Towards a gridded best estimate of accumulated precipitation from quantitative precipitation estimates (QPE) and forecasts (QPF) in mountainous regions:

A simplified Kalman Filter approach

Eric James and Russ Schumacher
Colorado State University
15 July 2020

OUTLINE

Motivation
Objectives
The simplified Kalman Filter: what is it?
The simplified Kalman Filter: construction of **B** and **R**
Eastern US cases
Western US cases
Comments on future directions and how to evaluate these products.

MOTIVATION

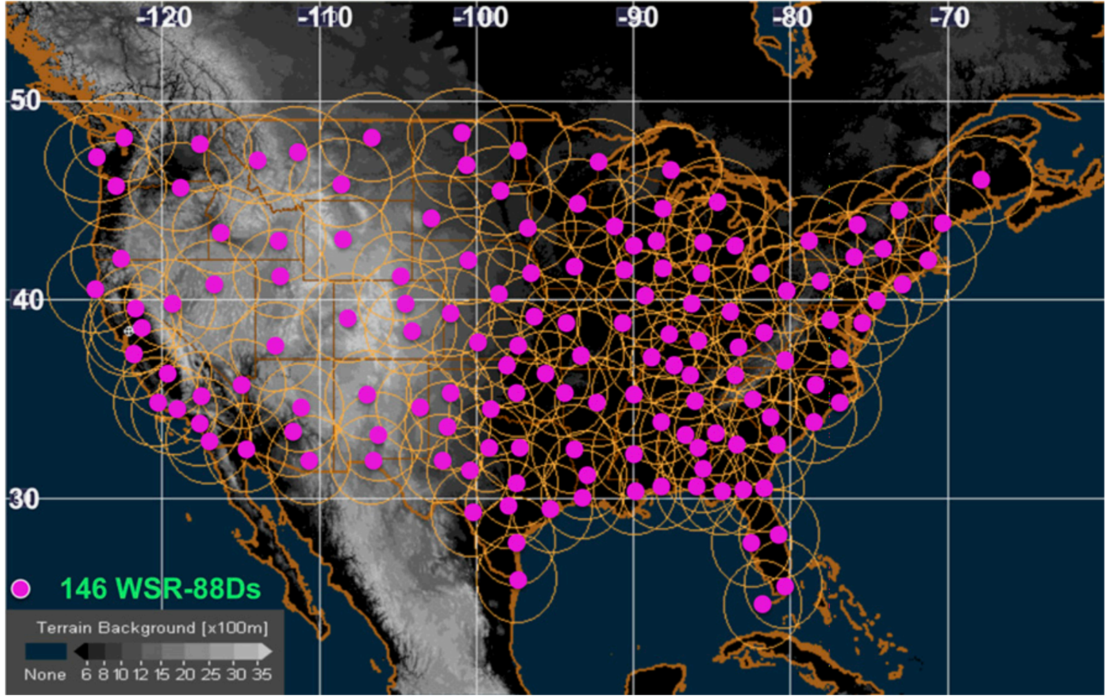
Estimates of precipitation (quantitative precipitation estimates or QPE) are important for a broad range of applications including:

- Flood monitoring and forecasting
- Inputs to hydrologic models
- Seasonal precipitation estimates for water resource quantification
- Agriculture
- Fire risk outlooks

And yet QPE is often poorly known, especially in remote complex terrain regions.

Aftermath of Spring Creek flash flood
28 July 1997

OBJECTIVES



We want to take account of strengths and weaknesses of the many different QPE/QPF datasets to

(1) quantify QPE uncertainty and
(2) get a best estimate deterministic QPE.

Multi-Radar Multi-Sensor (MRMS) Products:

- Radar-only QPE
- Gauge-only QPE
- Gauge-corrected QPE
- Mountain Mapper based QPE (based on PRISM)

Stage IV: Generated by RFCs as the final “analysis of record” for the National Weather Service; generating methodologies vary by RFC. CCPA is a bias-corrected Stage IV.

Others: satellite-based QPE, reanalyses, etc.

CAM guidance: may be our ***ONLY*** source of quantitative precipitation information in remote, observation-sparse regions.

THE SIMPLIFIED KALMAN FILTER

The community still generally uses deterministic QPE datasets as “truth”. However, the uncertainty associated with the various QPE/QPF products argues for an explicit treatment of uncertainty in a final, merged QPE dataset. A data assimilation framework is well-suited to this problem. In this work, we examine how a simplified Kalman Filter could be applied for this purpose.

$$x_a = x_f + (\boldsymbol{B}^{-1} + \boldsymbol{H}^T\boldsymbol{R}^{-1}\boldsymbol{H})^{-1}\boldsymbol{H}^T\boldsymbol{R}^{-1}(y - \boldsymbol{H}x_f), \qquad \boldsymbol{P}^{-1} = \boldsymbol{B}^{-1} + \boldsymbol{H}^T\boldsymbol{R}^{-1}\boldsymbol{H}$$

For this problem, x_f can be considered the CAM QPF at any given time. So it is a vector of length N (where N = number of model gridpoints). y is the vector of QPE datasets (interpolated to CAM QPF scale for simplicity), of length jN (where j is the number of QPE datasets considered).

B will be an N x N matrix which contains information on QPF errors, as well as spatial correlations in QPF. **R** will be a jN x jN matrix which contains information on QPE errors, as well as spatial correlations in QPE.

B and **R** determine how information is combined from the different sources.

THE SIMPLIFIED KALMAN FILTER

For this talk, I am only showing simple, illustrative examples:

QPF is HRRR 6h QPF (3km grid spacing).
QPE is MRMS 6h radar-only QPE (interpolated to HRRR scale).
R is based on the MRMS radar quality index (RQI), and is a diagonal matrix (i.e., MRMS radar-only QPE should not have any precipitation location errors)
B is a static value with an inverse distance weighting to take account of HRRR QPF location errors.
H is the identity matrix.
The actual calculation is carried out for small subdomains at a time (localization).

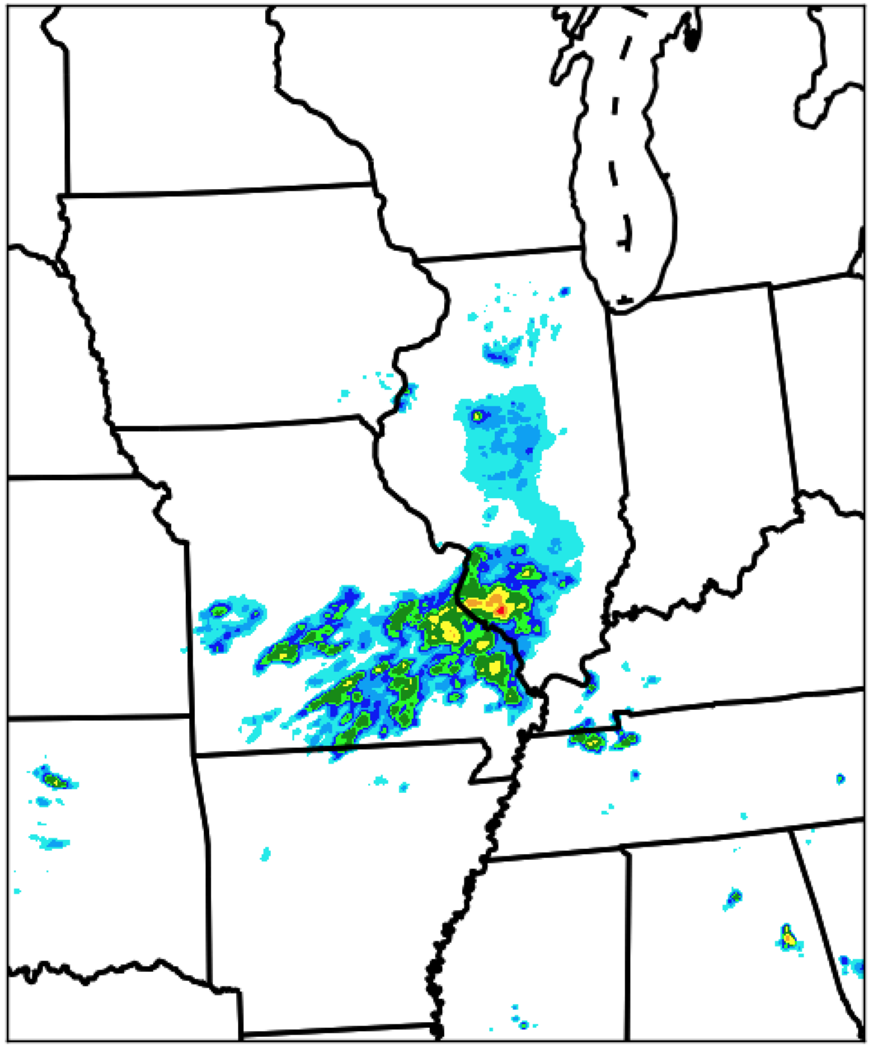
CASES:

Two non-complex terrain cases:
- Midwest Heavy Rain (15 July 2018)
- TS Imelda (19 Sep 2019)

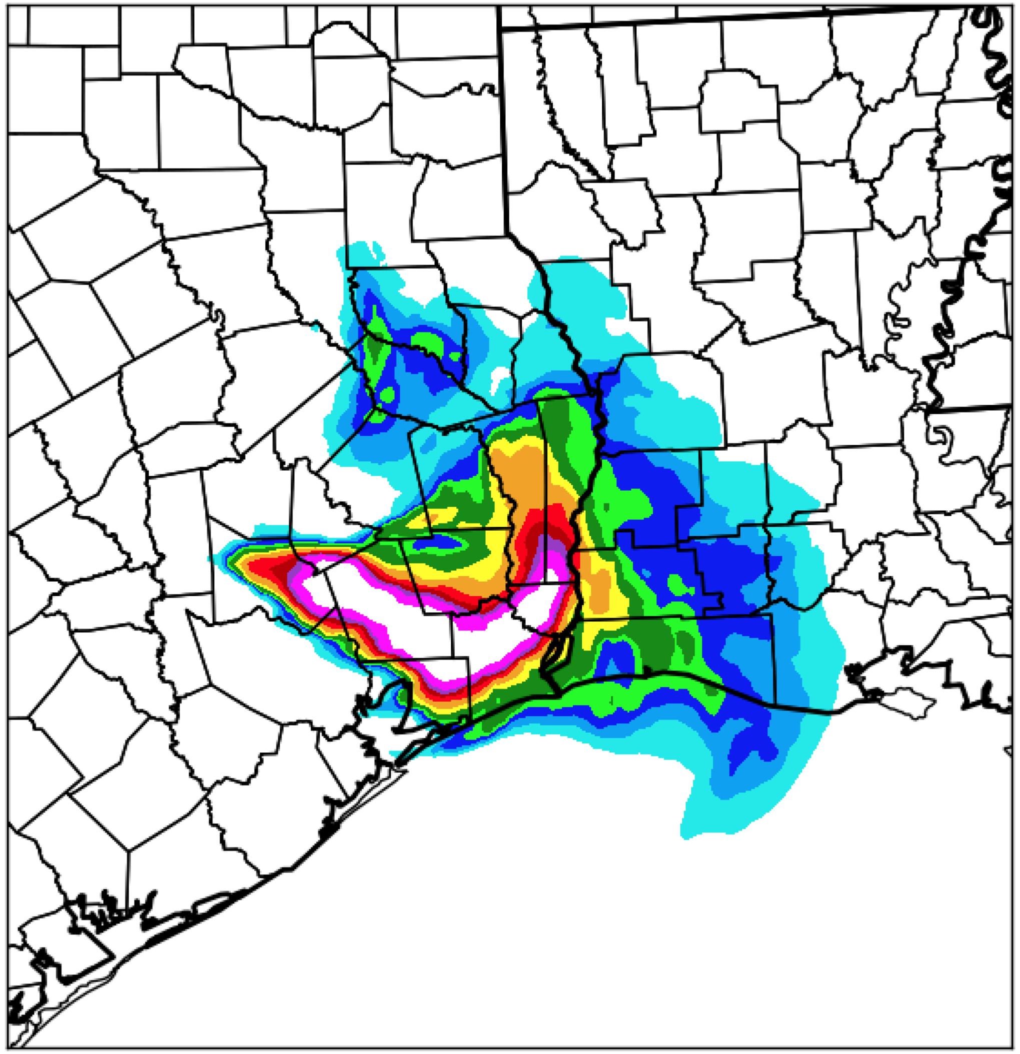
Two complex terrain cases:
- Globe, AZ, flash flood (23 July 2019)
- Southern CA cutoff low (6 April 2020)

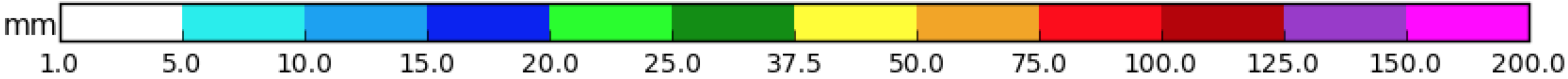
Relatively smooth terrain cases: Stage IV QPE

