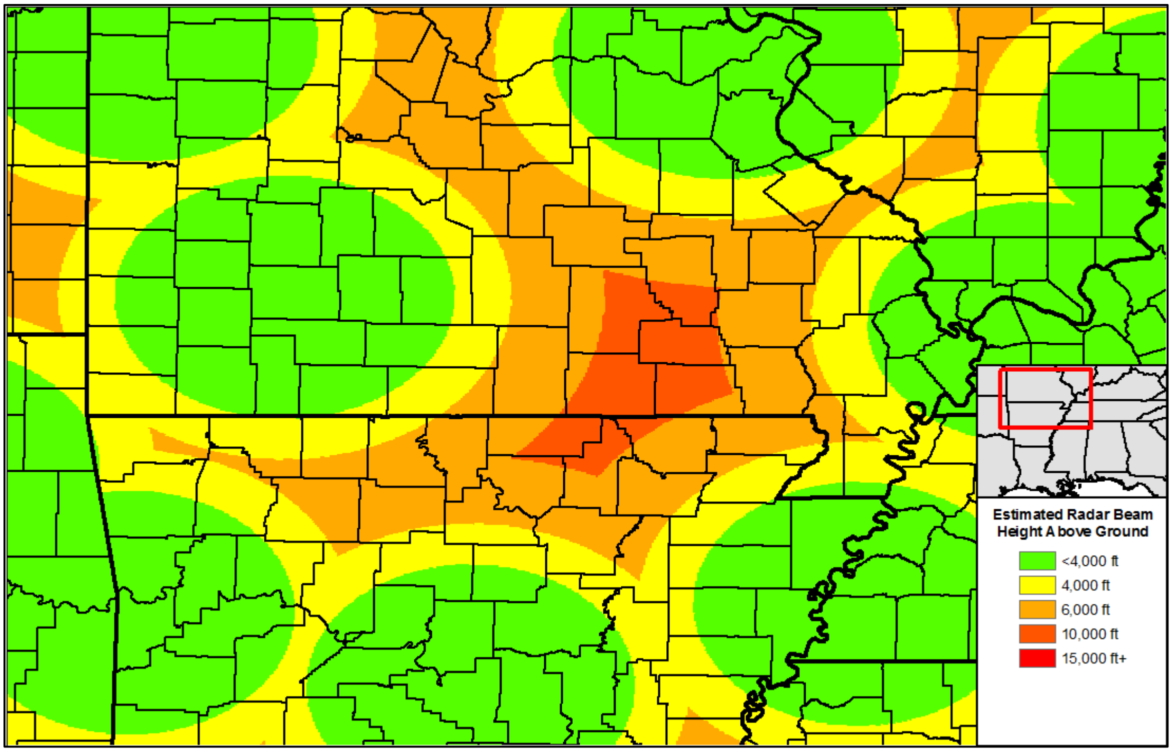

Figure 4. Estimated radar beam height above ground level. Areas of heaviest rainfall from this event were just northwest of areas where the estimated beam height is typically 10,000 ft or higher above ground level.

