How does extreme sub-daily rainfall in the CONUS404 simulation compare to observations, and what can we learn from it?

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COLORADO CLIMATE CENTER

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ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY

Questions to ponder

- When extreme convective rainfall occurs in complex terrain, how important is the terrain, and how important are the mesoscale-convective processes?
- What are the strengths and weaknesses of observations and simulations of these processes?

The Effect of the Balcones Escarpment on Three Cases of Extreme Precipitation in Central Texas

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(Manuscript received 16 April 2015, in final form 25 September 2015)

ABSTRACT

The proximity to the Gulf of Mexico and local topography makes central Texas particularly prone to heavy precipitation and deadly flood events. Specifically, the Balcones Escarpment, located in central Texas, creates extremely favorable hydrologic characteristics for damaging floods. Urban centers such as San Antonio and Austin, Texas, are located along this terrain feature and have suffered at times, even with mitigation strategies, catastrophic flood damage. While the hydrologic effects of the Balcones Escarpment are well known, the meteorological impacts are uncertain. The purpose of this study is to evaluate the effect of the Balcones Escarpment in three cases of extreme precipitation in which the rainfall was maximized near the escarpment. Numerical simulations for each event were run at convection-allowing grid spacing using the Weather Research and Forecasting (WRF) Model and were used as control runs. Then, the Balcones Escarpment was removed by moving the associated terrain gradient to the north and west. The removal of the Balcones Escarpment did not change the overall characteristics of any of the three rainfall events, with the spatial pattern and magnitude of precipitation similar between the control and terrain-modified simulations. However, the location of the maximum precipitation was slightly, but consistently, shifted to the north and west. These results show that the overall atmospheric conditions are much more important for determining the intensity and occurrence of extreme rainfall in central Texas than the local topography, but the Balcones Escarpment can cause subtle hydrologically important changes in the location of the maximum accumulation.

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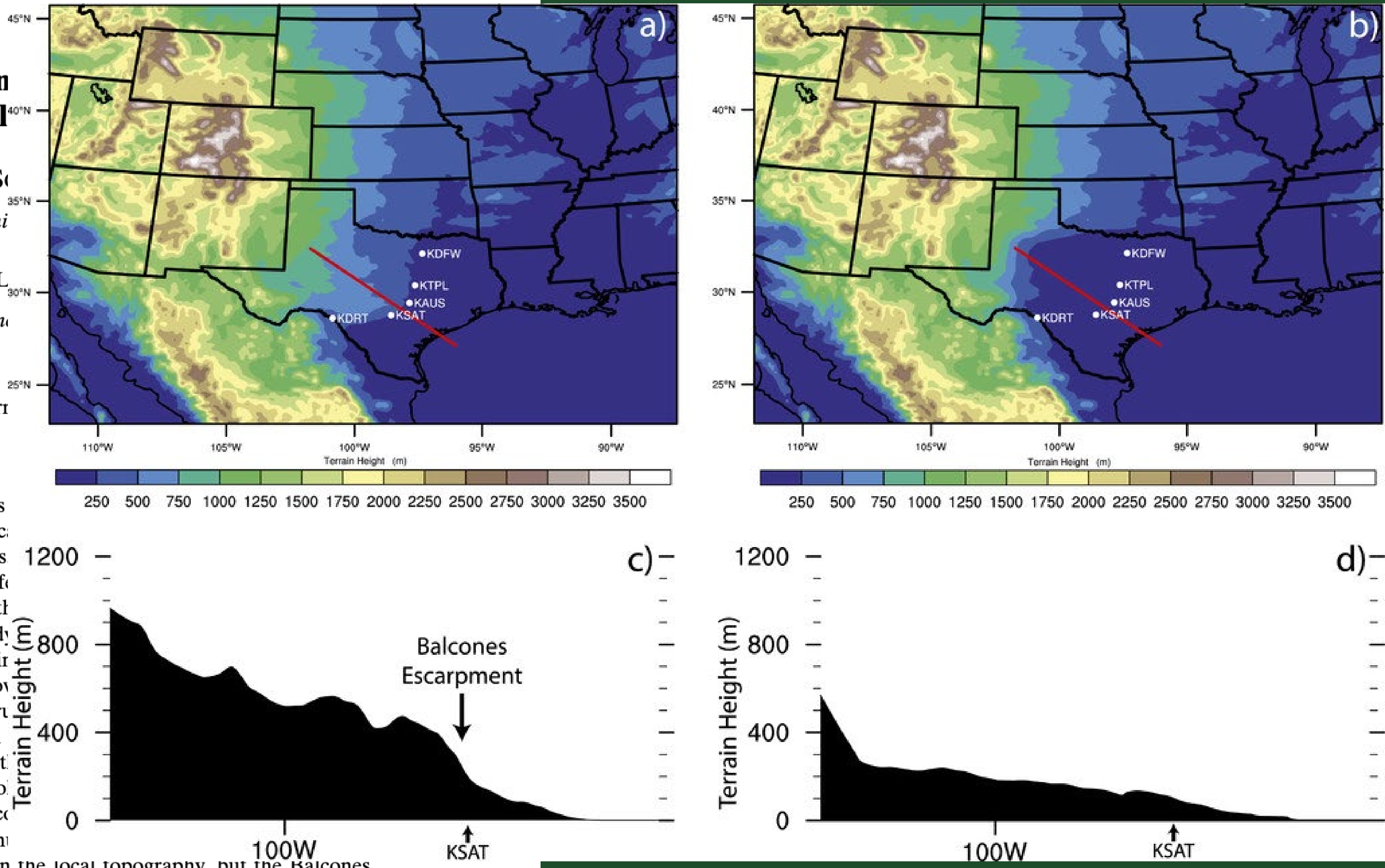

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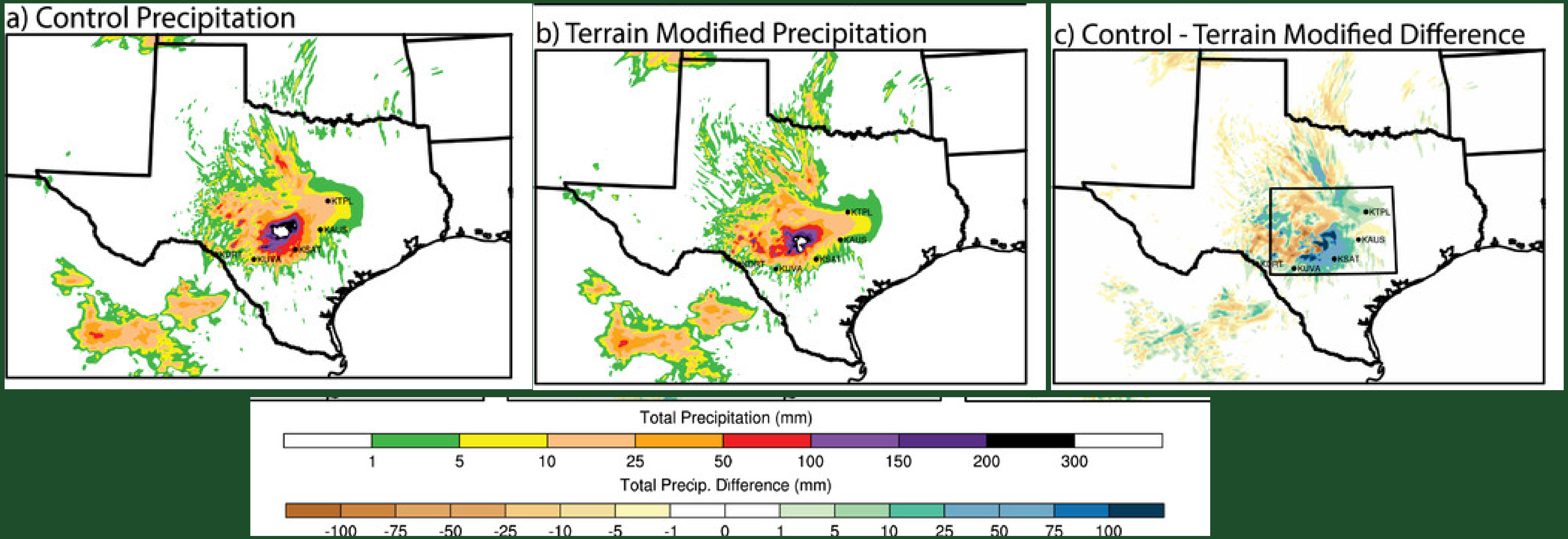
(Nielsen, Schumacher, and Keclik 2016, *MWR*)

