FINAL REPORT

University: Arizona State University

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NWS Office: Phoenix

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Type of Project (Partners or Cooperative): Partners

Project Title: Assessing the Accuracy of Multi-Radar/Multi-Sensor (MRMS) Precipitation Estimates in the Phoenix Metropolitan Area to Support Flash Flood Warning Operations

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Section 1: Summary of Project Objectives

The project had **three main objectives**:

(1) To quantify the accuracy of Multi-Radar, Multi-Sensor (MRMS) radar-based quantitative precipitation estimates (QPEs) relative to other QPE sources and a dense network of rain gauges across the Metropolitan Area of Phoenix, AZ for a variety of rainfall events during the North American Monsoon (NAM) season over the past five years (2015-2019).

(2) To evaluate what average recurrence interval (ARI) rainfall thresholds are associated with flood impacts in the Phoenix Metropolitan Area during the NAM season.

(3) To establish a research and educational collaboration between the Phoenix National Weather Service (NWS) Weather Forecast Office (hereafter, WFO Phoenix) and the Hydrosystems Engineering Program at Arizona State University (hereafter, ASU).

Section 2: Project Accomplishments and Findings

To address the **first two objectives**, Dr. Mascaro used the project funds to support a M.S. student – Annika Hjelmstad – for part of a semester. The project's activities became then part of Ms. Hjelmstad's M.S. thesis (see Section 5). The ASU team (Dr. Mascaro and Ms. Hjelmstad) has closely collaborated with the Phoenix NWS Office team (Dr. Larry Hopper and Paul Iñiguez) on the following activities.

Data collection

We downloaded and processed radar QPEs from MRMS (1-km, 2-min and 1-h), gage-corrected MRMS (GCMRMS; 1-km, 1-h), and Stage IV (4-km, 1-h) in our study region, the Phoenix Metropolitan Area (PMA). Data were acquired in Grib format and converted into GeoTIFF format in UTM coordinates. We also obtained data from 365 rain gages belonging to the network of the Flood Control District of the Maricopa County (FCMC), available at 5-min resolution. Figure 1 shows the gage location within the PMA and boundaries of Maricopa County.

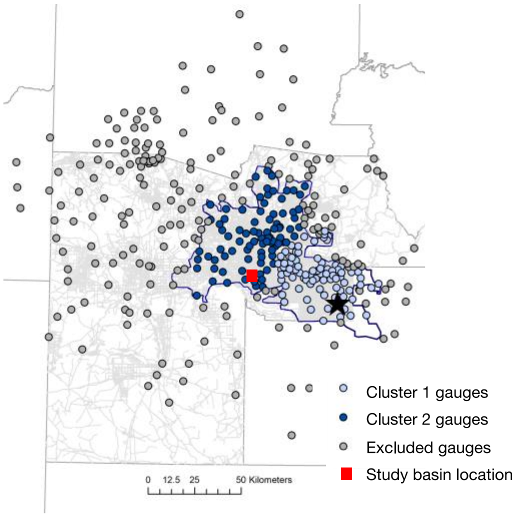


Figure 1. FCMC rain gage network, along with location of the KIWA WSR-88D weather radar (star).

Identification of gage clusters for comparison with radar QPEs

We focused our analysis on the PMA, whose boundaries are shown with a blue line in Figure 1. Within this region, we divided the rain gages into two clusters defined based on the distance between gages and radar, and density of the gages. The main characteristics of the two clusters are summarized in Table 1.

Table 1. Characteristics of the two clusters. Note: Cluster density is the number of gauges per 1,000 km^2.

Cluster	Density	Mean distance from radar (km)	Mean elevation (m MSL)	No. gauges	No. co-located radar pixels	
1	54	23	421	83	Stage IV	61
					MRMS	83
2	36	59	426	85	Stage IV	69
					MRMS	85

Storm selection

We followed criteria similar to Krajewski et al. (2010) to detect the start and end times of a number of storms. After preliminary analyses that showed that Stage IV QPEs exhibit low bias when compared to the gages, we decided to use Stage IV QPEs to identify the storms. We applied the following criteria over the summers from 2015 to 2019 for all pixels in the PMA:

1. A storm starts when 1 mm/h of rainfall is recorded in at least one pixel.
2. A storm ends at the beginning of a 5-hour hiatus in which less than 1 mm/h of rainfall is detected at all pixels.

A subset of these storms was retained based on the additional criterion:

3. A storm is kept if 50% or more gages recorded at least 1 mm total storm rainfall.

A total of 47 storms was identified, whose mean intensities and durations are summarized in Table 2.

