Heavy Rainfall Threat Analysis: 2022 Upgrades and Operations
for the Mile High Flood District

Introduction

History of the Tool

The Heavy Rainfall Threat Analysis (hereafter, Tool; known as the Heavy Rainfall Guidance Tool before 2019) was developed for the Mile High Flood District (hereafter, District or MHFD) in 2014 with the main goal of alerting the District about the daily heavy rainfall potential, and by extension, the accompanying threat of excessive runoff. Major upgrades to the Tool's appearance and Forecast Zones were completed in 2021, and the Tool continues to successfully provide a comprehensive look at the daily heavy rainfall risk across the District, including upstream areas that could produce runoff into the District. After several modifications over the years, the Tool's current Forecast Zones appear to appropriately balance reasonable spatial precision with the uncertainties constrained by our meteorological understanding of heavy rainfall forecasting (Figure 1). Notably, there are now 4 Forecast Zones within the immediate MHFD boundary. Other past upgrades have helped improve the Tool's performance, while outreach presentations have engaged a more diverse group of end-users. More details about the yearly updates and past performance can be found on the ***F2P2 website***.

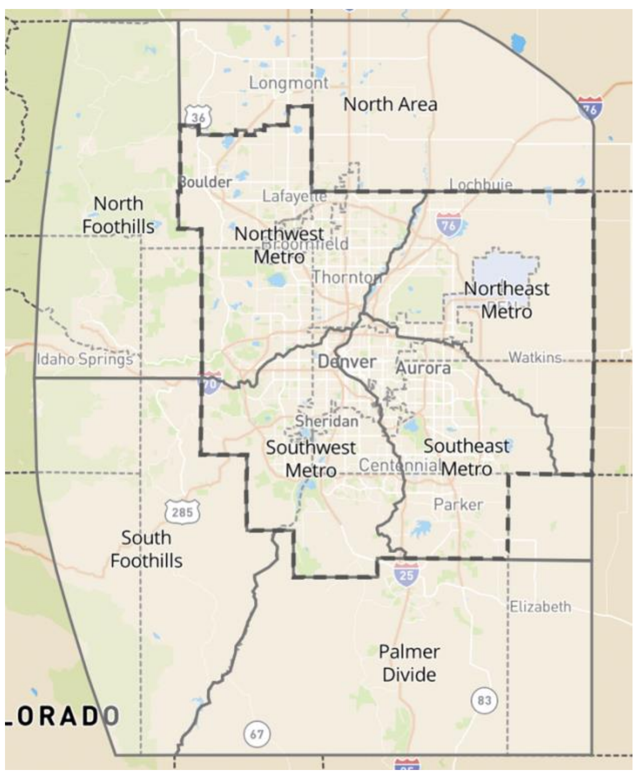

Figure 1: Heavy Rainfall Threat Analysis domain and zones with the MHFD overlaid in the dashed black line.

Objective for 2022 flood season

HydroMet Consulting (hereafter, HMC) proposes a general continuation of 2021 key operations, as summarized in Figure 2. The Tool will continue to rely strongly on objective guidance delivered from a suite of forecast model rainfall and non-rainfall fields. This data will be aggregated, bias-corrected and post-processed using at least five years of historical MHFD rain gauge data and other estimated rainfall fields, now formally called HMC's Bias-Corrected Quantitative Precipitation Forecast (BCQPF) product (more details in Task 1.1). The Tool forecasts will be updated numerous times over the course of a day, to ensure that rapidly evolving events are adequately captured. Finally, the morning after a forecast, MHFD rain gauge and estimated rainfall data will be obtained to verify forecast performance in near real-time. Forecast dissemination will primarily occur through the Tool's website, along with a social media component for particularly threatening days (high probability of widespread, heavy rainfall). This proposal outlines the details of the Tool's upgrades and operational support for the 2022 heavy rainfall season.

