USING PROBABILISTIC RAINFALL TOTALS TO IMPROVE FLASH FLOOD MESSAGING

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INTRODUCTION

My goal this summer was to enhance my meteorological knowledge and gain exposure to different career opportunities in operational meteorology. I also wanted to engage in research that could potentially improve weather forecasting and help save lives.

The National Weather Service (NWS) Weather Forecasting Office (WFO) in Huntsville, Alabama allowed me to accomplish both of these goals. Shadowing the meteorologists while they generate forecasts and perform other operational tasks provided behind-the-scenes insight into the multitude of services that the NWS provides and the responsibilities of an NWS forecaster, Warning Coordination Meteorologist (WCM), and Science Operations Officer (SOO). It has also helped strengthen my synoptic and mesoscale meteorology education.

Moreover, conducting a research project focused on flash flood messaging allowed me to learn more about probabilistic forecasting and the NWS initiative for Impact-Based Decision Support Services (IDSS). Flash flooding is responsible for an average of 88 deaths annually, making it the second deadliest weather-related cause in the United States. Flash Flood Warnings are a product issued by the NWS to alert the public of imminent or ongoing flash flooding. “Considerable” Flash Flood Warnings are issued rarely and indicate unusual severity. “Catastrophic” Flash Flood Warnings, issued exceedingly rarely, equate to a Flash Flood Emergency and indicate likely near-record-high floodwater levels and disastrous damage. Both warnings necessitate urgent action to protect lives and property, with “catastrophic” warnings being the most severe.

By examining ways to improve messaging for high-risk flooding events, we can help warn areas of higher-end rainfall amounts and save lives.

RESEARCH QUESTION

Can probabilistic rainfall totals from the High-Resolution Ensemble Forecast (HREF) identify higher-end rainfall totals and improve future Impact-Based Decision Support Services (IDSS) messaging for high-risk flooding events?

PREDICTION

The max value of the HREF 24-hour Quantitative Precipitation Forecast (QPF) will highlight the higher-end rainfall totals and the localized probability-matched mean (LPMM) value will highlight the spatial extent of the higher-end rainfall.

METHODOLOGY

I. VARIABLES

This study takes a comparative analysis approach between HREF forecasts and Multi-Radar Multi-Sensor (MRMS) observed rainfall totals. The variables in this study are the MRMS 24-hour Quantitative Precipitation Estimation (QPE) and the HREF 24-hour QPF Max, Mean, and LPMM.

QPE is a method to determine the amount of precipitation that has fallen at a location. It utilizes an ensemble of precipitation estimations and diagnostic products based on radar-estimated total rainfall and supplemental observational rainfall totals from nearby gauges. The HREF QPF Max displays the highest forecast values of the ensemble members while the HREF QPF Mean displays the average of the forecast values. The HREF QPF LPMM is a modification of the ensemble probability-matched mean (PMM), which is a technique that maintains the spatial distribution of the ensemble mean while retaining the peak values of individual members. The LPMM shrinks the domain of the PMM by using a radius of influence. For the HREF, the radius of influence is 110 kilometers. As a result, this prevents precipitation from geographically distant areas from impacting the mean (Clark, 2017).

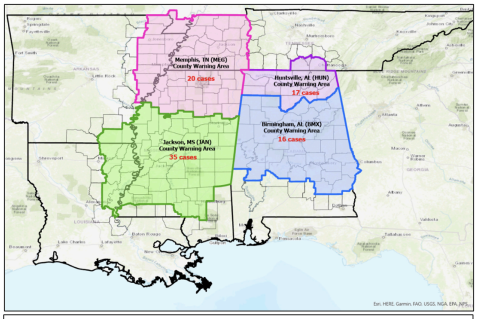


Figure 1a. *A map displaying the locations of the Huntsville, AL, Birmingham, AL, Memphis, TN, and Jackson, MS County Warning Areas (CWAs). These CWAs include portions of the southeastern states of Alabama, Mississippi, Tennessee, Louisiana, Arkansas, and Missouri.*

II. DOMAIN

For our study domain, we chose to examine the Huntsville, AL, Birmingham, AL, Memphis, TN, and Jackson, MS County Warning Areas (CWAs) for "considerable" and "catastrophic" Flash Flood warnings issued between January 2021 and May 2024 (Figure 1a). We used the Iowa Environmental Mesonet NWS Storm Based Verification System to identify these high-end flash flood warnings and recorded the date, time, warning type, and counties warned for each event (Figure 1b).