Table 2. Summary of selected storms

Duration →	**1 h – 3 h**	**3 h – 6 h**	**6 – 24 h**	**> 24 h**	**All storms**
Number	1	8	33	5	47
Mean intensity (mm/h)	1.90	0.59	0.49	0.66	0.56

The selected storms were classified based on their generating mechanisms and storm environments, including:

- **(i) Monsoon events** with a monsoonal flow at middle and upper-levels in agreement with Maddox et al. (1995) storm types (Type I-southeasterly flow, Type II-northeasterly flow, or Type III-westerly flow/other, or some hybrid) that is accompanied with a low-level moisture surge from the Gulf of California;
- **(ii) Transition events** with a strong westerly longwave or shortwave trough (i.e., > 25 knots at or below 500 hPa) and pronounced (i.e., > 40 knot) upper level jet streak with or without an associated surface front. The moisture contribution may come from the Gulf of California, Pacific Ocean (typically an atmospheric river), or a combination thereof;
- **(iii) Tropical/monsoon events** whose deep moisture contributions are associated with a named East Pacific tropical cyclone (TC) within 1200 km of Phoenix. Although they are more likely to be a "Predecessor Rain Event (PRE; see Galarneau et al. 2010 and Coribosero et al. 2009) associated with moisture advecting northeast of the TC into Phoenix, they may also be the direct TC remnants advecting over Phoenix;
- **(iv) Tropical/transition events** whose deep moisture contributions are associated with a named East Pacific TC within 1200 km of Phoenix that recurves due to a strong westerly trough as defined in (ii). Although they are more likely to be associated with the direct TC remnants advecting over Phoenix, they may also be associated with a "PRE"; and

- **(v) Undecided events** that initially did not clearly satisfy any category *(Note: Subsequent classifications during summer 2020 in preparation for the NWA Annual Meeting classified all these events definitively, but after A. Hjelmstad's thesis was published).*

Metrics used to compare radar QPEs with gage observations

In order to more directly compare radar products, the MRMS data were first re-gridded to the same 4 km x 4 km grid of Stage IV. We then used a set of metrics to compare radar QPEs with gage rainfall observations. These depend on the following variables:

$G_{ij} \equiv$ rainfall accumulated over storm *j* at gauge *i*.

$R_{ij} \equiv$ rainfall accumulated over storm *j* at the radar pixel containing gage *i*.

$g_{ijt}^{\Delta t}$: rainfall accumulated over duration Δt at time step *t* $\left(t \in 1, \ldots T\right)$ at gage *i* during storm *j* of duration $T \times \Delta t$. Note that $G_{ij} = \sum_{t=1}^{T} g_{ijt}^{\Delta t}$.

$r_{ijt}^{\Delta t}$: rainfall accumulated over duration Δt at time step *t* $\left(t \in 1, \ldots T\right)$ at the radar pixel containing gage *i* during storm *j* of duration $T \times \Delta t$. Note that $R_{ij} = \sum_{t=1}^{T} r_{ijt}^{\Delta t}$.

The spatial averages of precipitation over the *j*-th storm in a given cluster are computed as:

$$\begin{aligned} \bar{G}_j &= \frac{1}{I}\sum_{i=1}^{I} G_{ij} & \quad \bar{g}_{jt}^{\Delta t} &= \frac{1}{I}\sum_{i=1}^{I} g_{ijt}^{\Delta t} \\ \bar{R}_j &= \frac{1}{I}\sum_{i=1}^{I} R_{ij} & \quad \bar{r}_{jt}^{\Delta t} &= \frac{1}{I}\sum_{i=1}^{I} r_{ijt}^{\Delta t} \end{aligned}, \tag{1}$$

where *I* is the number of rain gages located in the considered cluster. The metrics used to compare radar and gage precipitation estimates include Bias, percent bias (% Bias), Pearson temporal correlation (i.e., correlation between the spatially-averaged time series), and Pearson spatial correlation (i.e., correlation between the total rainfall estimates at the gages):

$$\text{Bias} = \bar{R}_j - \bar{G}_j \tag{2}$$

$$\%\ \text{Bias} = \frac{\bar{R}_j - \bar{G}_j}{\bar{G}_j} \times 100\% \tag{3}$$

$$\text{Temporal correlation} = \frac{\operatorname{cov}\left(\bar{g}_j^{\Delta t}, \bar{r}_j^{\Delta t}\right)}{s_{\bar{g}_j^{\Delta t}} s_{\bar{r}_j^{\Delta t}}} \tag{4}$$

$$\text{Spatial correlation} = \frac{\operatorname{cov}\left(G_j, R_j\right)}{s_{G_j} s_{R_j}}. \tag{5}$$