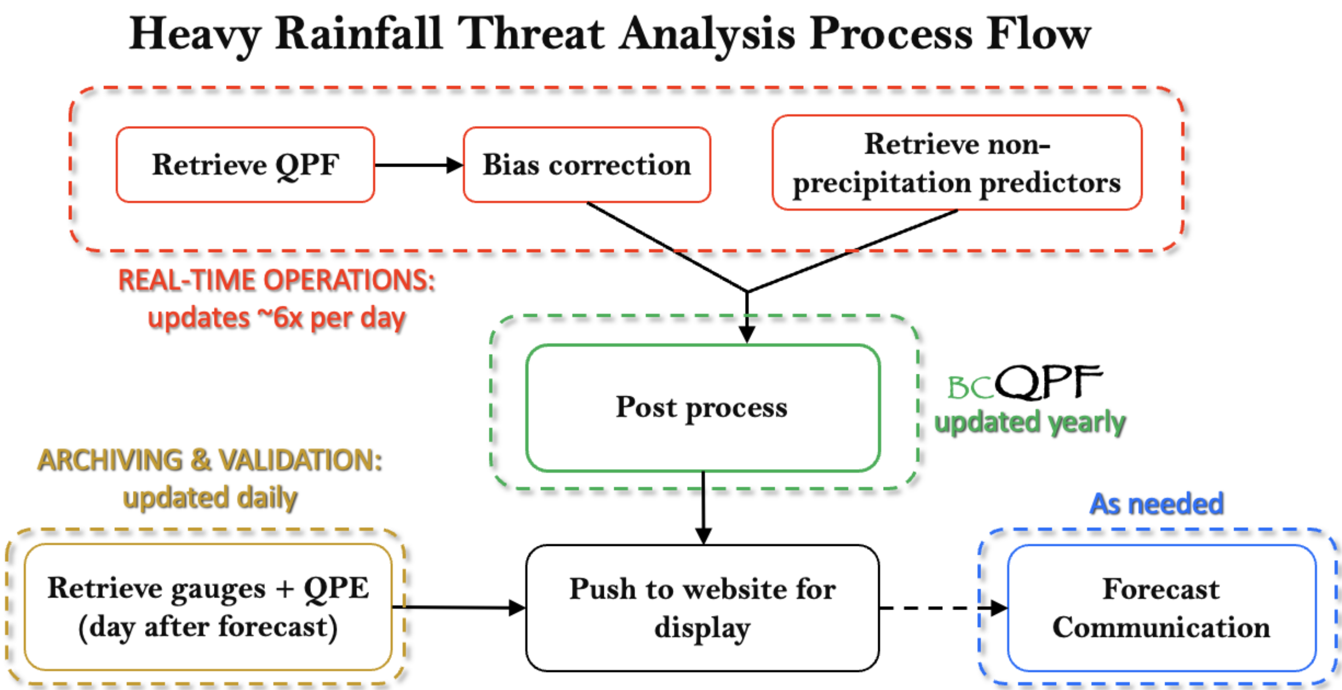

Figure 2: Proposed HRTA operational process flow chart for the 2022 season.

Work Plan

Task 1 – Scientific Upgrades

Task 1.1 – BCQPF Update

In 2021, HMC developed a formal heavy rainfall guidance product called BCQPF. Over the course of a forecast day, BCQPF aggregates dozens of multi-resolution weather model forecasts into a single ensemble, corrects for model biases using historical local rainfall data and other atmospheric fields, and then outputs key parameters such as the Probability of Exceedance (POE) of a given rainfall threshold. This approach is superior to using raw Quantitative Precipitation Forecast (QPF) data alone, especially during marginal probability days when the QPF tends to be overconfident (see Dewberry, 2016). BCQPF outputs several key metrics displayed by the Tool: (1) the maximum hourly QPF (QPF-Max) and (2) the POE (e.g., the chance of exceeding 1 inch in 1-hour) for each of the Forecast Zones over 1, 3, 6 and 24-hour durations that are capable of causing flooding issues over the District. The use of multiple durations and thresholds help determine the nature of the heavy rainfall threat for each event. Note that while BCQPF is a largely objective product, it is, at a minimum, updated annually to account for the most up-to-date scientific methods and evolving physical understanding of heavy rainfall processes, recent heavy rainfall events as well as HMC's hands-on forecast experience. Thus, HMC believes BCQPF carries an optimal subjective-objective blend that is superior to using either method alone.

HMC proposes to update three aspects of $_{BC}$QPF prior to the start of the 2022 heavy rainfall season. The first is a routine data update to include QPF, Quantitative Precipitation Estimate (QPE) and rain gauge data within the MHFD area over the 2021 rainfall season (last update was April 2021). The second is to include the long-standing Rapid Refresh weather model (RAP) into the $_{BC}$QPF model ensemble. The RAP contains the latest data assimilation methods, along with a long archive dating back to 2014, making it an ideal candidate for inclusion in the $_{BC}$QPF. It is also updated hourly, which provides an excellent opportunity to inform on early-identified, marginal events that may evolve into more severe flooding situations throughout the morning.