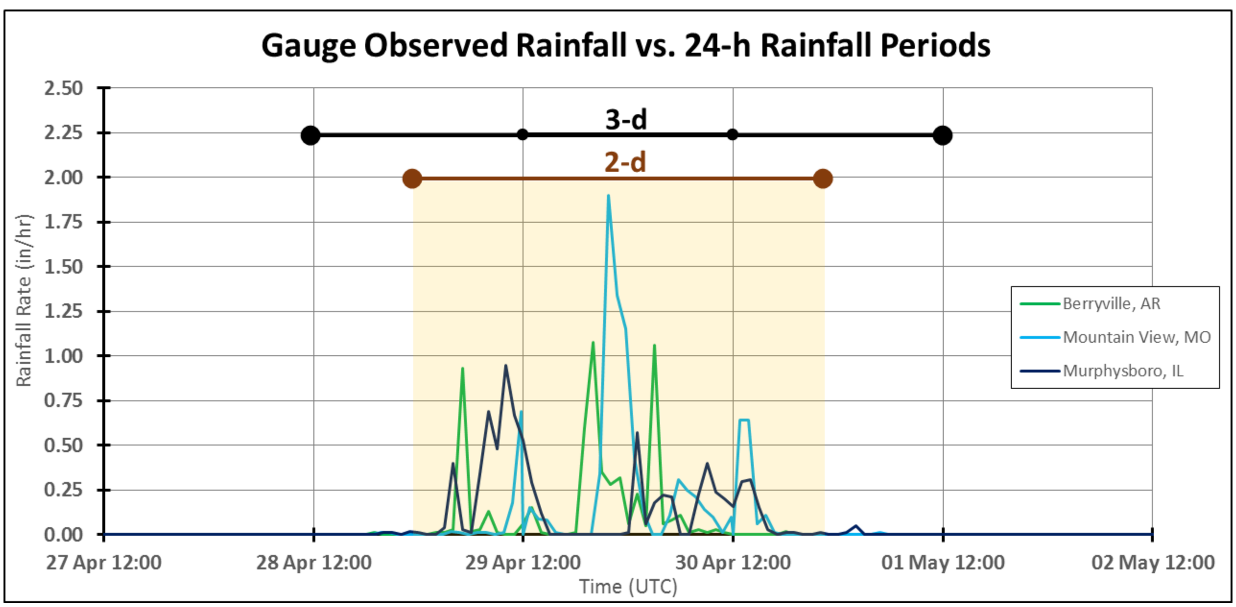

Figure 5. Comparison of selected rainfall gauge observations (Berryville, AR, Mountain View, MO, and Murphysboro, IL) to the typical 1200 UTC to 1200 UTC daily rainfall reporting period used by the NWS. Although the rainfall spanned three observation days, the actual duration was closer to two days (48-h), from 2300 UTC 28 April to 2300 UTC April 30, 2017.

3.0 Results

3.1 Point rainfall observations

Approximately 2612 daily and multi-day rain gauge reports were collected for the central United States of which 937 were removed immediately due to missing data. Of the remaining 1675 reports, 900 came from hourly gauges (and a small number of daily gauges) already available for realtime rainfall estimates at the NWS RFCs, 695 came from CoCoRaHS, 52 came from LSRs, and 28 came from the bucket survey (Table 1). After removing gauges that failed the QC process, there were 1498 rainfall reports from CoCoRaHS, LSRs, and the bucket survey (social media) available for the analysis (Figure 6). Requesting additional rainfall data from social media (bucket survey) was responsible for the majority of the additional rainfall reports in the area of heaviest rainfall.

Table 1. Gauge data collected for this analysis. Just under half of these gauges are visible in the study area shown by Figure 6. The rainfall observations collected for this analysis include hourly gauges accumulated to daily totals, daily rainfall totals (such as CoCoRaHS and NWS cooperative observers), and multi-day rainfall totals (such as multi-day CoCoRaHS reports and social media crowd-sourcing). The number of rain gauge reports that did not fail QC are also listed.

	Observations Collected for This Analysis	
	Hourly, Daily, Multi-Day	**Post QC**
Hourly	900	764
CoCoRaHS	695	654
LSR	52	52
Bucket Survey	28	28
TOTAL	1675	1498