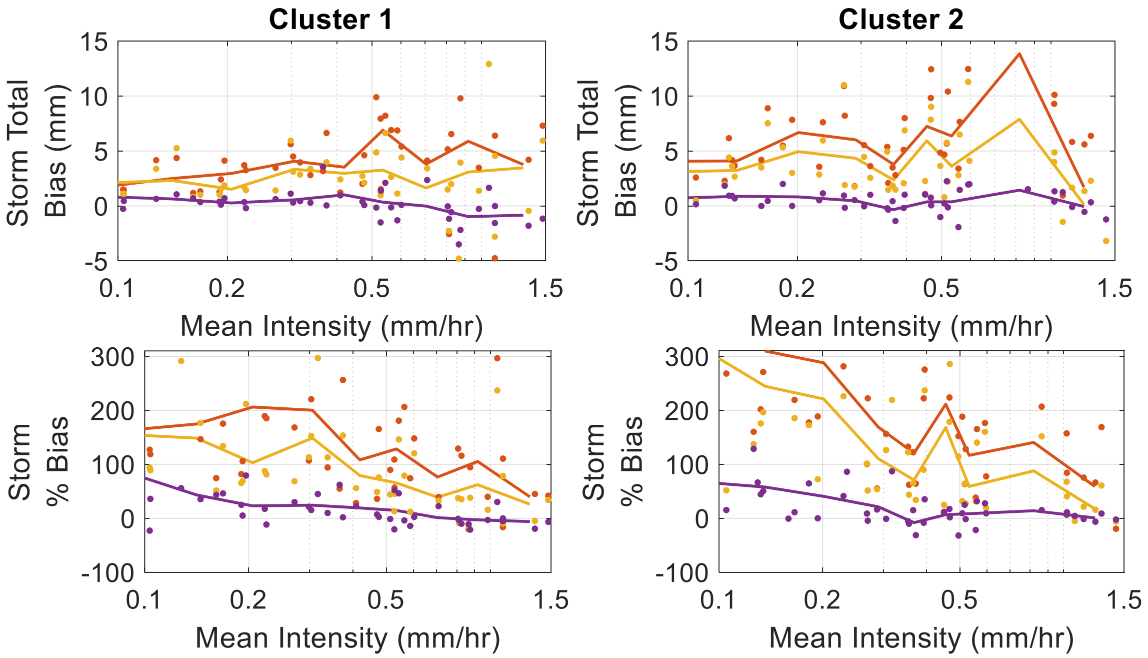
In equation (4), $\bar{g}_j^{\Delta t} = \left\{ \bar{g}_{jt}^{\Delta t} \mid t \in 1,\ldots,T \right\}$, $\bar{r}_j^{\Delta t} = \left\{ \bar{r}_{jt}^{\Delta t} \mid t \in 1,\ldots,T \right\}$, while in equation (5), $G_j = \left\{ G_{ij} \mid i \in 1,\ldots,N \right\}$, $R_j = \left\{ R_{ij} \mid i \in 1,\ldots,N \right\}$.

Results of comparison between radar products and gage observations

We begin by showing in Figure 2 the relations between all metrics and mean storm intensity for all storms, independently of the storm origin. The main results can be summarized as follows:

(1) Bias is close to zero for Stage IV, while it is positive (i.e., the radar overestimate gage observations) and increases with storm intensity for MRMS and GCMRMS. In contrast, Percent Bias decreases as the storm intensity increases. The gage-corrected GCMRMS have lower bias than MRMS.
(2) The spatial correlation is larger than 0.5 and increases with mean intensity. This is likely a consequence of the fact that storms with higher mean intensity have larger spatial coverage, which is well captured by radar QPEs. No significant difference emerges between the radar products.
(3) The temporal correlation is always high (>0.8 for almost all storms), independently of the mean intensity. As for the spatial correlation, no significant difference emerges between the radar products.

(4) No significant difference appears between results at the two clusters.



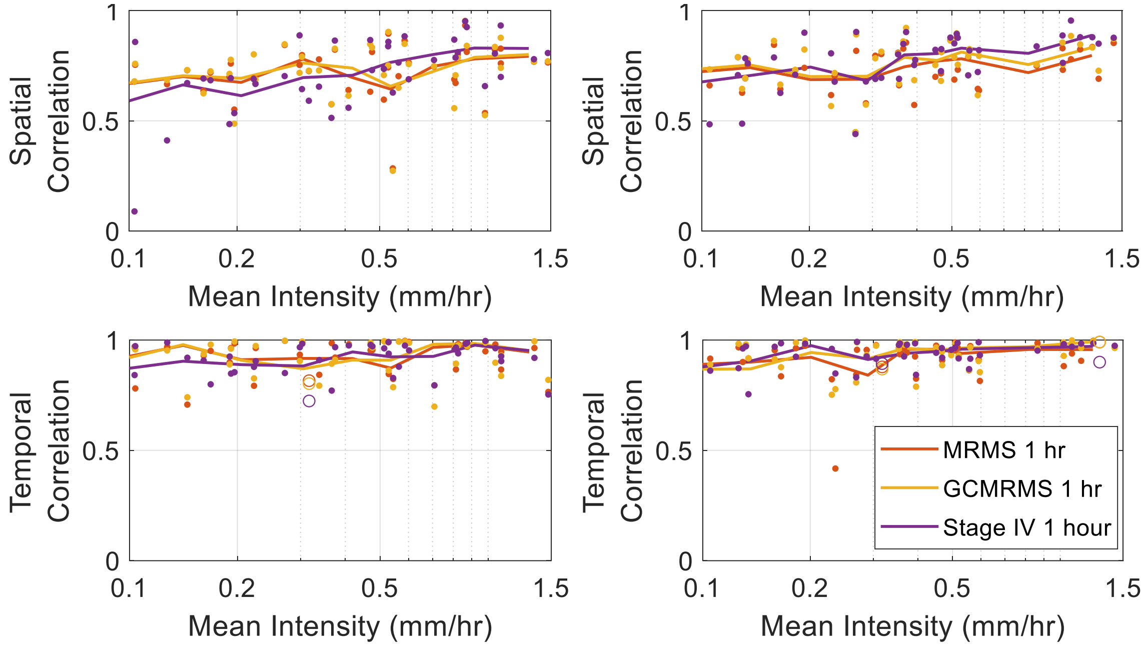


Figure 2. Relation between metrics and mean intensity for the three radar products in clusters 1 and 2. The lines represent moving averages to smooth the inter-storm variability. For the temporal correlation, storms with duration ≤ 5 h are marked with an open circle.