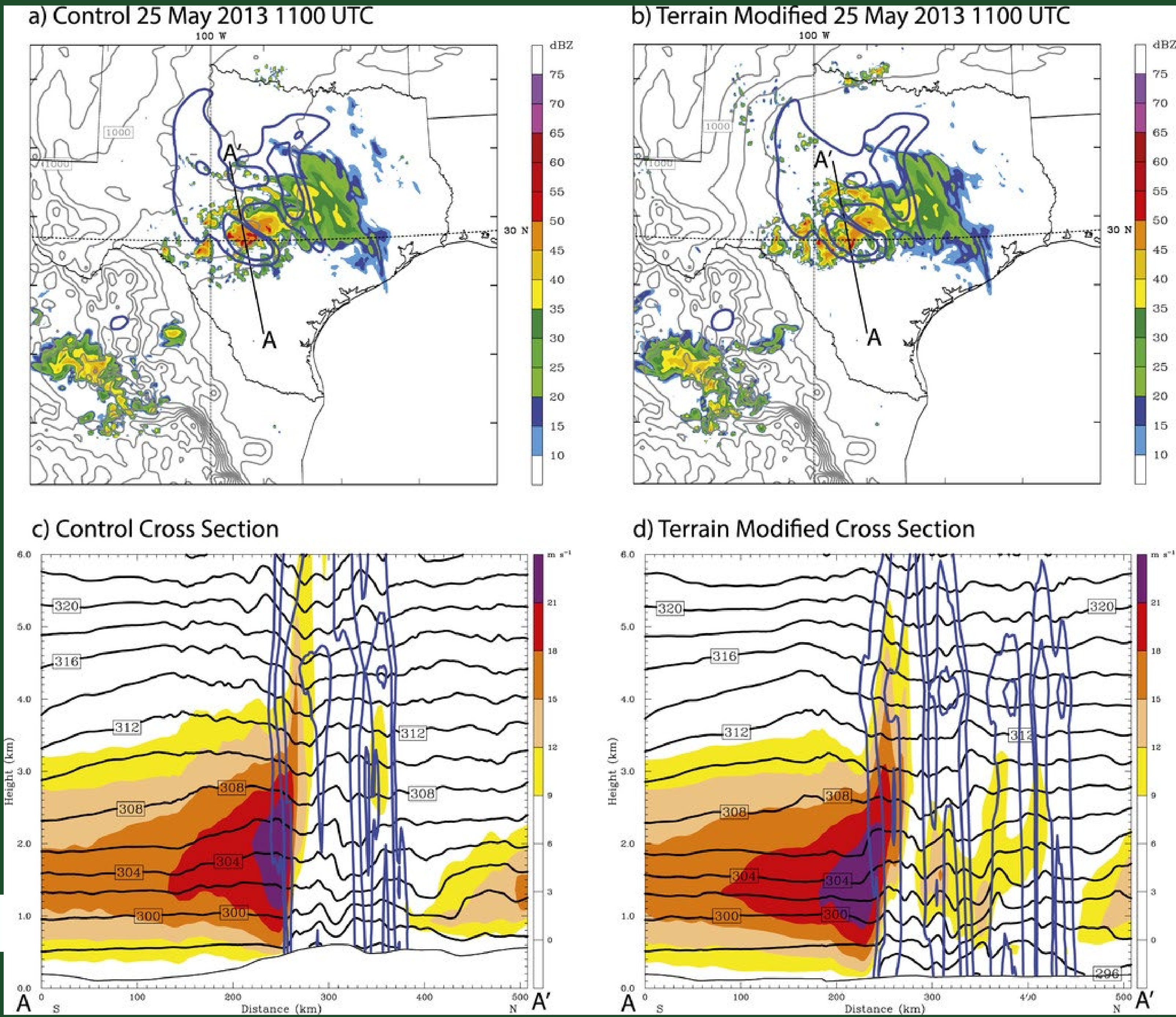
4-km WRF simulation with escarpment removed: slight decrease in precipitation, axis of heavy rain shifted NW



25 May 2013 extreme rainfall around San Antonio

Nielsen et al. (2016)

Mesoscale convective vortex, strong low-level jet are not strongly affected by the change in terrain

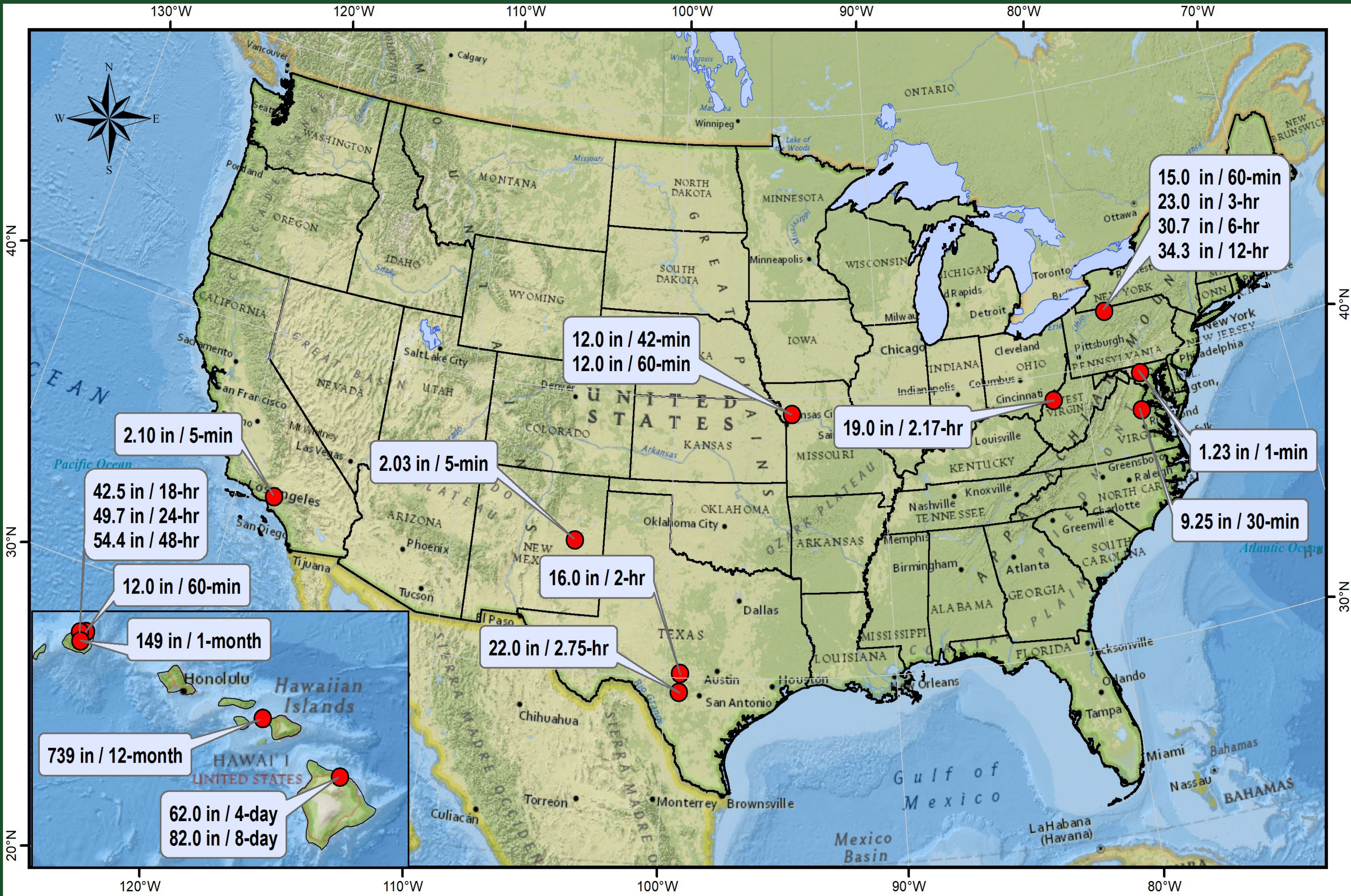


Top: simulated reflectivity and PV (blue contours)
Bottom: v-wind (color shading), potential temperature (black), reflectivity (blue)

Nielsen et al. (2016)

Many national and world-record short-duration rainfalls are in the complex terrain of the northeast US

(especially Smethport, PA, 18 July 1942)