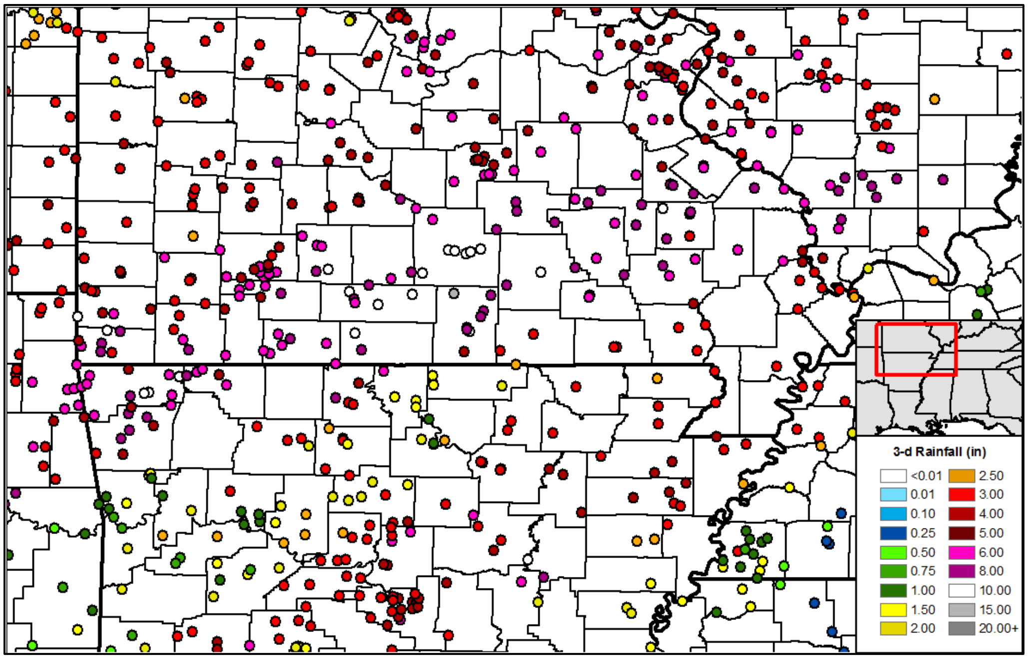

Figure 6. 3-day storm total rainfall observations for 1200 UTC 28 April to 1200 UTC 01 May from all point rainfall observations (hourly, daily, and multi-day) – including those added through crowd-sourcing (bottom). Gauges that failed the QC process (section 2.1.2) were excluded.

3.2 Radar rainfall estimates

Radar-derived rainfall estimates from MRMS for the 1-day period ending at 1200 UTC 29 April 2017 (Figure 7, top) were highest across portions of southern Missouri and southern Illinois. Many locations did not receive significant rainfall outside of this heavy band. Radar-derived rainfall estimates from MRMS for the 1-day period ending at 1200 UTC 30 April 2017 (Figure 7, middle) were highest in a small section of south-central Missouri and another area of northeast Arkansas, although rainfall amounts of 3 to 4-in were common throughout the area. Radar-derived rainfall estimates from MRMS for the 1-day period ending at 1200 UTC 1 May 2017 (Figure 7, bottom) were much lighter than previous days with most areas receiving less than 1-in. Radar-derived rainfall estimates for entire 3-day period ending 1200 UTC 1 May 2017 (storm total rainfall; Figure 8) indicated that the heaviest rainfall amounts (exceeding 10-in) occurred in southern Missouri near Cabool.