As a next step, we evaluated the metrics based on storm types. Figure 3 and Figure 4 show the relations between Bias and Percent Bias and mean rain intensity. The Stage IV control exhibited similar performances across storm types, with a tendency to slightly underestimate gage rainfall during the monsoon in cluster 1. MRMS and GCMRMS have positive Bias (and Percent Bias) for all storm types except for the tropical storms. In this case, the Bias is positive for low mean rain intensity and becomes negative for intensities larger than about 0.5 mm/h, with the most negative Bias occurring with three predominantly stratiform tropical transition cases associated with the direct remnants of East Pacific TCs Rosa and Sergio in October 2018 and TC Lorena in September 2019. Additional discussion of these MRMS QPE biases and how they are now applied to NWS flash flood warning operations is provided in Section 3.

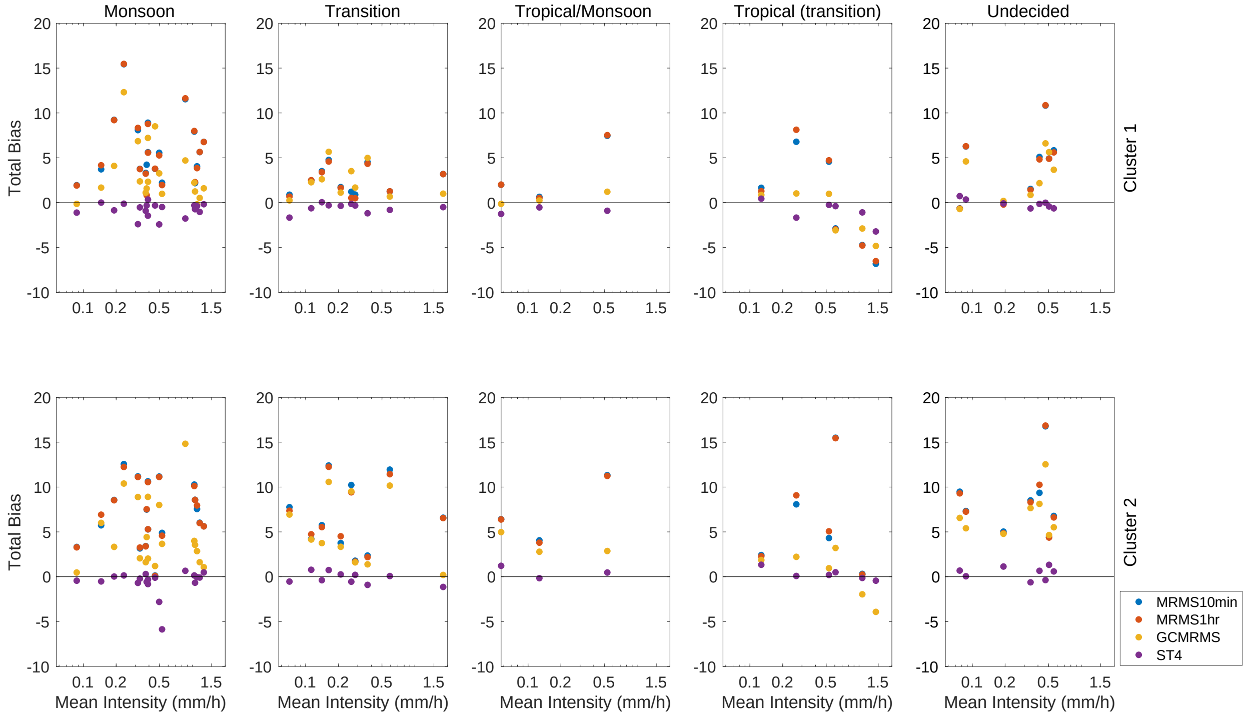


Figure 3. Relation between Bias and mean intensity for the three radar products in clusters 1 and 2 for the different storm types.