Lastly, HMC proposes to improve the QPE component of $_{BC}$QPF, which is a notoriously challenging aspect of heavy rainfall assessment. While model QPF is entirely objective and not open to interpretation, there can be numerous interpretations of QPE. The most challenging situation is during isolated, heavy rainfall events that skirt between rainfall gauges, seemingly a staple in the MHFD area (see HMC, 2021, for a more detailed description of this problem). Two common rainfall QPE products are NOAA Stage IV (Lin and Mitchell, 2005) and NSSL MRMS (Zhang et al., 2016; Gerard et al., 2021). Gridded data has the advantage of full spatial coverage, but it can both overestimate and underestimate true rainfall depending on the atmospheric conditions. To supplement this shortcoming, the District's data-rich, high-density ALERT rain gauge network is also ingested to the $_{BC}$QPF process, which is considered ground truth.

After the 2021 season, HMC closely inspected gridded QPE performance, which revealed systematic overestimates by both Stage IV and MRMS. There are many possible reasons for this from a meteorological perspective (see Zhang et al., 2016). Another possible (non-meteorological) reason is the fact that these products are national-scale and do not have explicit local-level corrections. For example, Figure 3 compares 24-hour rainfall from gauge observations (ALERT and CoCoRaHS) with their corresponding MRMS grid points, aggregated over the 26 Flood Days during the 2021 forecast season. Only points with *at least* 0.10 inches of observed rain *or* QPE were retained. In general, MRMS tended to overestimate QPE. Of the 6,549 data points included, 4,752 (72%) were overestimated. Stage IV had a slightly lower bias, but still tended to overestimate (not shown).

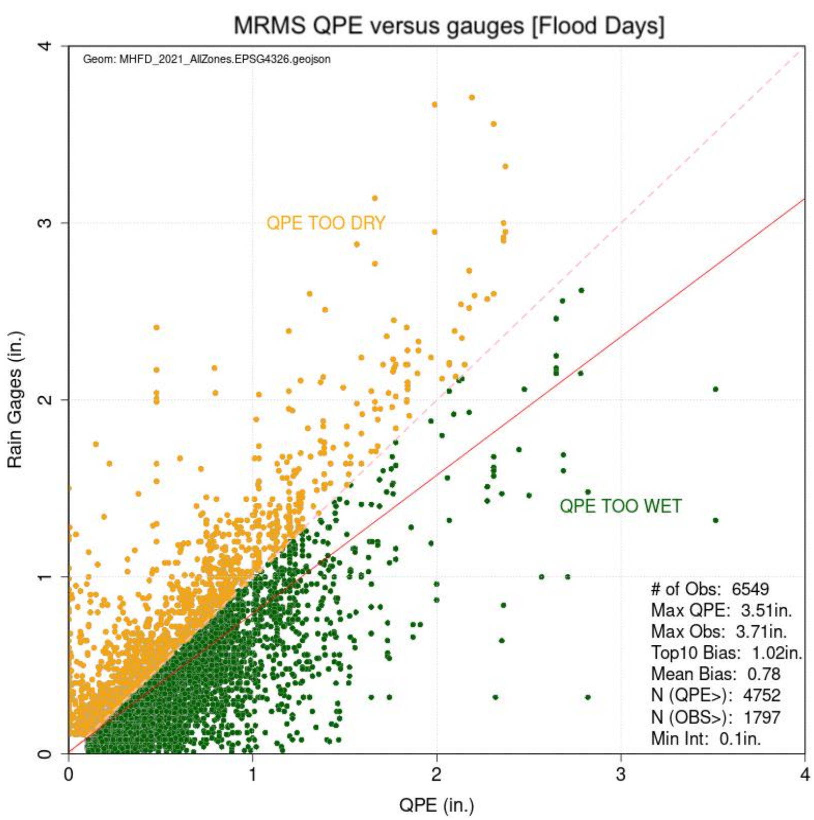

Figure 3: Comparison of MRMS QPE with gauge observations over all 26 Flood Days during the 2021 forecast season.