00-06 UTC 15 July 2018



06-12 UTC 19 Sep 2019

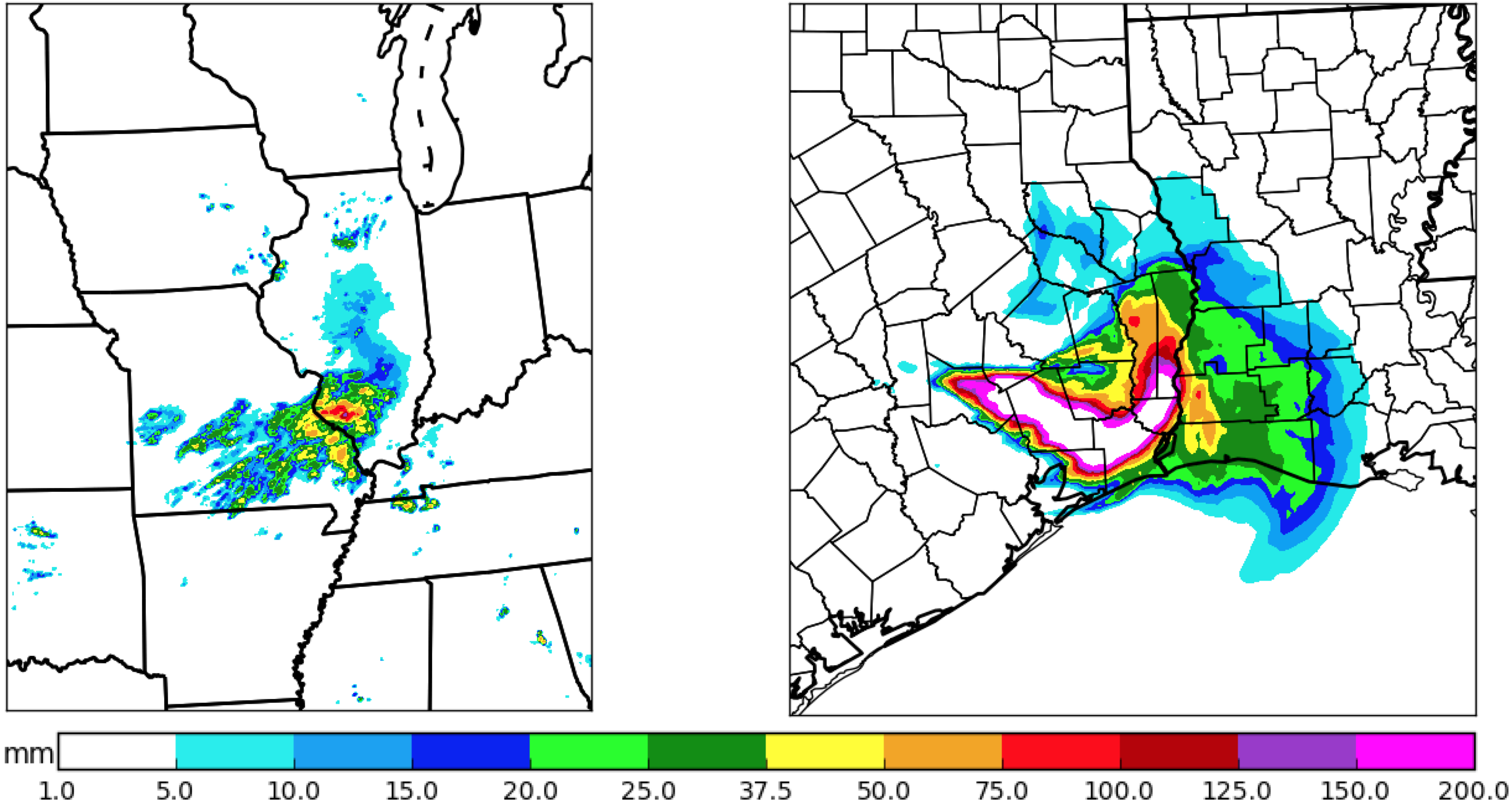




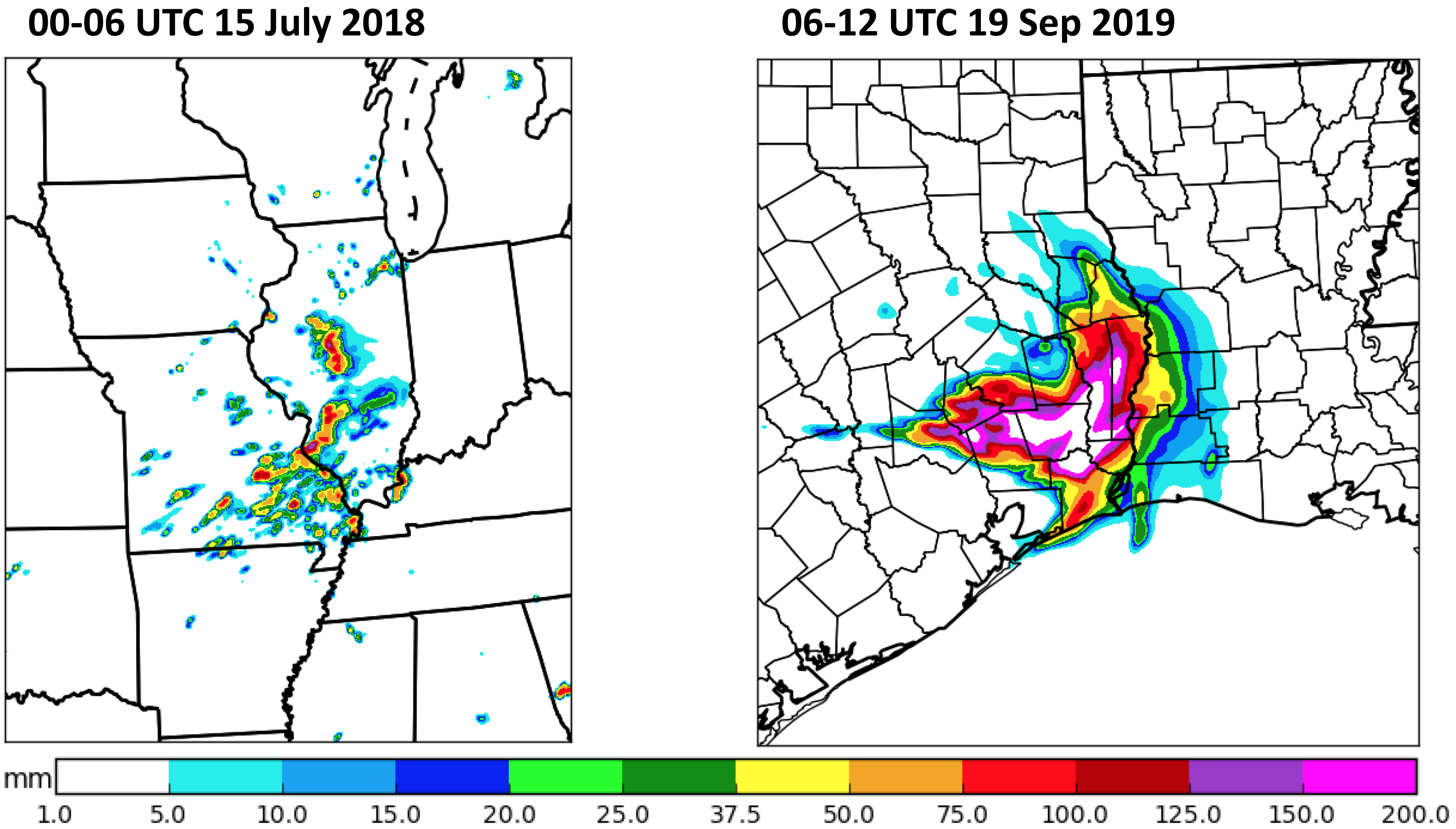
Relatively smooth terrain cases: MRMS radar-only QPE

00-06 UTC 15 July 2018

06-12 UTC 19 Sep 2019

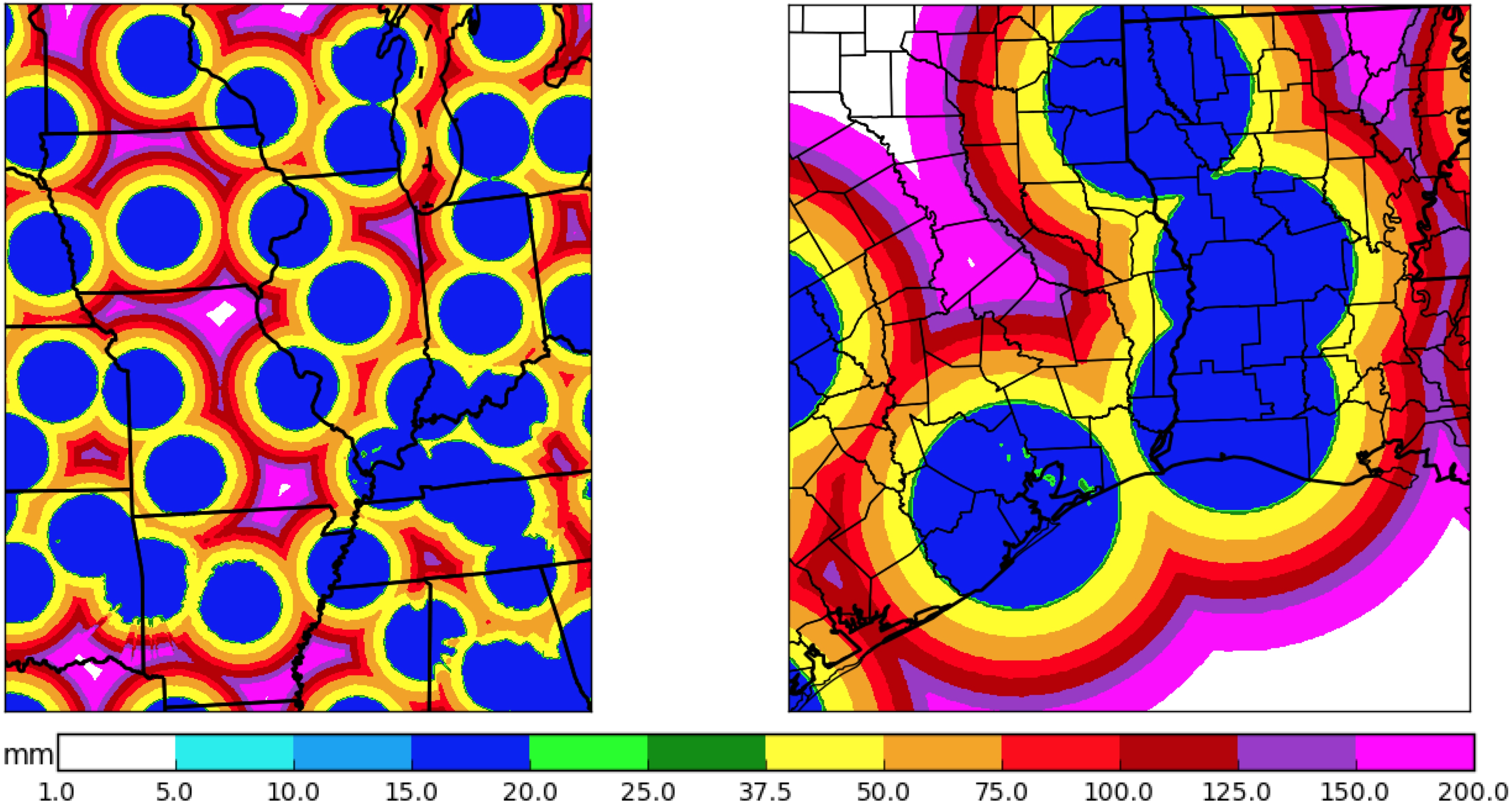


Relatively smooth terrain cases: HRRR 6h QPF



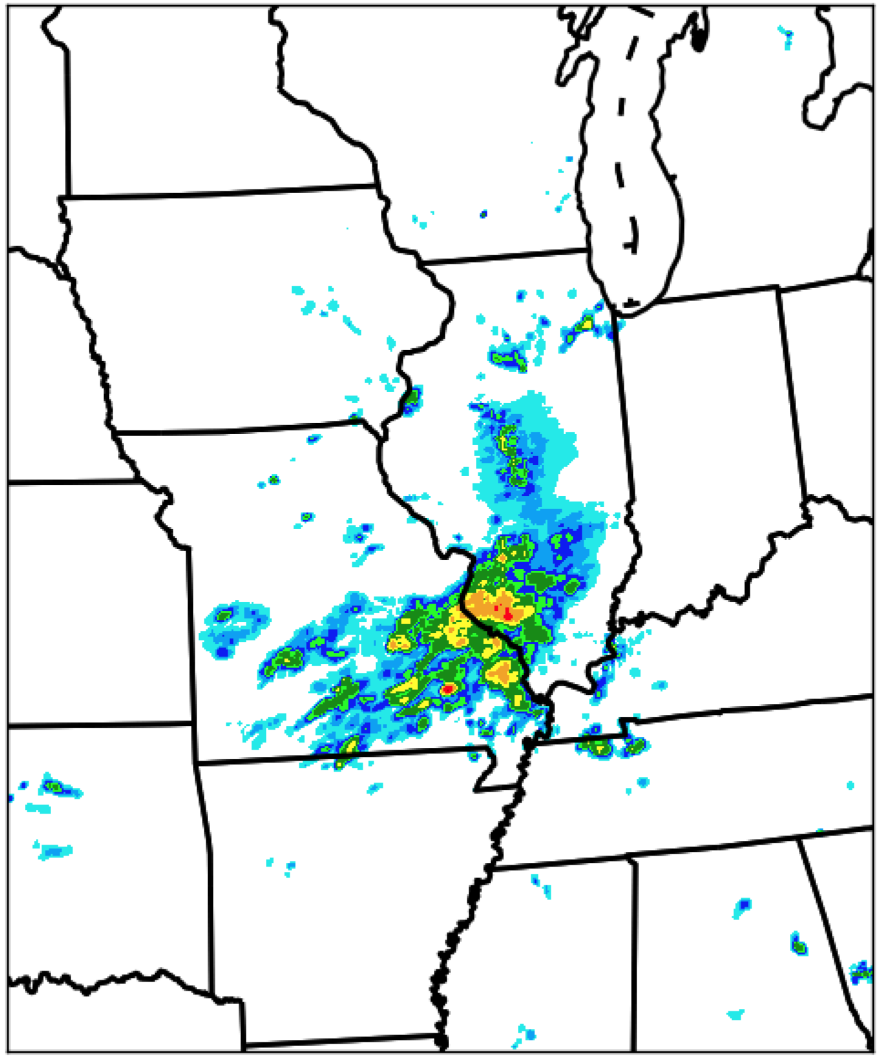
Relatively smooth terrain cases: MRMS RADAR QUALITY INDEX

00-06 UTC 15 July 2018 | **06-12 UTC 19 Sep 2019**

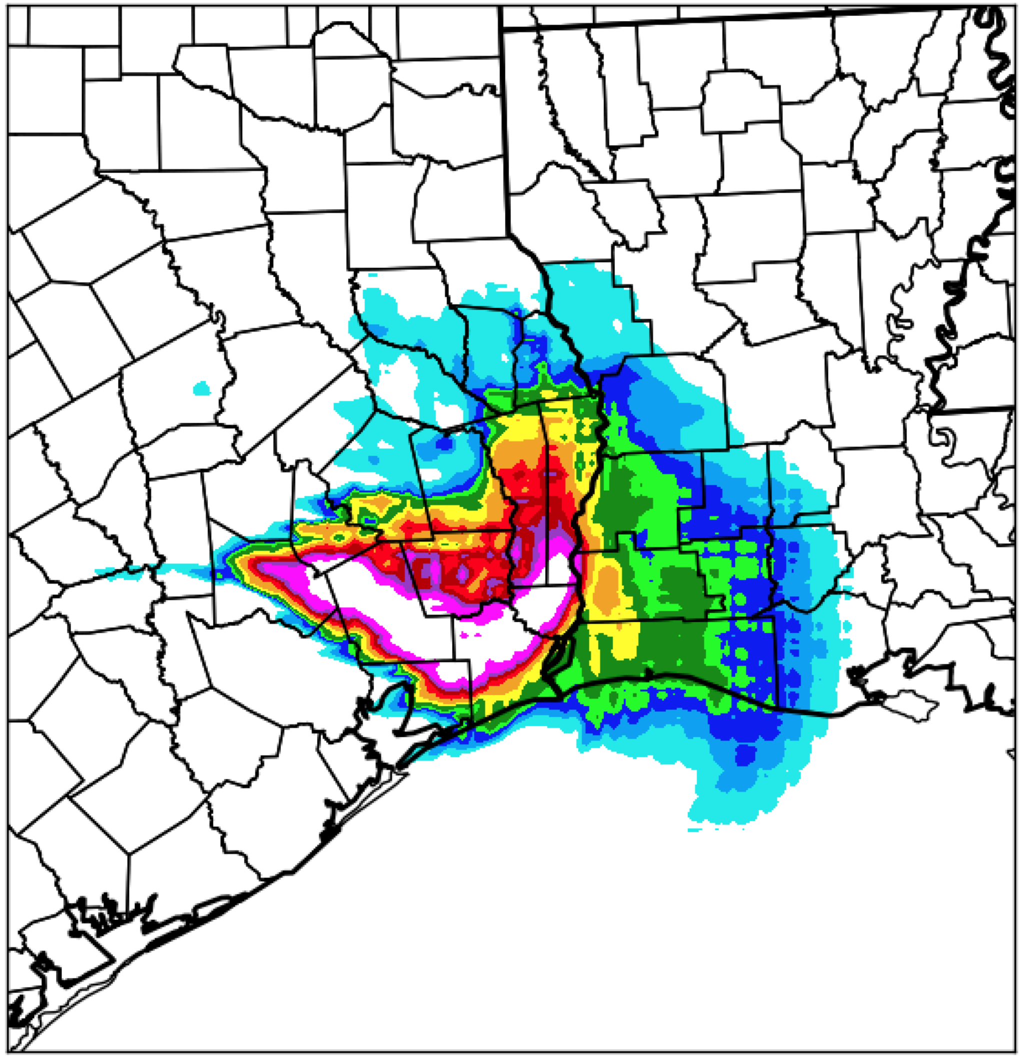


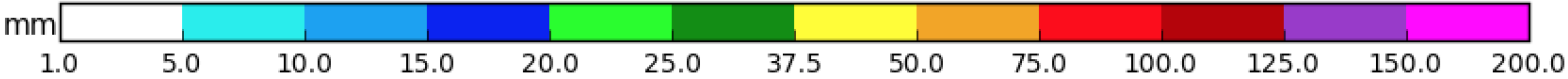
Relatively smooth terrain cases: B: 12.5mm R: 17.5 – 75mm