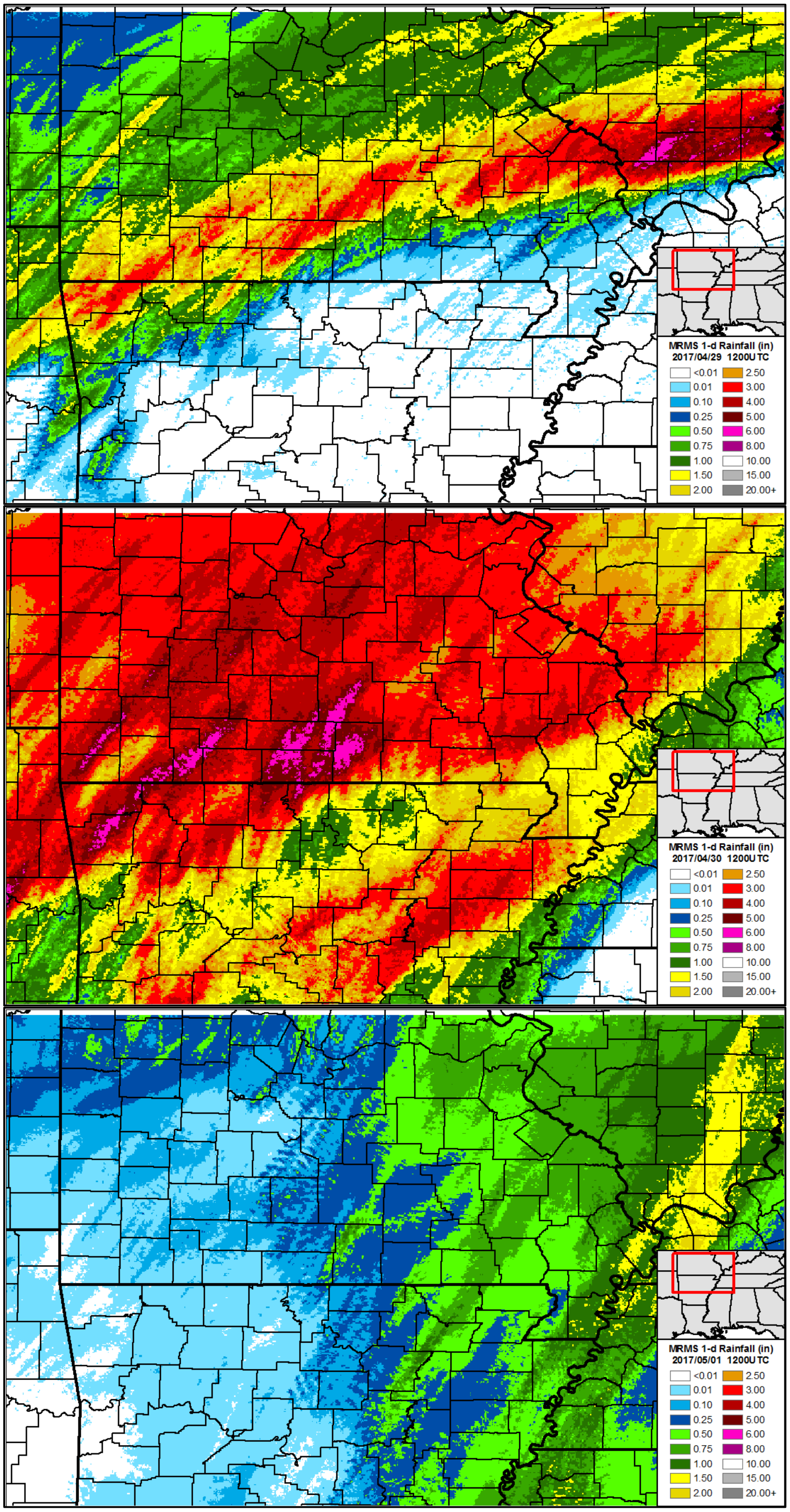

Figure 7. Daily raw radar rainfall estimates from MRMS ending at 1200 UTC 29 April 2017 (top), 1200 UTC 30 April 2017 (middle), and 1200 UTC 1 May 2017 (bottom). These estimates have no