What is a "100-year rainstorm?"
Return periods and what they can tell us about extreme rainfall

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COLORADO CLIMATE CENTER

CoCoRaHS WxTalk Webinar
June 2025

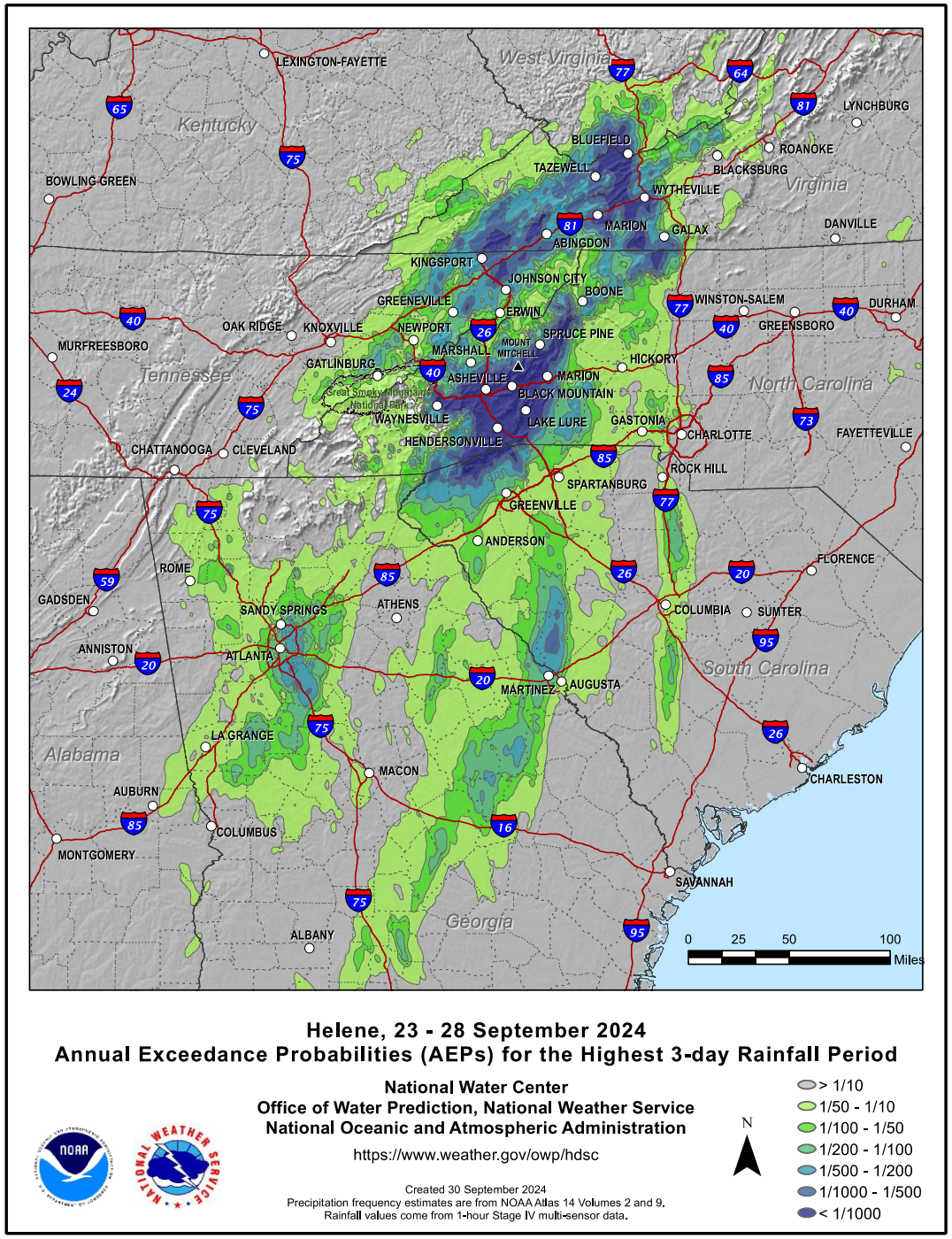
ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY

Hurricane Helene rainfall, September 2024

Annual exceedance probability

- > 1/10
- 1/50 - 1/10
- 1/100 - 1/50
- 1/200 - 1/100
- 1/500 - 1/200
- 1/1000 - 1/500
- < 1/1000

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



Helene, 23 - 28 September 2024
Annual Exceedance Probabilities (AEPs) for the Highest 3-day Rainfall Period

National Water Center
Office of Water Prediction, National Weather Service
National Oceanic and Atmospheric Administration

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

N

- > 1/10
- 1/50 - 1/10
- 1/100 - 1/50
- 1/200 - 1/100
- 1/500 - 1/200
- 1/1000 - 1/500
- < 1/1000

Created 30 September 2024
Precipitation frequency estimates are from NOAA Atlas 14 Volumes 2 and 9.
Rainfall values come from 1-hour Stage IV multi-sensor data.

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Terminology

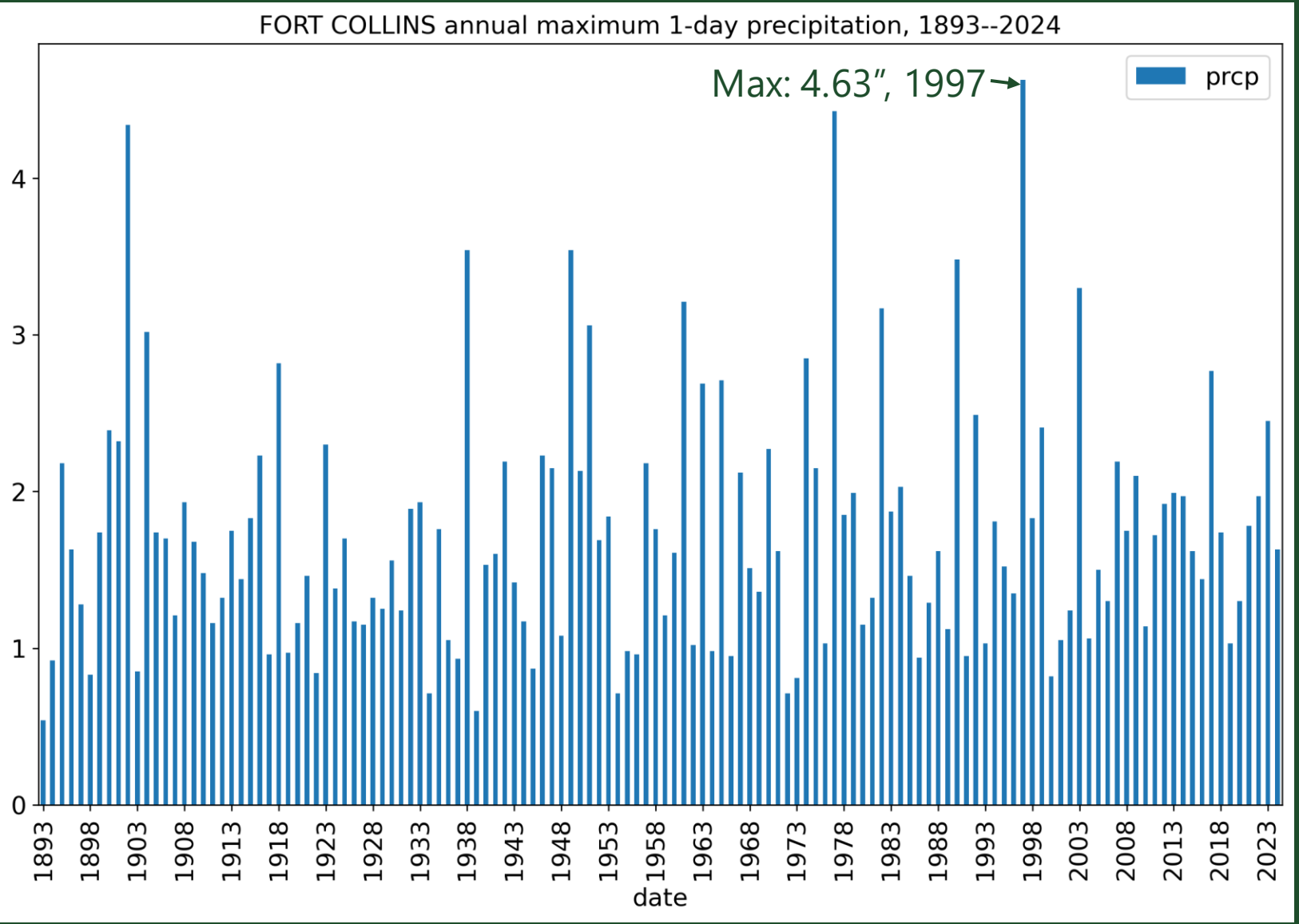
- **Annual exceedance probability (AEP):** based on past rainfall data and statistical methods, “the probability associated with exceeding a given amount for a specified duration and at a given location in any given year at least once”
- **Average recurrence interval (ARI), or return period:** the inverse of AEP. If a rainfall amount has a 1% AEP, it has an average recurrence interval of 100 years.
  - In other words, at that location, that rain amount should be expected to be exceeded, on average, once every 100 years

Terminology

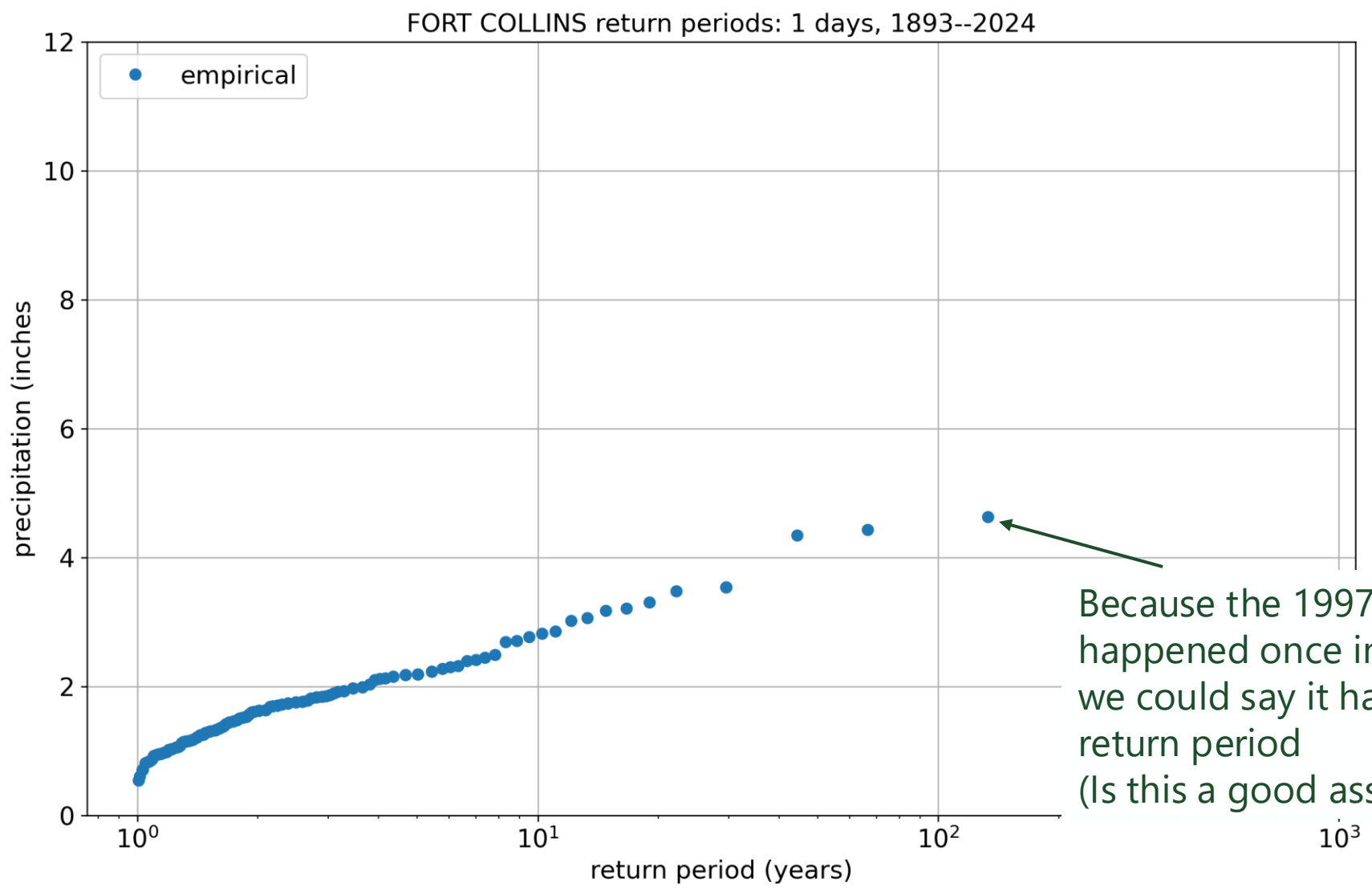
- AEPs and ARIs are also calculated for different rainfall **durations**
- Anywhere from minutes to weeks

- **NOAA Atlas 14:** the current official source of precipitation frequency estimates in the US.
  - Has been expanded across the country over the last ~20 years.
  - First editions released in 2004, most recent update was the interior northwest in 2024
  - Atlas 14 still does not exist for Washington and Oregon
- **NOAA Atlas 15:** updated precipitation frequency estimates currently in progress. Expected release in 2026.