https://www.weather.gov/owp/hdsc_usa_record

Data and methods

BAMS Article

CONUS404

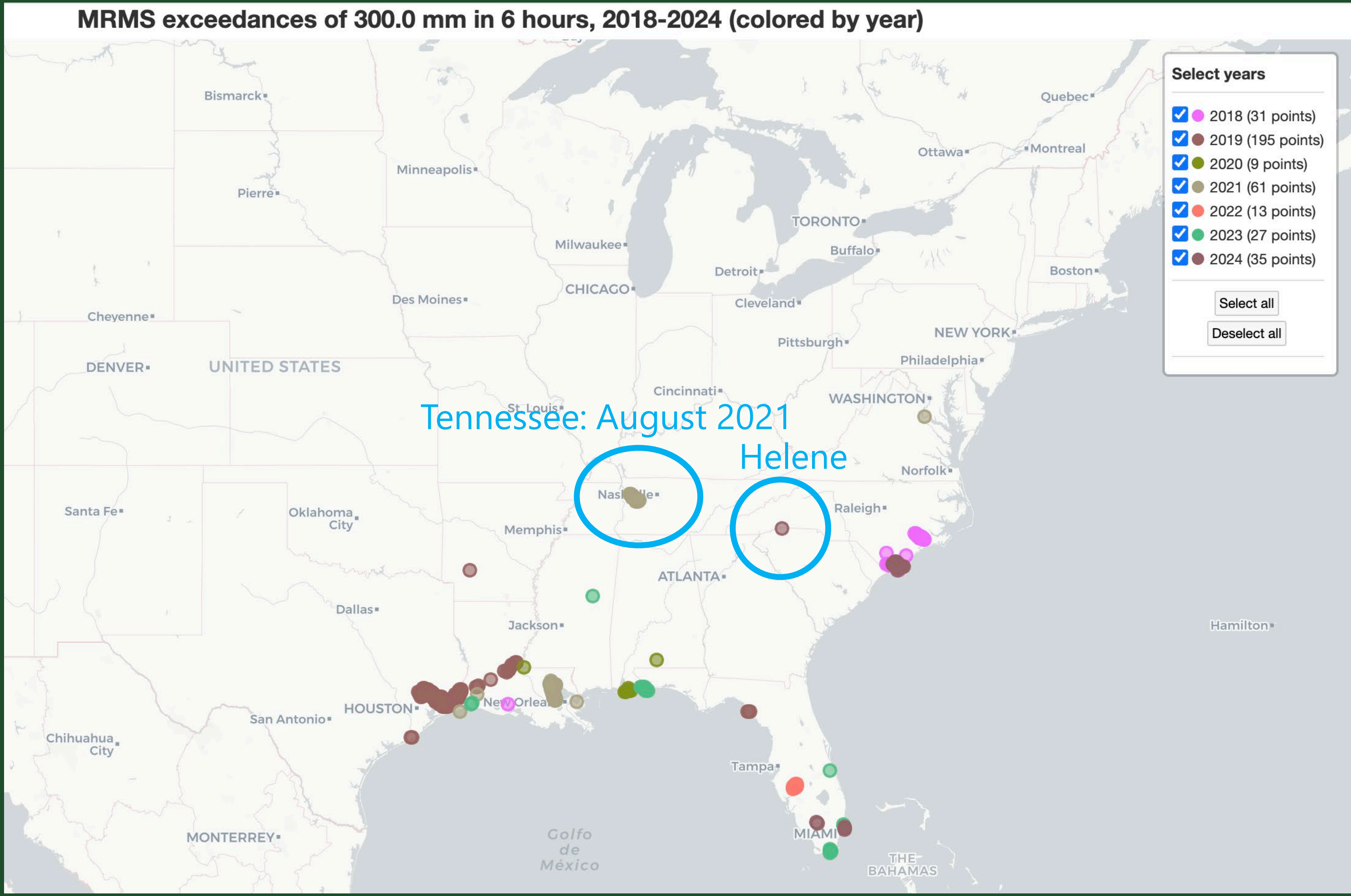
The NCAR–USGS 4-km Long-Term Regional Hydroclimate Reanalysis over the CONUS

R. M. Rasmussen, F. Chen, C.H. Liu, K. Ikeda, A. Prein, J. Kim, T. Schneider, A. Dai, D. Gochis, A. Dugger, Y. Zhang, A. Jaye, J. Dudhia, C. He, M. Harrold, L. Xue, S. Chen, A. Newman, E. Dougherty, R. Abolafia-Rosenzweig, N. D. Lybarger, R. Viger, D. Lesmes, K. Skalak, J. Brakebill, D. Cline, K. Dunne, K. Rasmussen, and G. Miguez-Macho

- CONUS404 (Rasmussen et al. 2023), 1981 through Sept. 2022
  - 40 years of WRF at 4-km grid spacing, using ERA5 boundary conditions
- Multi-Radar Multi-Sensor (MRMS), 2018-present
  - Pass 2 multi-sensor quantitative precipitation estimates, regridded to 4km

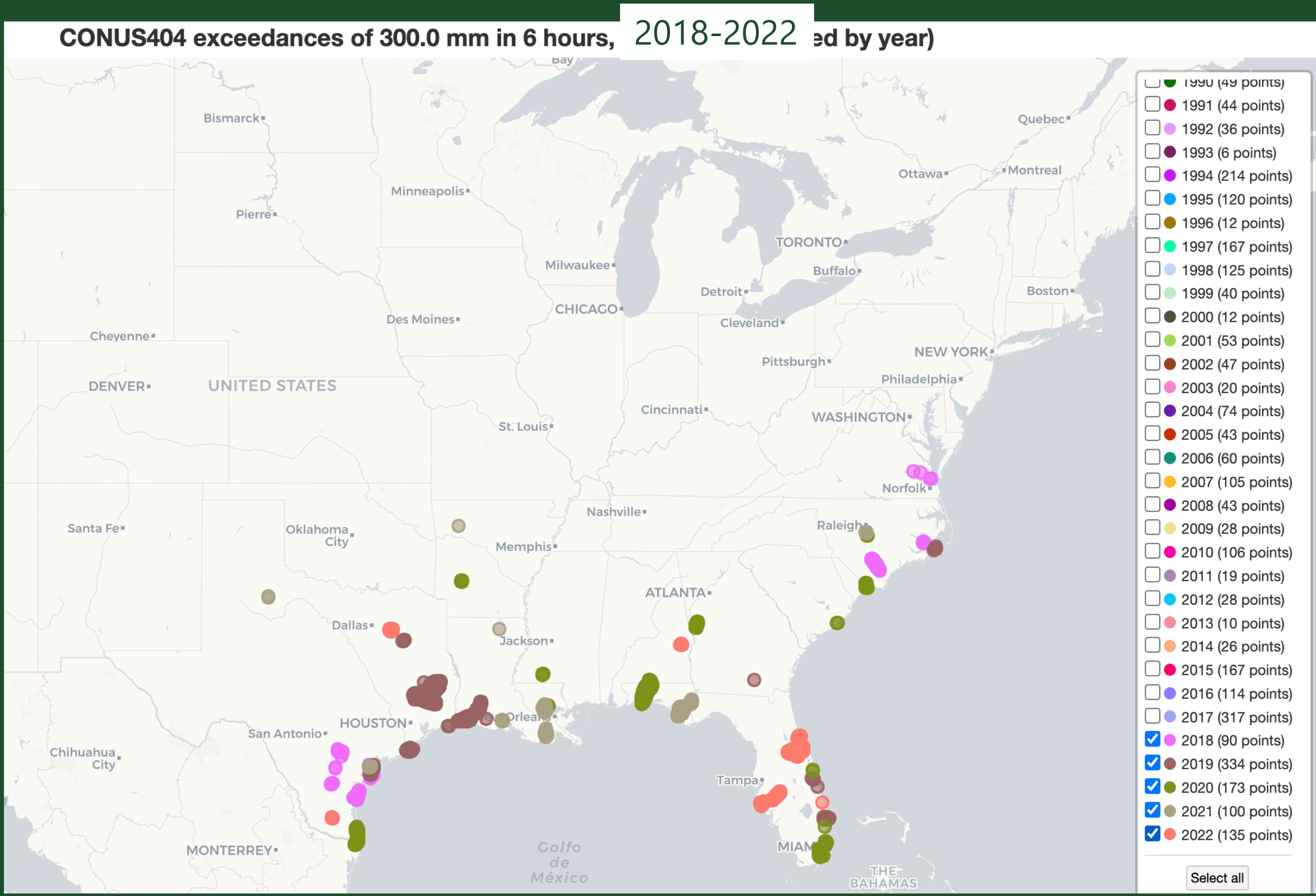
In MRMS from 2018-2024, extreme short-term rainfall is largely near the coasts, and largely associated with TCs

(Smethport: 780 mm in 6 h)