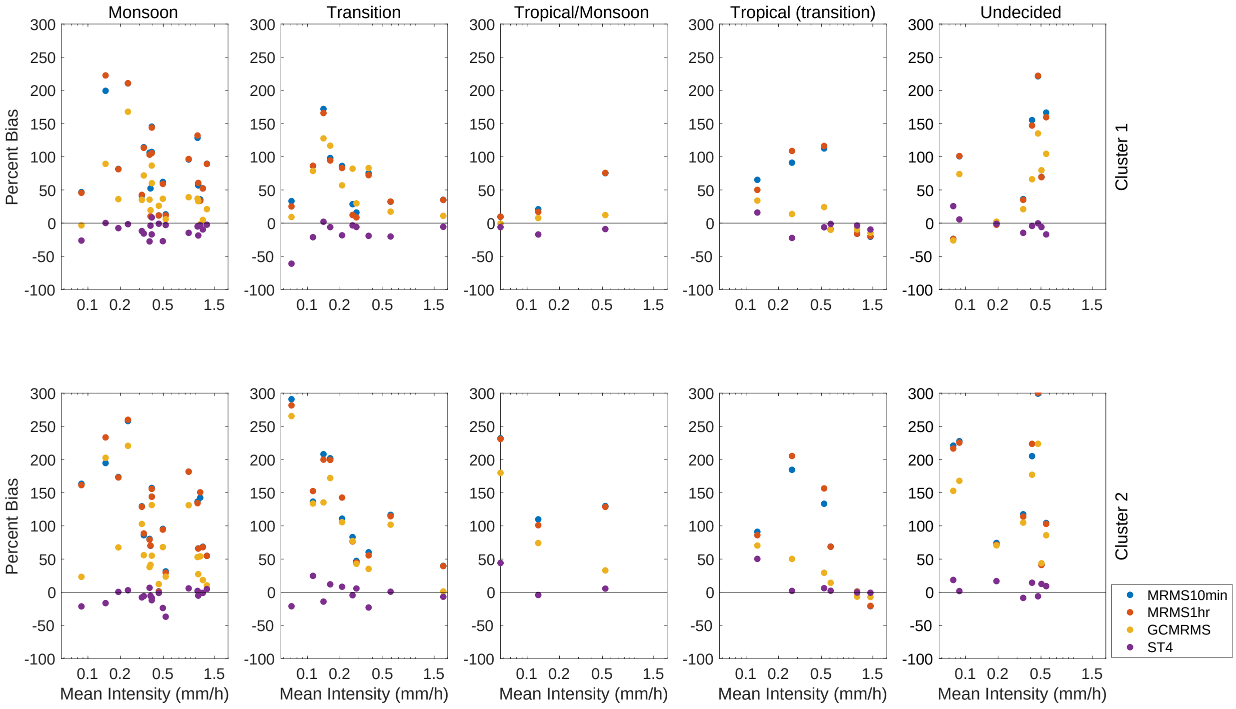


Figure 4. As in Fig. 3 but for Percent Bias.

Computation of storm impacts and associated ARIs

For each date of the storm events, we used the NOAA Storm Events Database to identify the occurrence of flooding impacts (e.g., “water rescues”, “standing water”, “house flooding”, etc.). In some cases, the reported latitude and longitude coordinates were found not to be consistent with the location of observed rainfall and were then corrected. Once the coordinates of the sites impacted by flooding were identified, we computed the average recurrence interval (ARI) of the maximum rainfall measured by gages and radars at durations of 1, 2, 3, and 6 hours. This was done by (i) searching for gages and radar pixel located within a radius of 10 km from the location of the impacts, (ii) extracting the maximum precipitation for the considered duration over all pixels and times, and (iii) interpolating the ARI from the NOAA Atlas 14 maps available for the region. Figure 5 shows results of these analyses for the duration of 1 hour. ARIs associated with Stage IV QPEs are mainly in the order of 1 to 5 years, which are slightly smaller than those computed from the gages. However, for this ground network, ARIs reach also values larger than 100 years in Downtown Phoenix and southeastern regions. In contrast, as expected, ARIs of MRMS are larger, with values between 1 and 100 years for several events. All products indicate that events with larger ARIs tend to cluster in southeastern regions of the PMA.