Fort Collins, CO: most 1-day rainfall in each year

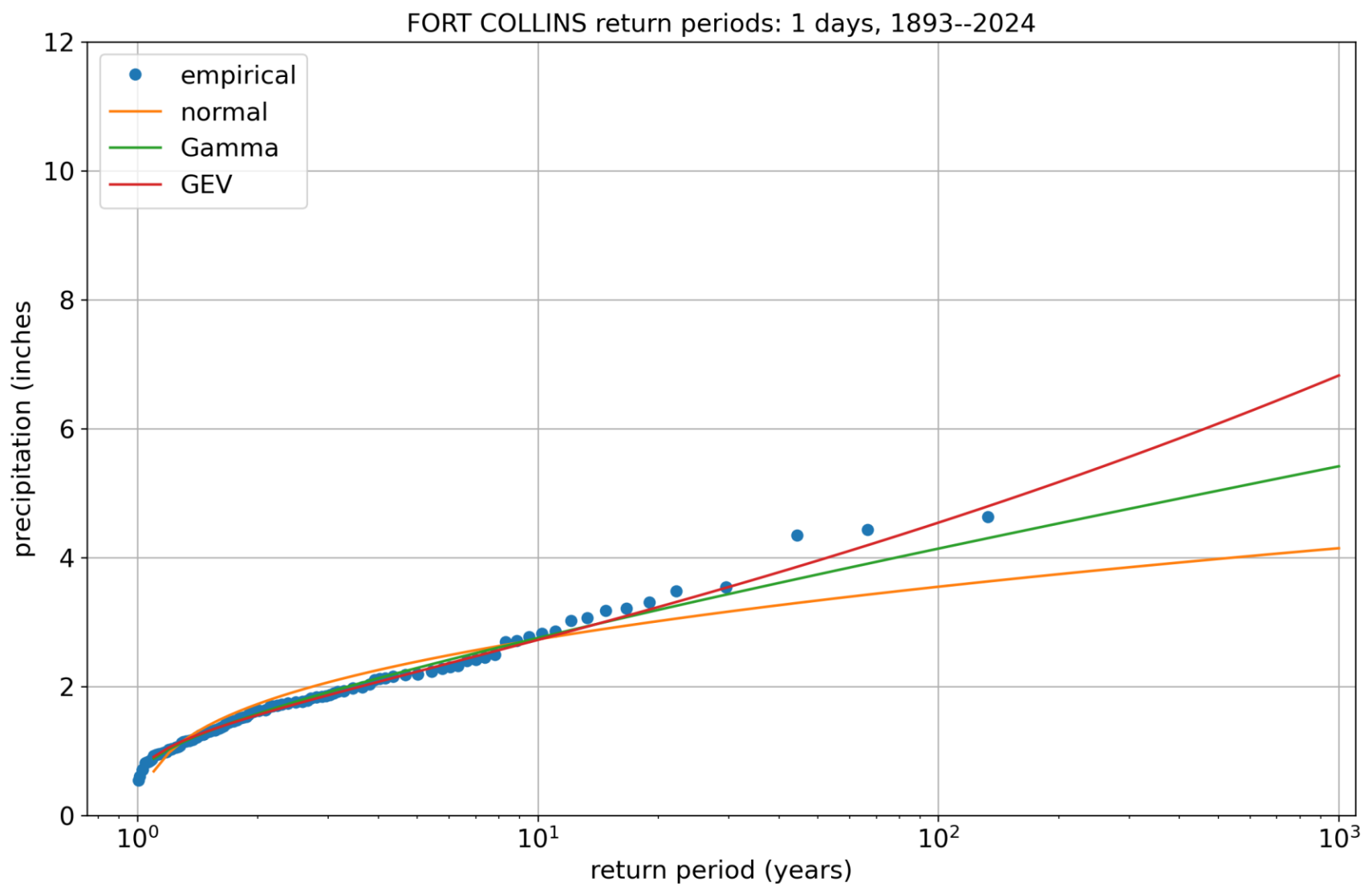


Sort these from lowest to highest, calculate a return period based on the data alone



Because the 1997 storm happened once in 132 years, we could say it has a 132-year return period
(Is this a good assumption?)

These points appear to follow a curve, so we can use statistics to estimate that curve

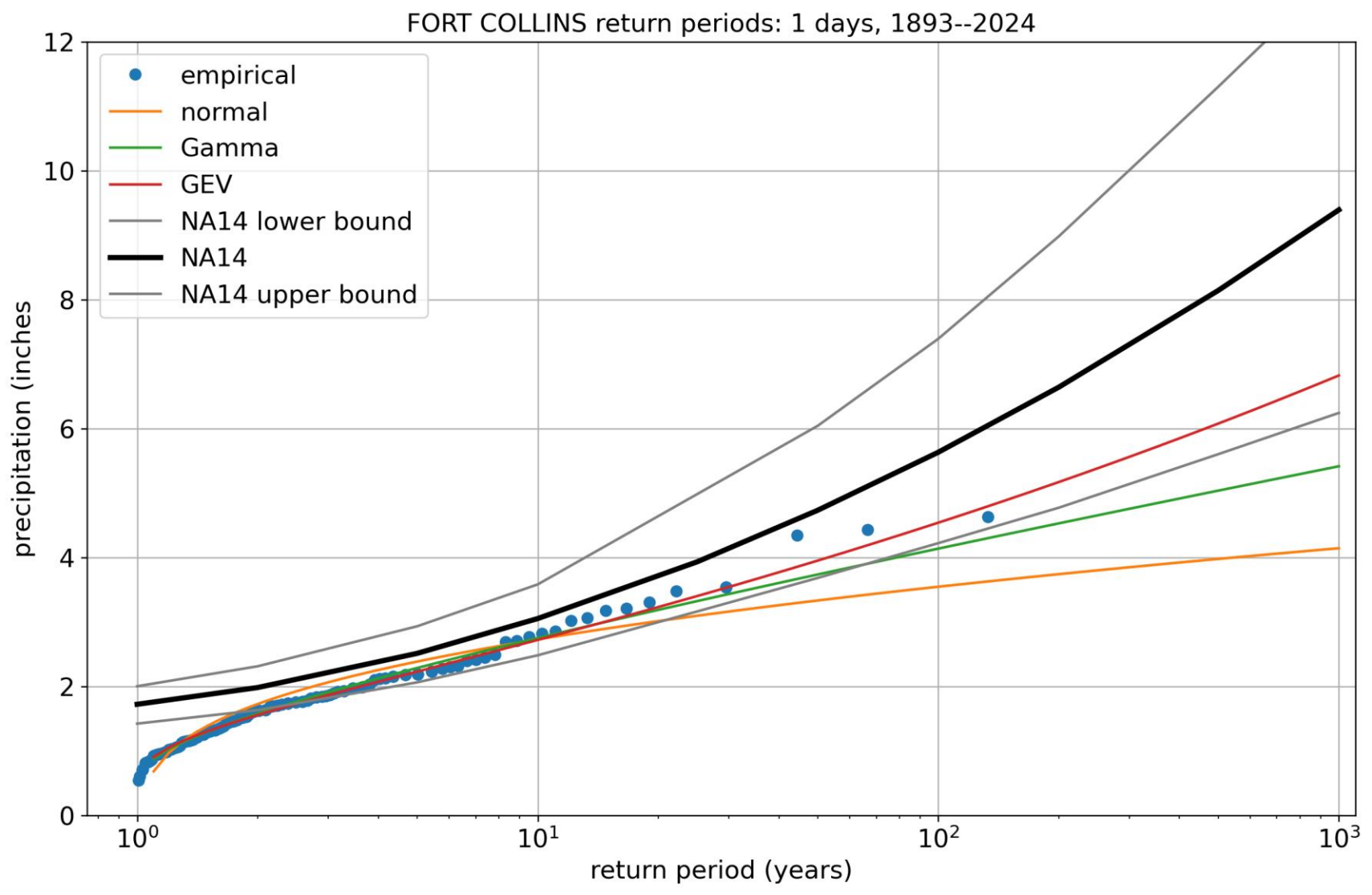


"GEV": Generalized Extreme Value distribution, which is commonly used

What else needs to be considered?

- If CoCoRaHS has taught us anything, it's that rainfall can vary a lot over small distances. So we should probably also consider data from nearby stations if we have them.
  - If it has rained that hard on the other side of town, it's possible it could rain that hard on your side of town too.
- The most rain that could fall in a 24-hour period might not line up exactly with the 24-hour period when the observations are taken. Should account for this also.

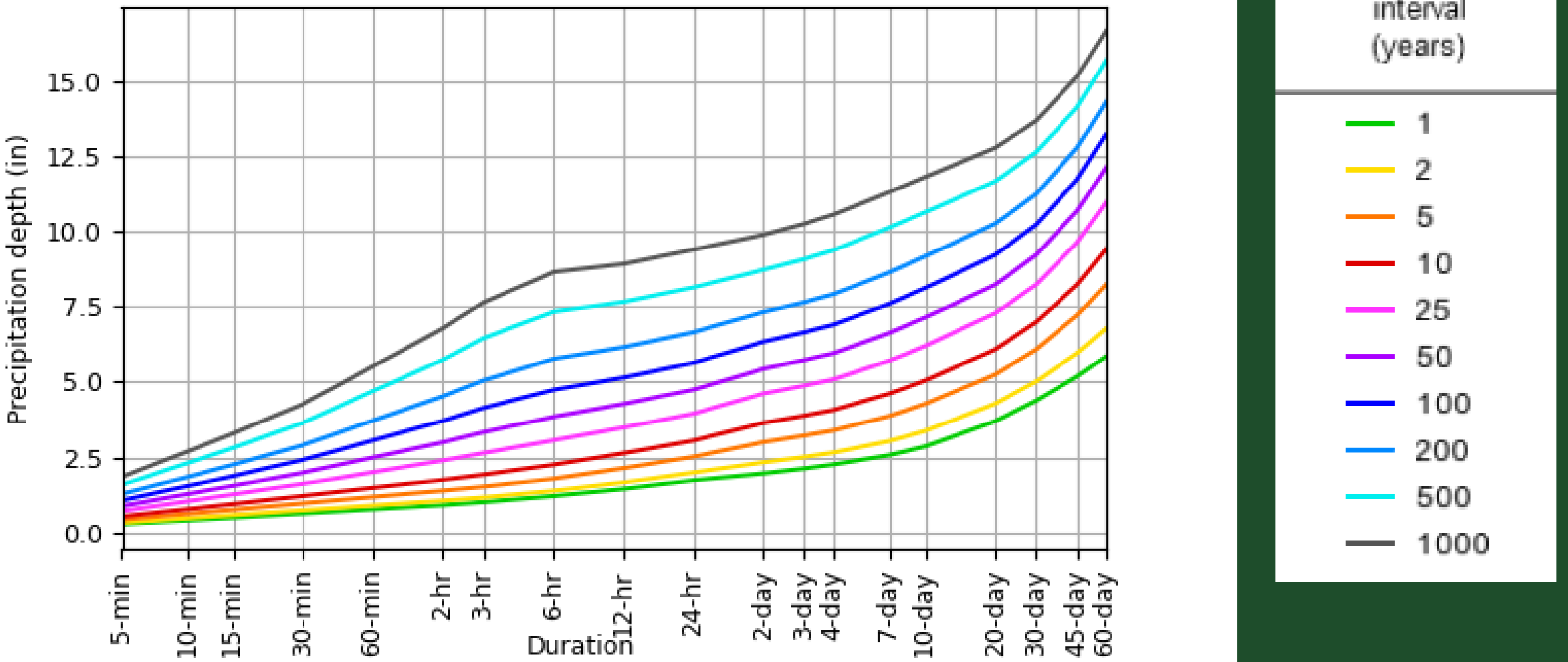
These factors are considered in NOAA Atlas 14, and their rain amounts are a little higher than our simple GEV fit



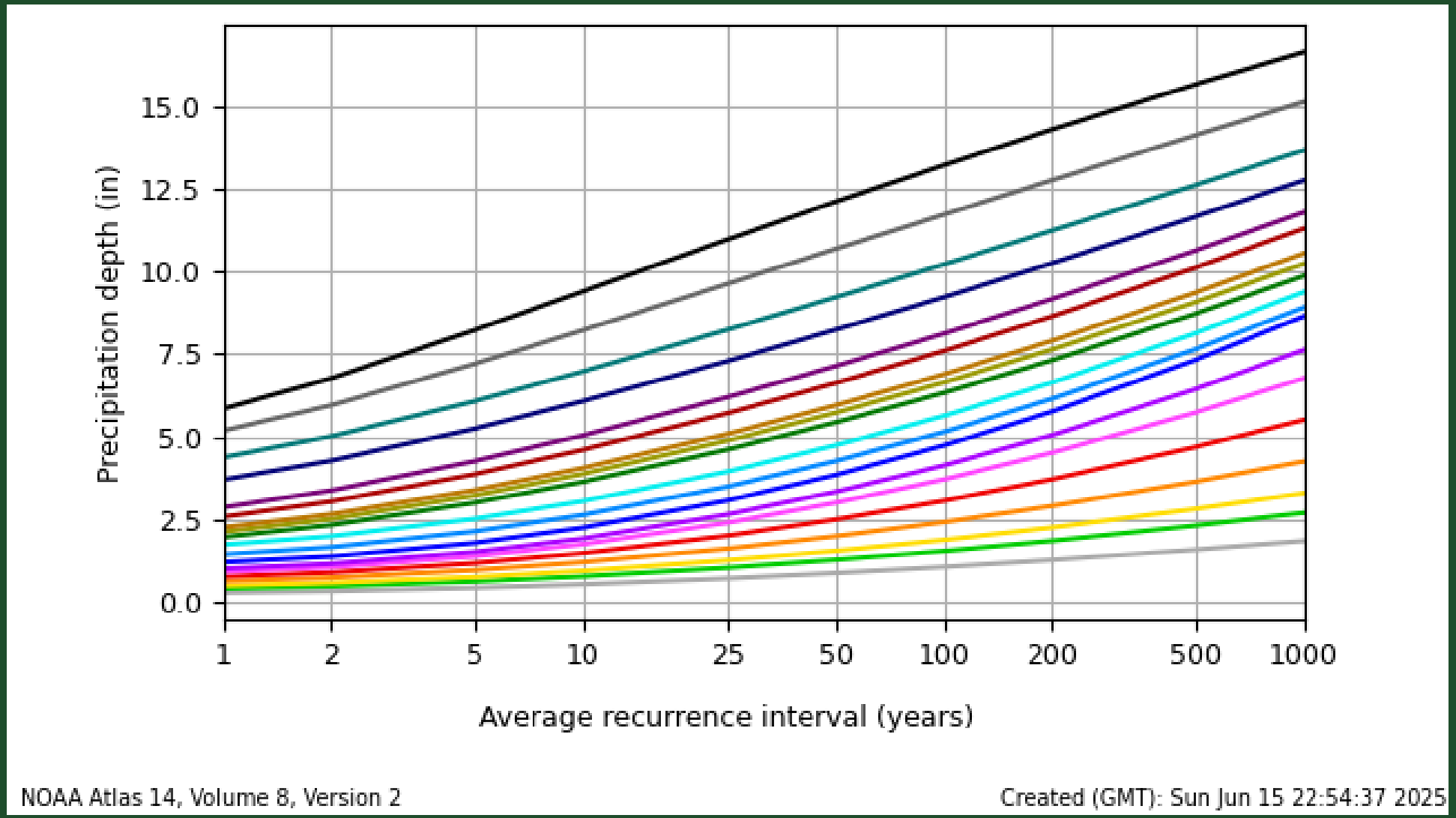
NOAA Atlas 14 in black

PDS-based depth-duration-frequency (DDF) curves
Latitude: 40.5747°, Longitude: -105.0825°