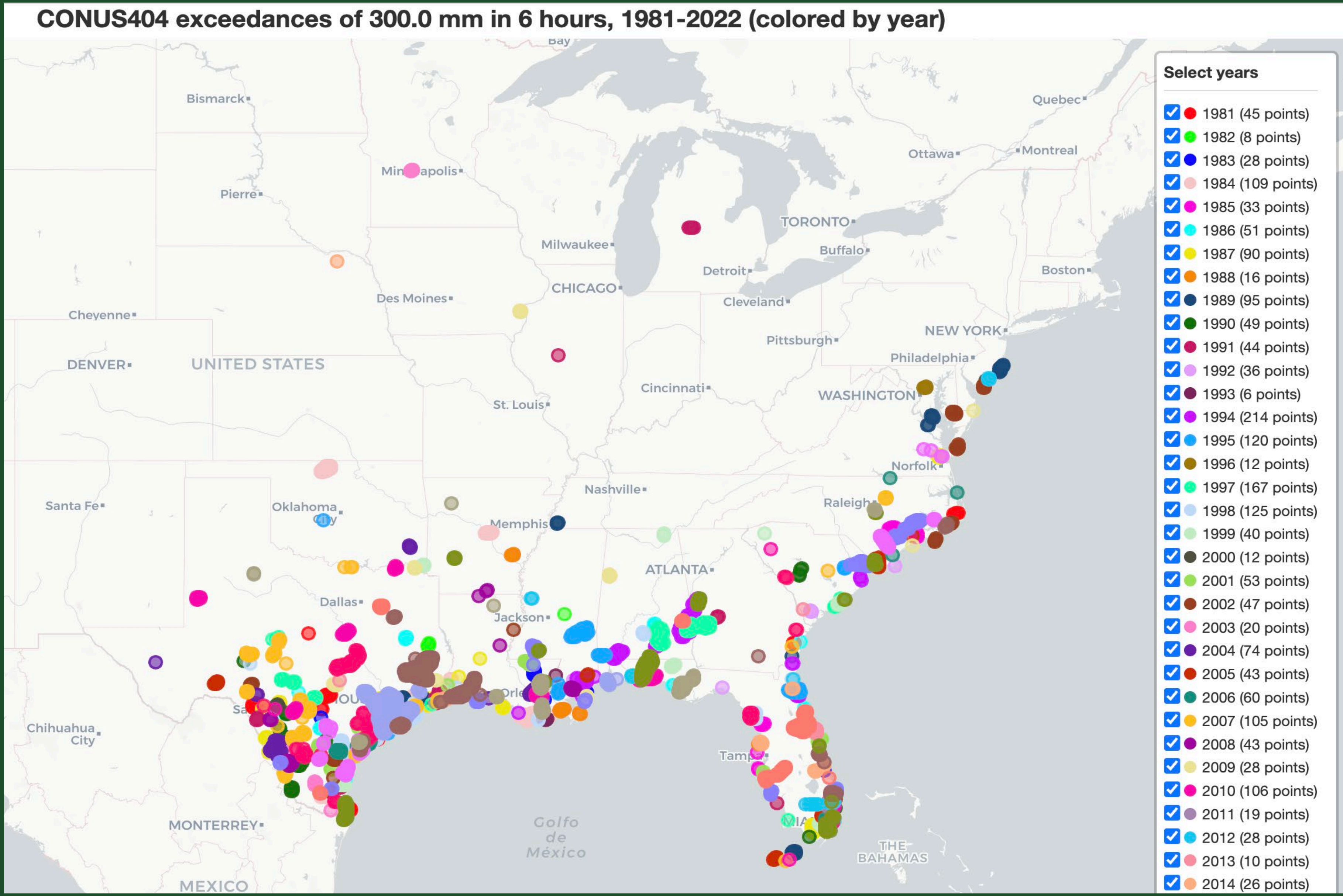
CONUS404 (2018-2022) has even more occurrences near the coasts

(Smethport: 780 mm in 6 h)

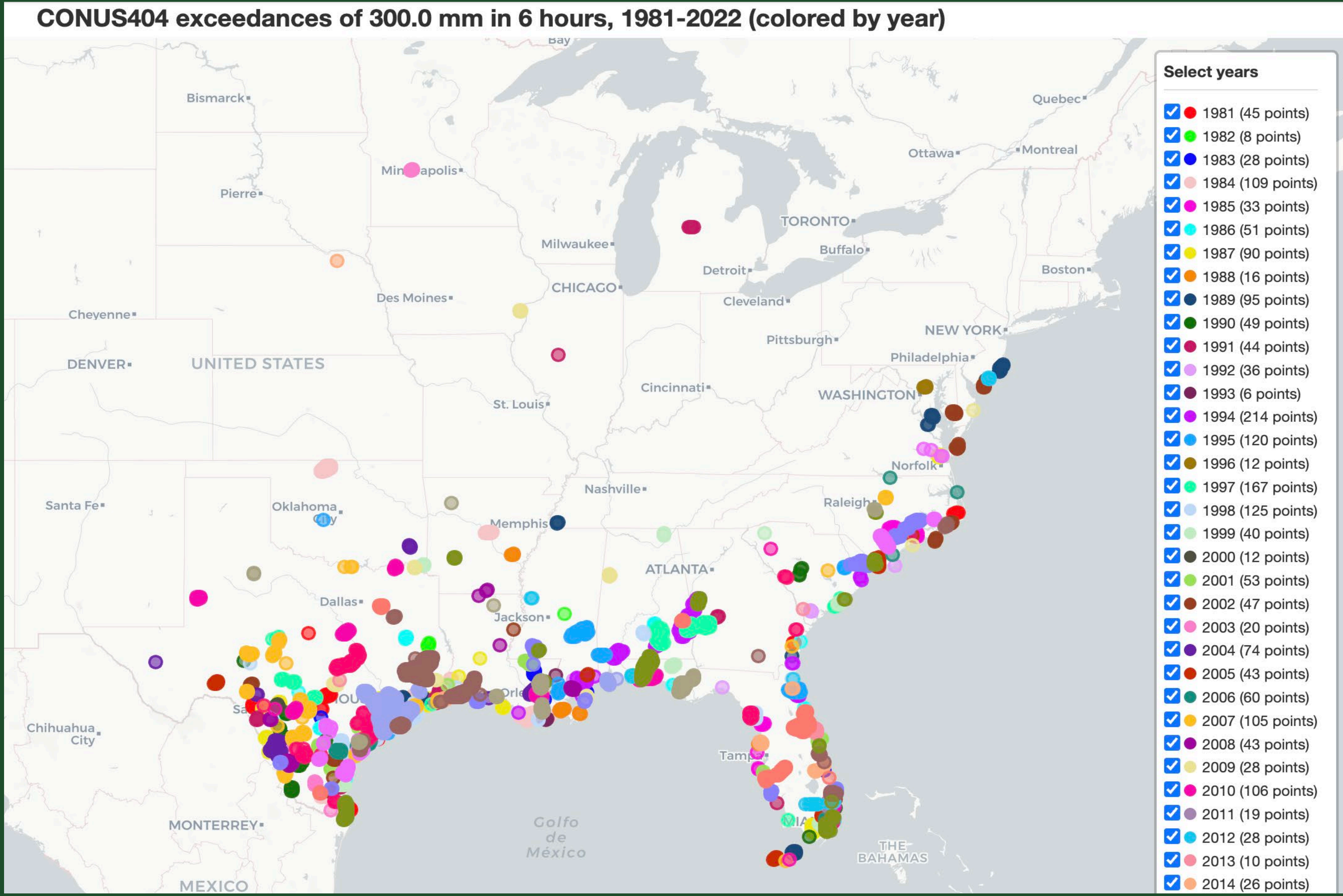


CONUS404 (1981-2022) has lots of extreme short-term rainfall near the coasts, but few occurrences near mountainous terrain

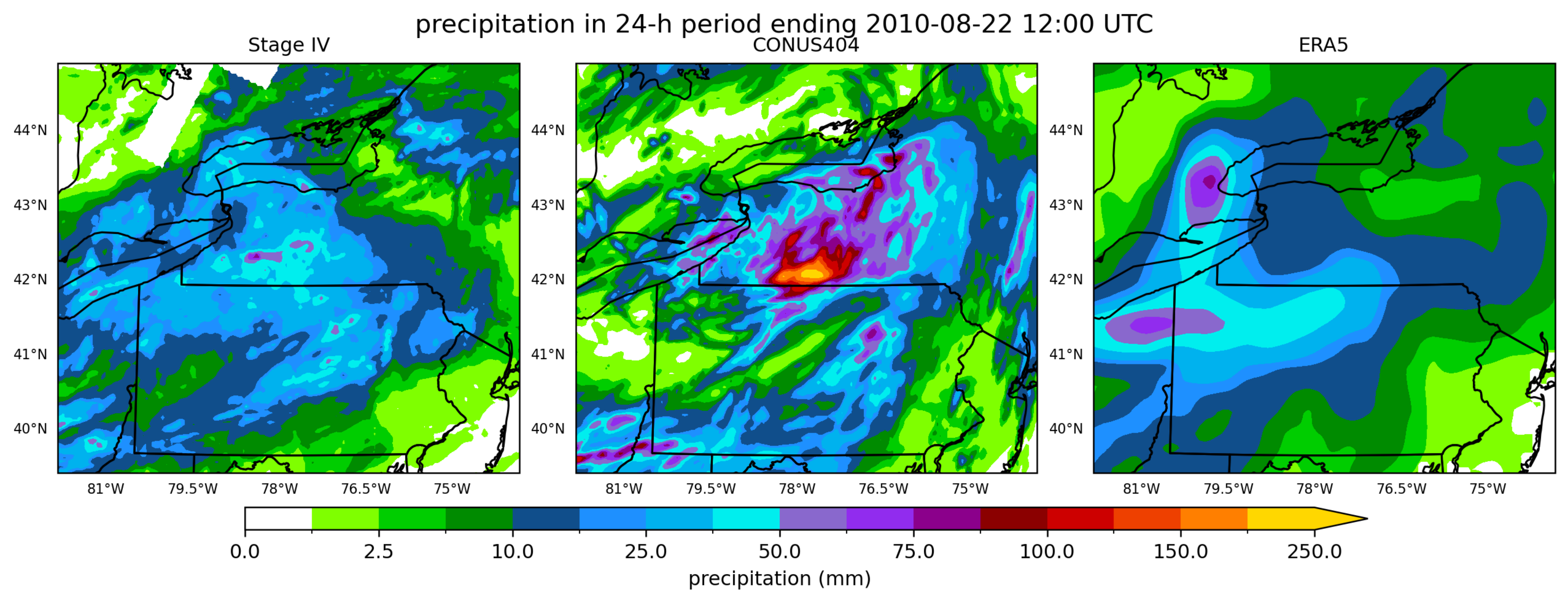
(Smethport: 780 mm in 6 h)