HMC proposes an investigation of historical QPE bias (over the 2015-period used by $_{BC}$QPF) by directly comparing high-quality rainfall gauge observations with the Stage IV and MRMS QPE products used within the Tool. The propensity for gridded QPE to overestimate rainfall implies that Flood Day climatology may also be overestimated, and this bias may then propagate into the Tool. Addressing the bias will provide better forecast reliability by lowering the number of False Alarms.

The main objective of Task 1 is to select and implement new methodology that will improve forecast accuracy, reliability, and resolution, with a particular emphasis on simultaneously minimizing forecast False Alarms and Misses. After the 2021 season, post-season verification work indicated that a slight decrease of the lower POE bound that triggers a Low threat significantly decreased the Miss Rate. Reducing the POE of 1 inch in

1 hour down by only 3%, from 20% to 17%, resulted in a significant improvement in performance across all metrics. The Threat Score, Miss Rate and False Alarm rate decreased with an increase in the Probability of Detection. HMC will utilize data from past seasons to select a new and appropriate Low threat threshold as well as examine other possible changes that need to be made to the other threat thresholds.

Task 1.2

30-Minute Rain Rate

The maximum 1-hour rainfall intensity forecast has been a pillar of the Tool since it's inception. However, due to the semi-arid climate and impervious areas of the MHFD, many threatening rainfall events may be less than 1 hour in duration, suggesting that portrayal of such an event over a 1-hour accumulation period may underestimate its severity. To account for this, HMC proposes including a maximum 30-minute rainfall intensity value in the Tool's output, via the QPF-Max layer in similar fashion to the current QPF-Max 1-hour value. This value will be bias-corrected using historical MHFD gauge data, ensuring an accurate portrayal of the local heavy rainfall climatology.

Rainfall Coverage

Although "rain rate" is the common language that binds meteorologists and hydrologists, properly conveying this information and the potential flooding that can arise, remains challenging due to the many factors involved (duration of peak intensity, spatial scale, etc). Initially, the Tool was designed to output multiple perspectives of the rainfall forecast including maximum intensity and POE at several durations and thresholds. One element that has been avoided thus far is the concept of rainfall coverage: What kind of area will a given storm cover? What portion of MHFD or a given Forecast Zone is expected to see meaningful rainfall today? These questions have conventionally been hard to answer. However, HMC believes (i) sufficient scientific knowledge and data now exists to develop these answers, and (ii) in conjunction with the existing information on QPF-Max and POE, an "expected rainfall coverage" forecast will benefit end-users by providing a more complete overall picture of a day's heavy rainfall potential.

To accomplish the objective above, HMC proposes adding a third tab to the existing web map. This "Rain Coverage" tab will provide two elements. First, a high-resolution grid-point based Probability of Precipitation (PoP) estimate, using $_{BC}$QPF, to depict what portion of the forecast area is expected to see the highest chances of rainfall. Currently, each Forecast Zone has a single PoP forecast, but no spatial information within that Forecast Zone. Second, an estimate on the rainfall coverage, conveyed either as an area, or a percentage (of a given Forecast Zone). This will also be completed for the full domain or All Zone forecast.

Key Outcomes & Benefits to the District:

- Improvement to Tool accuracy, reliability, and resolution, which in turn, should continue to encourage increased usage,
- By reducing the Low threat bound and examining possible changes to other threat level thresholds, an improved Miss Rate, False Alarm Rate and Probability Of Detection should be possible,
- An additional 30-minute rainfall rate will help better classify events with a duration that lasts less than 1 hour,
- Additional rainfall coverage statistics to the web map will help bridge the information gap between meteorology and hydrology, increasing the Tool's utility.

Task 2 – Visualization Upgrades

In 2021, a new web map was created for the Tool to simplify the most important forecast details and add a spatial component to the Tool's output. The more mobile friendly website aids the "on the go" nature of Emergency Mangers and other end-users. The Tool has two main tabs related to QPF: (1) the "Threat Layer", which is akin to the "most likely" scenario and (2) the "QPF-Max", which shows the "realistic worst-case scenario" across All Zones. To help build confidence in the Tool's output, by exploring how the Tool has handled past rainfall events, an archive was also built. It has access to the same QPF data mentioned above, but it also has an added QPE component that is updated each morning with data coming from three separate data sources: Stage IV, MRMS and MHFD ALERT gauged rainfall data. This allows the end-user to better identify the types of storm(s) that moved through the area for the selected date along with the presentation of several QPE stats for the selected 24-hour forecast period.