bias correction from rainfall gauges.

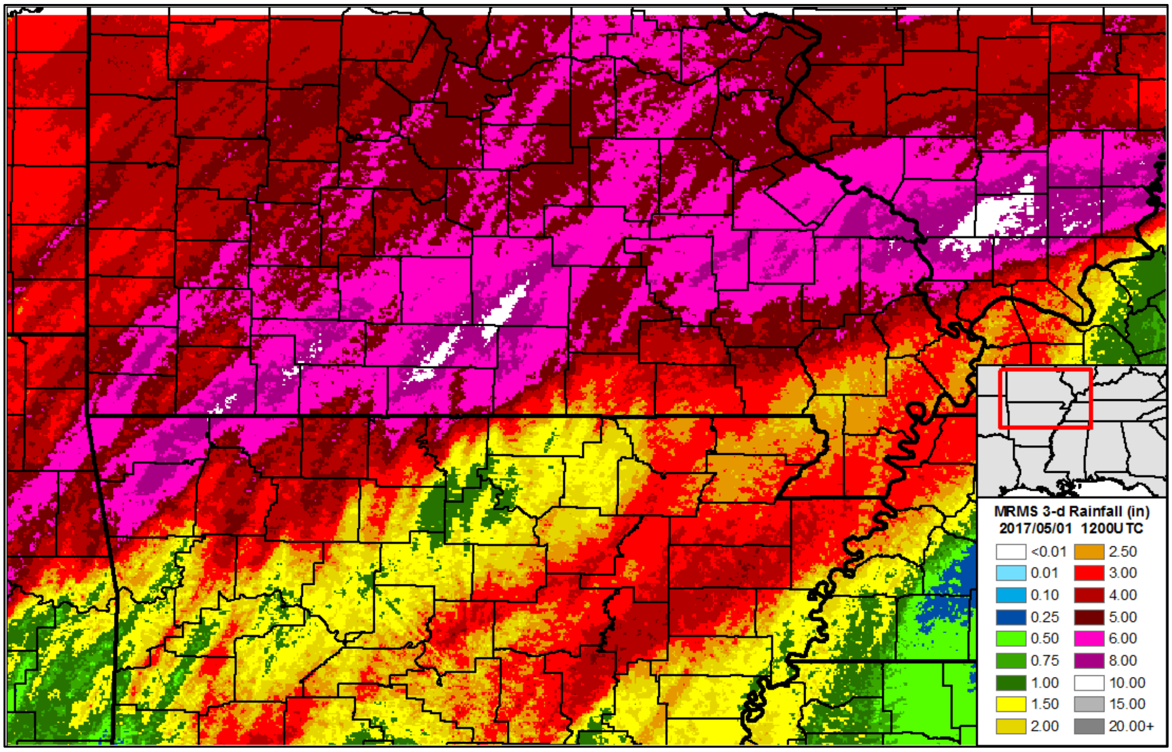

Figure 8. Storm total rainfall estimates from MRMS ending at 1200 UTC 1 May 2017. These estimates have no bias correction from rainfall gauges.