Very few, if any, “Smethport-like” storms even in 40+ years of convection-allowing simulation



This may be the nearest to a "Smethport-like" storm in CONUS404 – though not an event that actually happened, and "only" ~225 mm in 6 h

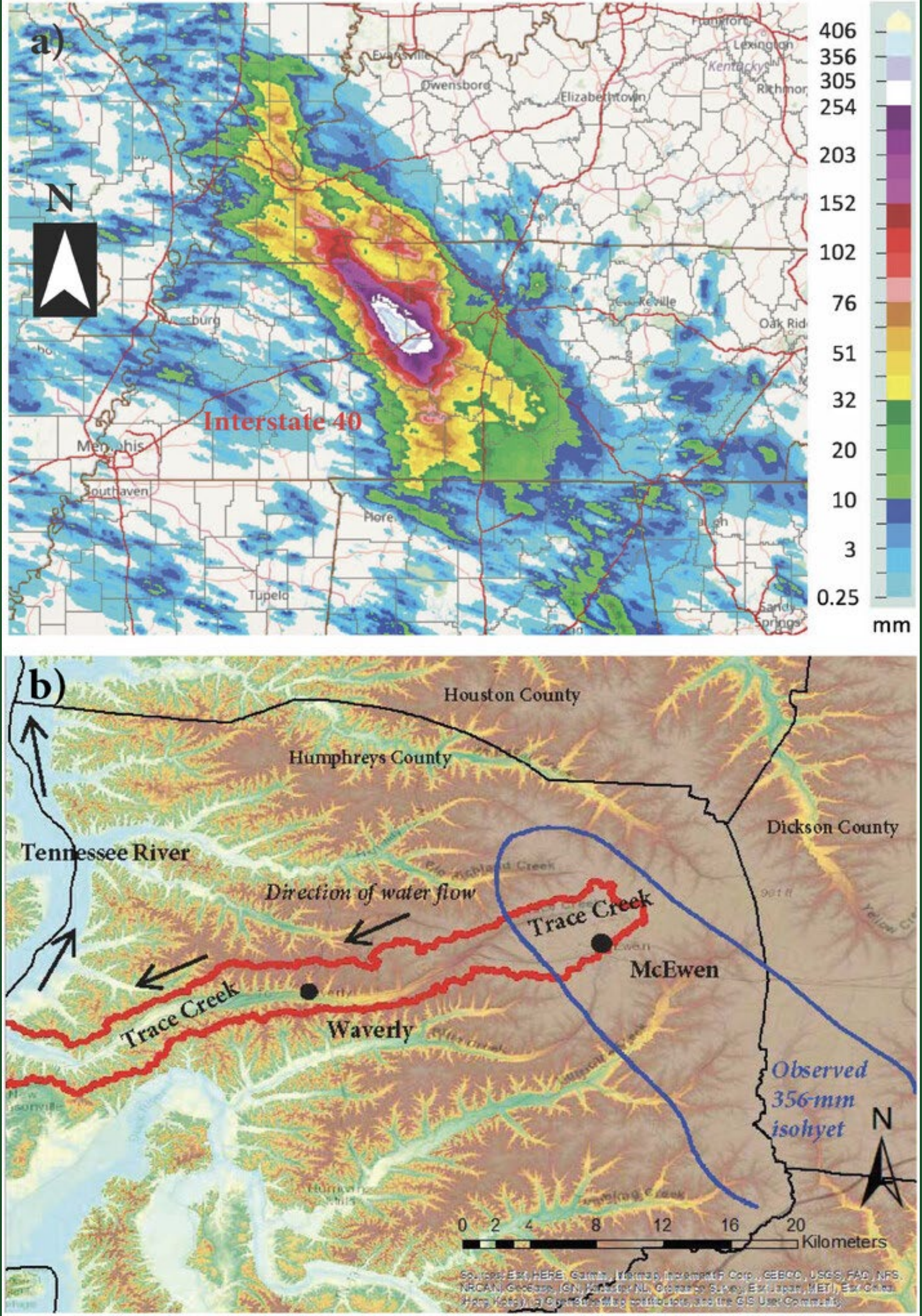


Tennessee state record rainfall, 21 August 2021

277 mm in 3 h
377 mm in ~9 h
526 mm in 24 h

Major flooding in Waverly

Storms organized as they approached the higher terrain in middle Tennessee

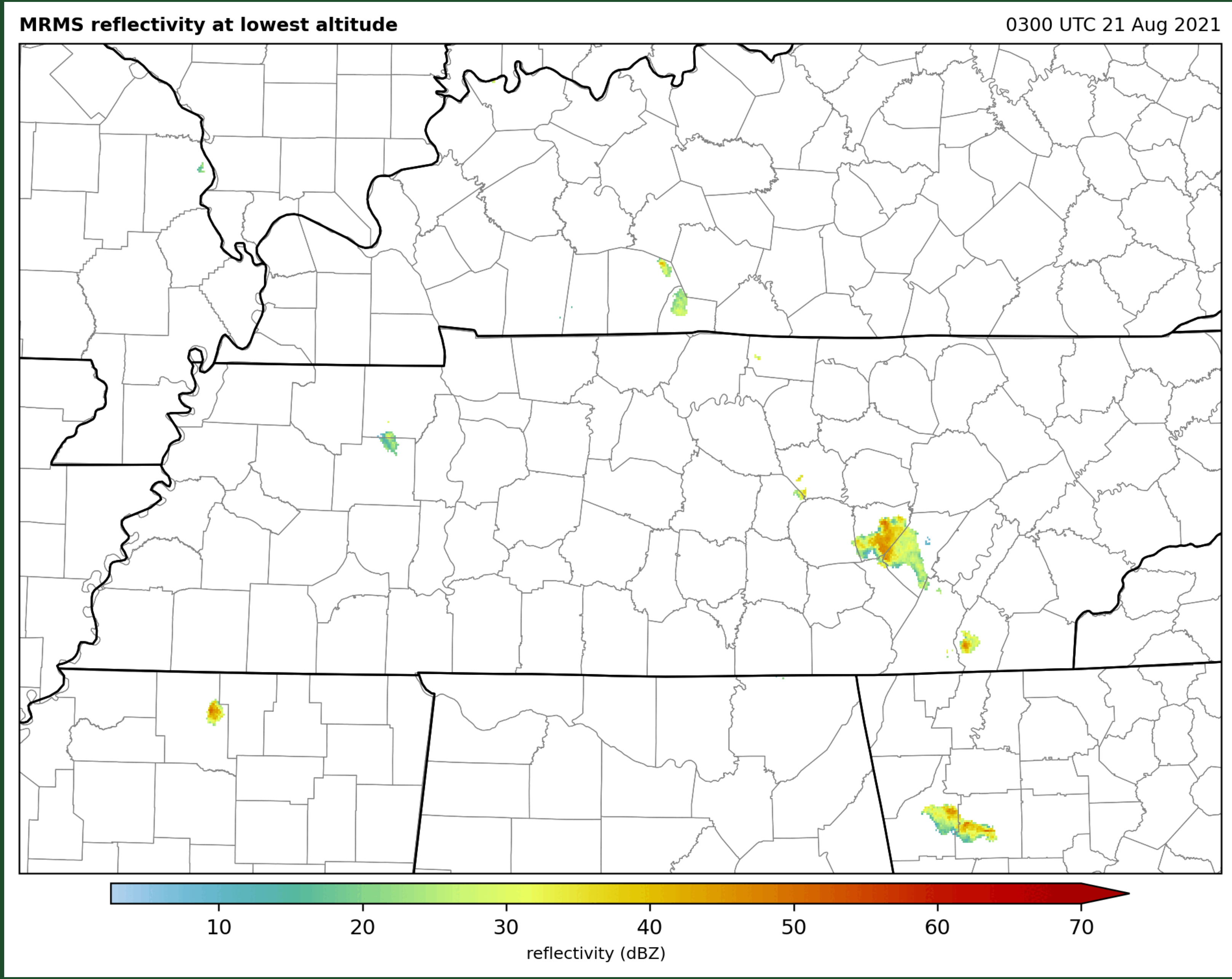


From Burke et al. (2024, BAMS)

Tennessee state record rainfall, 21 August 2021

Slow-moving MCS with training line of convection

See Burke et al. (2024, BAMS)