For the 2022 operational season, HMC proposes the following website modifications and additions to address the aforementioned elements in Task 1, as well as minor tweaks as noted from 2021 experience:

i) Add a “Rain Coverage” tab to depict high-resolution Probability of Precipitation, as well as fraction of Forecast Zone that is expected to see rainfall coverage,
ii) Tweak QPE data presentation to be better comparable across datasets with differing spatial resolution,
iii) Tweak QPF-Max bar charts to improve legibility,
iv) Add an additional QPF-Max rainfall rate line for the 30-minute duration,
v) Add hourly QPE to QPF-Max bar charts for easier comparison of forecast with observation.

Key Outcomes & Benefits to the District:

- New metrics that are helpful to the hydrology community.
- Visualization updates to the existing website to improve functionality.

Task 2 Deliverables:

1. An updated Tool web map with the features described above.

Task 3 – Daily Operations

Task 3.1 – Daily Quality Control/Assurance and Maintenance

Although the Tool is mostly automated, there is still the need for a HMC meteorologist to run daily quality control. While it has not been an issue in the last few years, it is possible that the output of NWP model(s) may be unavailable for a given run cycle, or the entire day, due to errors outside of HMC’s control. In practice, we foresee this only being an issue for the morning (i.e. first) update around 8AM MDT. With the addition of new runs throughout the subsequent updates, it is extremely unlikely that this issue would persist throughout the day. In the case that there are days that have four or less contributing models to the Tool, HMC will add a “use with caution” message at the top of the Tool.

An HMC meteorologist will also provide daily quality control and assurance that Tool output makes physical sense and is properly visualized on the website. Similar to year’s past, on days with an elevated flood threat, HMC will reach out to the MHFD project manager to provide situational awareness and prepare a social media post for the District’s Twitter account (see Task 3.2 for more details).

Since the incorporation of MHFD rain gauge data into the Tool’s daily archive during 2021, HMC will continue to work with MHFD and its partners to ensure questionable rain gauges are flagged.

Task 3.2 – Social Media and Outreach

The Twitter platform (@MHFDFWS) has proven adept to disseminate succinct, important messages quickly and simply to many end-users. Since 2019, HMC has provided Tweet's for the District's account to warn about the daily flood potential within and in the vicinity of the District's service area on High threat days identified by the Tool. Feedback and usage statistics over past seasons has been positive with 10+ "Likes" and 7 "Retweets" or shares with the District's two Tweets during the 2021 season. HMC proposes a continuation of this service for the 2021 season and a meeting with the District's project manager as early as possible to finalize details for the campaign. Updates to last year's image templates will mimic any Tool upgrades from this proposal.

Training held in 2021 helped educate end-users on the Tool's methods, features, and forecasts. The training had around 20 attendees from backgrounds ranging from emergency management to local on-air meteorologists. A recording of the training can be found on the MHFD's website. Public outreach continues to build both awareness and confidence in Tool usage by end-users, which helps increase the overall utility of the Tool. HMC proposes a more targeted, on-demand training for 2022 to end-users that may have specific questions about the Tool or how to use it in application. Additionally, this service could also include outreach about how to improve the Tool for end-users.

Key Outcomes & Benefits to the District:

- Quality assurance by a HMC meteorologist will ensure the Tool's functionality and output is as accurate as possible,
- Early communication about potentially threatening rainfall days to end-users on a widely used social media platform,
- Targeted outreach about the Tool may help improve its utility within a more diverse group of end-users.

<u>Task 3 Deliverables:</u>

1. All QC logs and manual messages will continue to be archived and made available online,
2. HMC meteorologists will update image templates for social media use and presentations for outreach,
3. Minutes of all outreach events will be available upon request.

Other Direct Costs: Hosting and Computing Platform

HMC will continue to host the Tool using Amazon Web Services (AWS), which ensures maximum uptime of files and Tool output. Archiving of the Tool's daily updates will continue and be available through the Tool's website ("Archives" page) along with the daily verification maps. Weekly backups of the data will continue to ensure the website works properly, and HMC will keep the website SSL certified to insure it's properly working on all internet platforms. The collective cost for hosting and computing will be **$200 per month** during the Tool's warm season operations (May to September).