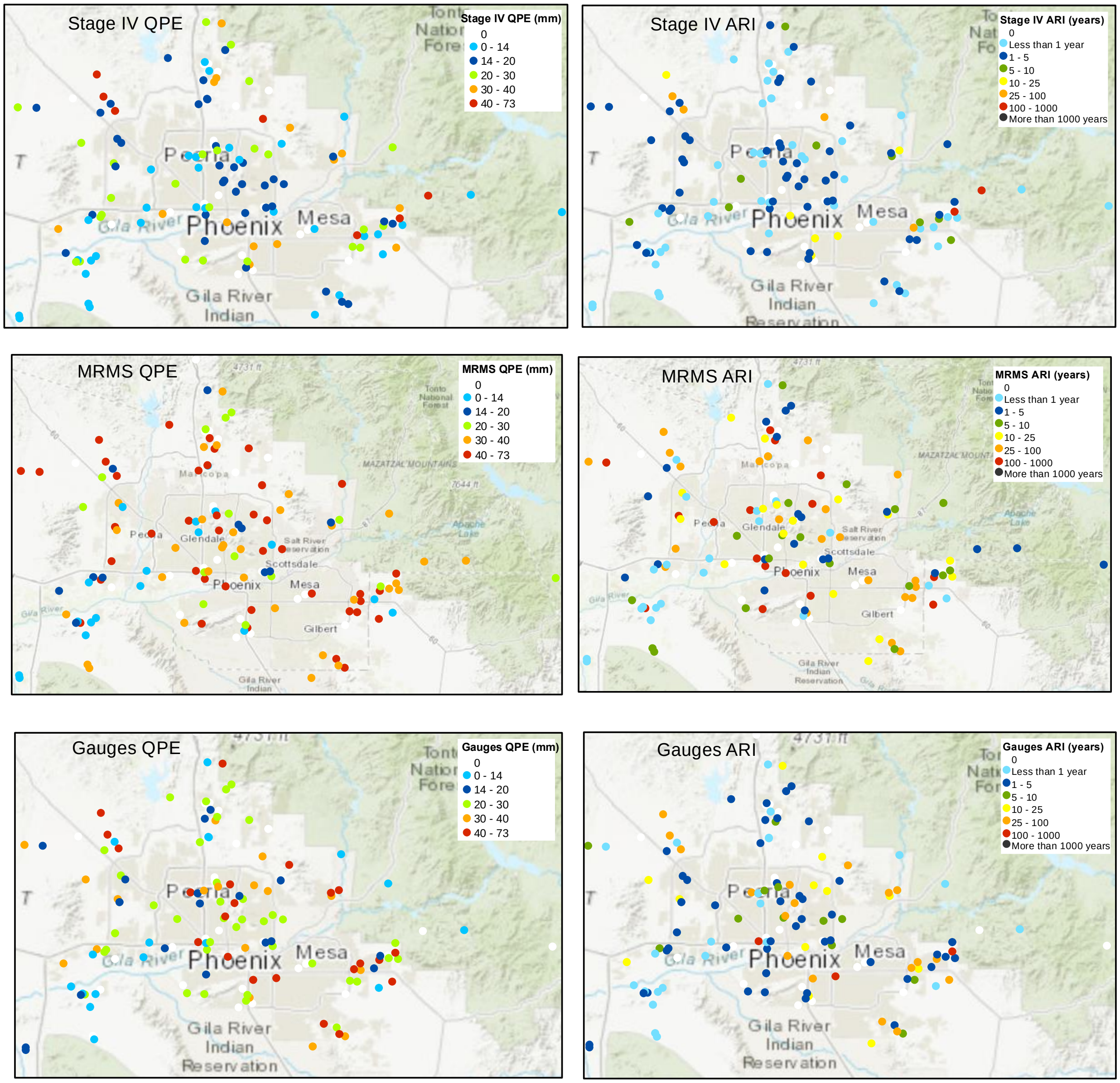


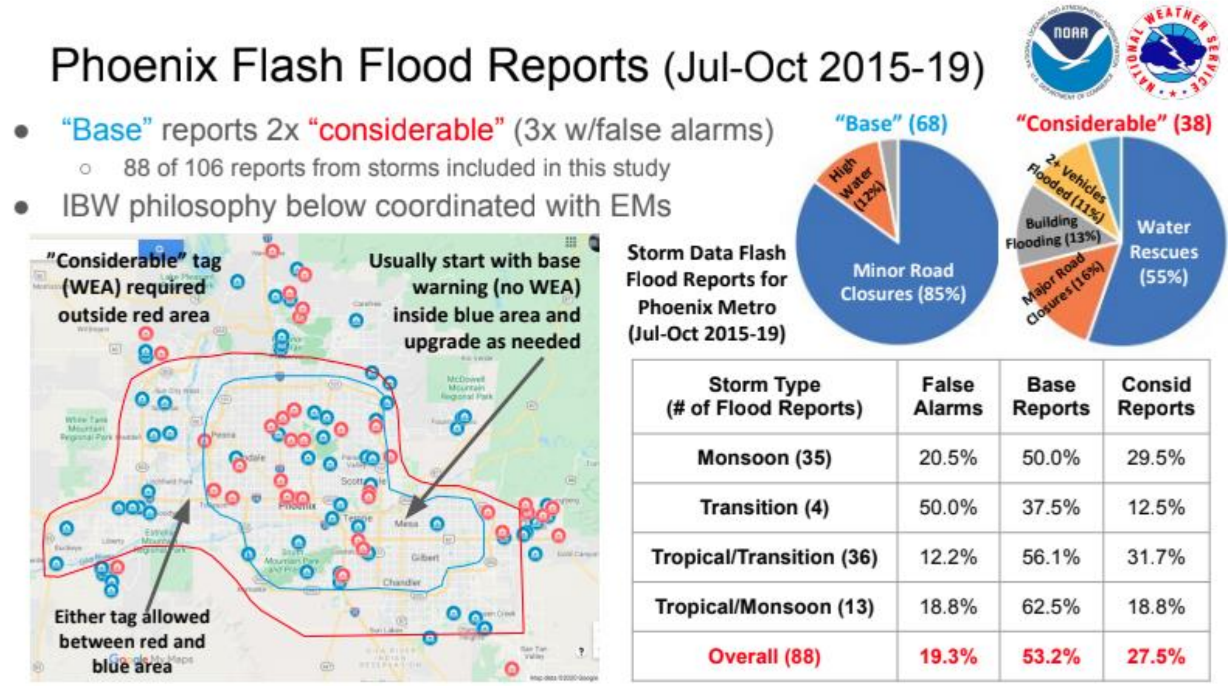
Figure 5. Maximum precipitation at 1-hour duration and associated ARI from NOAA Atlas 14 for the selected storm events for Stage IV QPEs (top), MRMS QPEs (middle) and gages (bottom).

Section 3: Benefits and Lessons Learned: Operational Partner Perspective

Findings from this project have increased awareness of QPE biases in the Desert Southwest for forecasters at WFO Phoenix in a variety of warm season environments. Although MRMS radar-only QPE typically overestimates rainfall by factor of two (+50 to 150% IQR; +25 to 100% for flood events) for monsoon and transition events, it was much less biased in tropical events (+15 to 100% IQR; -10 to +70% for flood events) associated with named tropical cyclones within 1200 km of Phoenix. Therefore, having an awareness of the thermodynamic environment and general mesoscale and synoptic pattern may help forecasters reduce the number of false alarms in drier monsoonal environments where sub-cloud layer evaporative processes may lead to a wet bias in radar-only MRMS QPE. In addition, forecasters may also have more confidence in higher QPE values during tropical events occurring in more moist environments.