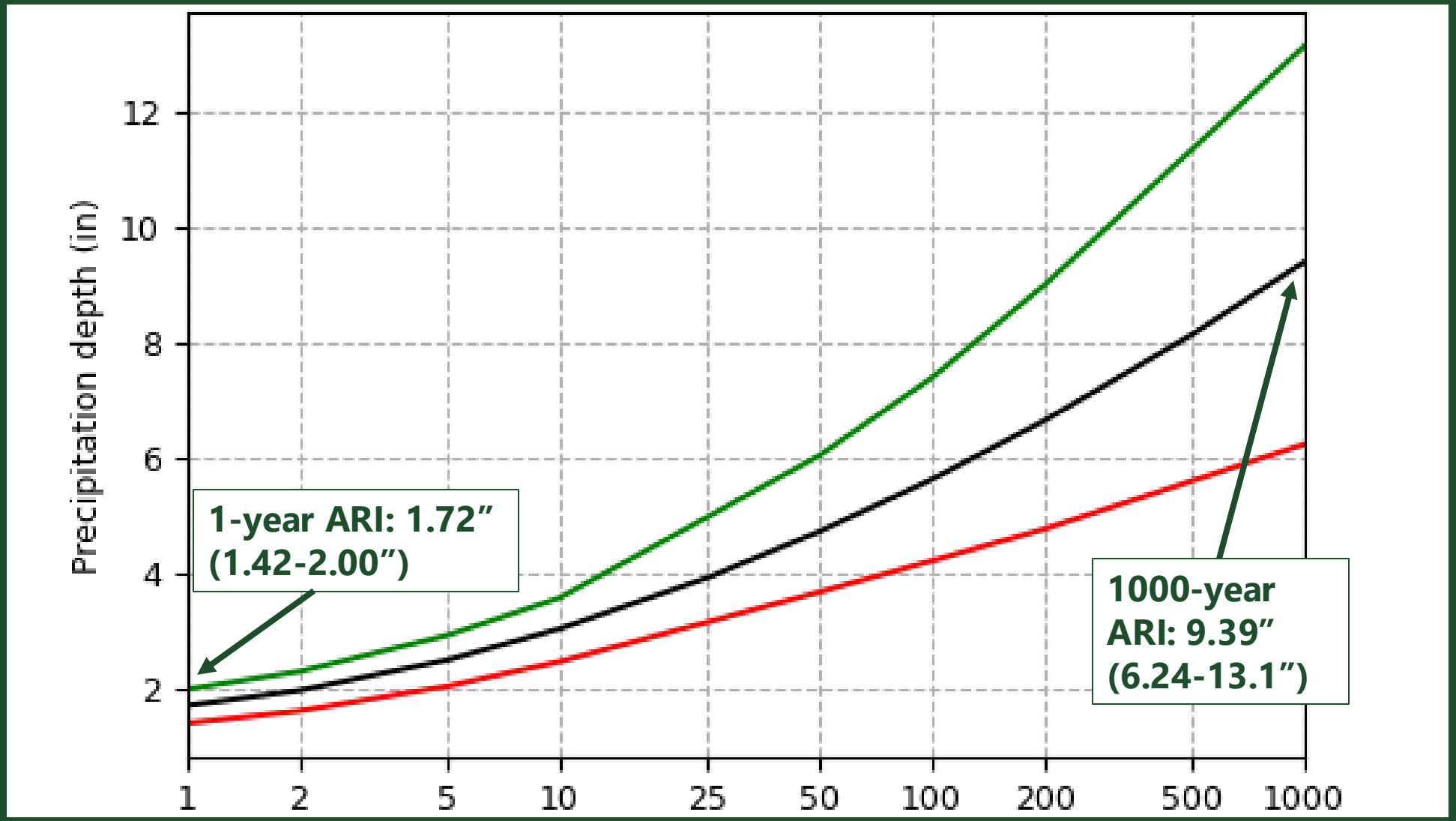
Fort Collins, Colorado



Fort Collins, Colorado



Fort Collins, Colorado, 24-hr duration, confidence intervals



https://hdsc.nws.noaa.gov/pfds/pfds_map_cont.html?bkmrk=co

Why do the ranges get so large?

- We generally have 100-200 years of data at best, so there is a lot more uncertainty for the rarer events
  - But still possible to make an estimate of the 1000-year rain amount even without 1000 years of data!

Interested in trying this yourself? There's a nice tutorial with example code at:
https://comptools.climatematch.io/tutorials/W2D3_ExtremesandVariability/student/W2D3_Tutorial2.html

Adding more data can change the estimates in a significant way

Atlas 14 was updated for Texas in 2018, after Hurricane Harvey

100-year, 24-hour ARI amounts increased by >20%, in large part because data from Harvey was included

https://www.weather.gov/media/owp/oh/hdsc/docs/Atlas14_Volume11.pdf

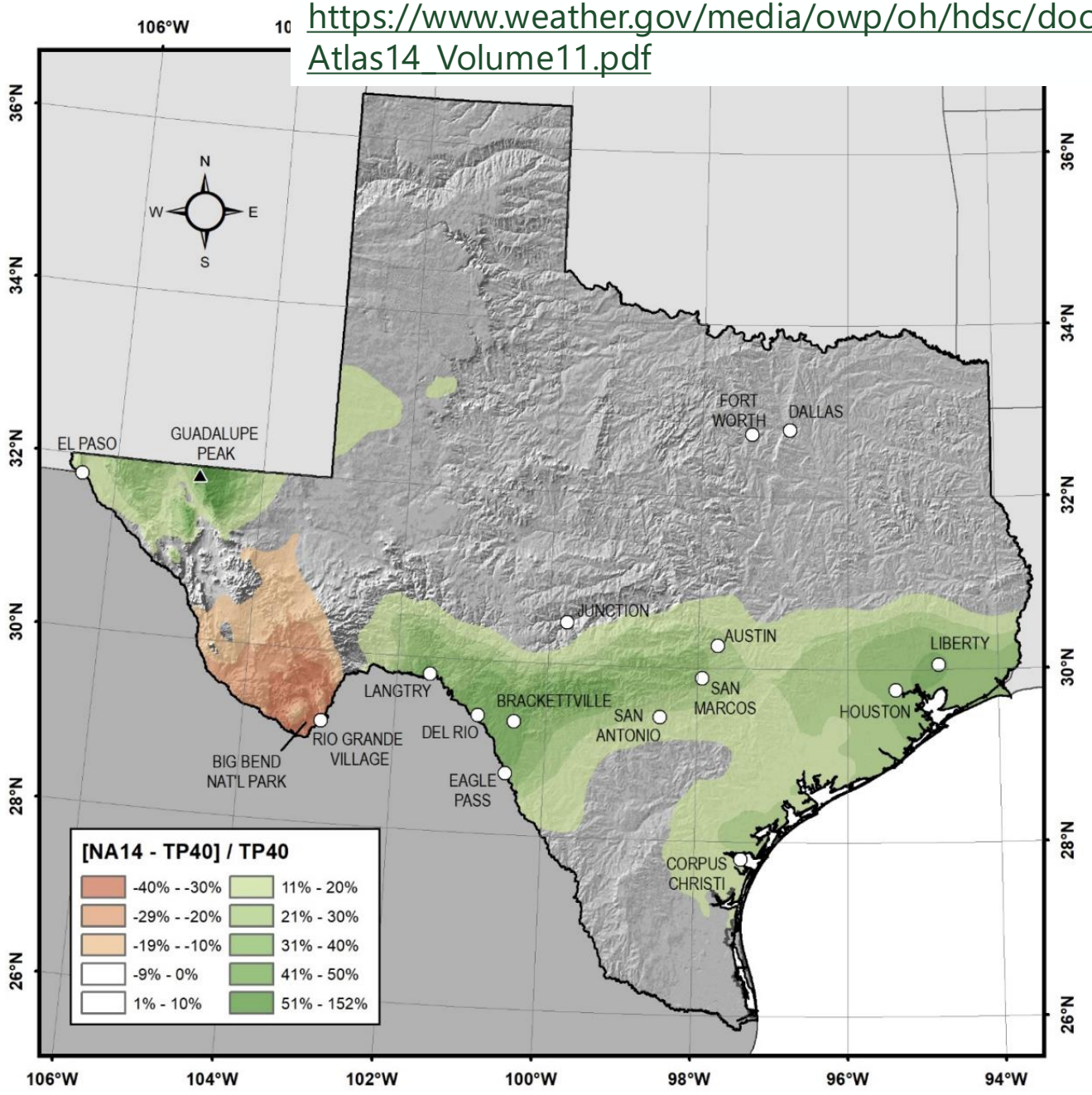


Figure 7.4. Map showing percent differences in 100-year 24-hour estimates between NA14 and TP40.