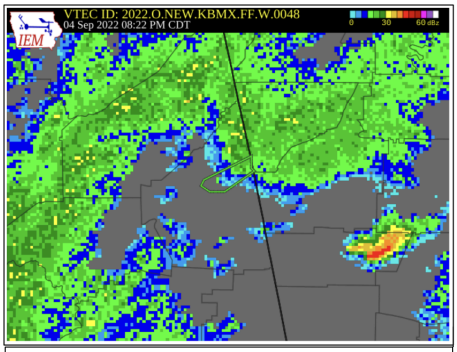


Figure 1b. *An image of the Flash Flood Warning issued by the BMX Weather Forecasting Office for Cherokee County, Alabama on September 5, 2022, at 0122 UTC. Courtesy of the Iowa Environmental Mesonet.*

III. COLLECTION OF FORECAST DATA

From there, we used the Storm Prediction Center HREF Ensemble Viewer to collect the highest QPF Max, Mean, and LPMM values estimated across the entire CWA during the time of the rainfall event (Figures 2-4). The QPFs are generated from ten operational hi-resolution 3-km Numerical Weather Prediction models and can provide information on precipitation likelihood, along with the magnitude and location of rainfall events (Ebert, 2001). The HREF model runs used were from roughly 24 hours before the warning issuance time. Specifically, if the warning was issued between 12 UTC and 00 UTC on the day of the event, the previous day's 12 UTC run was used and if issued between 00 UTC and 12 UTC, the previous day's 00 UTC was used. The majority of the data was collected from

the run's 36-hour lead time forecast (F36), with some collected using the 24-hour lead time forecasts (F24). The rainfall totals were deciphered using the corresponding color legend and recorded.

To examine spatial extent, we compared the coverage of the higher-end rainfall from the HREF QPF Max and LPMM to the counties listed in the Flash Flood Warnings. In other words, we examined the HREF QPF Max and LPMM to determine which product better aligned its swaths of higher rainfall forecasts over or within the vicinity of the areas that observed flash flooding. The vicinity is defined as the county itself or bordering counties. A yes or no response was recorded for each product and each event.

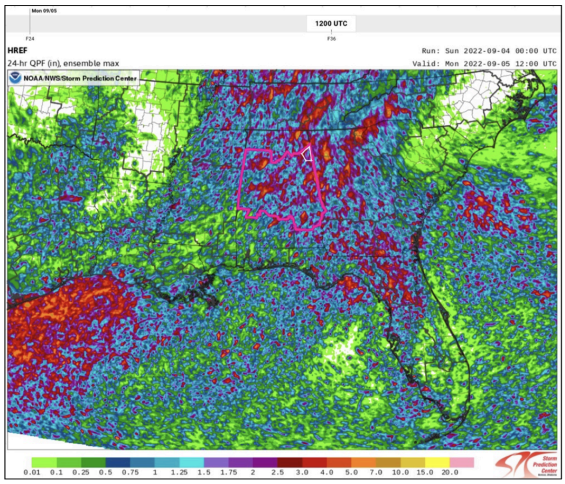


Figure 2. *This run is from September 4, 2022, at 00 UTC and forecasted the 24-hour QPF max rainfall totals for the period that would encompass the September 5th Flash Flood Warning issued for Cherokee County, Alabama. A swath of the highest estimations for the Max was not positioned over Cherokee County.*
**The BMX CWA is outlined in pink and Cherokee County is outlined in white.*