00-06 UTC 15 July 2018

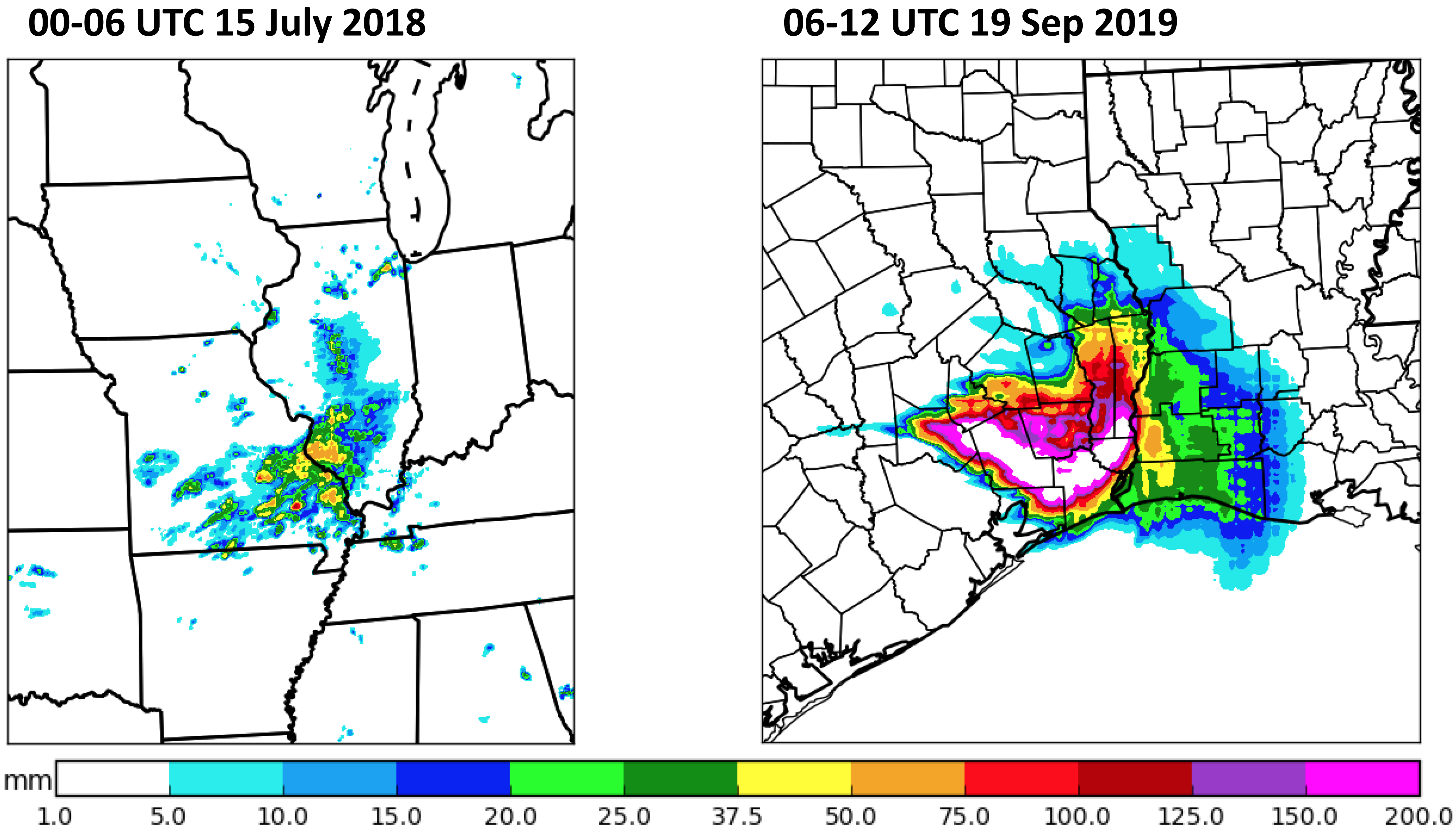


06-12 UTC 19 Sep 2019

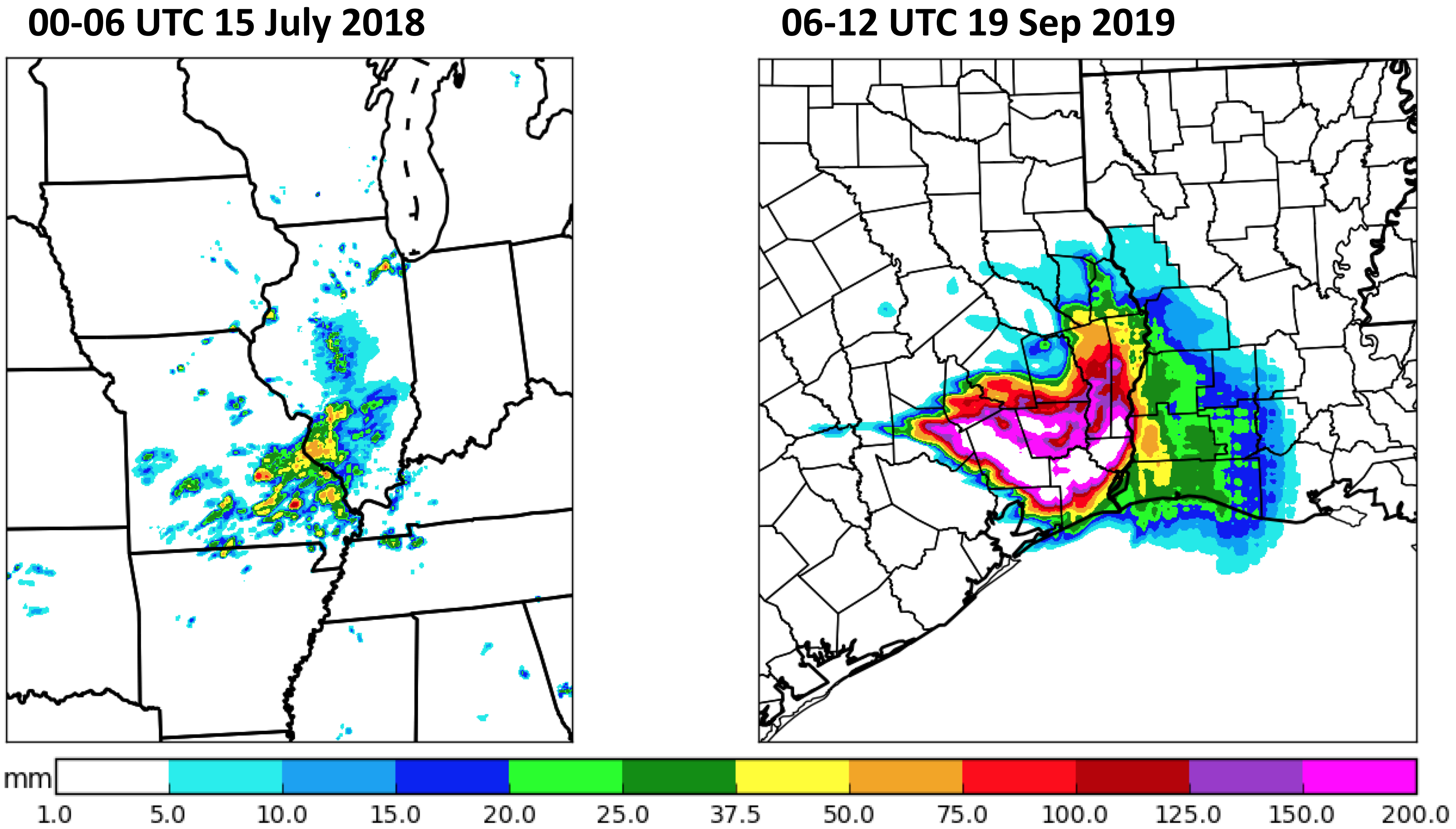




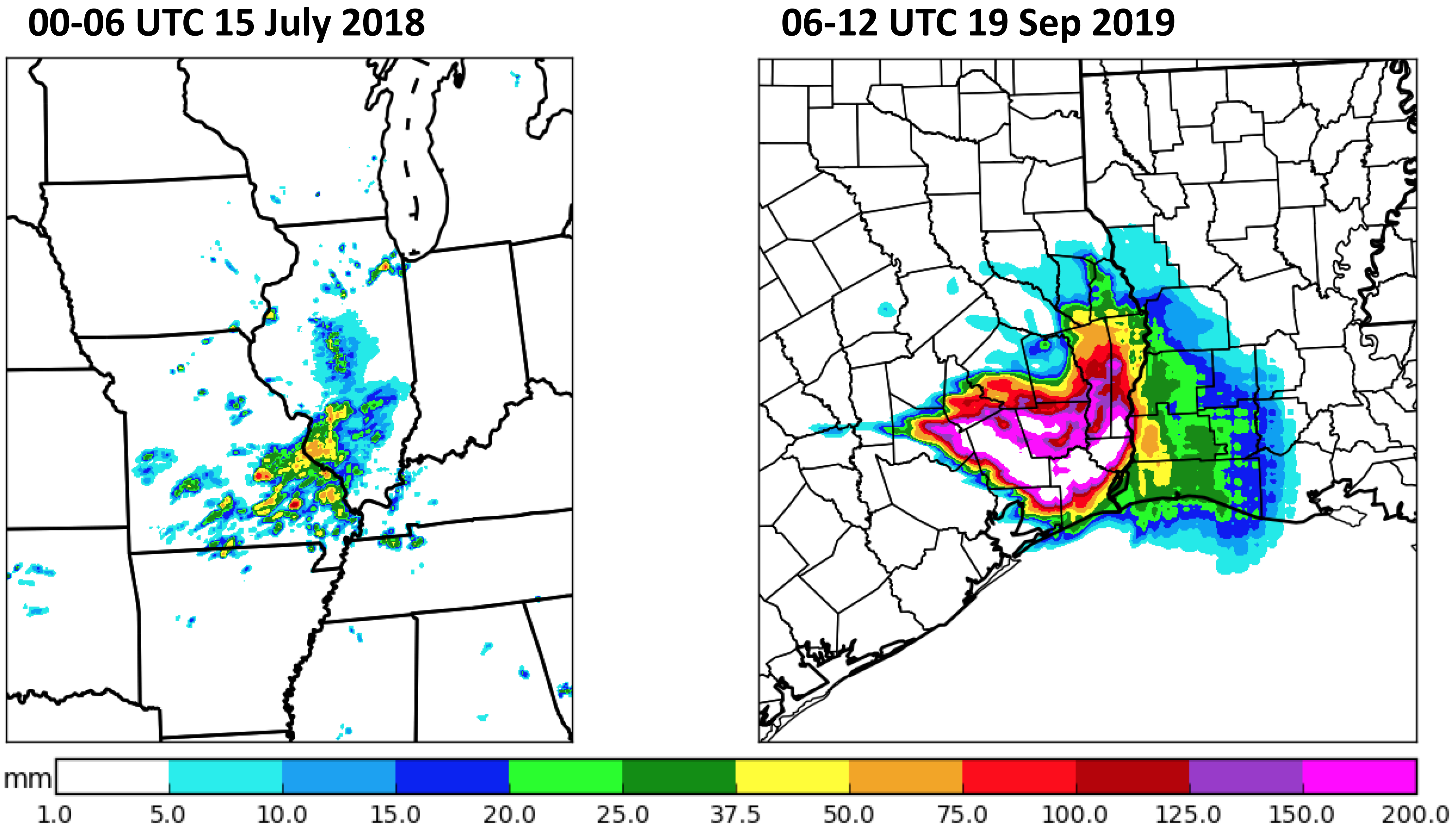
Relatively smooth terrain cases: B: 12.5mm R: 17.5 – 137.5mm



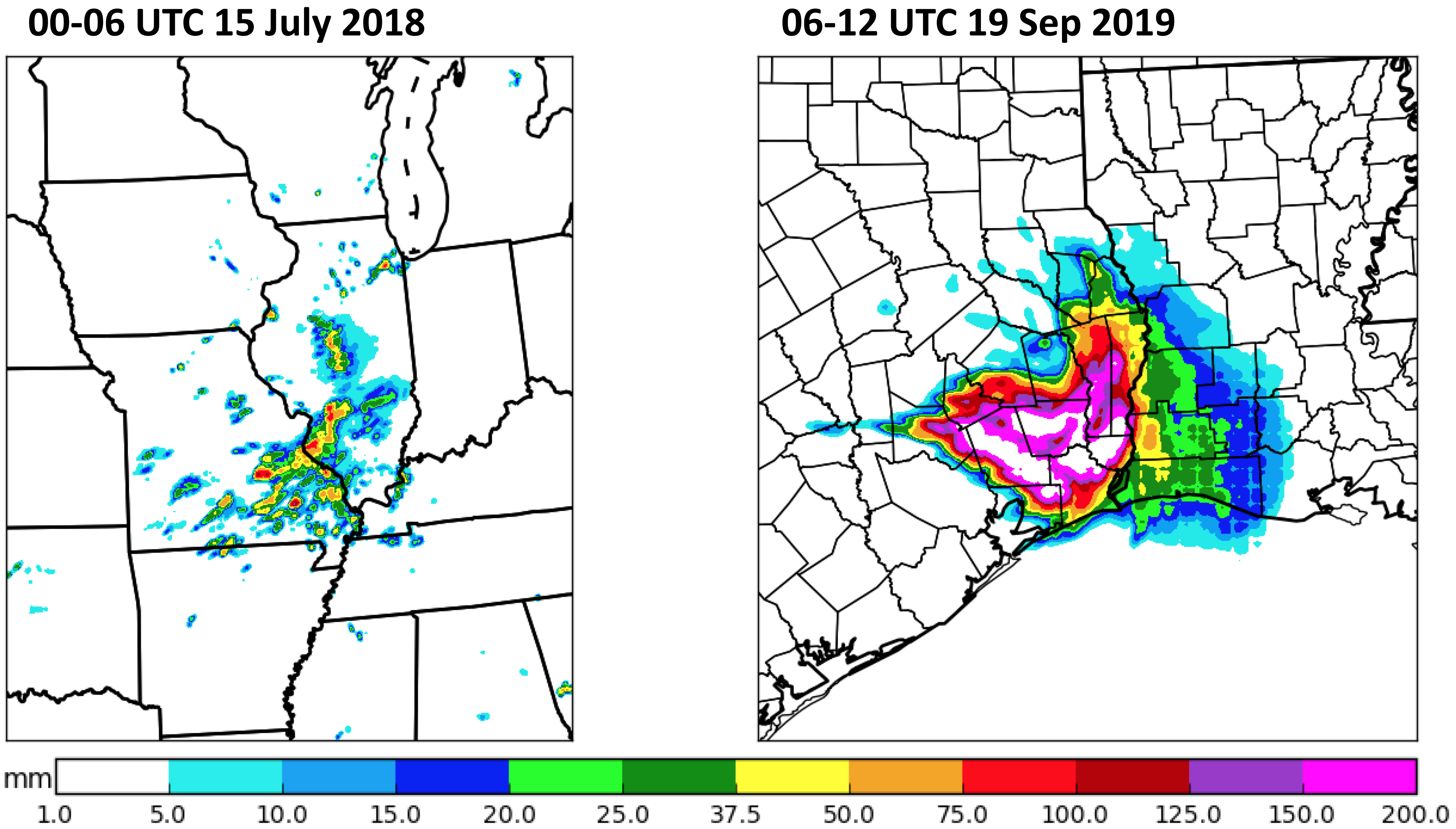
Relatively smooth terrain cases: B: 12.5mm R: 17.5 – 262.5mm