3.3 Bias-corrected radar rainfall estimates

For both bias correction methods, areas of southern Missouri, northeastern Arkansas, and central Arkansas were indicated as areas where the raw radar rainfall estimates were too low (Figure 9). Both bias correction methods also indicated far eastern Oklahoma, northwestern Arkansas, and southern Illinois as areas where the raw radar rainfall estimates were too high. There was also a general tendency for radar estimates to be too low at distance from radar locations and about right or too high close to radar locations, although this did not hold true for the radar near Little Rock, Arkansas. The second bias correction method (co-kriging with radar beam height as secondary variable) generally had more extremes. Each method placed the storm total rainfall maximum near Cabool, Missouri, with an estimated 17.3-in (method 1) and 19.4-in (method 2). Despite these differences, the rainfall estimates were generally similar.

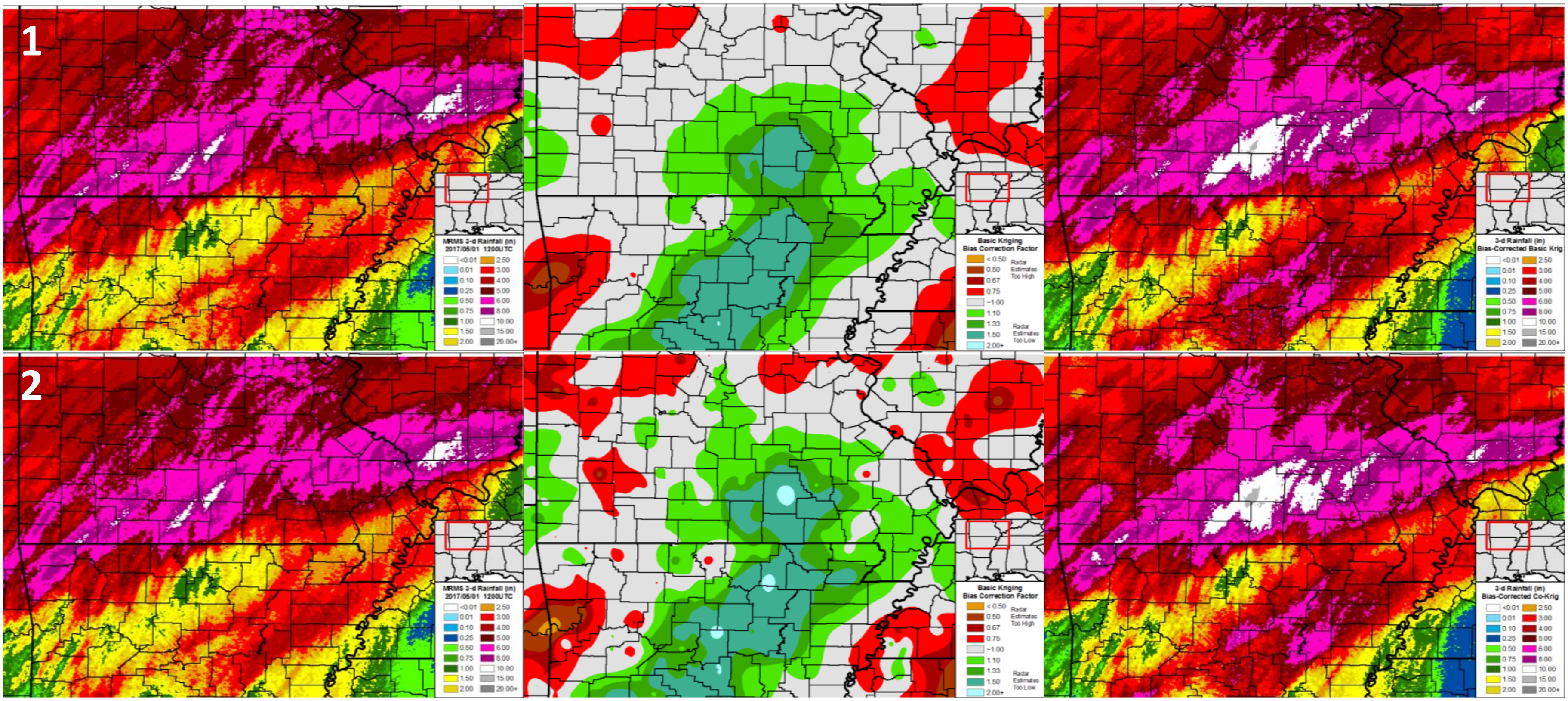

Figure 9. The bias correction process of method 1 (top; utilizing basic kriging) and method 2 (bottom; utilizing co-kriging). Raw radar-only rainfall estimates (left) are multiplied by the bias correction factor (middle) to produce the bias-corrected rainfall estimate (right). For the bias correction factor, areas that needed minimal adjustment (bias correction factor ~1.0) are indicated by gray, areas where the raw radar estimates were too low (bias correction factor >1.0) are indicated by greens and blues, and areas where the raw radar estimates were too high (bias correction factor <1.0) are indicated by reds and browns.

3.4 Bias-corrected radar rainfall estimate AEPs

Because rainfall estimates produced from each bias-correction method described in this report were generally similar, the AEP values were also quite similar. The AEP for the bias-corrected rainfall produced by both methods indicated widespread areas of extreme rainfall (defined by a 1% or less annual chance) across numerous counties in southern Missouri, several counties in southern Illinois, and a couple counties in far northwestern Arkansas. Rainfall estimates exceeded - in some cases by several inches - the 0.1% AEP (1-in-1000 annual chance) across portions of six counties in south-central Missouri roughly centered near the rainfall maximum at Cabool, Missouri.