Task 4 – Verification

A verification of the Tool's performance is necessary at the end of each season to evaluate its accuracy and impact. In addition to noting the Tool's progress compared to previous years, the verification often reveals shortcomings of the Tool, which can frequently be corrected to increase the Tool's reliability and accuracy in subsequent seasons. In turn, the compounding effect of yearly verification helps keep the Tool, and the District, on the frontier of the rapidly evolving field of heavy rainfall forecasting. HMC recommends an end-of-season validation for 2022, very similar to previous years. This includes using multiple data sources, including the District's ALERT data, gridded QPE estimates, and CoCoRaHS data for manual quality control, which was found to be important to classify marginal Flood Days (HMC, 2021). Key aspects of the validation report will investigate the Tool's performance on the metrics for which it was developed:

- Was a flood threat realized (both across the full Tool domain and within each zone)?
- Was the timing reasonably forecasted?
- Was the forecasted QPF-Max consistent with observations?

- Was the probability forecast reliable? For example, if an event was forecasted 20% of the time, did it occur 20% of the time?

The validation report will provide a rigorous assessment of the Tool's 2022 performance as well as research completed for Tool improvements (Task 1). It will continue to compare its forecast to other forecasts such as the National Weather Service and the F2P2 Heavy Precipitation Outlook. The validation report will be presented in manner appealing to both the District's technical and non-technical stakeholders.

Key Outcomes & Benefits to the District:

- Identifying areas of success and shortcomings by the Tool will help drive improvements for future seasons.

<u>Task 4 Deliverables:</u>

1. A detailed validation report assessing the Tool's 2022 overall performance (see F2P2 website for an example of previous validation reports).

Daily Logistics

For 2022 Tool operations, HMC proposes at least 6 forecast updates. On days where a threat is elevated or an HMC meteorologist detects questionable Tool output, updates will be adjusted as necessary to reflect the latest forecast trend. The first update is proposed at 7AM MDT with the last update occurring at 5PM MDT. HMC proposes a similar operational season as in previous years: May 1st through September 30th, with possible early and later extension if threatening rainfall chances appear likely.

Schedule

The following schedule assumes a Notice to Proceed (NTP) date of March 15, 2022. An earlier or later NTP will allow us to adjust the schedule accordingly.

Task	Completion Date
1. Scientific Upgrades: Task 1.1	May 1, 2022
2. Visualization Upgrades: Task 1.2 & Task 2	June 15, 2022; Minor upgrades completed by May 1
3. Daily Operations: Task 3.1	May 1, 2022
4. Daily Operations: Task 3.2	June 1, 2022
5. Final Report: Task 4	November 31, 2022

Staff

Staff	Proposed Role
Dana McGlone *Project Manager & Lead Meteorologist*	Dana will provide project quality assurance and be the administrative and technical point of contact for the client. She will be in charge of the day-to-day quality control of the Tool's output and will also work closely with Dmitry on Tool upgrades.
Dmitry Smirnov *Chief Scientist*	As chief scientist, Dmitry will serve as the architect to develop the scientific upgrades ensuring the project's scientific integrity through quality control. In addition, Dmitry will assistance with the forecast equation development and Tool output. Dmitry will also help with day-to-day quality control of the Tool's output.
Graham Emde *Developer*	Graham will provide application development for the Tool's operation and help build the new visualization features for the Tool.

References

Dewberry, 2016: UDFCD Heavy Rainfall Guidance Tool – Upgrades for 2016 Operational Season. Technical Memo. Report submitted to Mile High Flood District in May 2016. 27p. https://udfcd.org/FWP/F2P2_Reports/2016QPFTool_TechMemo.pdf

HMC, 2021: Heavy Rainfall Threat Analysis: 2021 Final Report. Report submitted to Mile High Flood District January 2022. 33p. https://udfcd.org/FWP/F2P2_Reports/2021QPF-Max_HRG_FinalReport.pdf

Gerard, A., et al., 2021: An Overview of the Performance and Operational Applications of the MRMS and FLASH Systems in Recent Significant Urban Flash Flood Events. *Bulletin of the American Meteorological Society*, **102.11,** E2165-E2176.

Lin, Y., and K. E. Mitchell, 2005: The NCEP stage II/ IV hourly precipitation analyses: Development and applications. *19th Conference on Hydrology*, San Diego, CA, American Meteorological Society Annual Meeting. https://ams.confex.com/ams/Annual2005/techprogram/paper_83847.htm

Zhang, J. et al., 2016: Multi-Radar Multi-Sensor (MRMS) Quantitative Precipitation Estimation: Initial Operating Capabilities. *Bulletin of the American Meteorological Society*, **97**, 621-638.