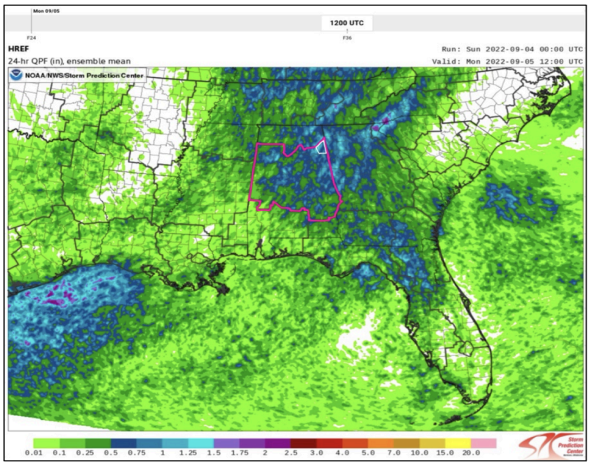


Figure 3*. This run is from September 4, 2022, at 00 UTC and forecasted the 24-hour QPF mean rainfall totals for the period that would encompass the September 5th Flash Flood Warning issued for Cherokee County, Alabama. A swath of the highest estimations for the Mean was positioned over Cherokee County.*
**The BMX CWA is outlined in pink and Cherokee County is outlined in white.*

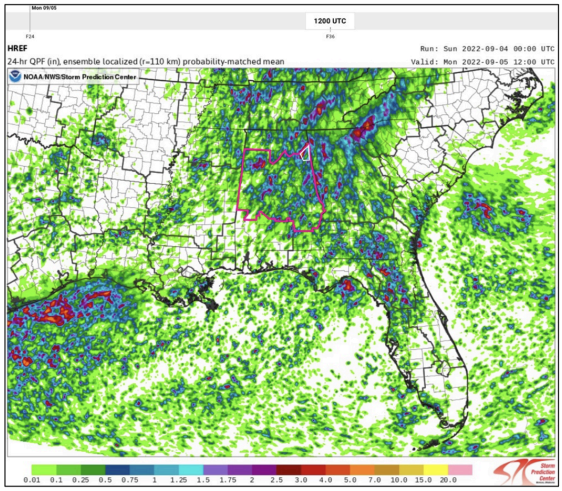


Figure 4. *This run is from September 4, 2022, at 00 UTC and forecasted the 24-hour QPF LPMM rainfall totals for the period that would encompass the September 5th Flash Flood Warning issued for Cherokee County, Alabama. A swath of the highest estimations for the LPMM was positioned over Cherokee County.*
**The BMX CWA is outlined in pink and Cherokee County is outlined in white.*

IV. COLLECTION OF OBSERVATION DATA

To collect the observed rainfall totals, we used the 24-hour QPE from the National Severe Storms Laboratory MRMS Operational Product Sensor (Figure 5). We viewed the product for the hour closest to the time the "considerable" or "catastrophic" tags were added to the Flash Flood Warnings. Particularly, if the tag was added within the first 30 minutes, the time was rounded down to the hour and if issued within the latter 30 minutes, it was rounded up to the next hour. Using the corresponding color legend to decipher the values, the greatest rainfall total observed across the CWA was recorded.

V. CALCULATIONS AND DATA ANALYSIS

Each event's HREF QPF and MRMS QPE values are presented in ranges, so the end points of the analyzed range were averaged. The MRMS QPE values were compared to the HREF QPF Max, Mean, and LPMM values via difference and percent error calculations. The values were also compared using one-sample and two-sample Kolmogorov-Smirnov (KS) tests via MATLAB.

All results were recorded in a Google Sheets spreadsheet. Graphs and maps were created using MATLAB, Google Sheets, and ArcGIS software.

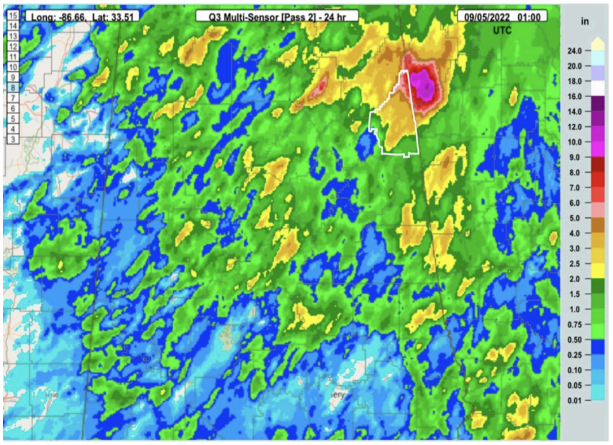


Figure 5. *This is MRMS 24-hour QPE for September 5th at 01 UTC, which is the near the time the "considerable" tag was added to the Flash Flood Warning issued for Cherokee County, Alabama. Those higher rainfall amounts were positioned over Cherokee County, justifying the warning. *Cherokee County is outlined in white.*

RESULTS

A total of 88 cases were collected and examined. Interestingly, the majority of the intense rainfall events seem to be the result of diurnally-driven, warm season rains (Figures 6-7).