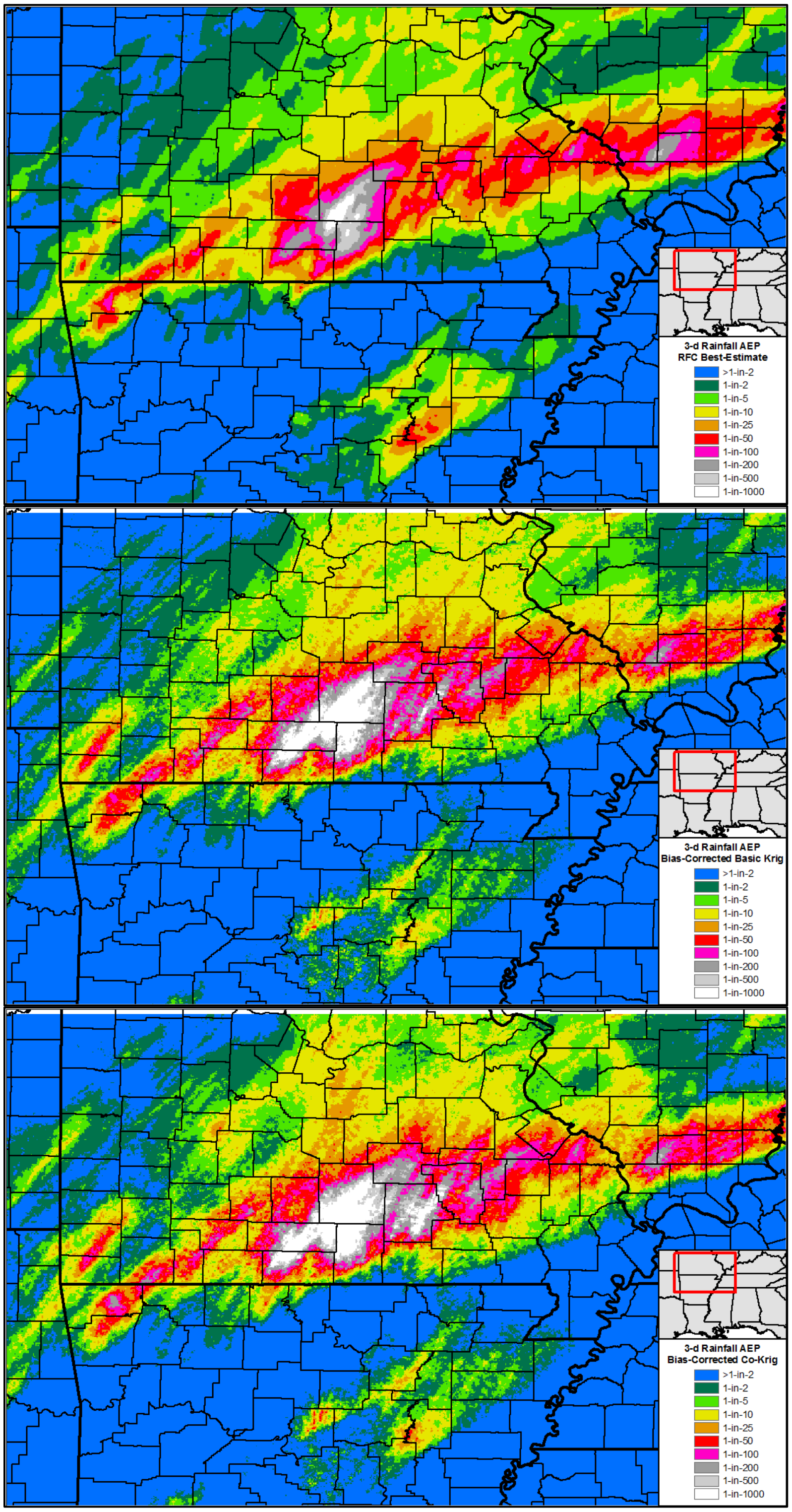

Figure 10. AEP for the bias-corrected rainfall produced by three different techniques. The AEP for the RFC best-estimate rainfall (biased corrected using only hourly gauges; top), the AEP for the bias-corrected rainfall produced for this analysis by method 1 (basic kriging; middle), and the AEP for the bias-corrected rainfall produced for this analysis by method 2 (co-kriging; bottom). Both methods from this analysis produced very similar results with rainfall severity increased (compared to RFC best-estimate rainfall) in many areas.

4.0 Discussion

Over 300 additional daily and multi-day rainfall observations (compared to the gauges available for realtime NWS RFC rainfall analysis) were used in this analysis to try increasing the precision of rainfall estimates for the late April 2017 flood event. Due to the substantial number of gauges utilized, manual QC of each observation was not plausible and an automatic, objective QC method was used. No automated QC method is perfect - such methods leave the possibility of some good observations being removed and some bad observations being kept. To better quantify the effect of these additional rainfall reports on the rainfall analysis, the rainfall estimates from each of bias-correction methods were compared to the official NWS RFC best estimate rainfall (Figure 11). The majority of the study area was changed by 0.5-in or less, but a few areas had substantial changes. In particular, the rainfall maximum was increased using both bias correction methods on the order of 4 to 6-in. These increases in rainfall appear plausible due to several factors: 1) the spatially-consistent pattern of increases and decreases throughout the study area, 2) the rainfall maximum occurring away from radar sites which often causes an underestimate of rainfall from radar-based estimates, and 3) the widespread, record flooding that was recorded downstream of areas of heavy rainfall.

It is difficult to determine which bias correction method is best. Although it makes conceptual sense that there would be a relationship between distance from the nearest radar site (and thus, radar beam height) and the over/under-estimating of rainfall estimates, the addition of variables to an already complicated interpolation technique (kriging) may increase uncertainty in ways that are difficult to quantify. The kriging method attempts to quantify uncertainty due to the interpolation by calculating the error at each observation location; this is done by iteratively removing one value at a time and re-interpolating. Verification statistics for each of these bias correction techniques ended up quite similar; each had a tendency to poorly predict isolated gauges that were higher or lower than the surroundings. This had the effect of smoothing out point minima and point maxima. Despite the differences between bias correction techniques, each consistently increased rainfall values near the rainfall maximum and the resulting AEP analysis was similar.