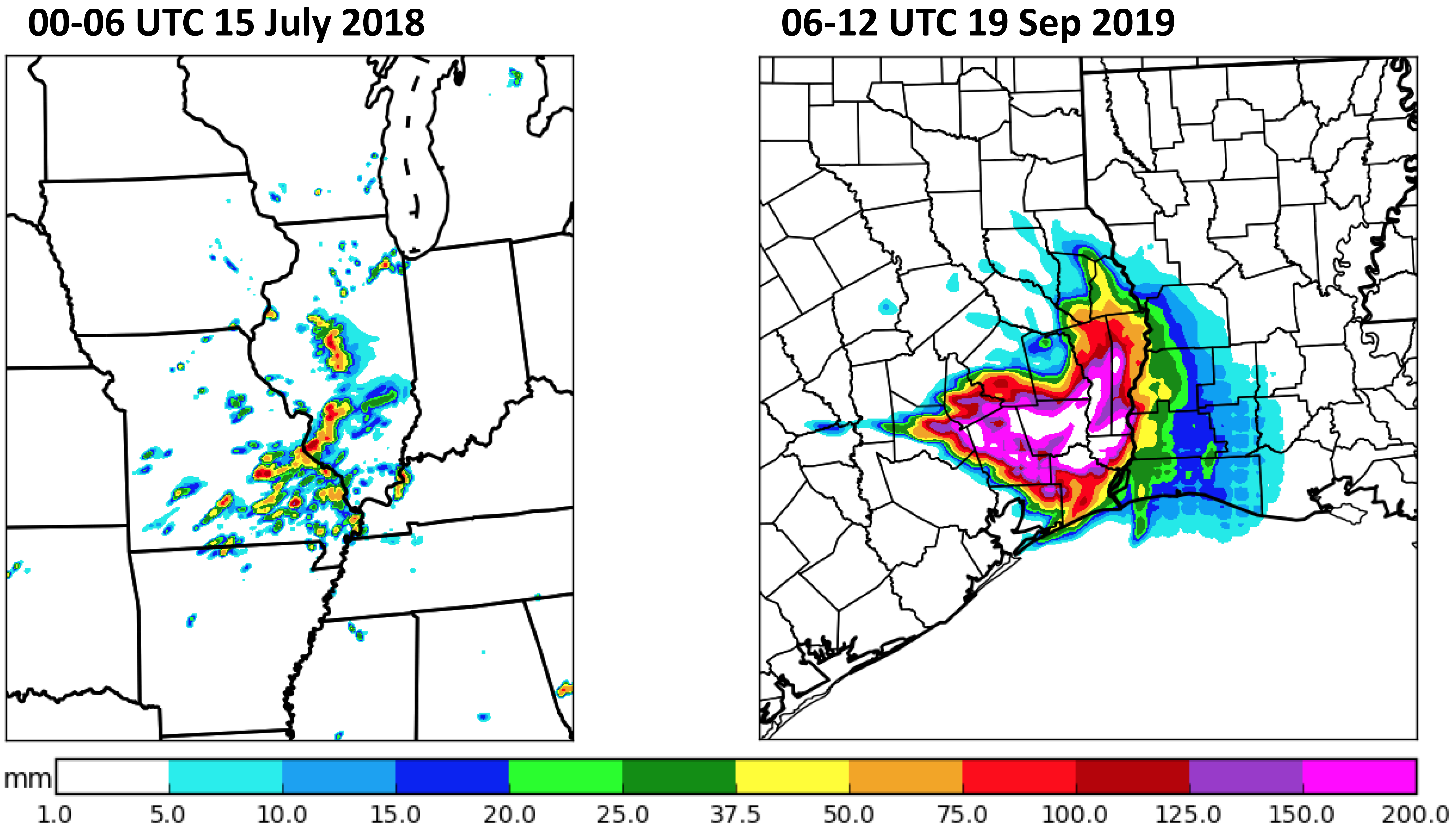
Relatively smooth terrain cases: B: 12.5mm R: 17.5 – 262.5mm



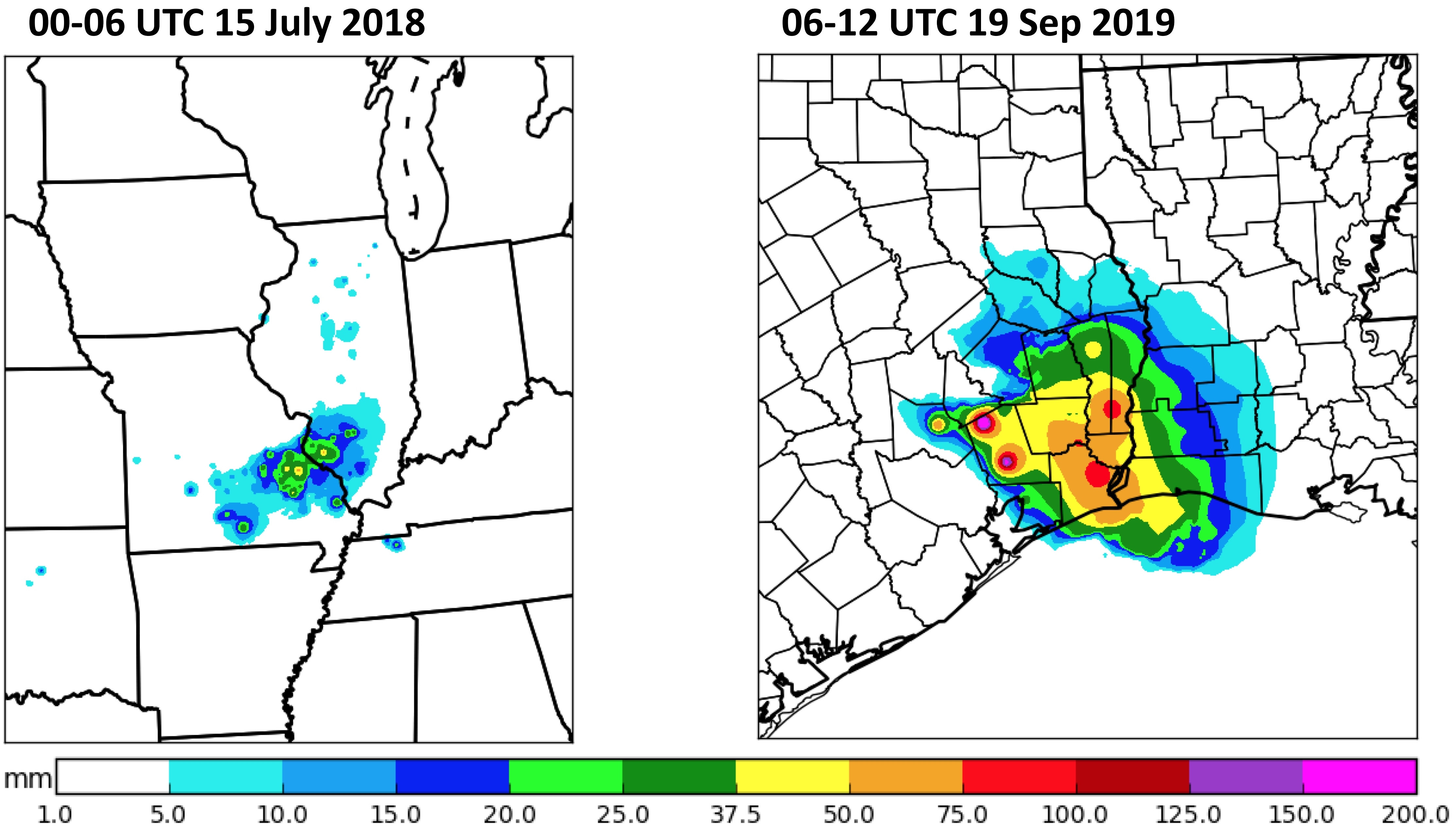
Relatively smooth terrain cases: B: 6.25mm R: 17.5 – 262.5mm