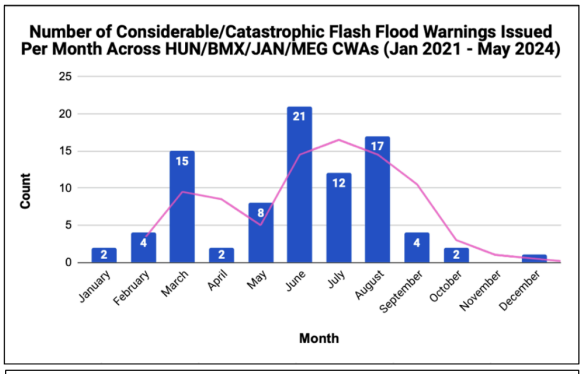


Figure 6. *The months that the Flash Flood Warnings were issued in. Throughout the study period, June received the most warnings and November received the least. This implies that the intense rainfall events were warm season rain.*

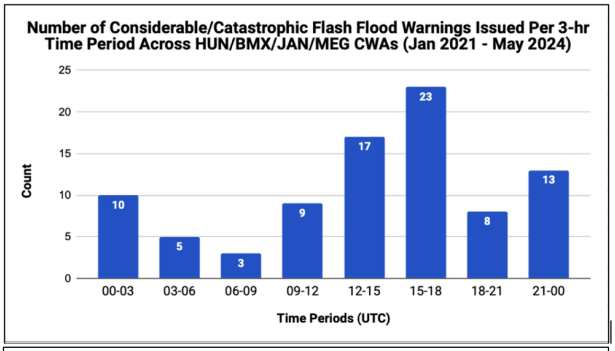


Figure 7. *The times that the Flash Flood Warnings were issued. Throughout the study period, most warnings were issued from 15-18 UTC. This implies that the intense rainfall events were diurnally driven.*

As for spatial extent, the HREF QPF LPMM did slightly better than the HREF QPF Max with including the warning location(s) in its swaths of higher-end rainfall totals (Figure 8a/8b). 60.2% of the cases had HREF QPF LPMM swaths that included the warning locations, compared to 50.0% for the HREF QPF Max. 5.7% of the cases had HREF QPF LPMM and Max swaths that

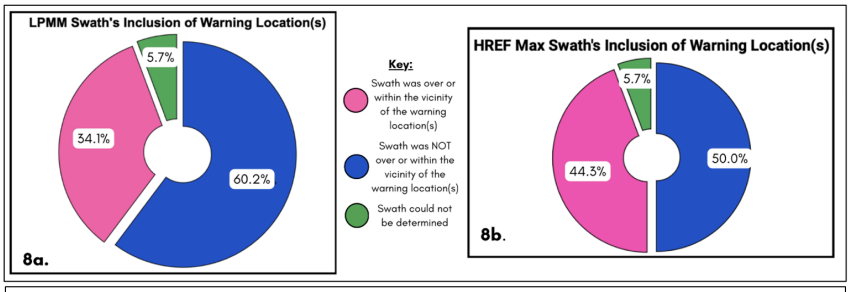


Figure 8. *The percentage of HREF QPF LPMM (8a.) and Max (8b.) swaths that included the warning county(ies). The LPMM did a better at including the warning locations into its swaths.*

could not be determined. It is worth noting that although both HREF QPF LPMM and Max swath proximity were comparable, the swath size for LPMM was smaller than Max for most cases.

In regard to statistical analyses, the null hypotheses of the one-sample KS tests stated that there would be no significant differences between a normal distribution and the MRMS QPE, and HREF QPF Max, Mean, and LPMM distributions. The null hypotheses were rejected as each test produced an extremely small p-value (Table 1). In other words, the distributions for the MRMS QPE and HREF QPF Max, Mean, and LPMM were not normal.