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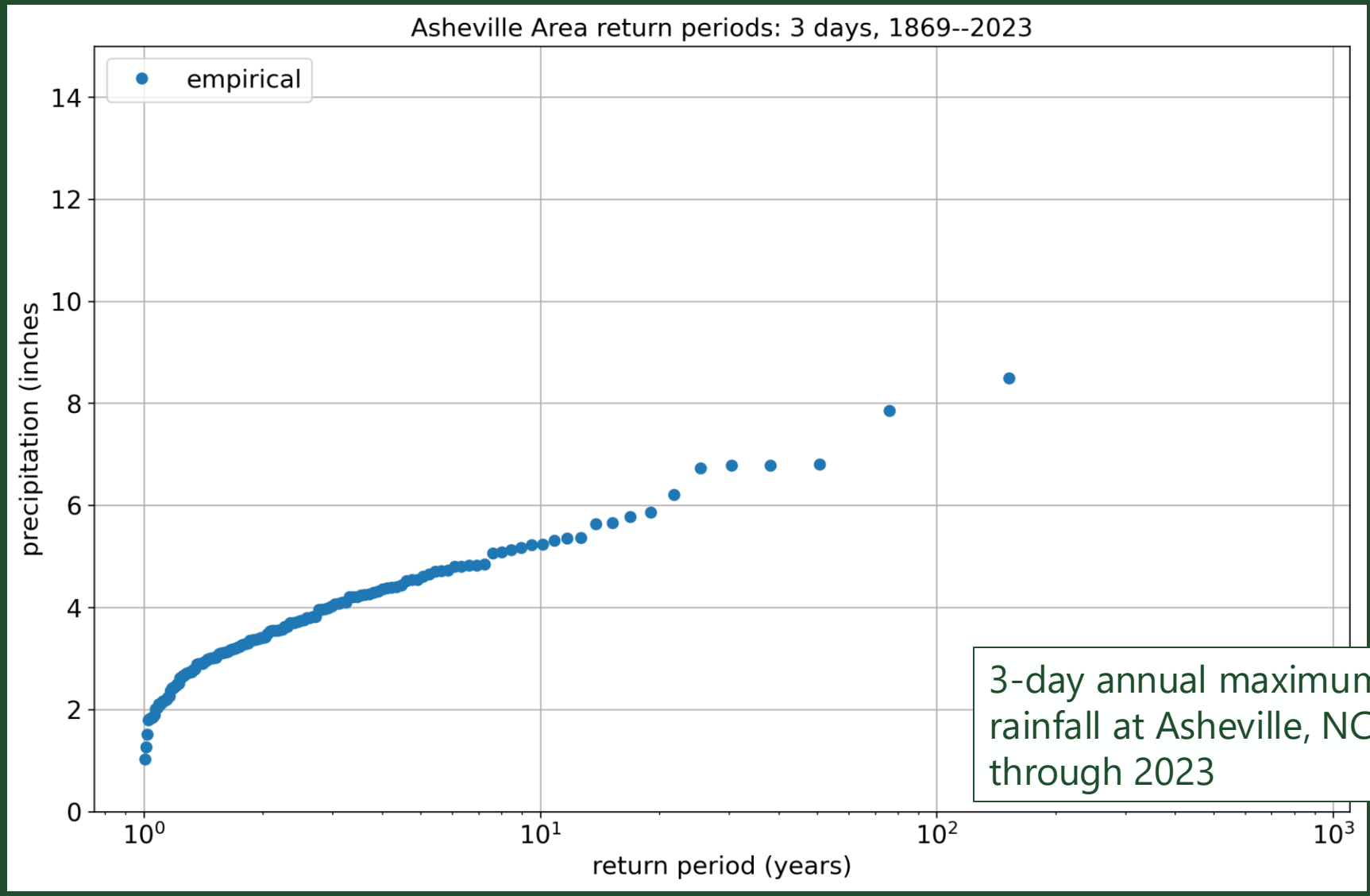
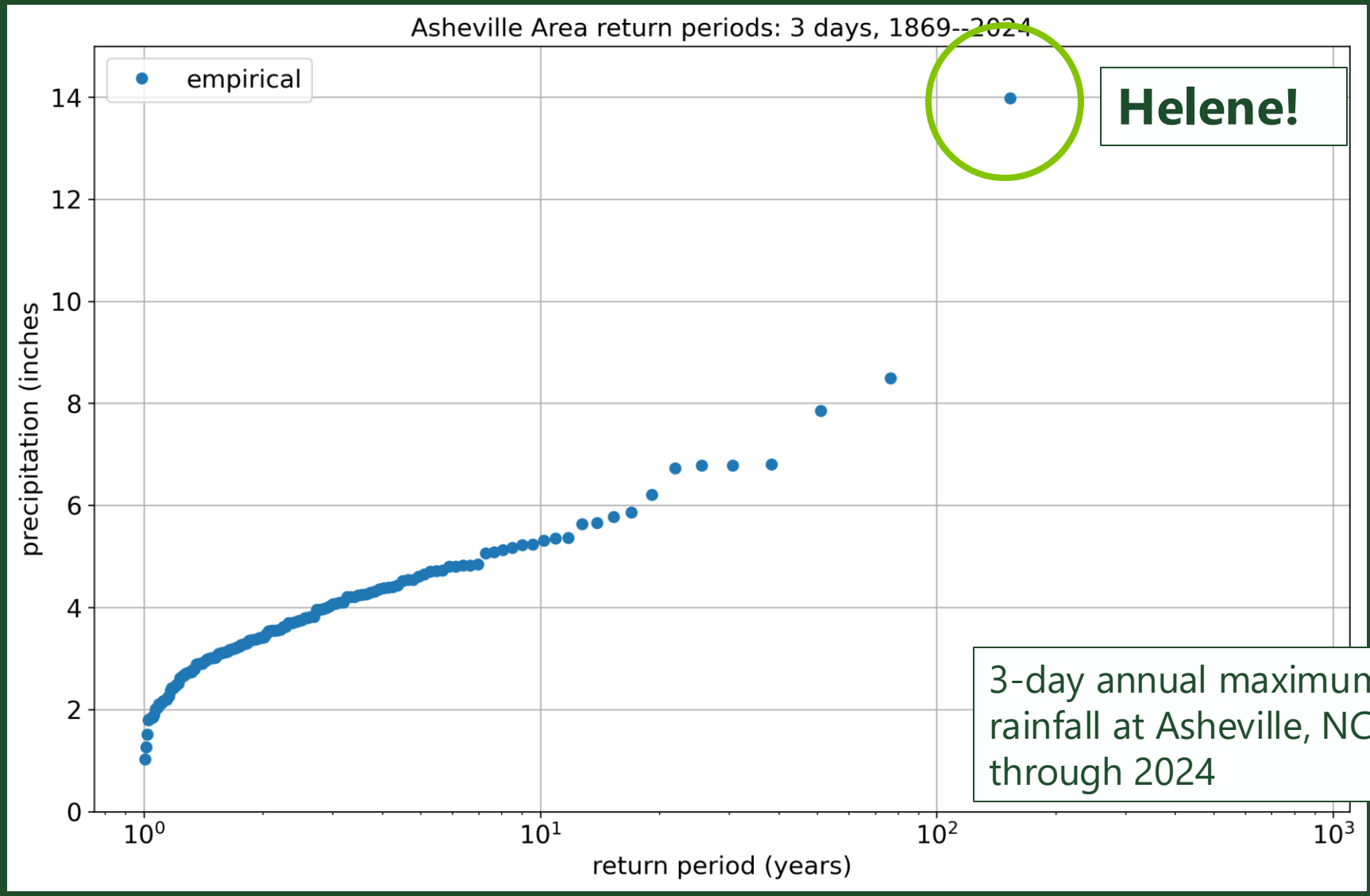
Adding more data can change the estimates in a significant way



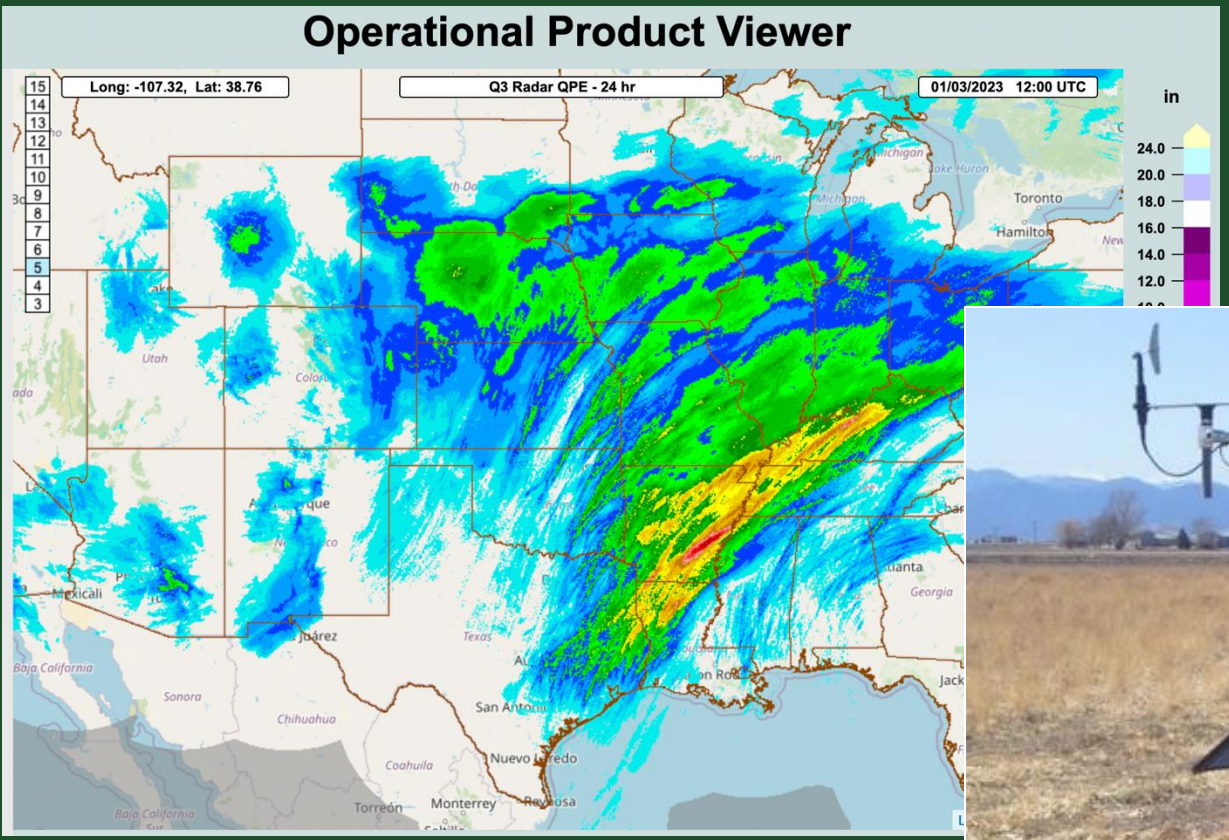
3-day annual maximum rainfall at Asheville, NC, data through 2023

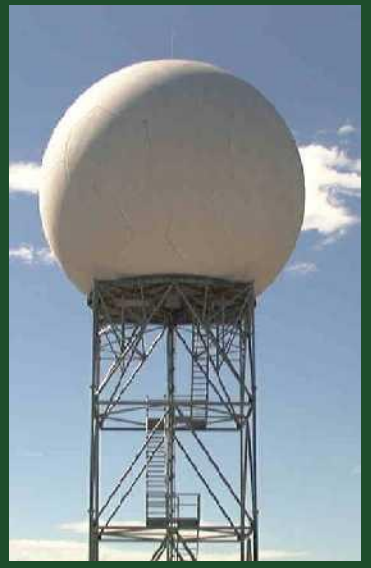
Adding more data can change the estimates in a significant way



3-day annual maximum rainfall at Asheville, NC, data through 2024

And measuring rainfall is difficult!





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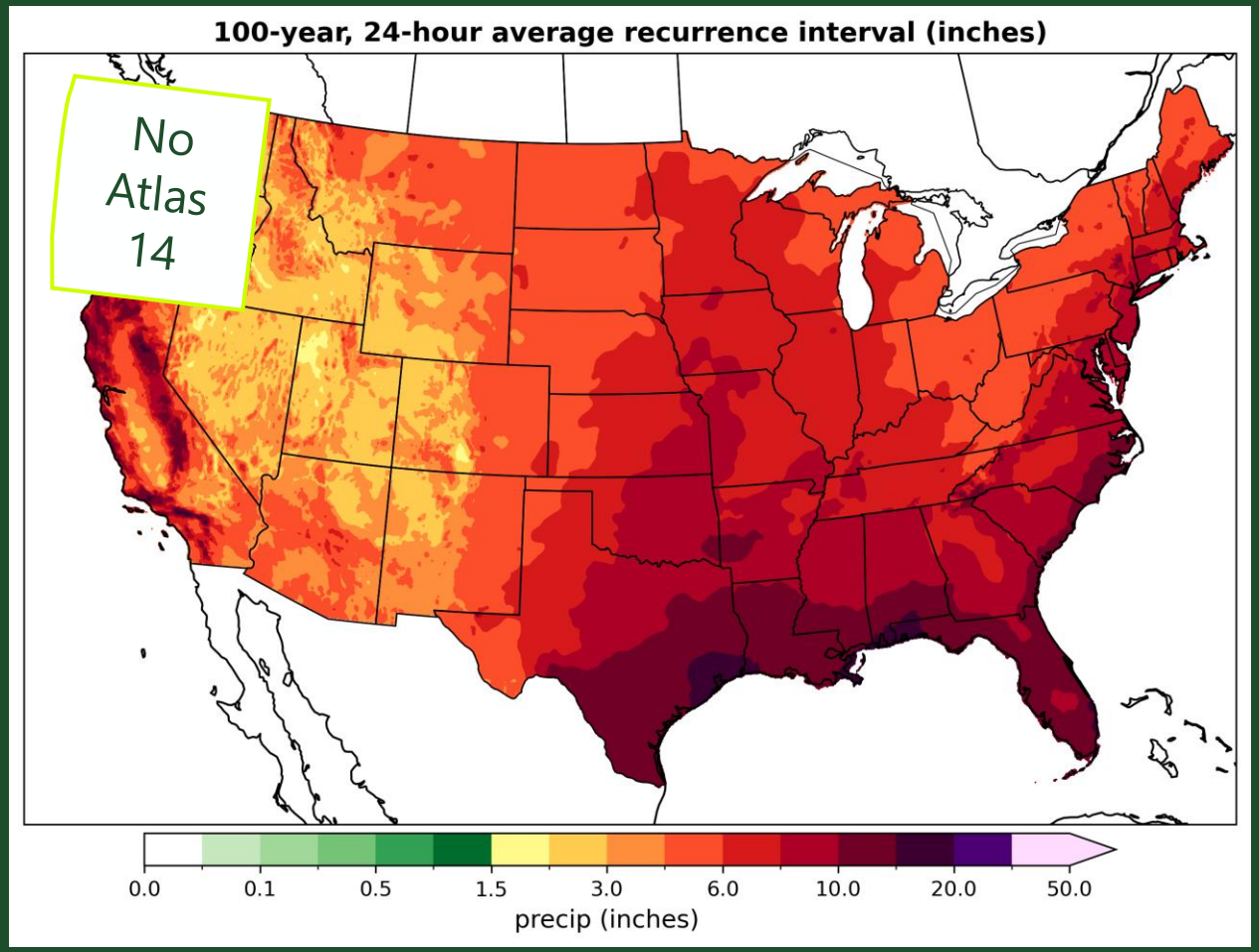
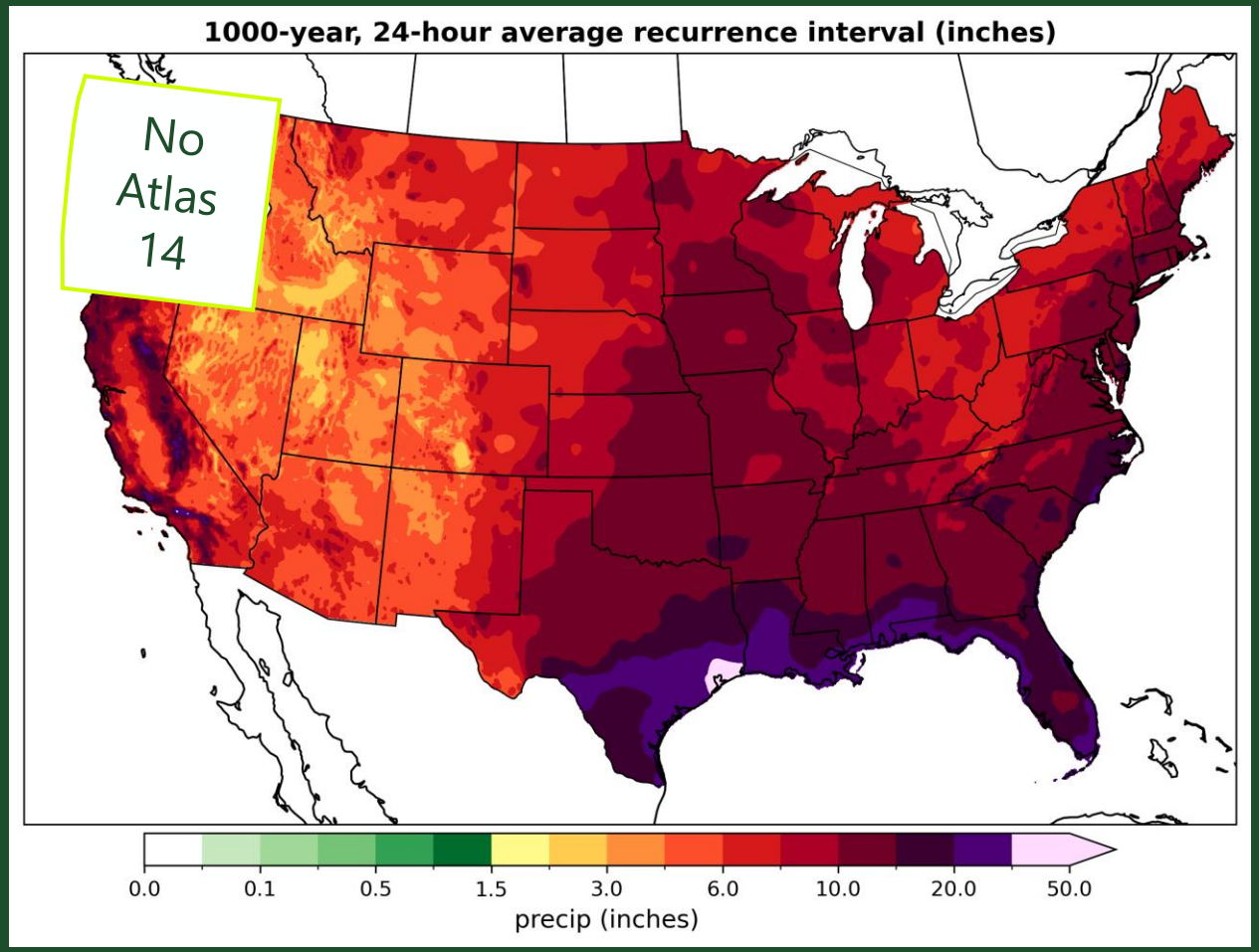
NOAA Atlas 14 maps