Relatively smooth terrain cases: B: 3mm R: 17.5 – 262.5mm

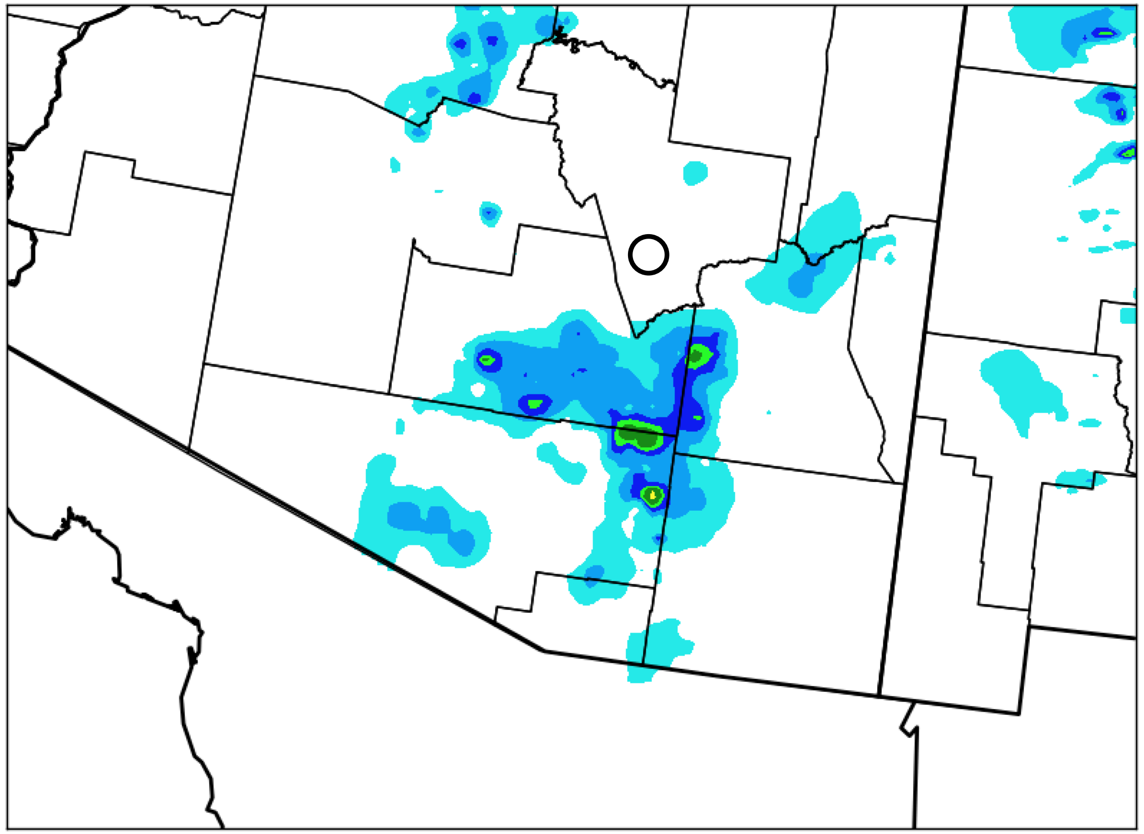


Relatively smooth terrain cases: MRMS gauge-only QPE

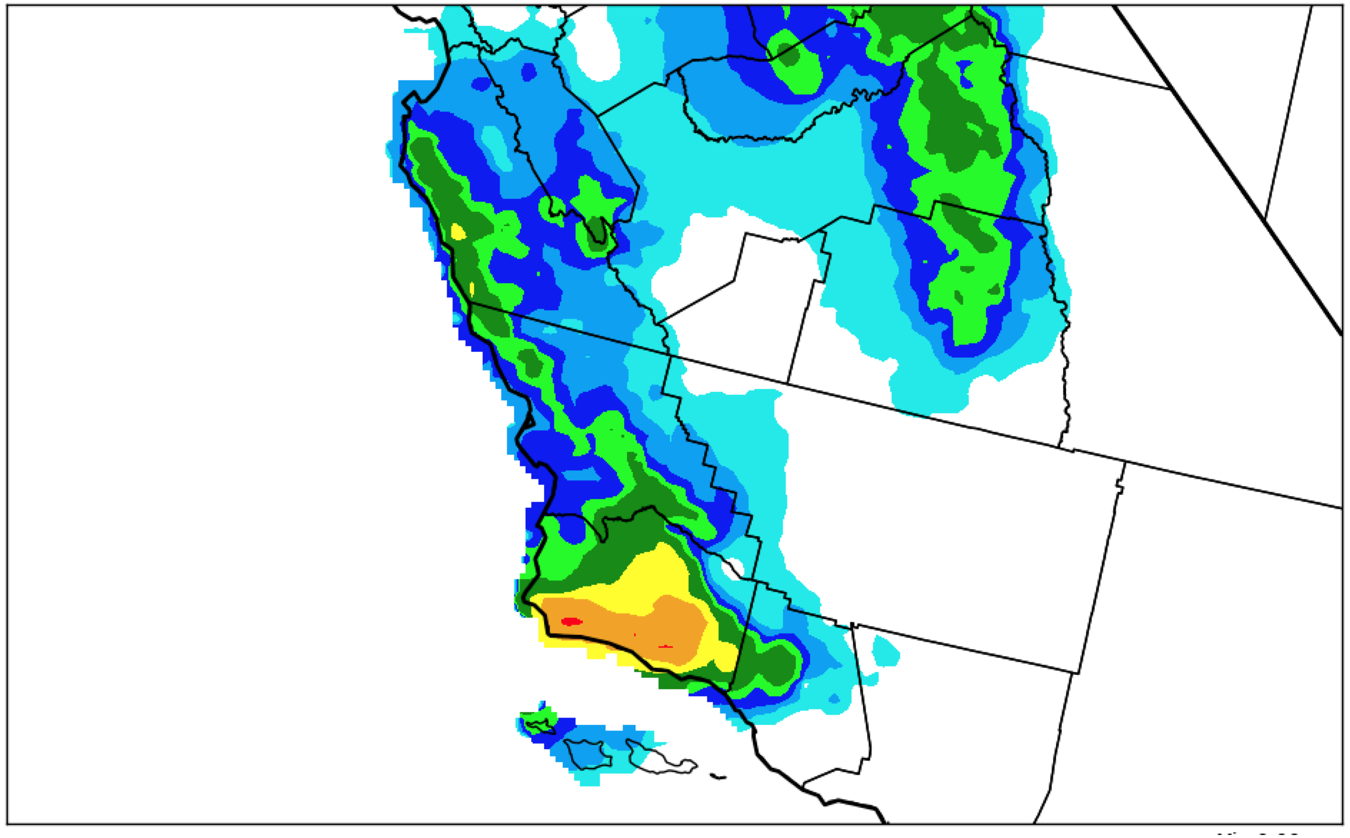


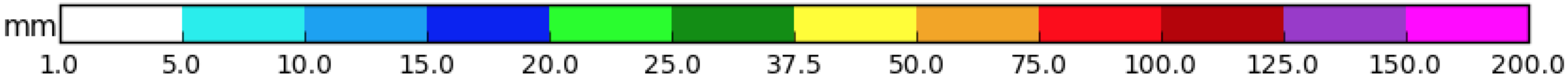
Complex terrain cases: Stage IV QPE

00-06 UTC 23 July 2019



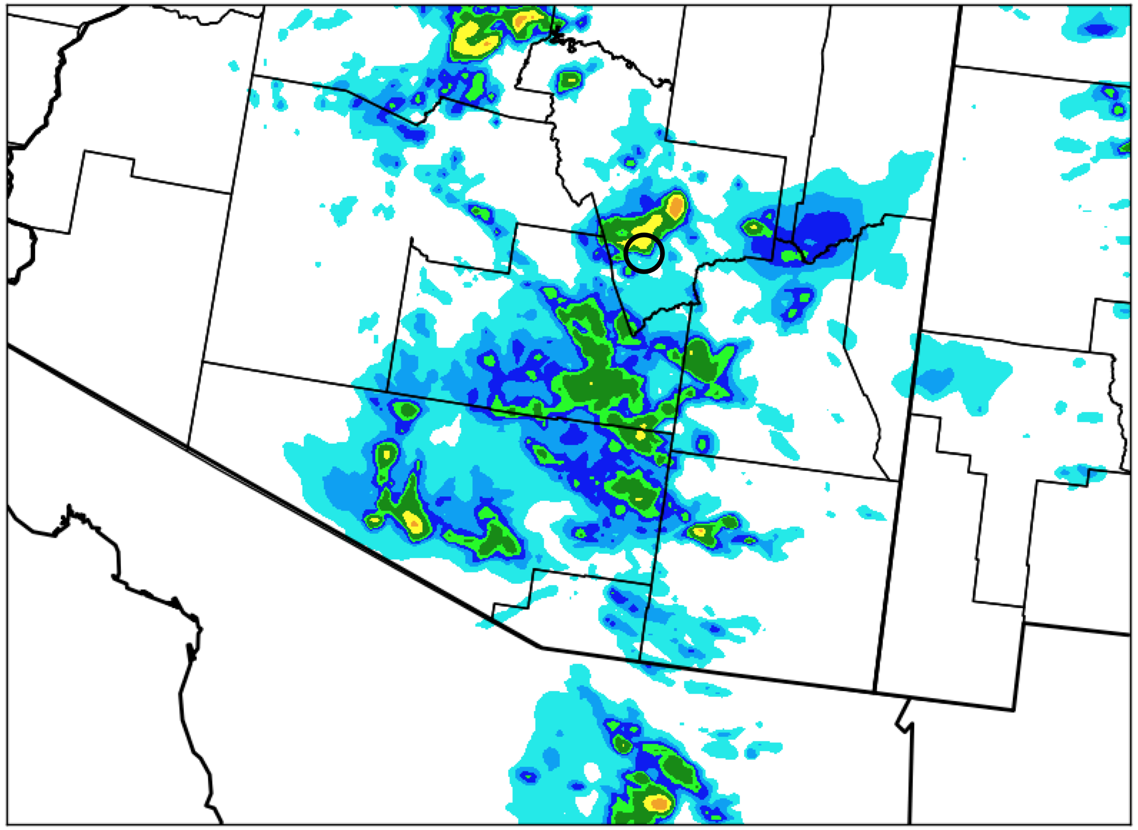
06-12 UTC 04 Apr 2020



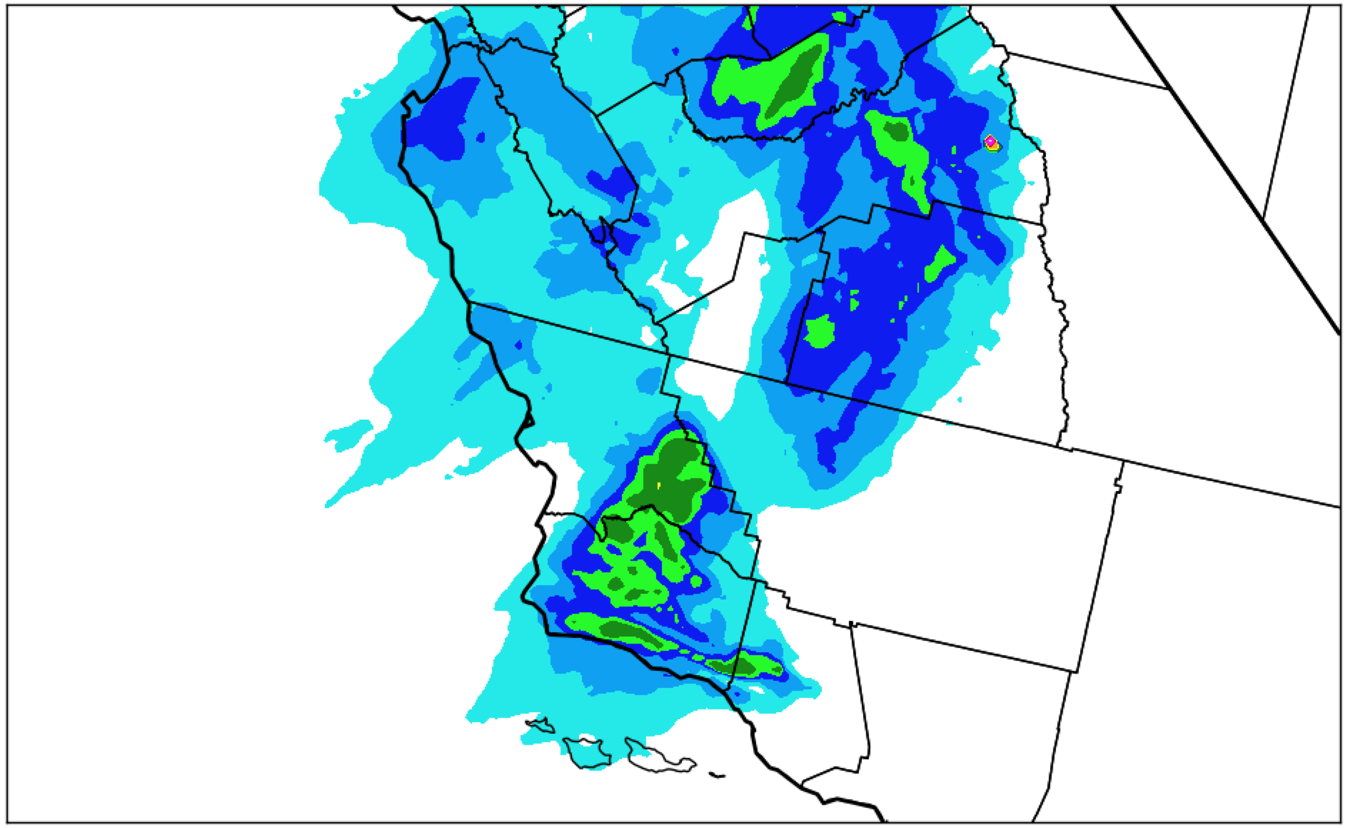


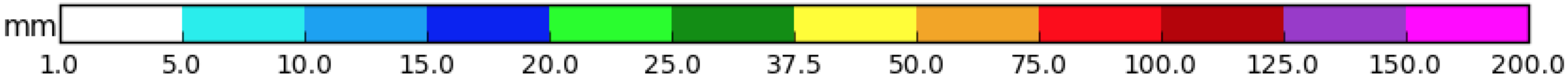
Complex terrain cases: MRMS radar-only QPE

00-06 UTC 23 July 2019



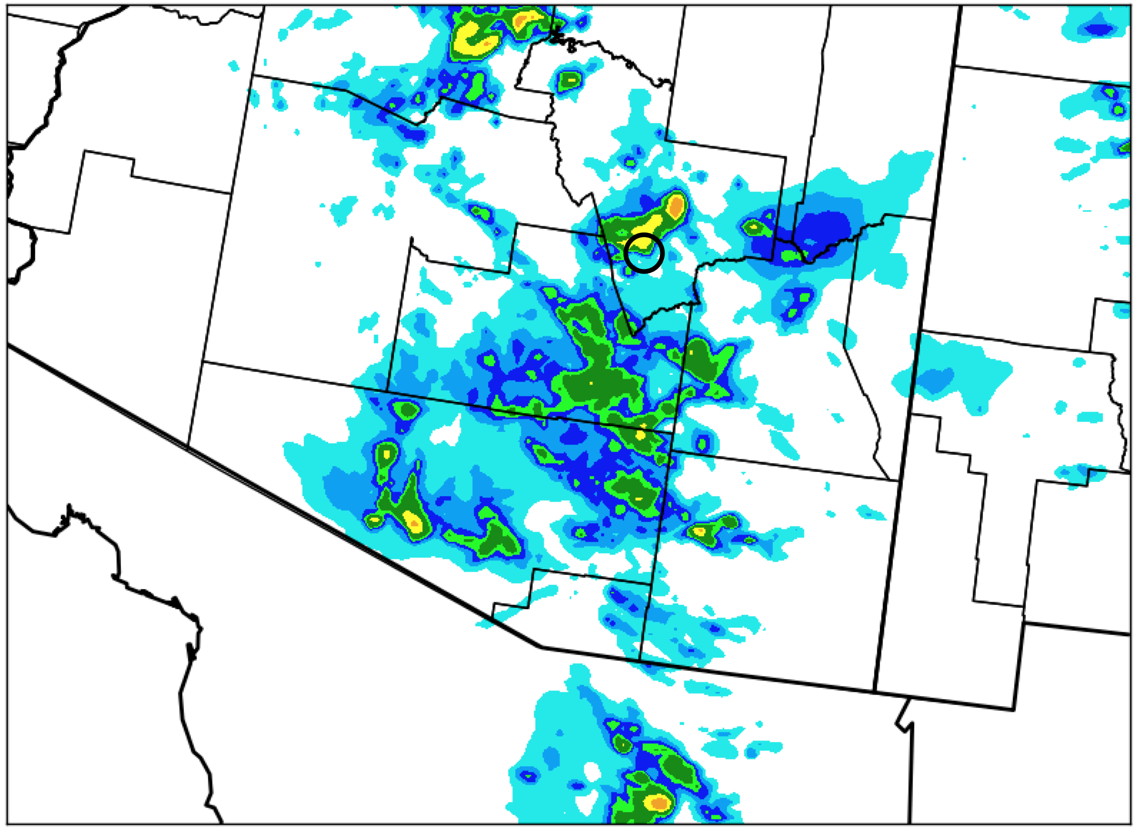
06-12 UTC 04 Apr 2020



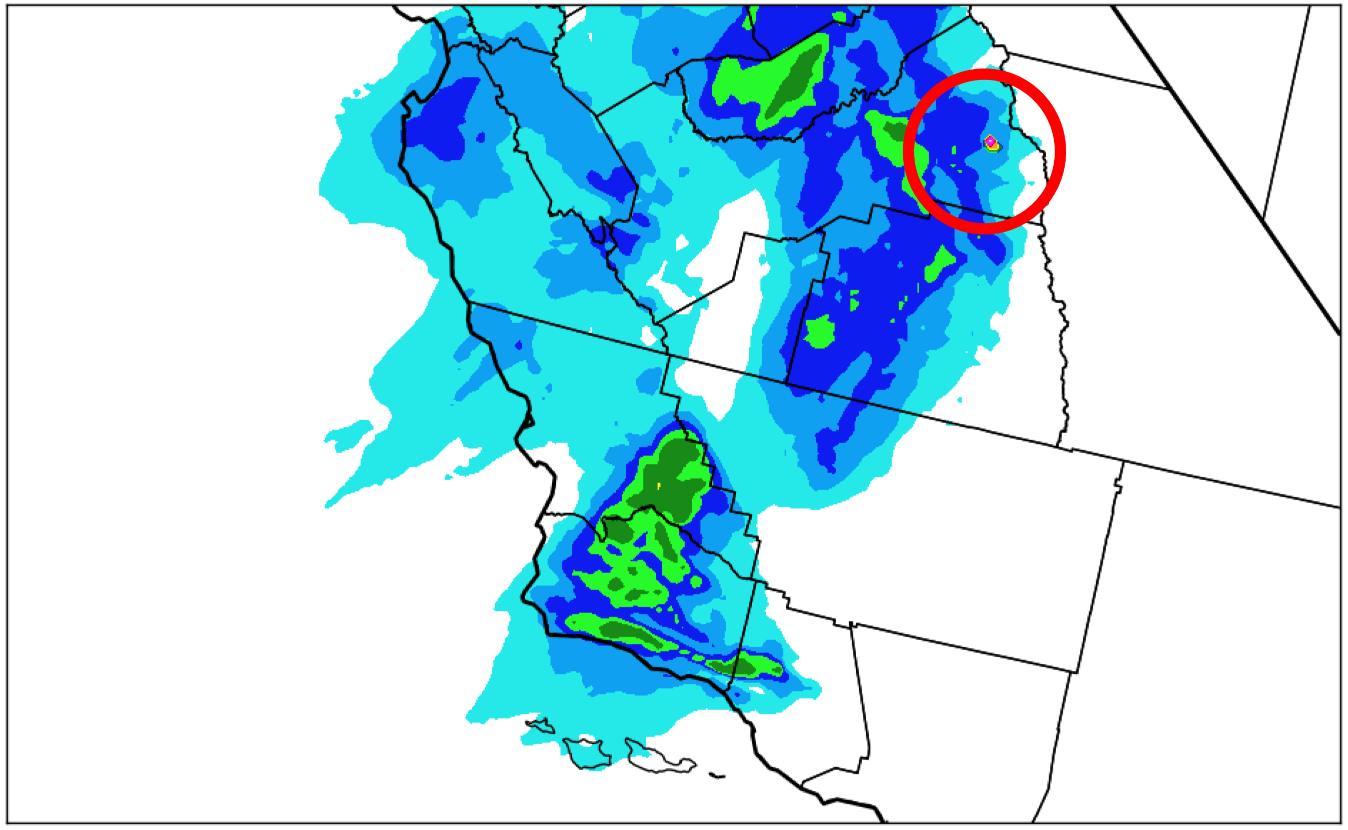


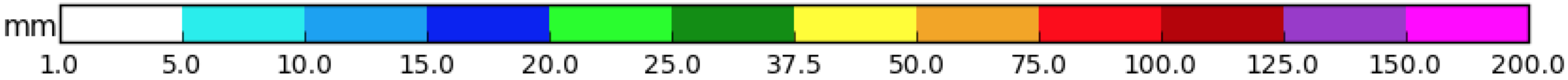
Complex terrain cases: MRMS radar-only QPE