This study has also stressed the importance of cross-checking MRMS QPE with gauges, particularly monsoonal events where GCMRMS QPEs typically cannot be used to make Flash Flood Warning (FFW) decisions due to the rapid (<1 hr) flood response from causative rainfall and data latency issues associated with MRMS. However, it also identified that gauge correction reduced biases most in the longer duration tropical cases, particularly widespread tropical stratiform cases where data latency issues are less of a concern and MRMS QPE actually may exhibit a negative bias in agreement with studies evaluating stratiform rain east of the Rocky Mountains. This philosophy combined with knowledge of QPE biases has also transferred to FFW performance associated with 13 burn scars currently over the higher terrain north and east of Phoenix. Examples of this include the 23 September 2019 Woodbury Fire debris flows associated with the remnants of East Pacific TC Lorena and recent July 2021 burn scar flash flooding associated with a moisture surge associated with East Pacific TC Enrique.

Finally, knowledge gained from this study has proven most beneficial in establishing warning guidance for impact-based Flash Flood Warnings (IBW FFWs) in the Phoenix metro to reduce the use of “considerable” FFW tags that activate Wireless Emergency Alerts (WEAs). Figure 6 shows research presented at the 2020 NWA Annual Meeting indicating that default “base” flash flood reports (e.g., minor road closures, high water) whose FFWs ideally would not trigger WEAs outnumber “considerable’ flash flood reports (e.g., water rescues, major road closures) by a ratio of 2:1 (3:1 if “false alarm” FFWs are considered). Therefore, implementing IBWs in a way that defaults to issuing “base” FFWs and upgrading to “considerable” FFWs based on impacts, QPE sources, gauge reports, or a combination thereof may reduce WEA usage during flash flood events by a factor of 2-3 in the Phoenix metro. Preliminary research shown in Figure 7 indicates that observed average recurrence intervals (ARIs) of 10-25 yrs (basin averages of 1.3-1.6 in/hr according to NOAA Atlas 14) may be a good indicator of when forecasters should consider issuing a “considerable” FFW in the Phoenix metro. Future research correcting the location of local storm reports that will more directly tie their occurrence to MRMS QPEs and associated ARIs after the conclusion of this grant along with having more active monsoon seasons than what we saw during 2019 and 2020 to better evaluate changes made to MRMS QPE algorithm in version 12 will hopefully improve upon this guidance.



Phoenix Flash Flood Reports (Jul-Oct 2015-19)

- "Base" reports 2x "considerable" (3x w/false alarms)
  - 88 of 106 reports from storms included in this study
- IBW philosophy below coordinated with EMs

"Considerable" tag (WEA) required outside red area

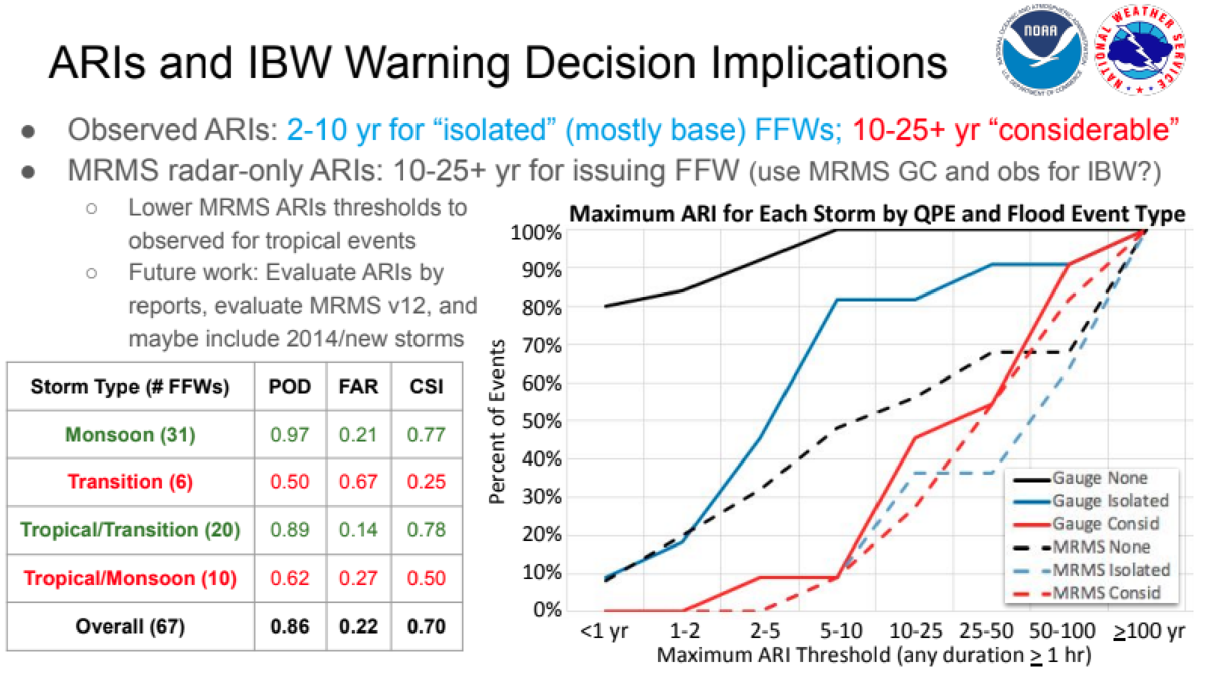
Usually start with base warning (no WEA) inside blue area and upgrade as needed

Either tag allowed between red and blue area

Storm Data Flash Flood Reports for Phoenix Metro (Jul-Oct 2015-19)

Storm Type (# of Flood Reports)	False Alarms	Base Reports	Consid Reports
Monsoon (35)	20.5%	50.0%	29.5%
Transition (4)	50.0%	37.5%	12.5%
Tropical/Transition (36)	12.2%	56.1%	31.7%
Tropical/Monsoon (13)	18.8%	62.5%	18.8%
Overall (88)	**19.3%**	**53.2%**	**27.5%**

Figure 6. Research presented at the NWA Annual Meeting in September 2020 on the implementation of impact-based Flash Flood Warnings IBW FFWs) in the Phoenix metro using local storm reports and past event analyses from 2015-2019.