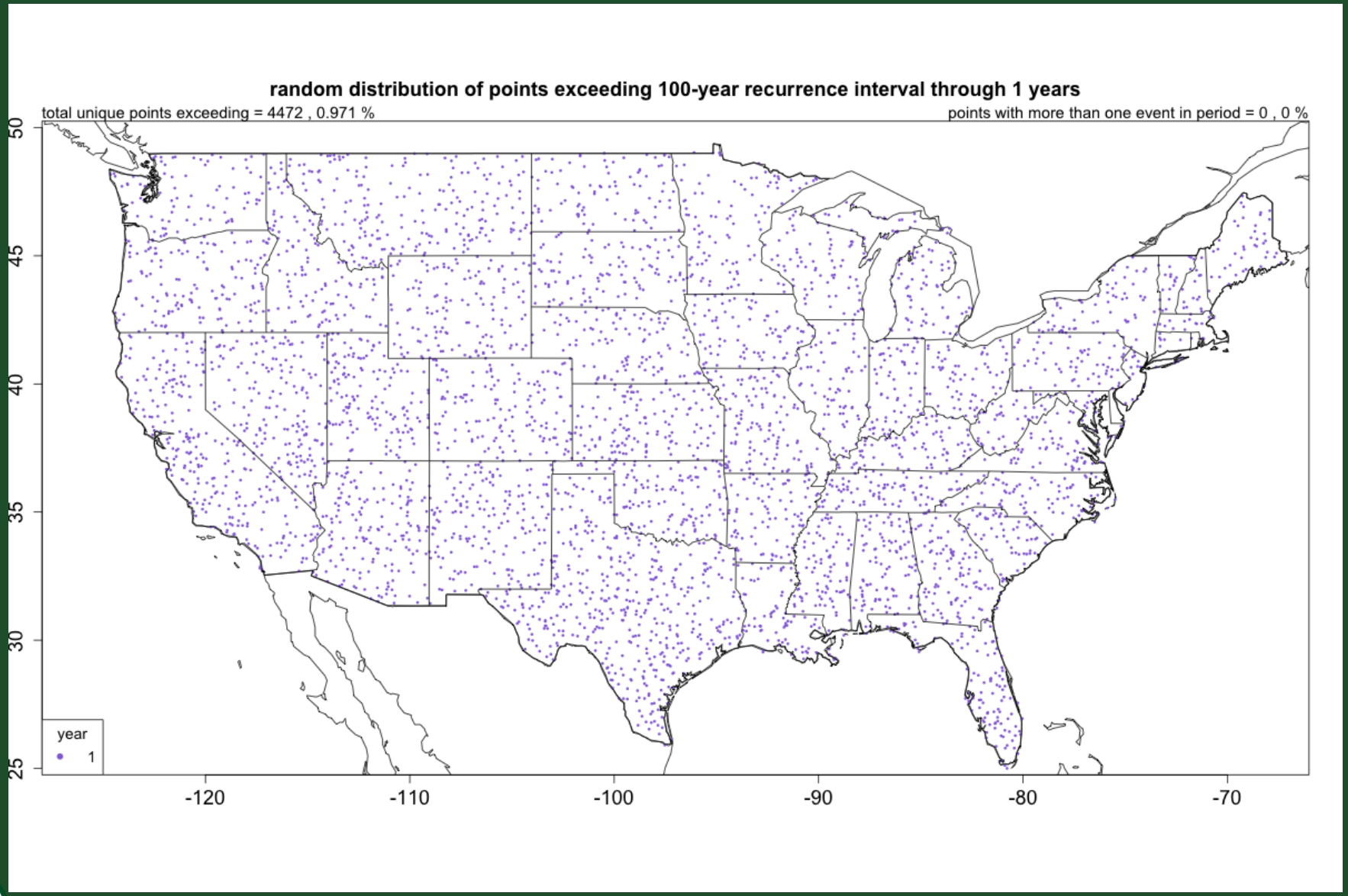
1% AEP (100-year), 24 hour



0.1% AEP (1000-year), 24 hour

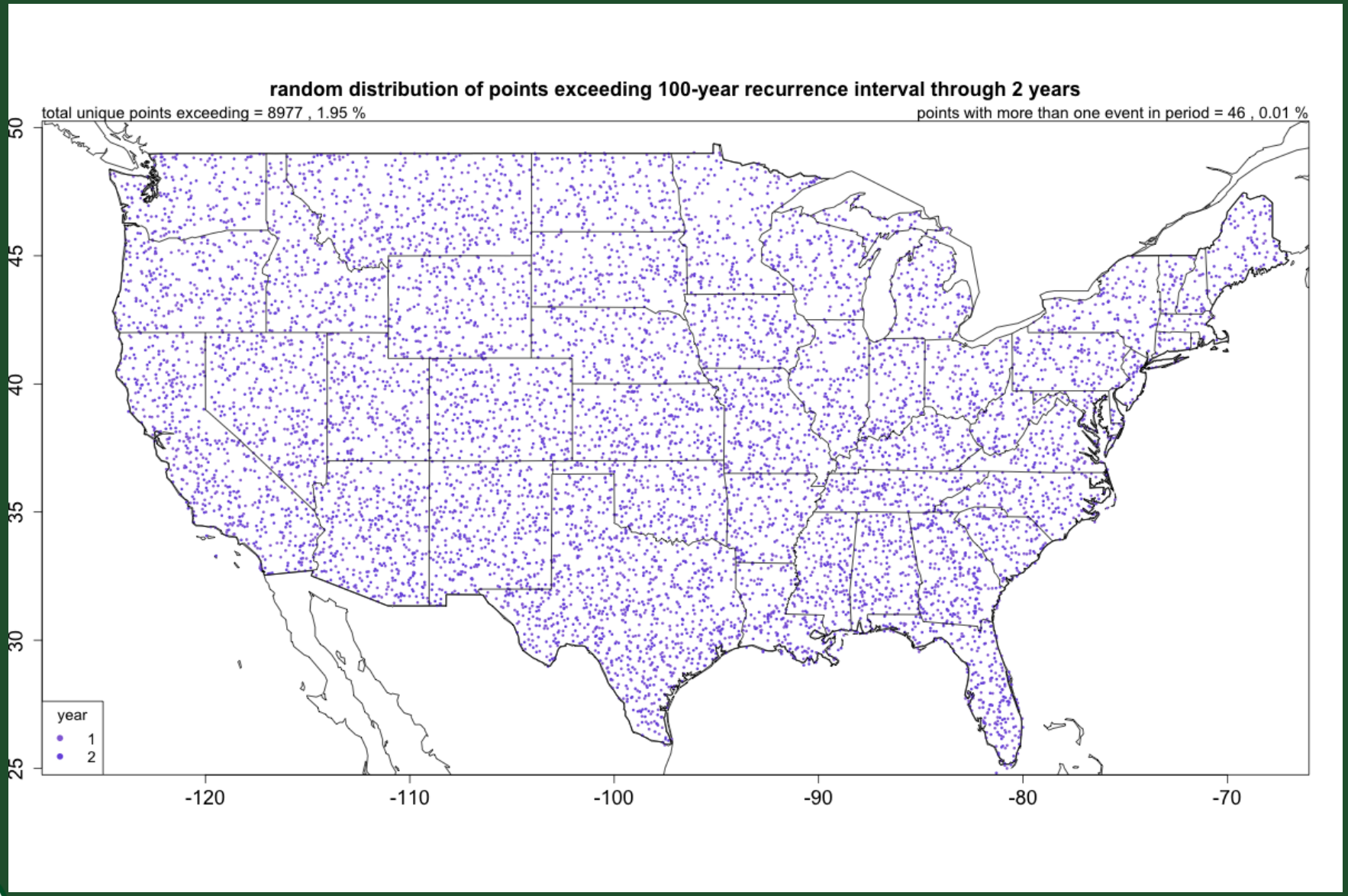


What if we had a random scattering of “100-year rain events”?



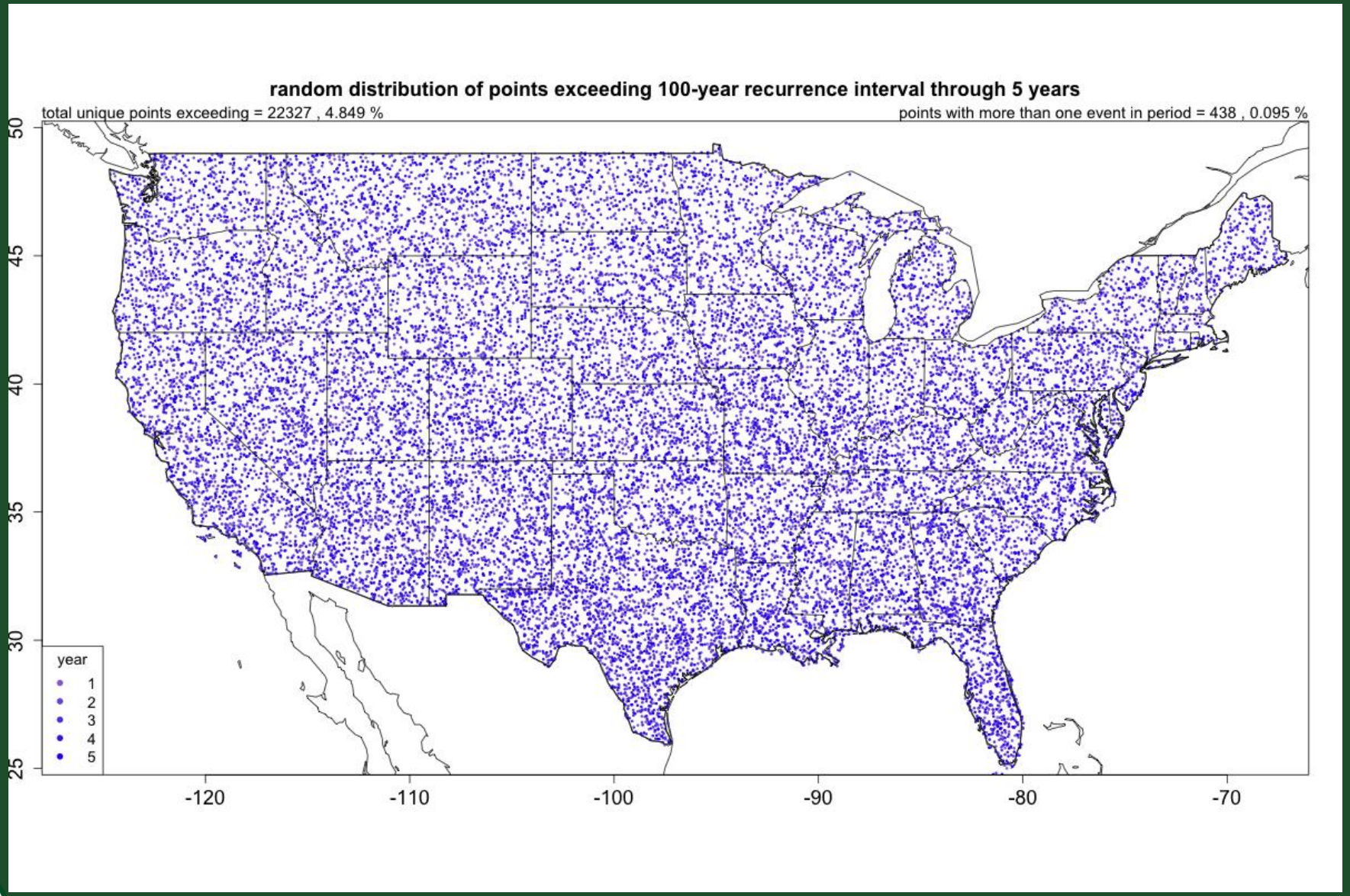
After 1 year: 4472 “100-year rainstorms” on this map

What if we had a random scattering of “100-year rain events”?