00-06 UTC 23 July 2019



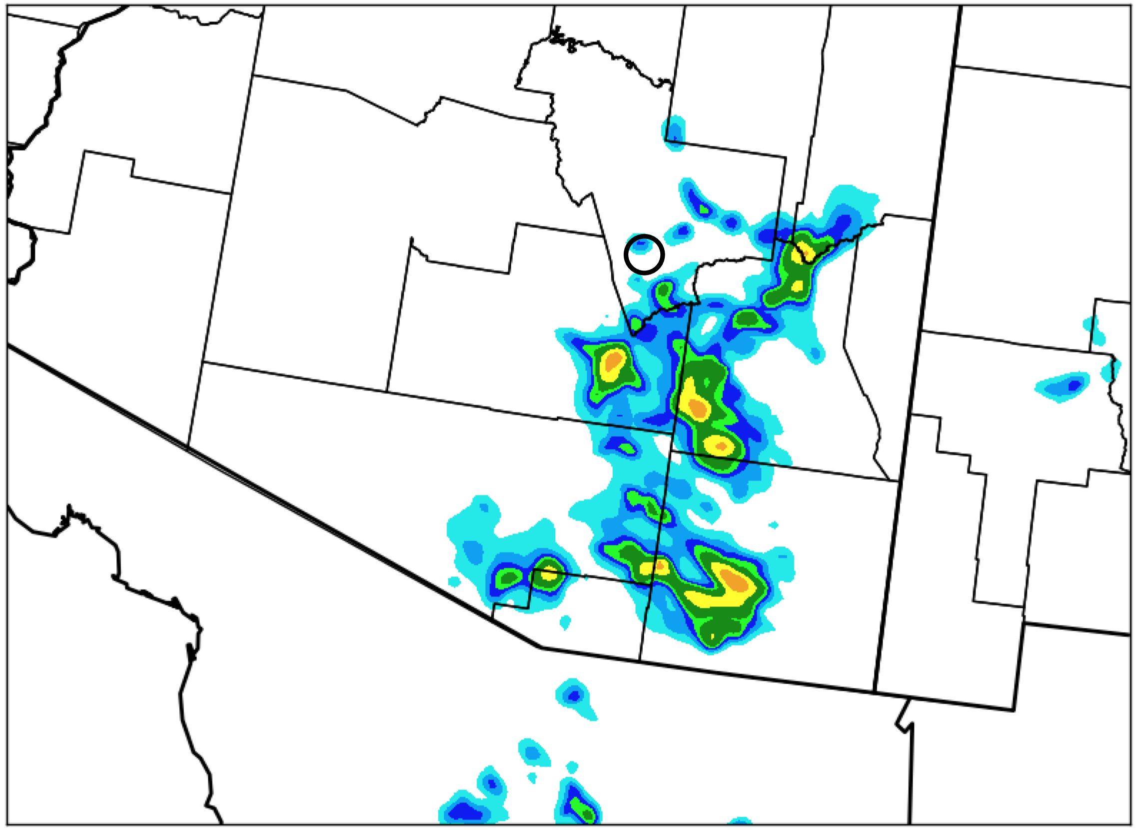
06-12 UTC 04 Apr 2020



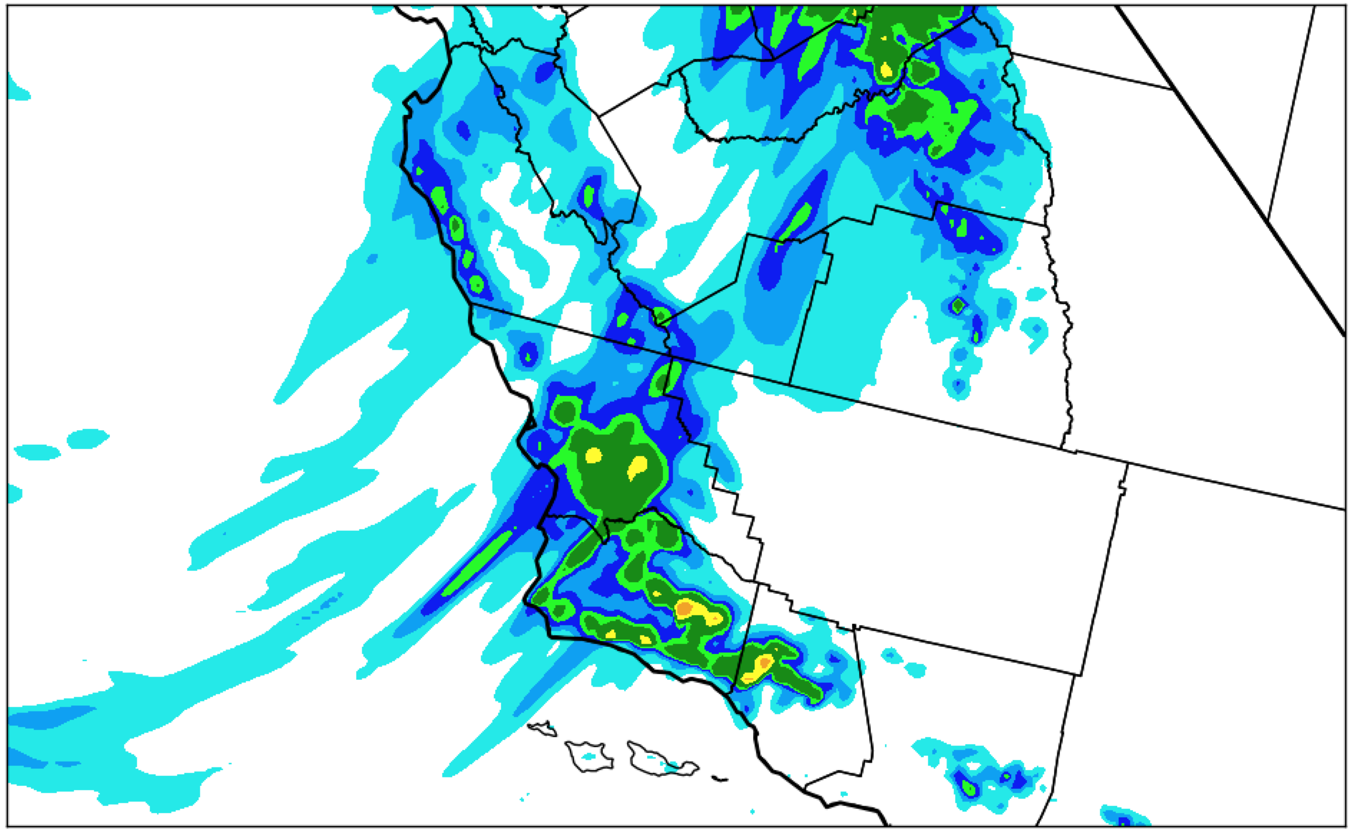


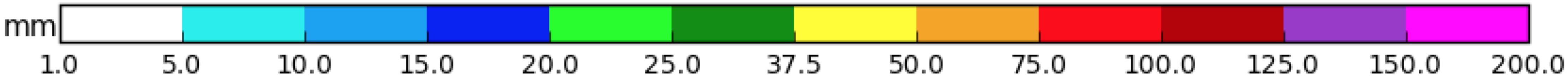
Complex terrain cases: HRRR 6h QPF

00-06 UTC 23 July 2019



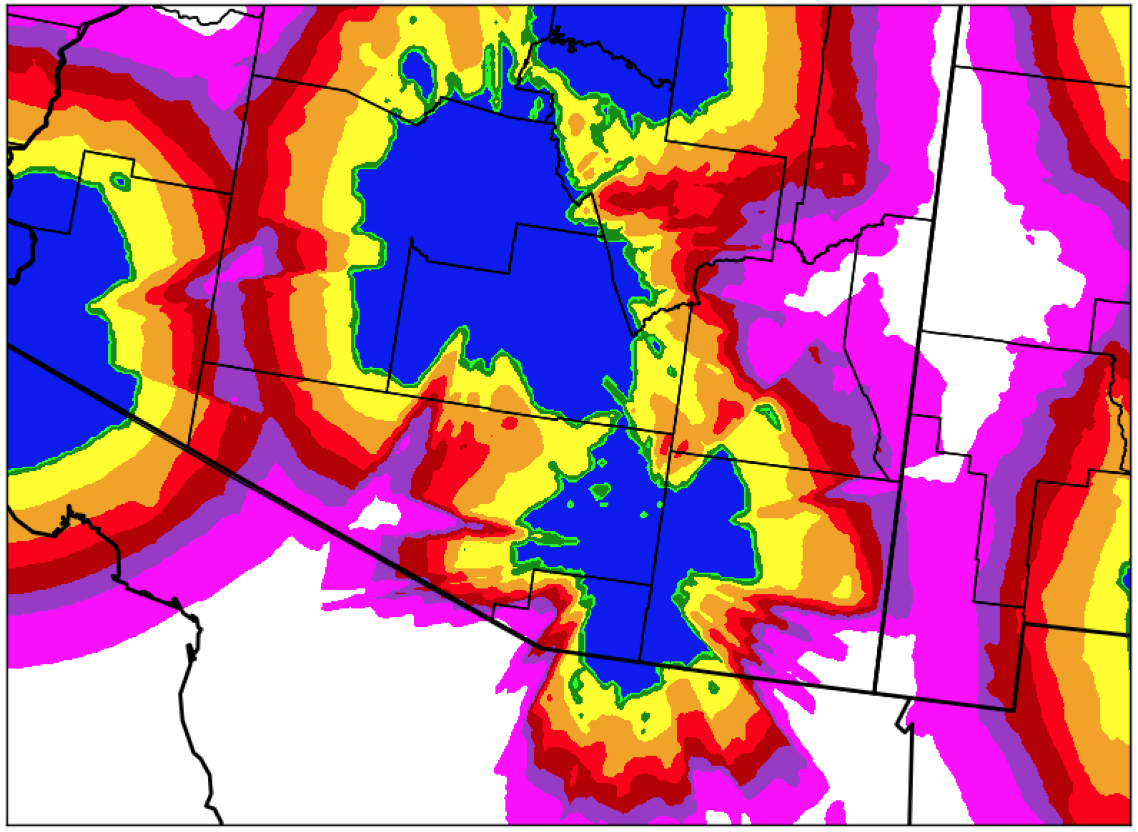
06-12 UTC 04 Apr 2020



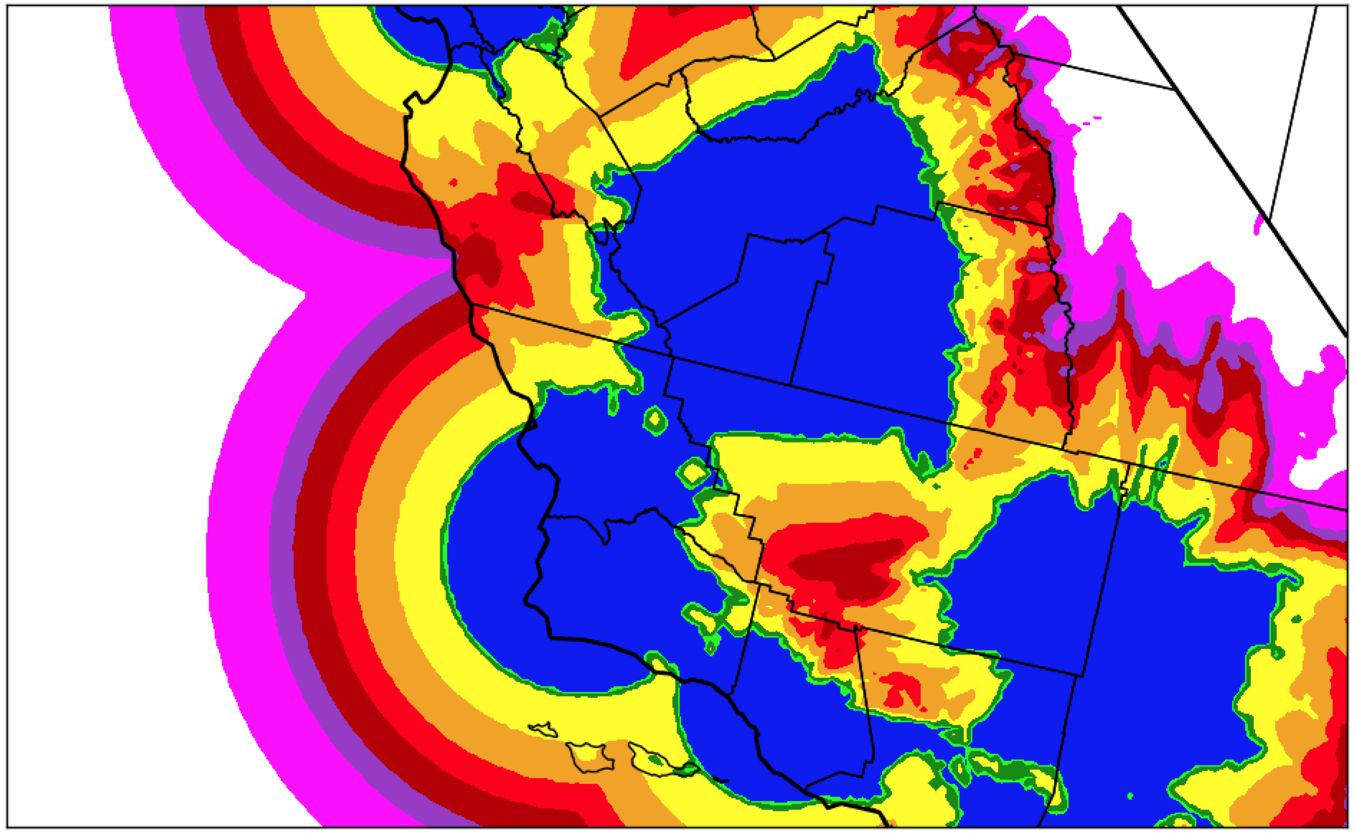


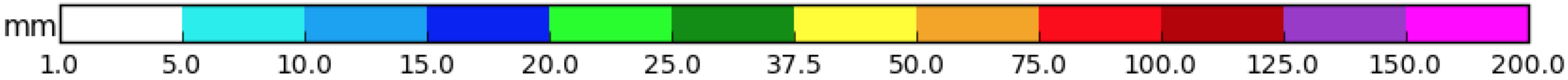
Complex terrain cases: MRMS RADAR QUALITY INDEX