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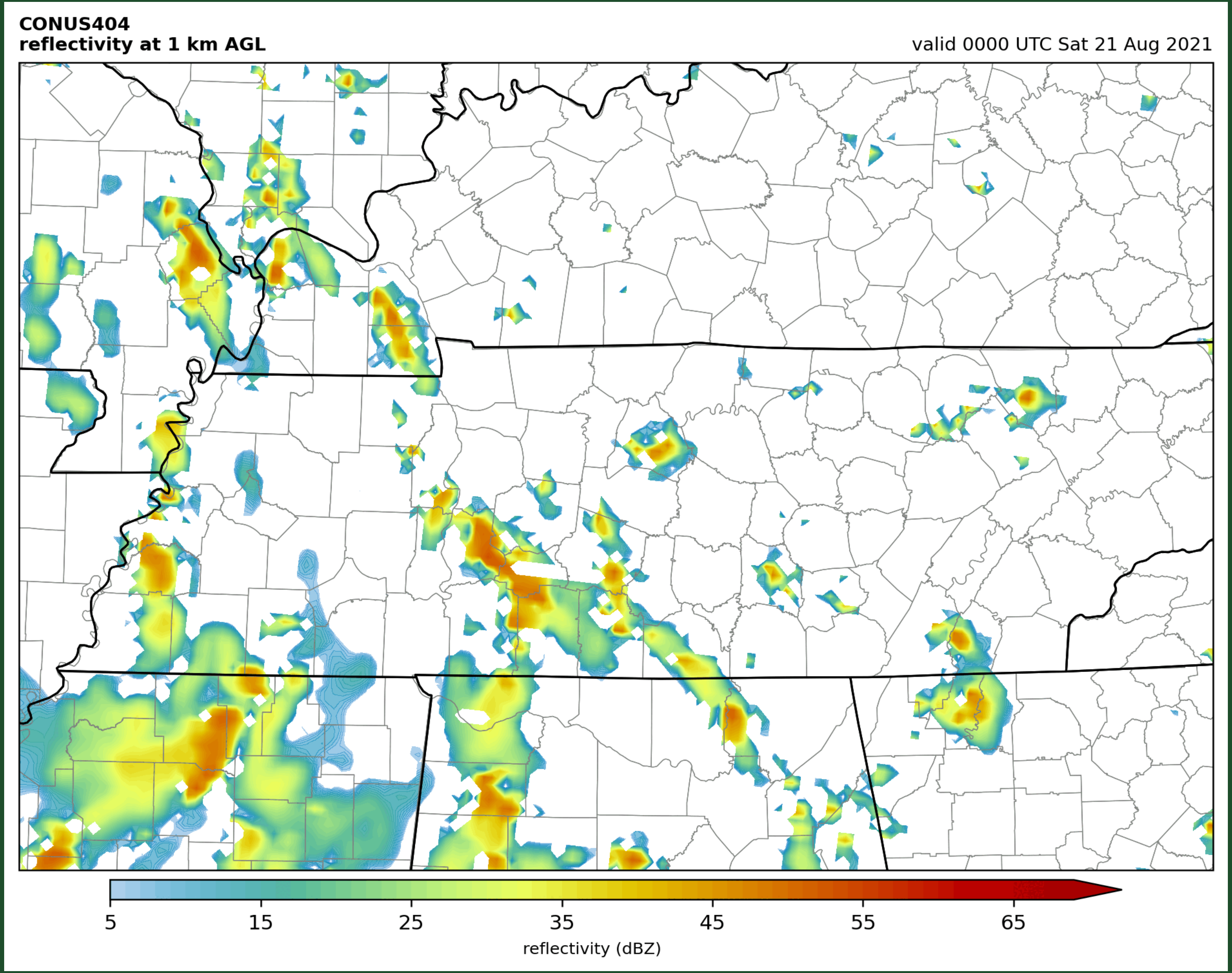
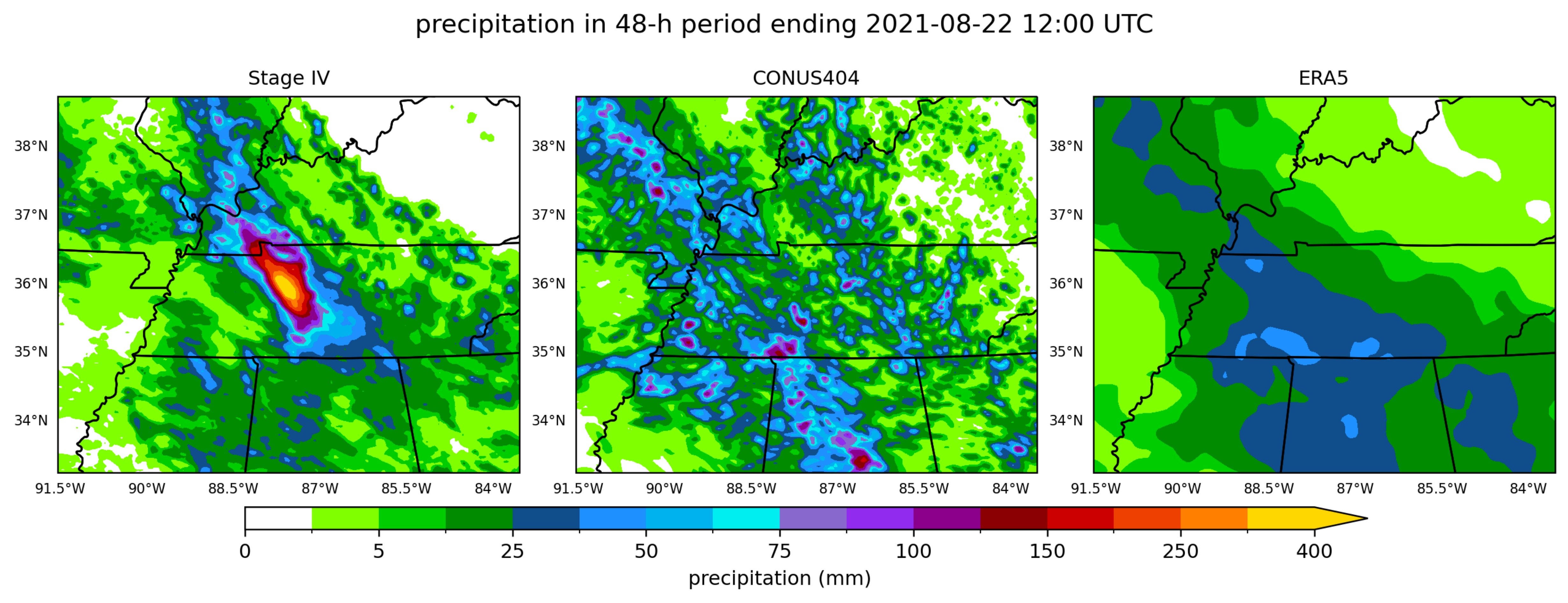
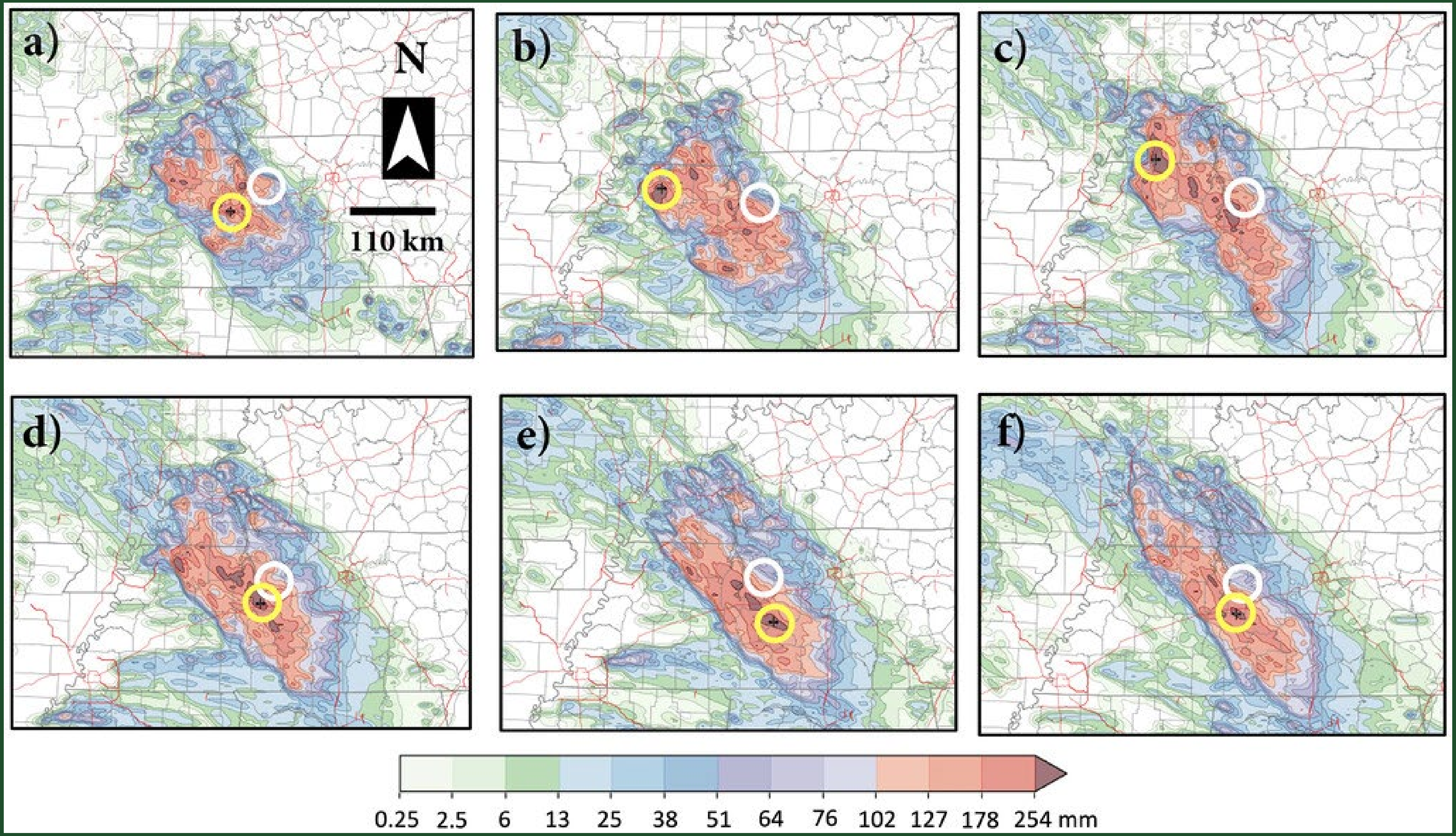