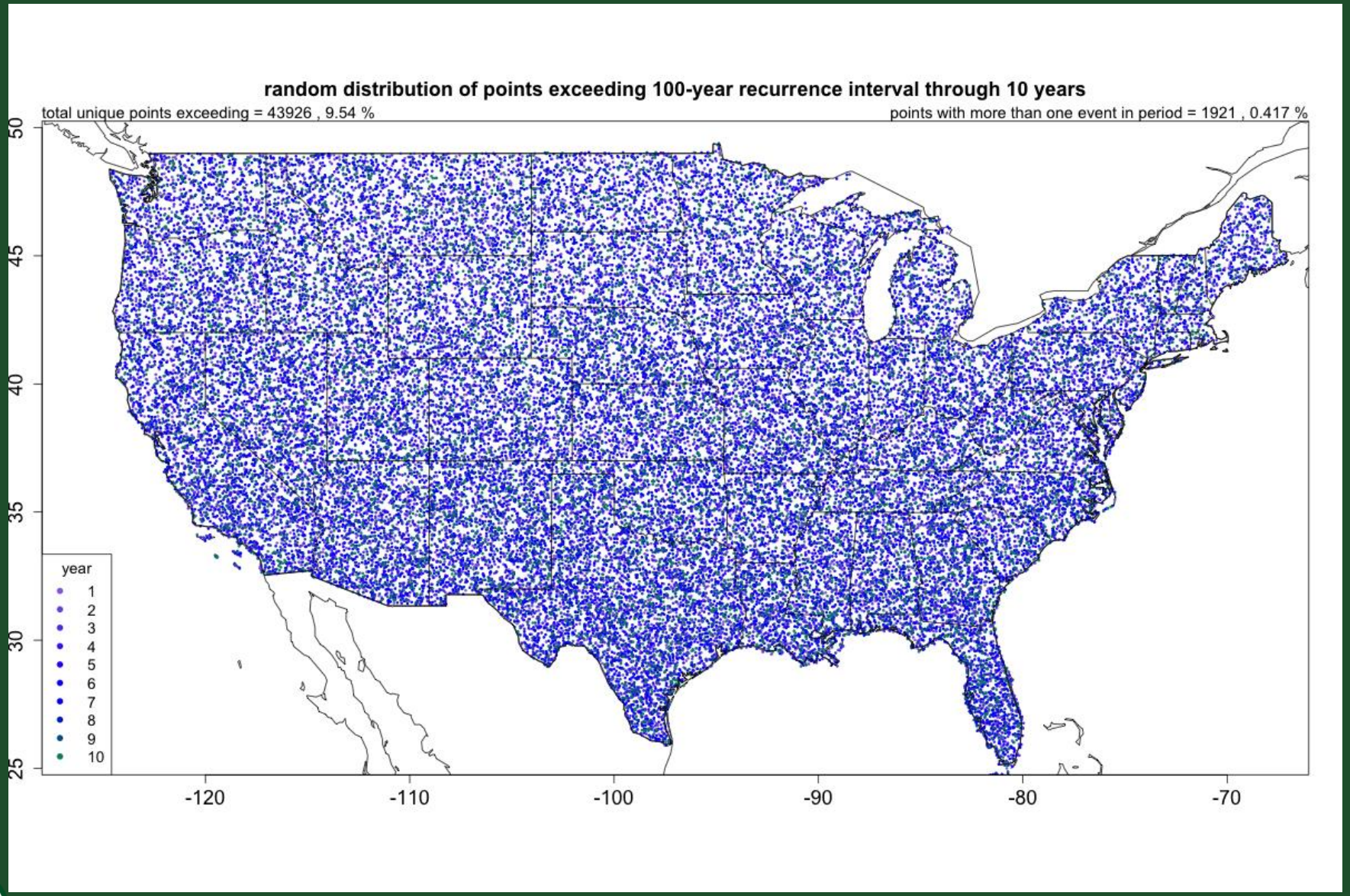
After 2 years

What if we had a random scattering of “100-year rain events”?



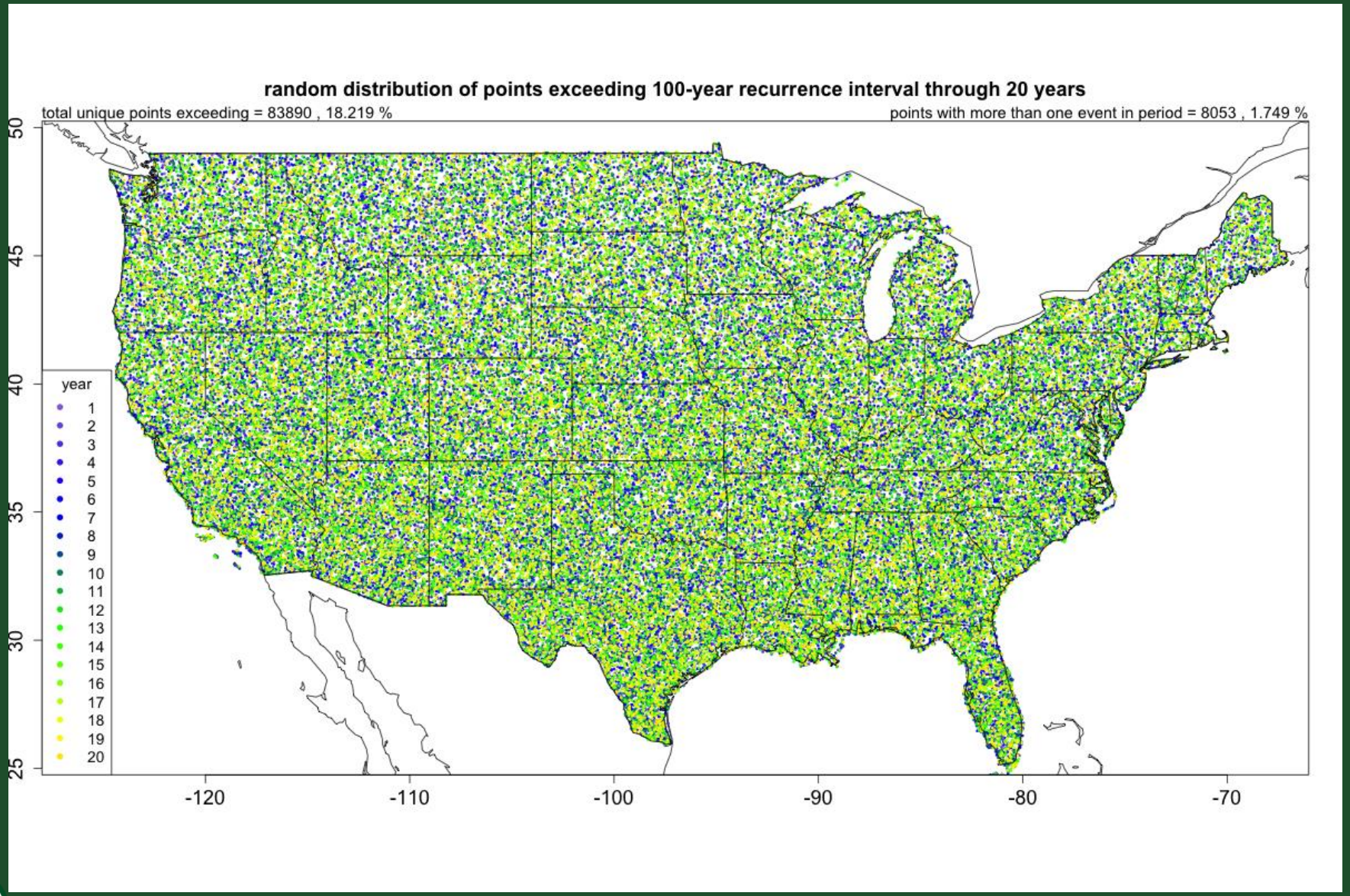
After 5 years

What if we had a random scattering of “100-year rain events”?



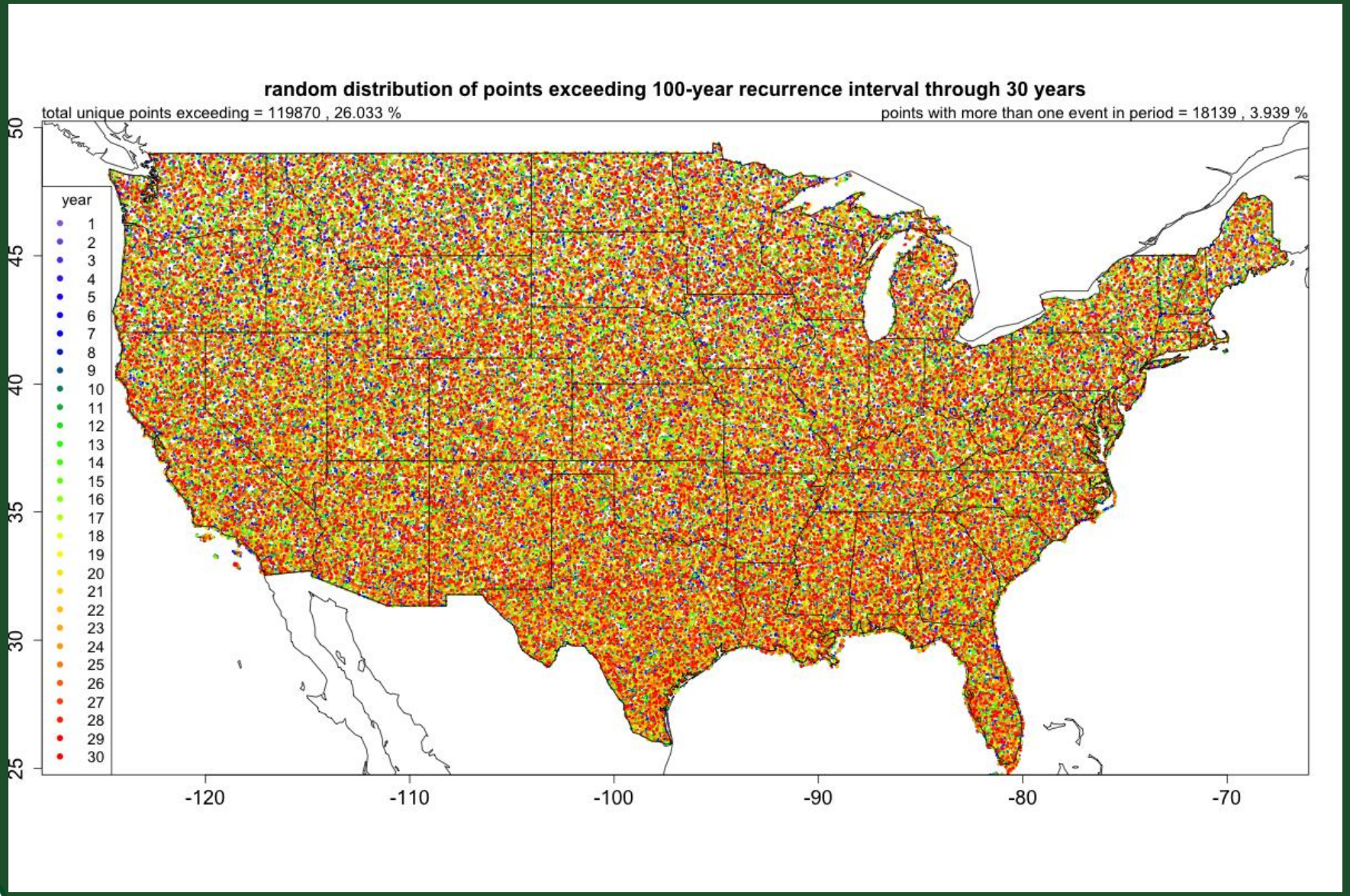
After 10 years

What if we had a random scattering of “100-year rain events”?



After 20 years

What if we had a random scattering of “100-year rain events”?



After 30 years, each point has a 26% chance of seeing a 100-year rain event!

And nearly a 4% chance of getting more than one of them!

A 100-year rainstorm is rare at any given location, but we expect many of them to occur *somewhere* each year

Return periods are defined by the probability at a single point

The chance of occurrence is the same in each year, so it is possible (though unlikely) to get a 100-year storm in back-to-back years

(assuming the estimate of the 100-year threshold reflects the “true” frequency of occurrence)

A 100-year rainstorm does not necessarily lead to a 100-year flood!

The flooding could be more or less extreme, depending on the spatial extent of the rain, the characteristics of the watershed, the terrain, whether soils are wet, and so on

We also know that rainfall isn’t randomly scattered – let’s take a look at maps of real rainstorms in the US!