Table 1. *The p-value results of the one-sample KS tests for the MRMS 24-hour QPE and the HREF 24-hour QPF sources. P-values were below 0.05, meaning the null hypotheses were rejected.*

Variable 1	One-Sample KS Test P-Value Result
HREF 24-hour QPF Max	$2.34\ x\ 10^{-78}$
HREF 24-hour QPF Mean	$1.58\ x\ 10^{-47}$
HREF 24-hour QPF LPMM	$9.91\ x\ 10^{-72}$
MRMS 24-hour QPE	$7.46\ x\ 10^{-78}$

For our two-sample KS tests, the null hypotheses for our study were that the HREF QPF Max, Mean, and LPMM distributions would be similar to the MRMS QPE distribution. The null hypotheses were rejected, with each test generating a p-value less than 0.05 (Table 2). This implies that the distribution from the MRMS observed rainfall totals are not similar to any of the distributions produced from the HREF Max, Mean, and LPMM predicted rainfall totals. In other words, it cannot be assumed that the forecasted higher-end rainfall totals from the HREF Max, Mean, and LPMM accurately predicted the higher-end rainfall totals observed within these 88 cases.

Table 2. *The p-value results of the two-sample KS tests between MRMS 24-hour QPE and HREF 24-hour QPF sources. P-values were below 0.05, meaning the null hypotheses were rejected.*

Variable 1	Variable 2	Two-Sample KS Test P-Value Result
HREF 24-hour QPF Max	MRMS 24-hour QPE	$2.79\ x\ 10^{-2}$
HREF 24-hour QPF Mean	MRMS 24-hour QPE	$3.40\ x\ 10^{-24}$
HREF 24-hour QPF LPMM	MRMS 24-hour QPE	$3.58\ x\ 10^{-4}$

Given this information, percent error and difference calculations were performed to determine which HREF QPF source best matched the higher-end MRMS QPE analyses. The largest percent error was between the HREF QPF Mean and MRMS QPE, followed by the HREF QPF LPMM and MRMS QPE (Figure 9). The HREF QPF Max and MRMS QPE had the smallest percent error, implying that the HREF QPF Max values were the closest to the observed higher-end rainfall detected via

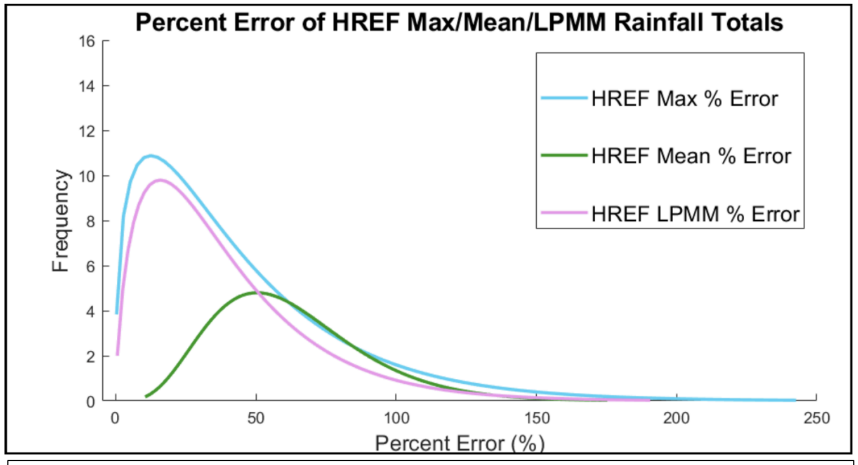


Figure 9. *Graph displaying the percent error between forecast rainfall totals via HREF QPF sources and observed rainfall totals via MRMS QPE. The HREF Max had the lowest percent error followed by the HREF LPMM. The HREF Mean had higher percent error.*

MRMS. The difference calculations showed how the HREF QPF sources deviated from a perfect forecast or a difference of zero (Figure 10). The HREF QPF Max was the closest to generating perfect forecasts of higher-end rainfall, with some slight overestimation. It was closely followed by the HREF QPF LPMM, which slightly underestimated the higher-end rainfall totals. The HREF QPF Mean deviated far from a perfect forecast, having significant underestimation.