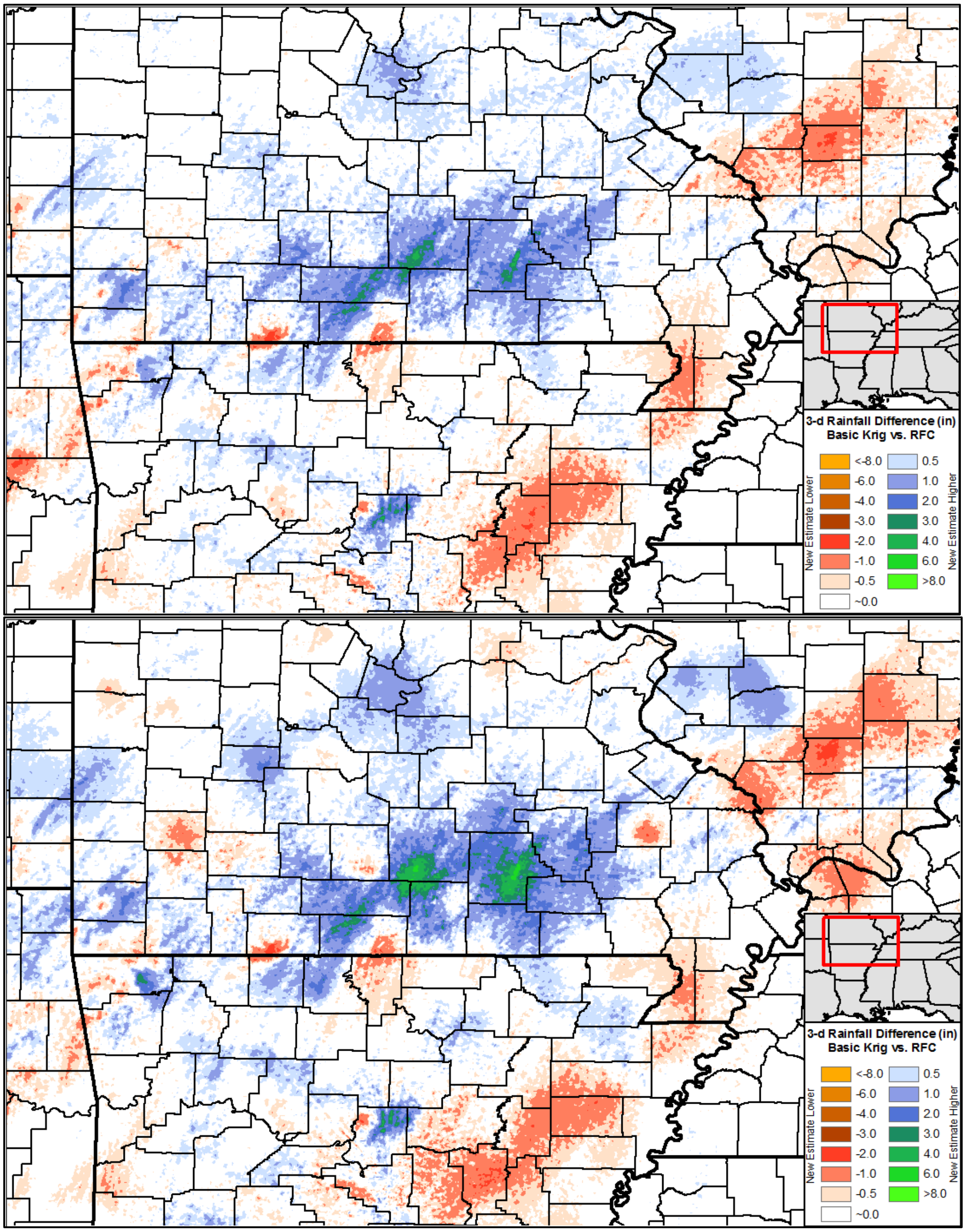

Figure 11. Difference between the bias-corrected rainfall produced by method 1 (basic kriging; top) and method 2 (co-kriging; bottom) and the official RFC best estimate rainfall. Positive values indicate areas where this new analysis raised rainfall estimates and negative values indicate areas where this new analysis lowered rainfall estimates.

5.0 Conclusions

Very heavy rainfall which occurred between 1200 UTC 28 April 2017 and 1200 UTC 1 May 2017 caused widespread flooding across multiple states in the Midwest United States. Additional rainfall data was collected to better analyze this extreme rainfall event. The additional gauges changed the storm total maximum near Cabool, Missouri, from just over 10-in to at least 17.3-in (depending on the bias correction method used). Away from the area of heaviest rainfall, these new rainfall estimates were similar to earlier estimates, within 1 to 2-in. Rainfall AEPs for the 48-h duration indicated that extreme rainfall occurred across a large portion of southern Missouri and portions of northern Arkansas with rainfall exceeding the 1-in-1000 annual chance rainfall for parts of at least six Missouri counties. Widespread, significant flooding occurred as a result of this extreme rainfall, with numerous stream gauge locations setting new stage records.

6.0 Acknowledgements

The author would like to thank Suzanne Van Cooten at the NWS LMRFC for the data extraction of point rainfall observations and David Welch for his review and helpful comments.

7.0 Works Cited

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