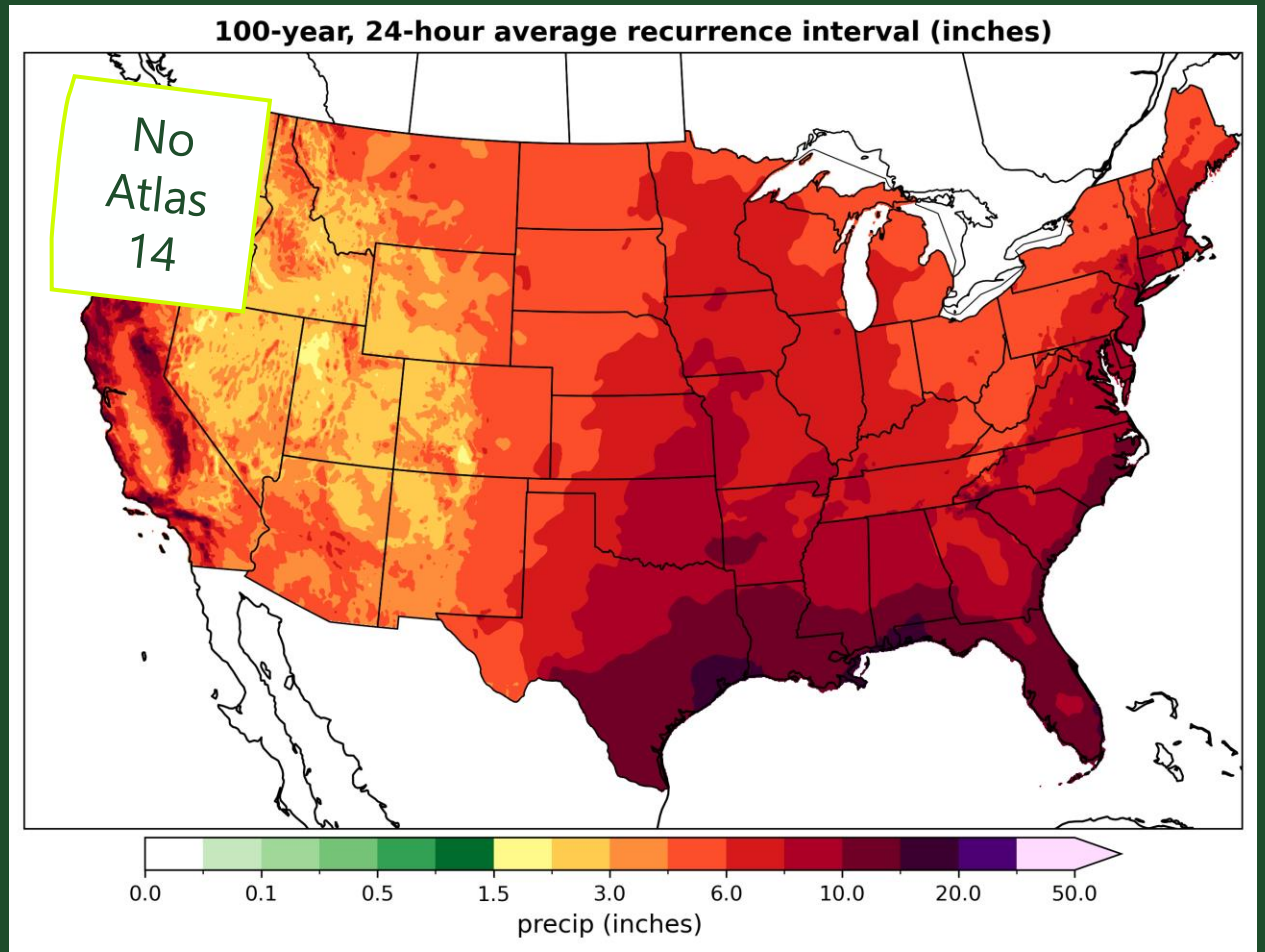
Data and methods

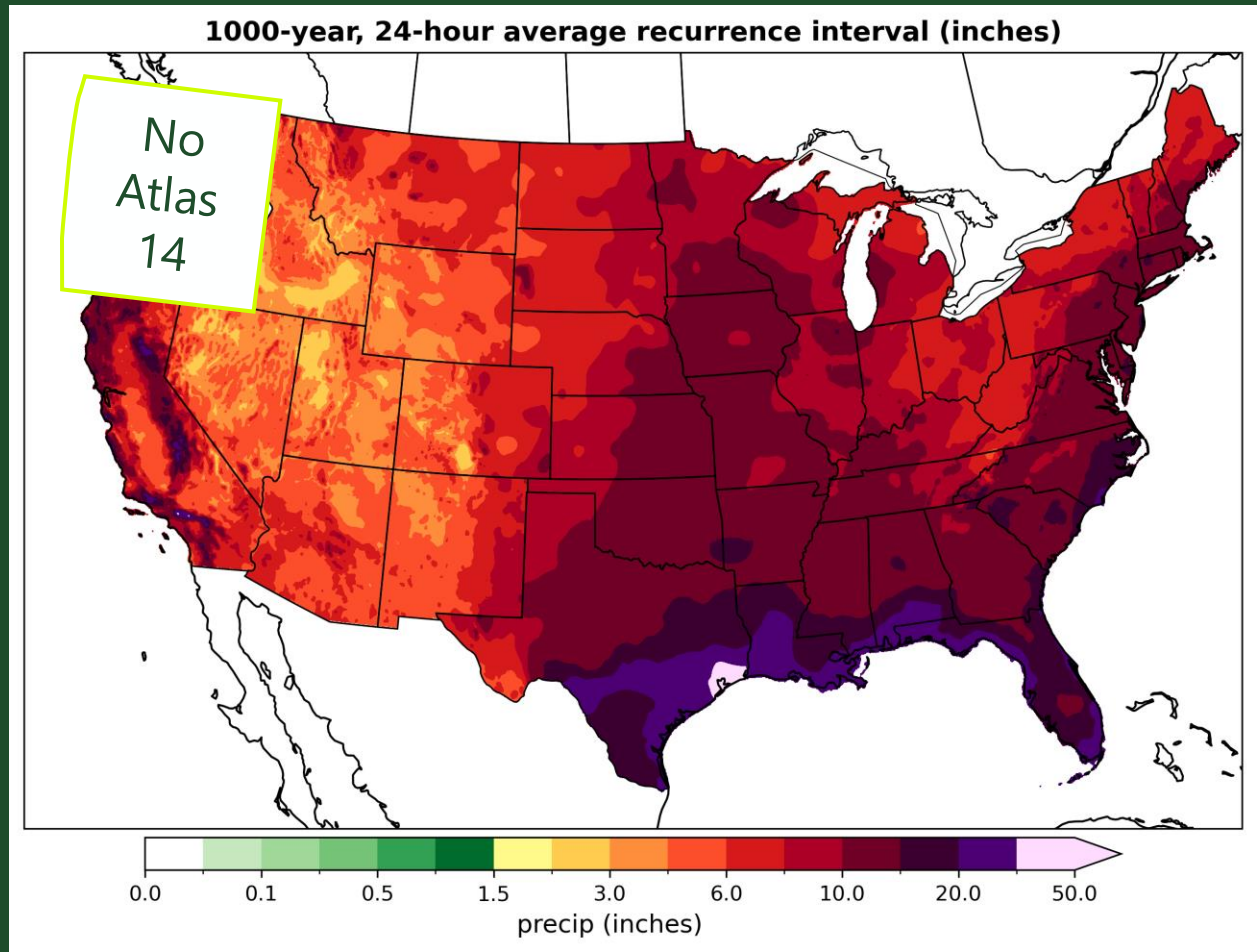
- PRISM daily precipitation analysis (Daly et al. 2021), 1981-2023
  - Gauges + radar
  - Leans heavily on CoCoRaHS observations!
- NOAA/NCEP Stage IV analysis (Nelson et al. 2016), 2002-2024
  - Radar + gauges
- Datasets analyzed for 24-h periods ending at 1200 UTC, all regridded to a consistent grid (4-km PRISM lat/lon grid) over the CONUS

- CoCoRaHS observations, 2002-2024, matched to nearest grid point

Data and methods

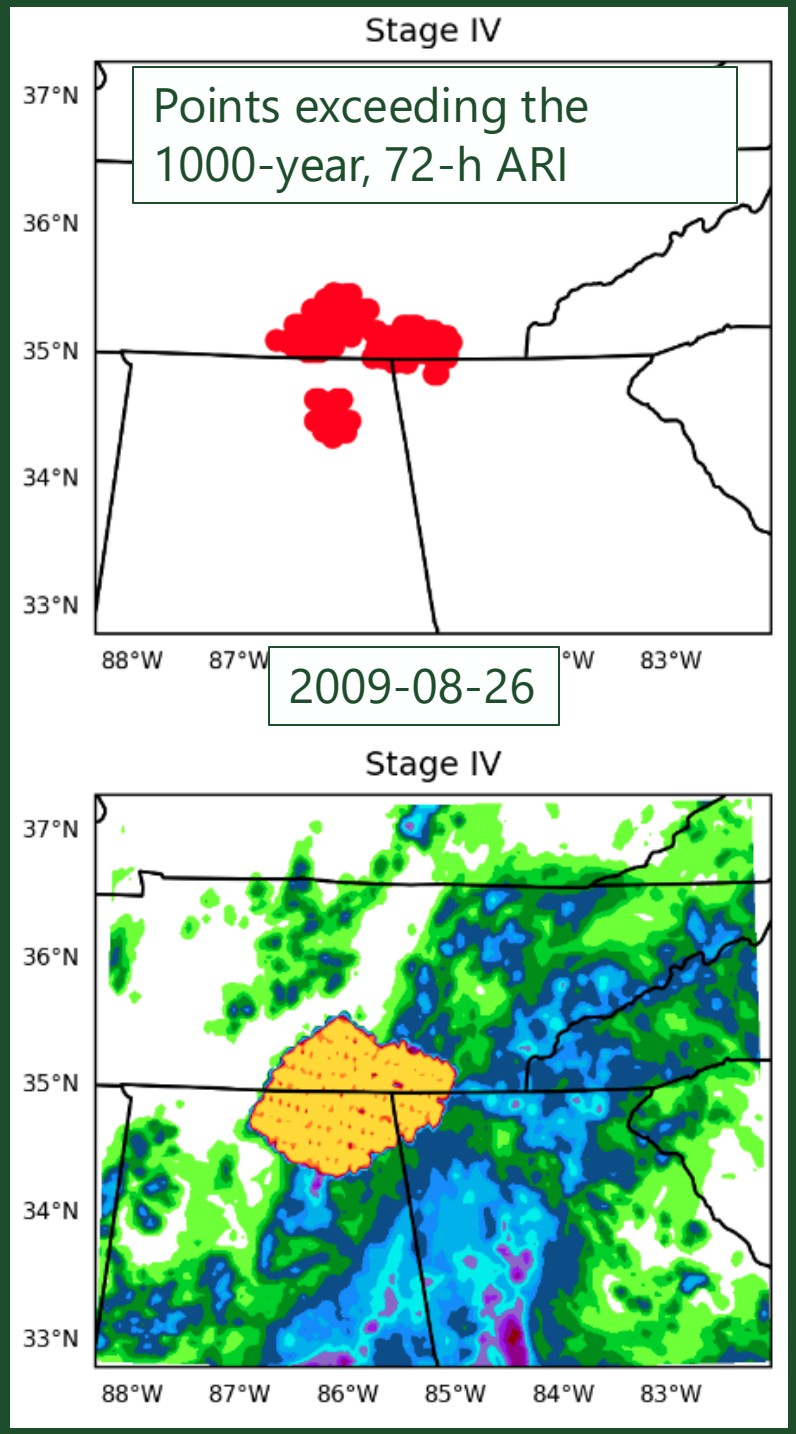
- Extreme rainfall is defined by exceedances of average recurrence interval thresholds from NOAA Atlas 14
  - Here, focusing on 100-year (1% AEP) and 1000-year (0.1% AEP) over durations of 24-72 hours. Pacific Northwest excluded from analysis because Atlas 14 is unavailable.





Example problem

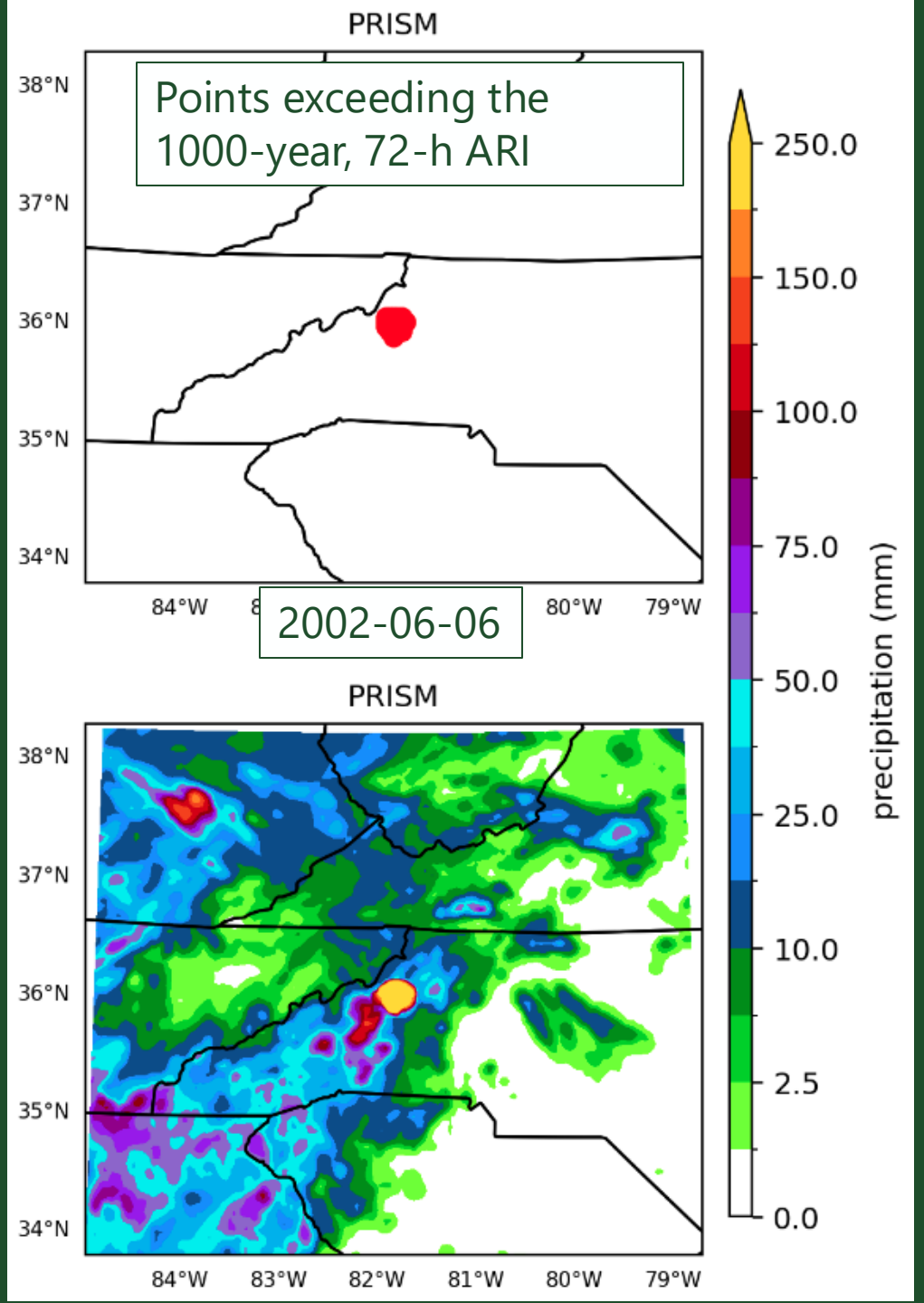
- Biggest rain event in Tennessee/Alabama history?
- No, some kind of weird radar artifact