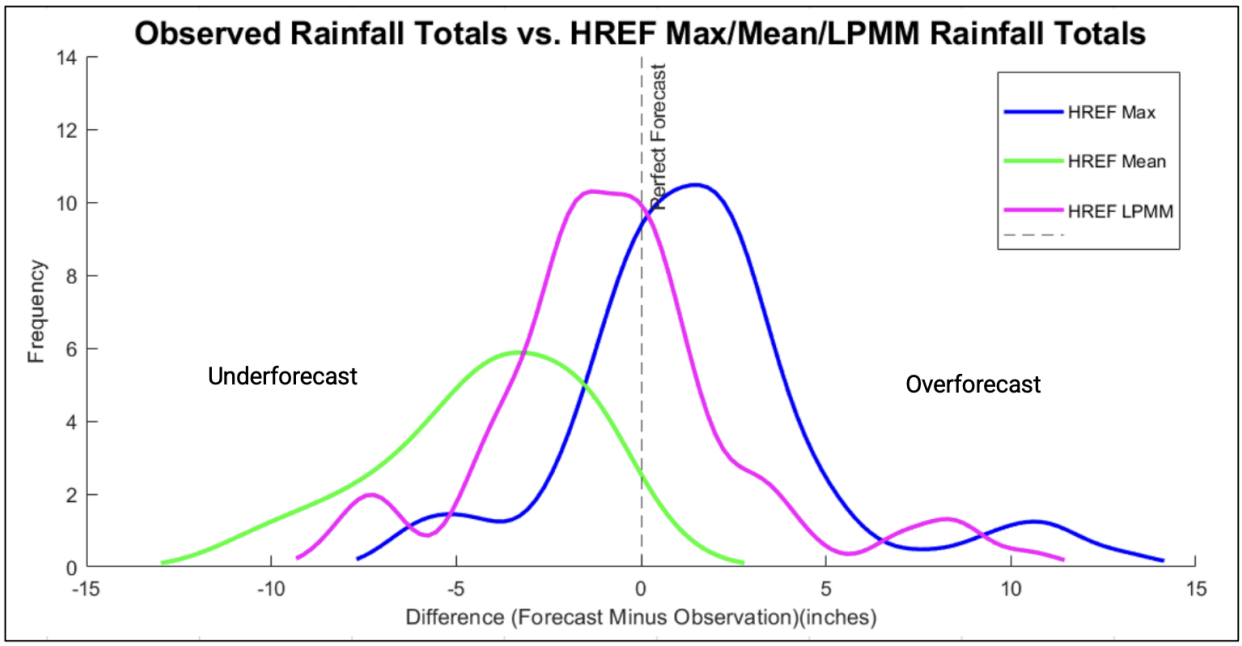


Figure 10. *Graph displaying the difference between forecast rainfall totals via HREF QPF sources and observed rainfall totals via MRMS QPE. Perfect Forecast represents a difference of zero. The HREF Max and LPMM were closer to generating a perfect forecast, with Max having slight overestimation and LPMM having slight underestimation.*

CONCLUSION

This study deduced the following takeaways:

- The HREF 24-hour QPF Max is the better representation of higher-end rainfall totals, with a slight overestimation, followed by the HREF 24-hour QPF LPMM which slightly underestimates.
- The HREF 24-hour QPF LPMM is the better representation for the spatial extent of higher-end rainfall, when compared to the HREF 24-hour QPF Max.
- The HREF 24-hour QPF Mean is not a good representation of higher-end rainfall.

Flash flood messaging can potentially be improved to incorporate these findings in the following way: *"Flash flooding is expected with widespread rainfall totals between {HREF Mean value} and possible localized higher-end rainfall totals between {HREF Max values} near {HREF LPMM swath area}."*

It is recommended that future research incorporate spatial differences in heavy

rainfall and events influenced by complex terrain.

ACKNOWLEDGMENTS

I would like to extend a special thanks to my mentors, Katie Magee and Todd Barron, and the entire NWS Huntsville WFO staff for their assistance, guidance, and support. I would also like to thank the NOAA Ernest F. Hollings Scholarship Program for serving as the funding sponsor.

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