00-06 UTC 23 July 2019



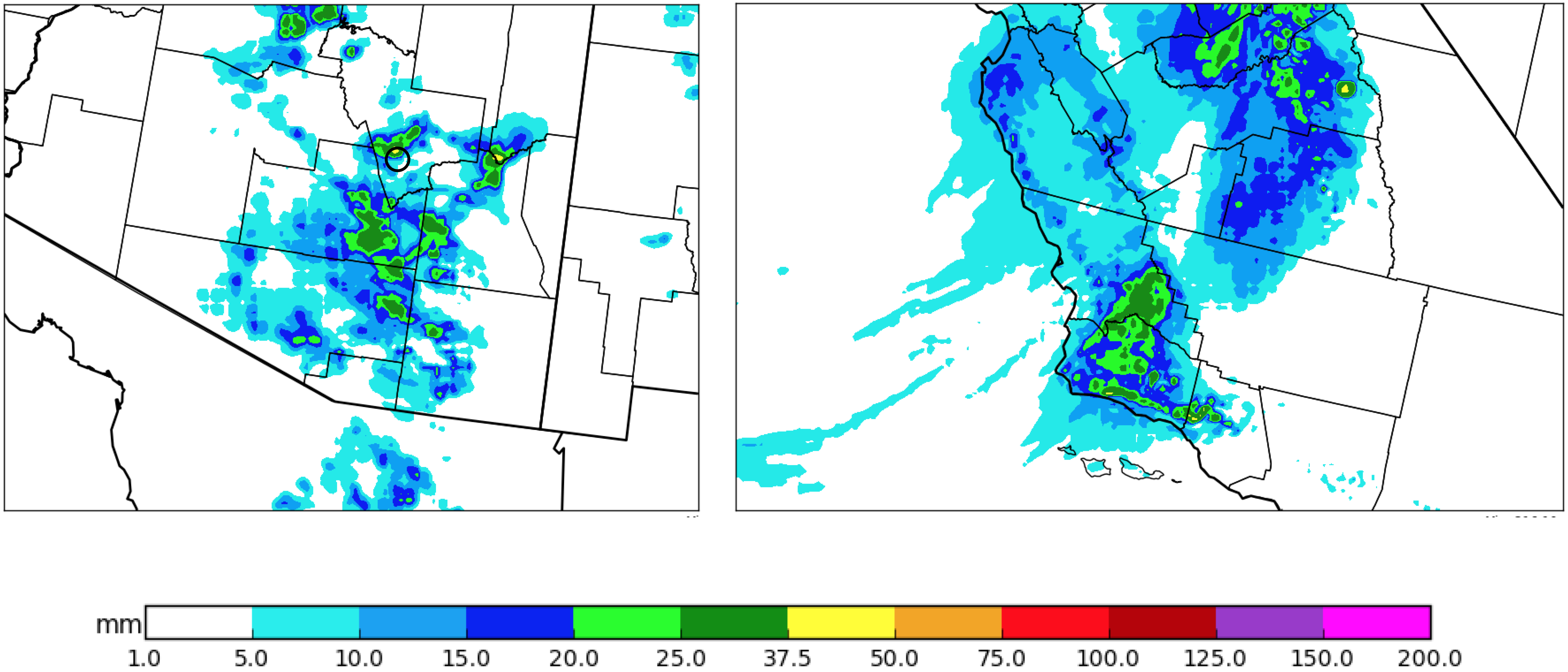
06-12 UTC 04 Apr 2020





Complex terrain cases: B: 12.5mm R: 17.5 – 75mm

00-06 UTC 23 July 2019 06-12 UTC 04 Apr 2020

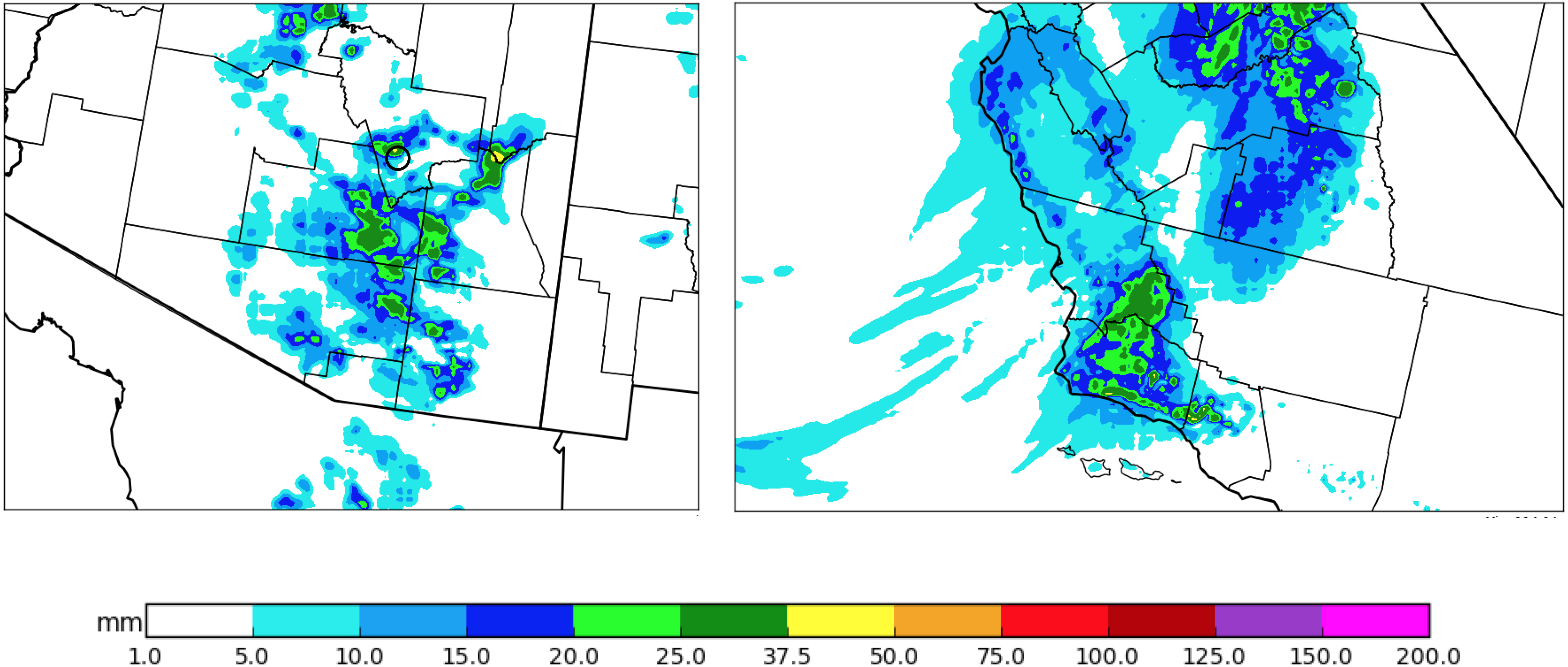


Complex terrain cases: B: 12.5mm

R: 17.5 – 137.5mm

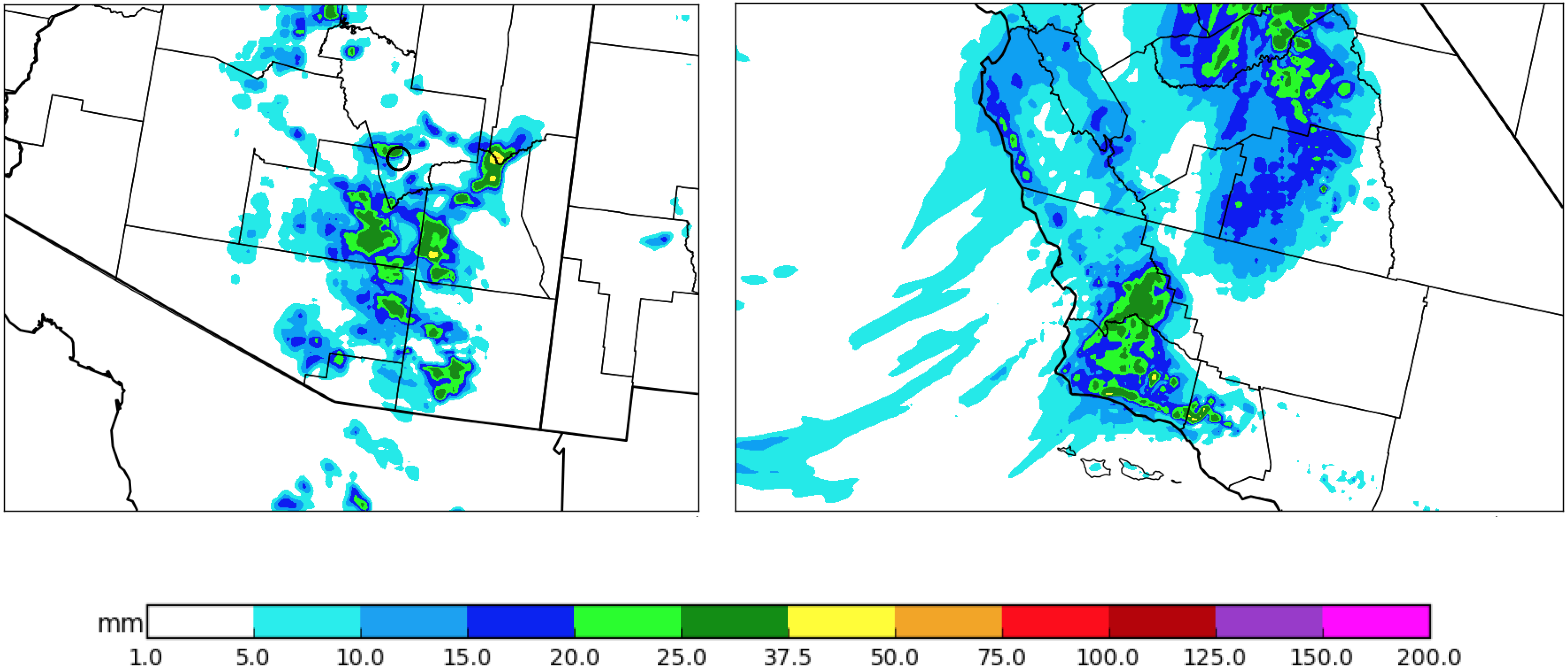
00-06 UTC 23 July 2019

06-12 UTC 04 Apr 2020



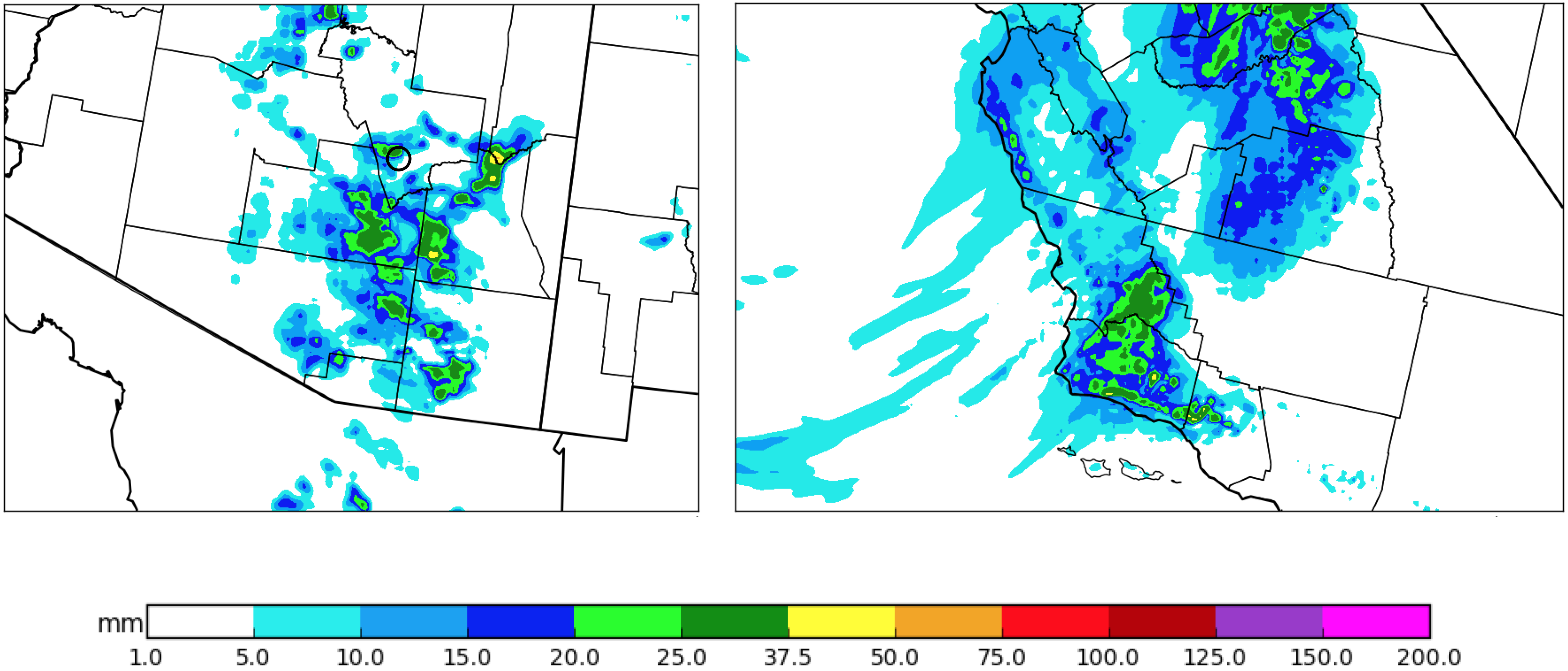
Complex terrain cases: B: 12.5mm R: 17.5 – 262.5mm