CONUS404 does not show anything like the observed event (and unsurprisingly ERA5 doesn't either)

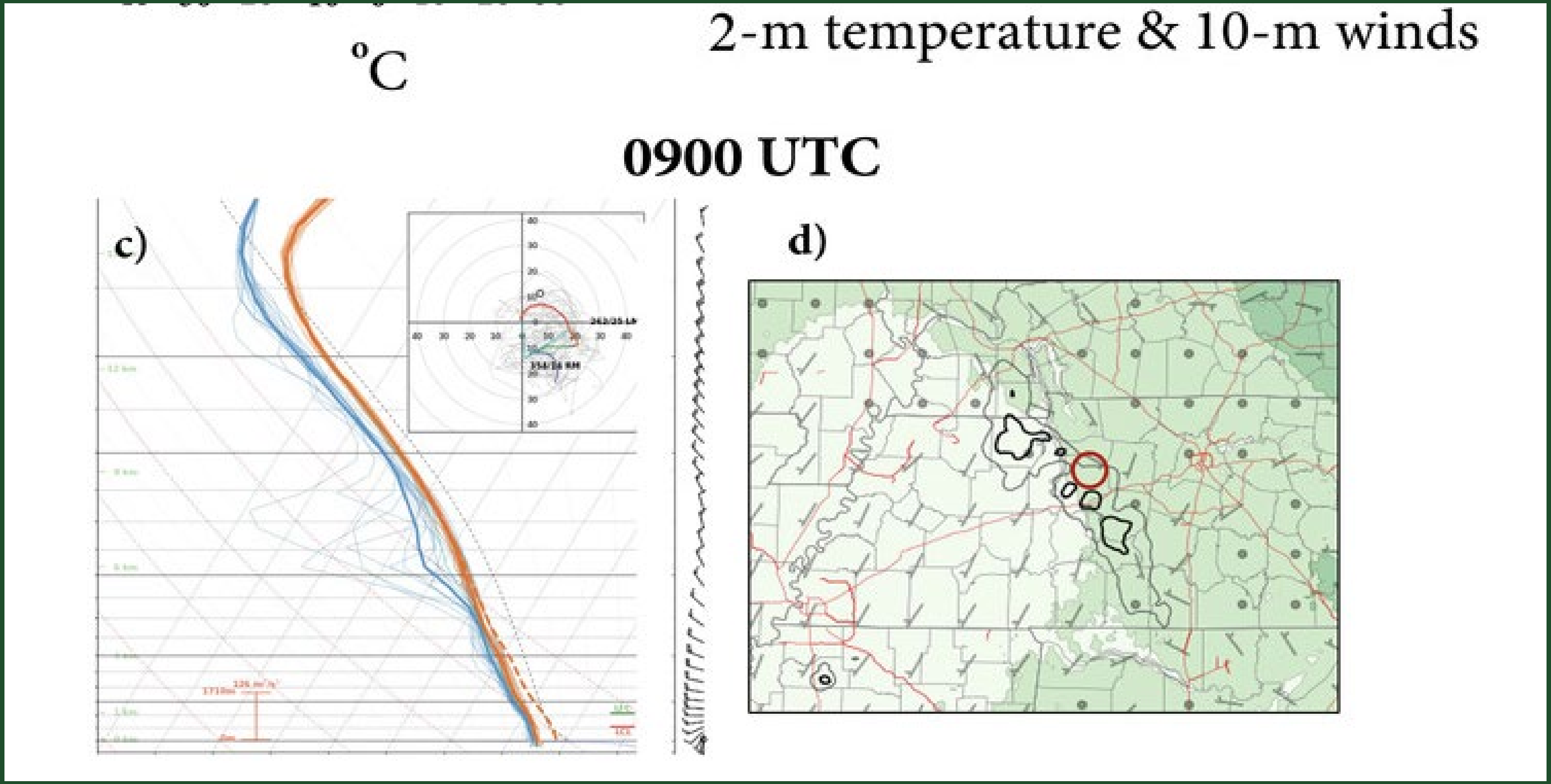


NSSL warn-on-forecast system produces rainfall rates with similar magnitude and intensity as observations



From Burke et al. (2024, BAMS)

The environment supported very efficient precipitation, along with storm rotation



From Burke et al. (2024, BAMS)

Current operational models and CONUS404 could not represent this event, but WoFS can – what can we take away from this?

- Models with 3-km grid spacing are capable of accurately representing extreme-rain-producing MCSs
- Assimilation of mesoscale observations (including radar) may be critical to accurate prediction of this type of MCS
- Did the terrain matter much for the precipitation distribution?

- Can we expect "PMP-type" model configurations to capture these events, given enough ensemble members (or other methods to sample climatological mesoscale variability)?

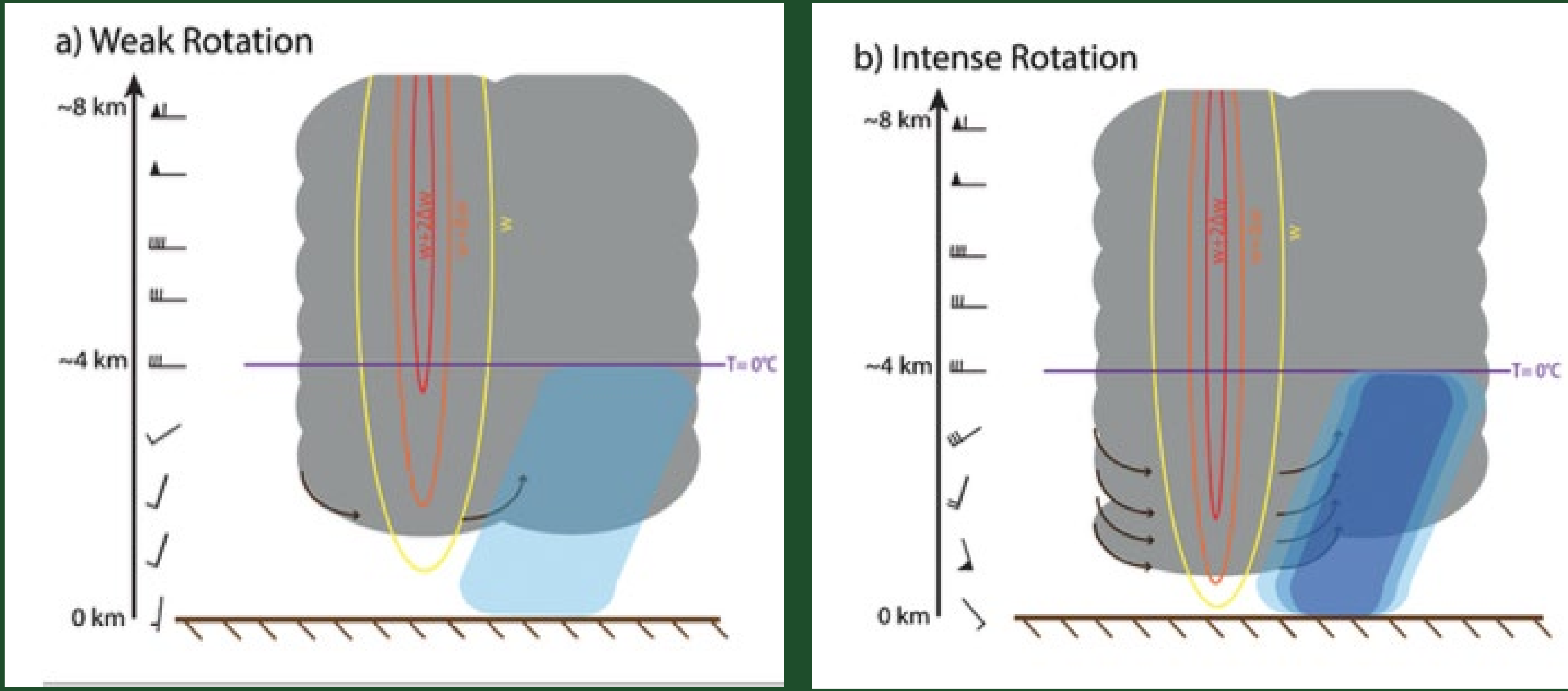
Key points for discussion

- The CONUS404 regional climate simulation produces plenty of extreme short-term convective rainfall, but it is focused more along the coasts than in regions of complex terrain
- Rather than a "reanalysis", CONUS404 should probably be thought of like one member of a convection-permitting forecast ensemble