ARIs and IBW Warning Decision Implications

- Observed ARIs: 2-10 yr for "isolated" (mostly base) FFWs; 10-25+ yr "considerable"
- MRMS radar-only ARIs: 10-25+ yr for issuing FFW (use MRMS GC and obs for IBW?)
  - Lower MRMS ARIs thresholds to observed for tropical events
  - Future work: Evaluate ARIs by reports, evaluate MRMS v12, and maybe include 2014/new storms

Storm Type (# FFWs)	POD	FAR	CSI
Monsoon (31)	0.97	0.21	0.77
Transition (6)	0.50	0.67	0.25
Tropical/Transition (20)	0.89	0.14	0.78
Tropical/Monsoon (10)	0.62	0.27	0.50
Overall (67)	**0.86**	**0.22**	**0.70**

Maximum ARI for Each Storm by QPE and Flood Event Type

Figure 7. Research presented at the NWA Annual Meeting in September 2020 on the observed and MRMS radar-only QPE average recurrent intervals (ARI) recommended for "considerable" FFWs in the Phoenix metro using past event verification from 2015-2019.

Section 4: Benefits and Lessons Learned: University Partner Perspective

This project provided several benefits to ASU, including:

- Dr. Hopper and Mr. Iñiguez were separately invited as speakers to the Hydrosystems program seminar series, which is a 1-credit course attended every semester by 15-20 graduate students from Civil Engineering, Earth Sciences, and Geography. The seminars presented by Dr. Hopper and Mr. Iñiguez exposed the students to (i) operational forecasting tools and products used at NWS Phoenix Office; and (ii) advancements in hydrometeorological forecasting.

- The collaboration with the NWS Phoenix Office significantly contributed to the training of a M.S. students, Ms. Annika Hjelmstad.

- The collaboration with the NWS Phoenix Office advanced knowledge of limits and utility of radar rainfall in the Phoenix Metropolitan Area. We expect that our findings will lead to improvements of MRMS QPEs in the NAM region, and stimulate the development of urban hydrologic models.

- No major problem has been identified.

Section 5: Publications and Presentations

This project led to the following publications and presentations:

1. Hjelmstad, A., A. Shrestha, M. E. Garcia, L. J. Hopper, Jr., P. Iñiguez, and G. Mascaro. Propagation of radar rainfall uncertainty into urban flood predictions during the North American monsoon. 101st AMS Annual Meeting, January 2021 (virtual).

2. Hjelmstad, A., A. Shreshta, M. Garcia, and G. Mascaro, 2021. Propagation of radar rainfall uncertainties into urban pluvial flood modeling during the North American monsoon. Under review in *Hydrological Sciences Journal*.

3. Hjelmstad, A., 2020. *Propagation of Radar Rainfall Uncertainties into Urban Flood Predictions: An Application in Phoenix, AZ*, MS Thesis, Arizona State University, 127 pp

4. Hopper, L. J., Jr., A. Hjelmstad, P. Iñiguez, and G. Mascaro, Leveraging flash flood reports and QPE skill to implement impact-based warnings in the Phoenix metro. 45th NWA Annual Meeting, September 2020 (virtual).

5. Hopper, L. J., Jr., 2020. Insights into hydrometeorological factors constraining flood prediction skill during the May and October 2015 Texas Hill Country Flood Events. Hydrosystems Seminar Series, ASU, April 2020 (virtual).

6. Iñiguez, P., 2019. Drinking From the Fire Hose: The Continual Explosion of Data in the Meteorology Field and Its Application to Our Daily Lives. Hydrosystems Seminar Series, ASU, October 2019 (in-person).

Section 6: Summary of University/Operational Partner Interactions and Roles

The interactions between ASU and the Phoenix NWS Office occurred as follows:

- Dr. Mascaro gave a presentation of his research on precipitation in the Phoenix Metropolitan Region at the Phoenix NWS Office.

- Dr. Hopper and Mr. Iñiguez gave one seminar each at the Hydrosystems Seminar Series at ASU.

- Dr. Mascaro, Ms. Hjelmstad (MS student), Dr. Hopper and Mr. Iñiguez met periodically (on average every three weeks) to discuss research progress for 1–1.5 hours. This occurred first in person at ASU or the Phoenix NWS Office, and remotely during the pandemic.

- Dr. Mascaro, Ms. Hjelmstad (MS student), Dr. Hopper and Mr. Iñiguez interacted via email as needed to exchange data and ideas on research.

- WFO Phoenix had planned to invite Dr. Mascaro and Ms. Hjemstad to directly observe flash flood warning operations in person, but relatively inactive monsoon seasons in 2019 and 2020 along with the COVID-19 pandemic beginning early in 2020 prevented them from doing so.