00-06 UTC 23 July 2019 06-12 UTC 04 Apr 2020



Complex terrain cases: B: 12.5mm R: 17.5 – 262.5mm

00-06 UTC 23 July 2019 06-12 UTC 04 Apr 2020

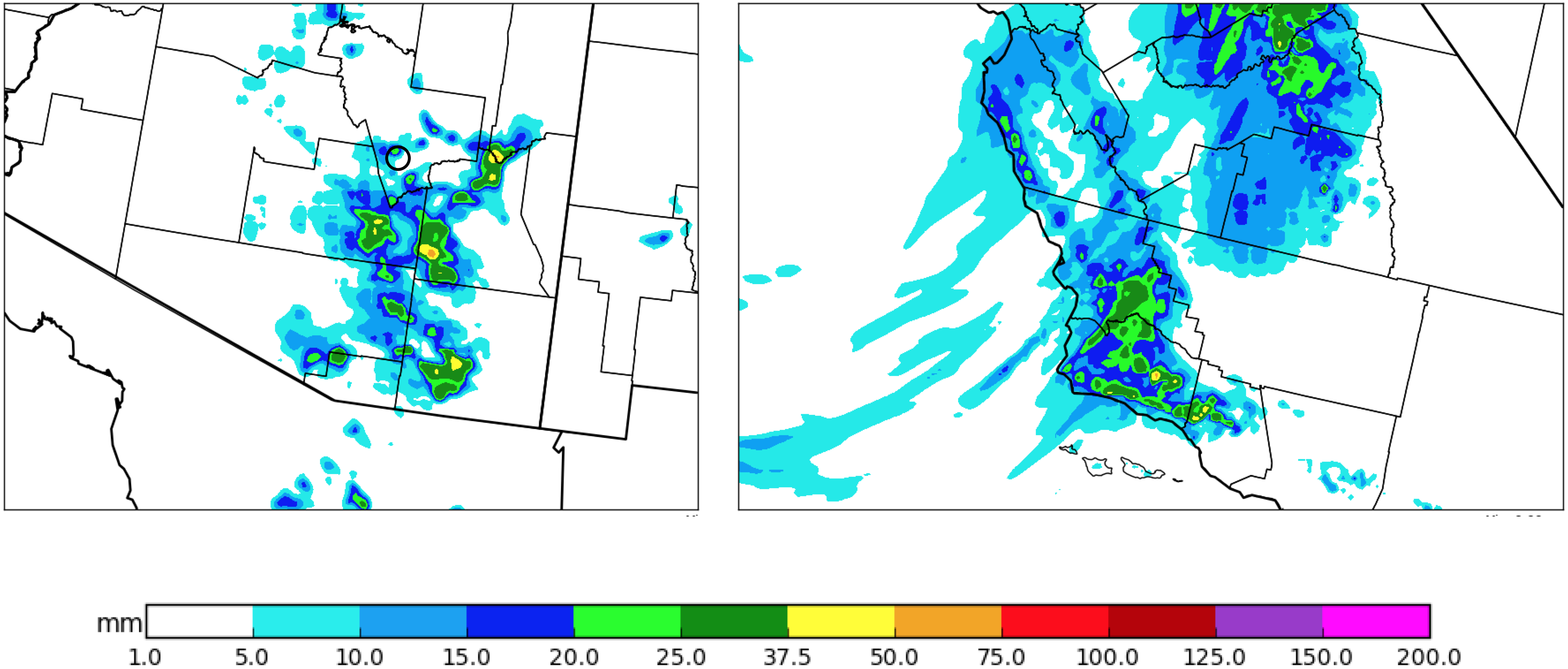


Complex terrain cases: B: 6.25mm

R: 17.5 – 262.5mm

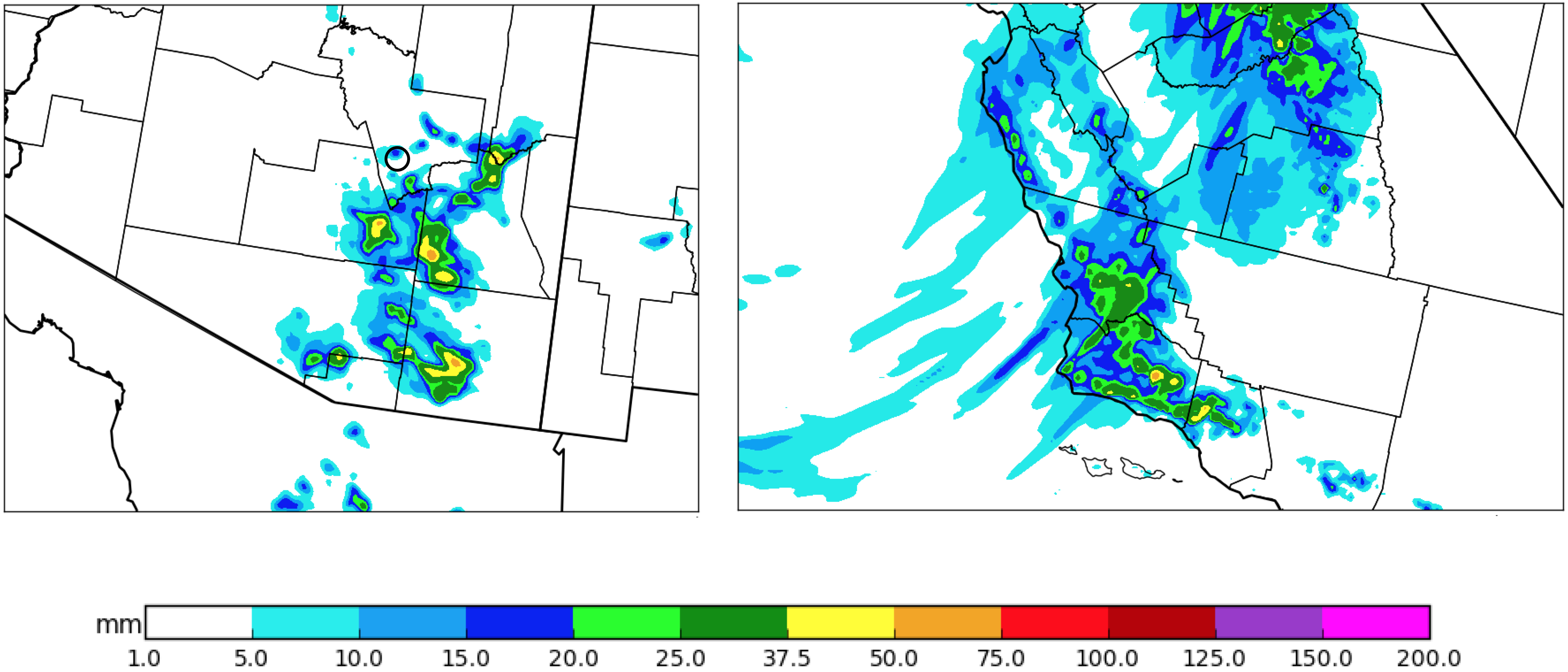
00-06 UTC 23 July 2019

06-12 UTC 04 Apr 2020



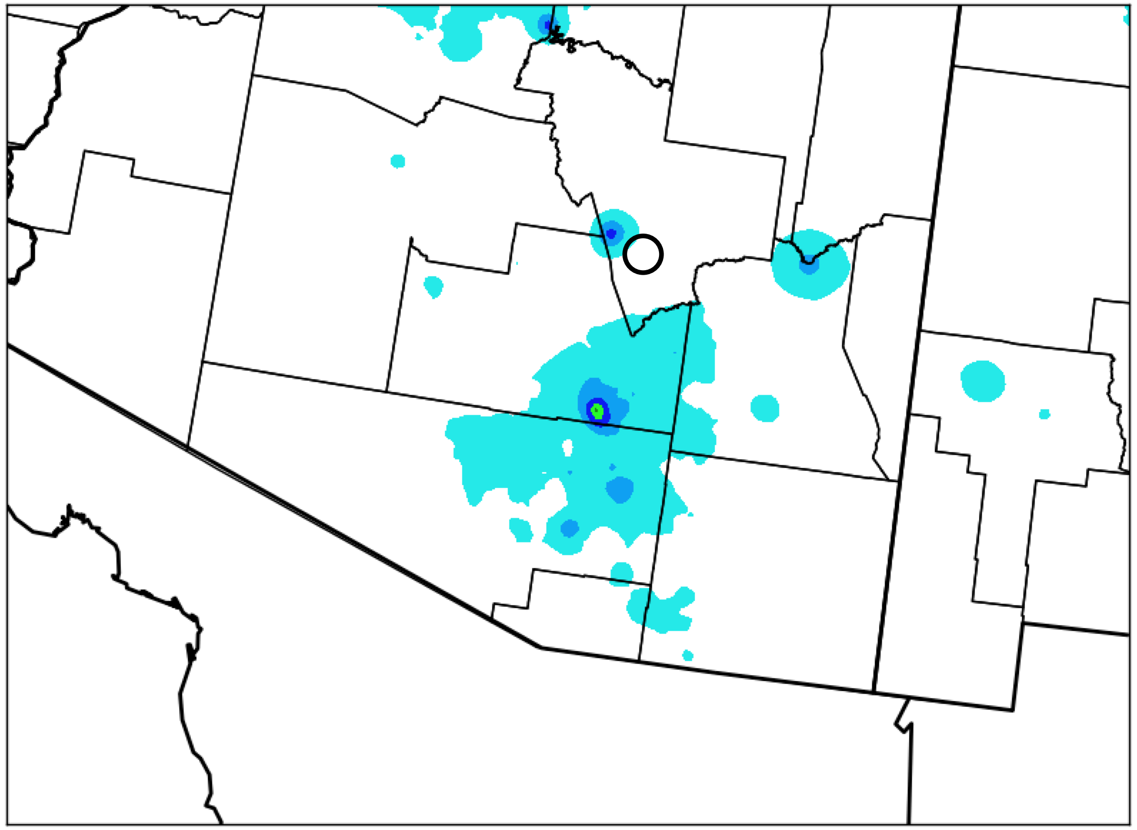
Complex terrain cases: B: 3mm R: 17.5 – 262.5mm

00-06 UTC 23 July 2019 06-12 UTC 04 Apr 2020

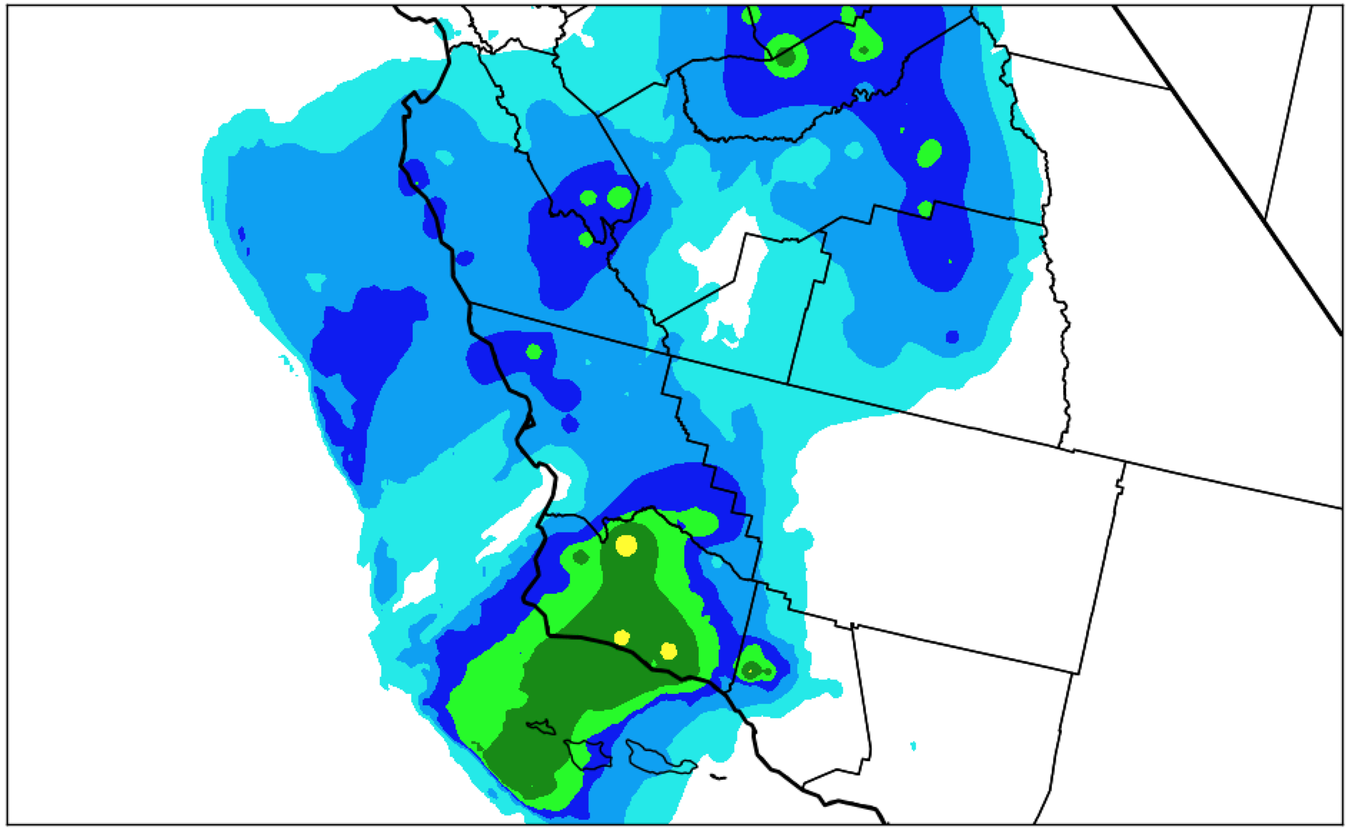


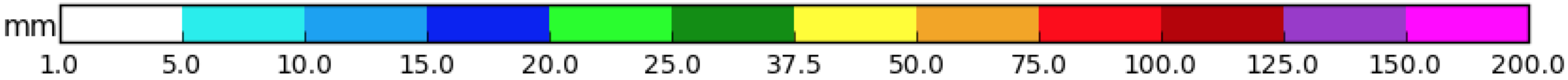
Complex terrain cases: MRMS gauge-only QPE

00-06 UTC 23 July 2019



06-12 UTC 04 Apr 2020





DISCUSSION AND CONCLUSIONS

This is very much a work in progress. Cannot conclude much about the performance of the framework without quantitative verification. Comparison against high-quality rain gauges, over a large number of cases.

The framework really needs to account for the non-Gaussian nature of precipitation. This may be possible through a Gaussian transformation (as proposed by Lien et al. 2013).

$$y_{\text{trans}} = G^{-1}[F(y)] \quad 1 \qquad G^{-1}(x) = \sqrt{2}\,\text{erf}^{-1}(2x-1), \quad 2$$

Future work:

Inclusion of additional QPE datasets (being careful to maintain independent verification)

More advanced specifications of **B** and **R** (better quantification of uncertainty)

Can this framework be expanded to other time intervals (i.e., 1h precip)?

How to deal with snow?

REFERENCES

Ashley, S. T., and W. S. Ashley, 2008: Flood fatalities in the United States. *J. Appl. Meteor. Climatol.,* 47, 806-818, https://doi.org/10.1175/2007JAMC1611.1

Beck, H. E., and Coauthors, 2019: Daily evaluation of 26 precipitation datasets using Stage-IV gauge-radar data for the CONUS. *Hydrology and Earth System Sciences,* **23,** 207-224, https://doi.org/10.5194/hess-23-207-2019

Benjamin, S. G., and Coauthors, 2016: A North American hourly assimilation and model forecast cycle: The Rapid Refresh. *Mon. Wea. Rev.,* **144,** 1669-1694, https://doi.org/10.1175/MWR-D-15-0242.1

Clark, R. A., J. J. Gourley, Z. L. Flamig, Y. Hong, and E. Clark, 2014: CONUS-wide evaluation of National Weather Service flash flood guidance products. *Wea. Forecasting,* **29,** 377-392, https://doi.org/10.1175/WAF-D-12-00124.1

REFERENCES (continued)

Gourley, J. J., and Coauthors, 2017: The FLASH project: Improving the tools for flash flood monitoring and prediction across the United States. *Bull. Amer. Meteor. Soc.,* 98, 361-372, https://doi.org/10.1175/BAMS-D-15-00247.1

Hamill, T. M., and Coauthors, 2013: NOAA's second-generation global medium-range ensemble reforecast dataset. *Bull. Amer. Meteor. Soc.,* **94,** 1553-1565, https://doi.org/10.1175/BAMS-D-12-00014.1

Herman, G. R., and R. S. Schumacher, 2018a: Money doesn't grow on trees, but forecasts do: Forecasting extreme precipitation with random forecasts. *Mon. Wea. Rev.,* **146,** 1571-1600, https://doi.org/10.1175/MWR-D-17-0250.1

Herman, G. R., and R. S. Schumacher, 2018b: "Dendrology" in numerical weather prediction: What random forests and logistic regression tell us about forecasting extreme precipitation. *Mon. Wea. Rev.,* **146,** 1785-1812, https://doi.org/10.1175/MWR-D-17-0307.1

REFERENCES (continued)

Herman, G. R., and R. S. Schumacher, 2018c: Flash flood verification: Pondering precipitation proxies. *J. Hydrometeor.,* **19,** 1753-1776, https://doi.org/10.1175/JHM-D-18-0092.1

Lien, G.-Y., E. Kalnay, and T. Miyoshi, 2013: Effective assimilation of global precipitation: simulation experiments. *Tellus A,* **65(1),** https://doi.org/10.3402/tellusa.v65i0.19915

Prein, A. F., C. Liu, K. Ikeda, S. B. Trier, R. M. Rasmussen, G. J. Holland, and M. Clark, 2017: Increased rainfall volume from future convective storms in the U.S. *Nat. Climate Change,* **7,** 880-884, https://doi.org/10.1038/s41558-017-0007-7

Smith, T. L., and Coauthors, 2008: Convection forecasts from the hourly updated, 3-km High-Resolution Rapid Refresh (HRRR) model. *24th Conf. on Severe Local Storms,* Savannah, GA, Amer. Meteor. Soc., 11.1. [Available online at https://ams.confex.com/ams/24SLS/techprogram/paper_142055.htm.]

REFERENCES (continued)

Yussouf, N., J. S. Kain, and A. J. Clark, 2016: Short-term probabilistic forecasts of the 31 May 2013 Oklahoma City tornado and flash flood event using a continuous-update-cycle storm-scale ensemble system. *Wea. Forecasting,* **31,** 957-983, https://doi.org/10.1175/WAF-D-15-0160.1

Yussouf, N., K. A. Wilson, S. M. Martinaitis, H. Vergara, P. L. Heinselman, and J. J. Gourley, 2019: The coupling of NSSL Warn-on-Forecast and FLASH systems for probabilistic flash flood prediction. *J. Hydrometeor.,* in press.