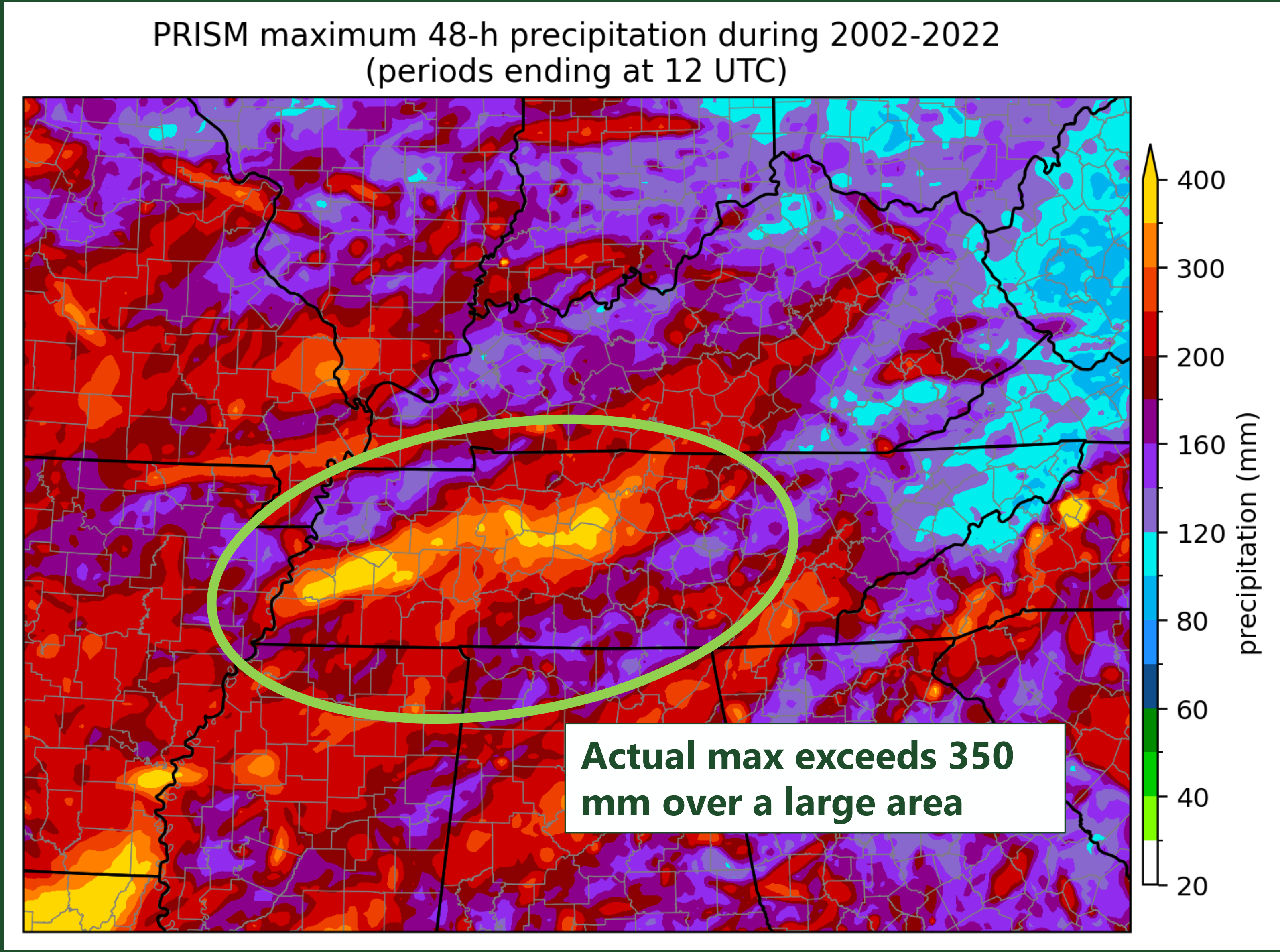
Key points for discussion

- It would be reasonable to expect that extreme convective rainfall in mountainous terrain would be *easier* to predict/simulate, but this does not appear to be true
  - Mesoscale-convective processes are generally just as important if not more important than the interactions with topography
  - This has important implications for model-based PMP, and for using simulations as a proxy for observations
  - And also has important implications for flooding, which very much depends on the topography!

Influence of storm-scale rotation on rainfall production

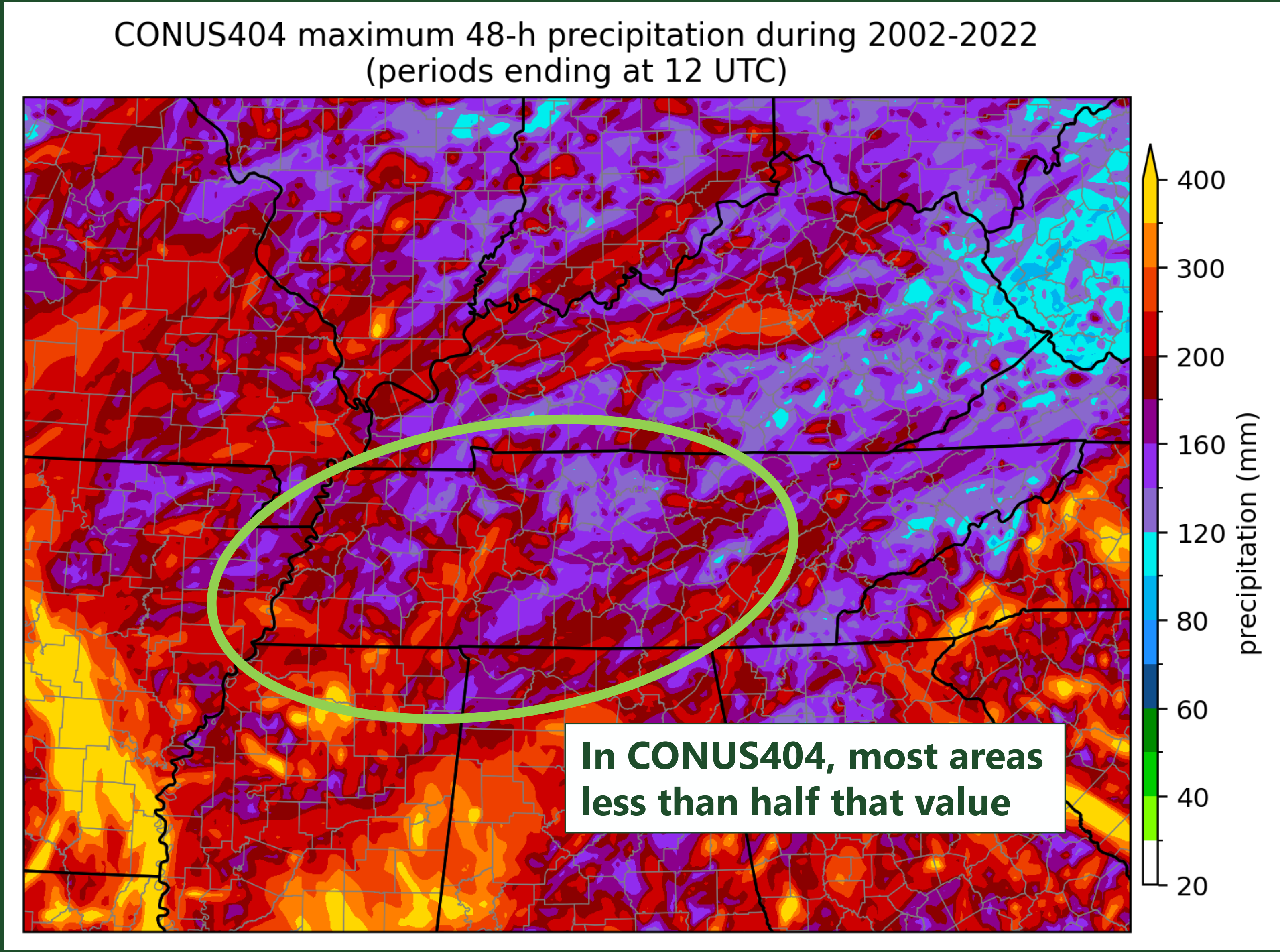


Precipitation Enhancement Mechanism. Schematic diagram illustrating the structural differences between (a) weakly rotating and (b) intensely rotating storm elements, as seen locally in the "Tax Day" event. Updrafts (warm contours) and cloud (gray shading) base are closer to the ground in the rotating regions (curved black arrows) of (b) the more intensely rotating storm compared to (a) the weakly rotating storm. These dynamical and thermodynamical changes lead to an increase in precipitation production (blue shading) in (b) the more intensely rotating storm.



What is the maximum 48-precipitation accumulation from 2002-2022?

PRISM



What is the maximum 48-precipitation accumulation from 2002-2022?

CONUS404

*Also does not accurately represent August 2021 record-breaking MCS, not shown here