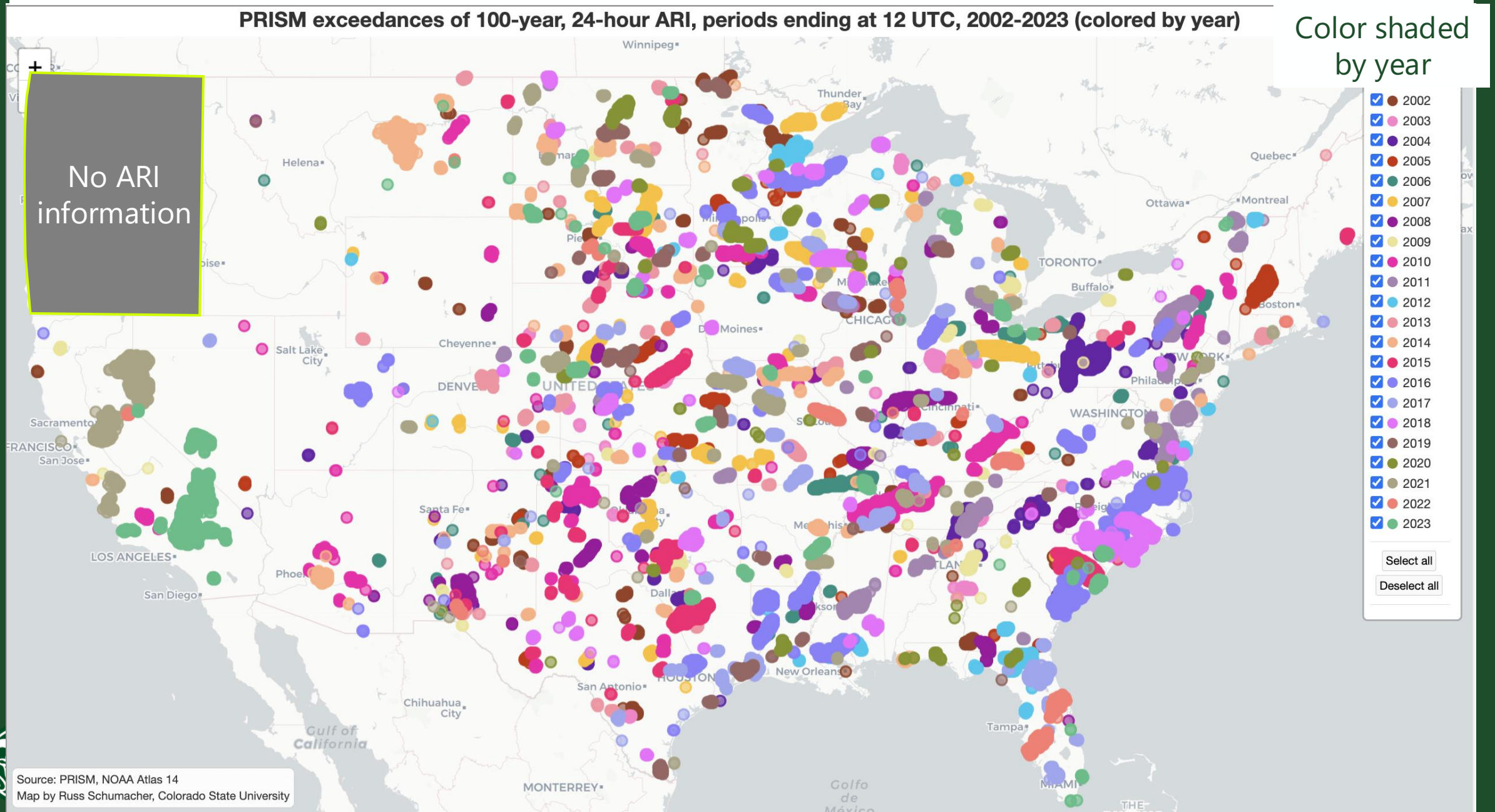
Example problem

PRISM has fewer of these, but still quite a few…

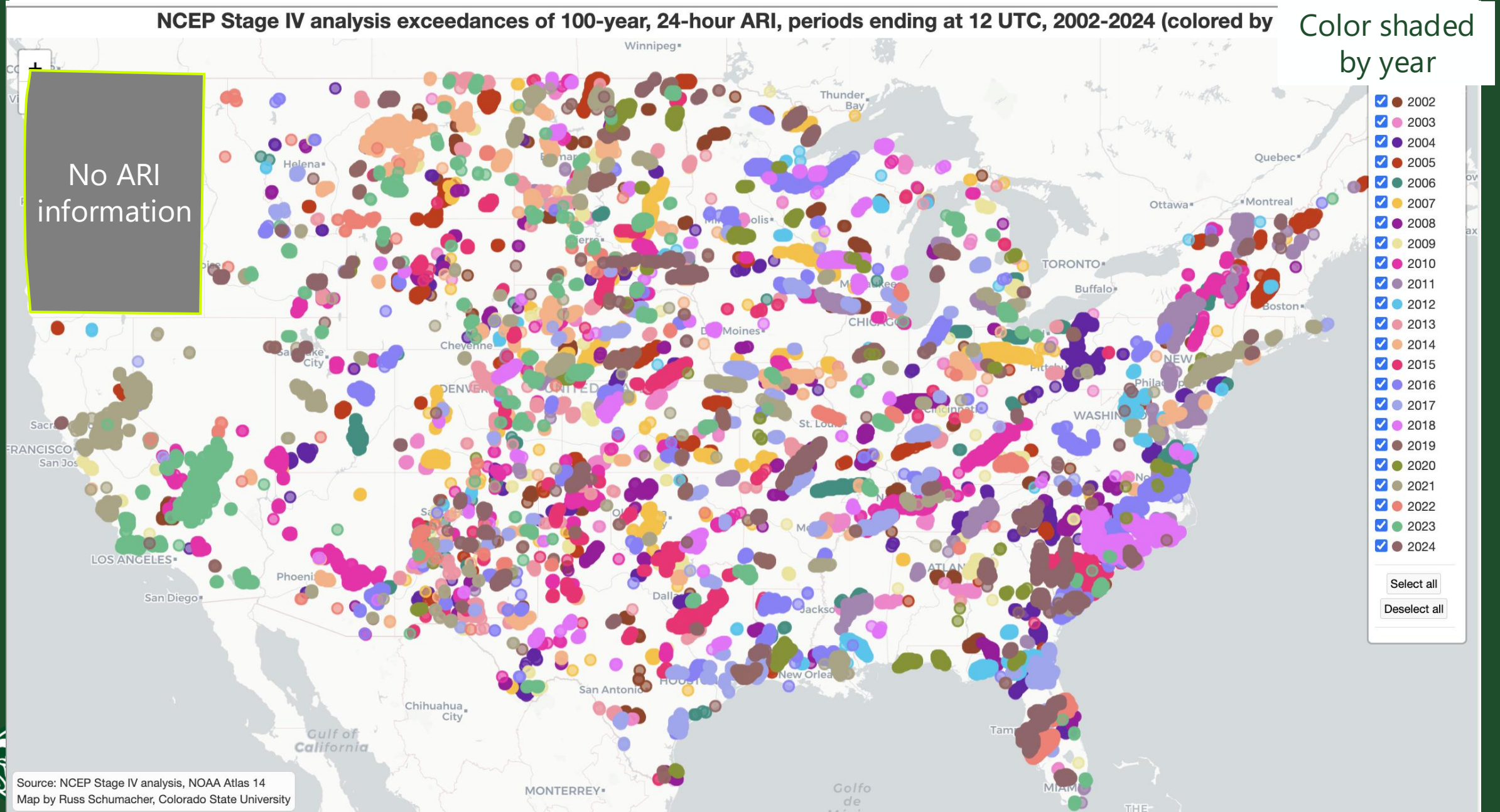
Use a combination of automated and manual processes to remove spurious "events", resulting in a QC'd database for each precipitation dataset



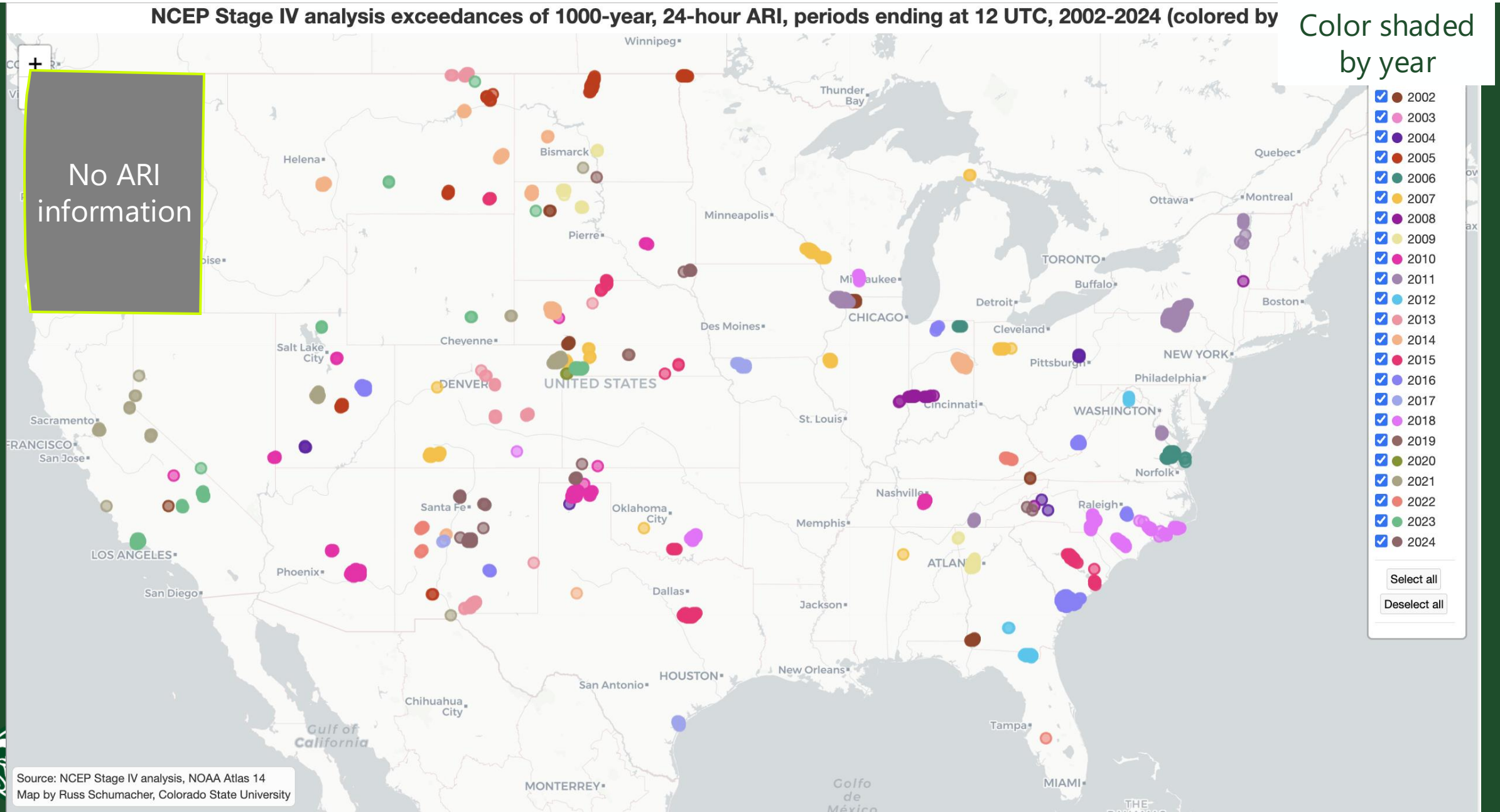
Points exceeding the 1% annual exceedance probability ("100-year rainfall"), 24 hours, 2002-2023 PRISM analysis (gauge + radar), periods ending 1200 UTC



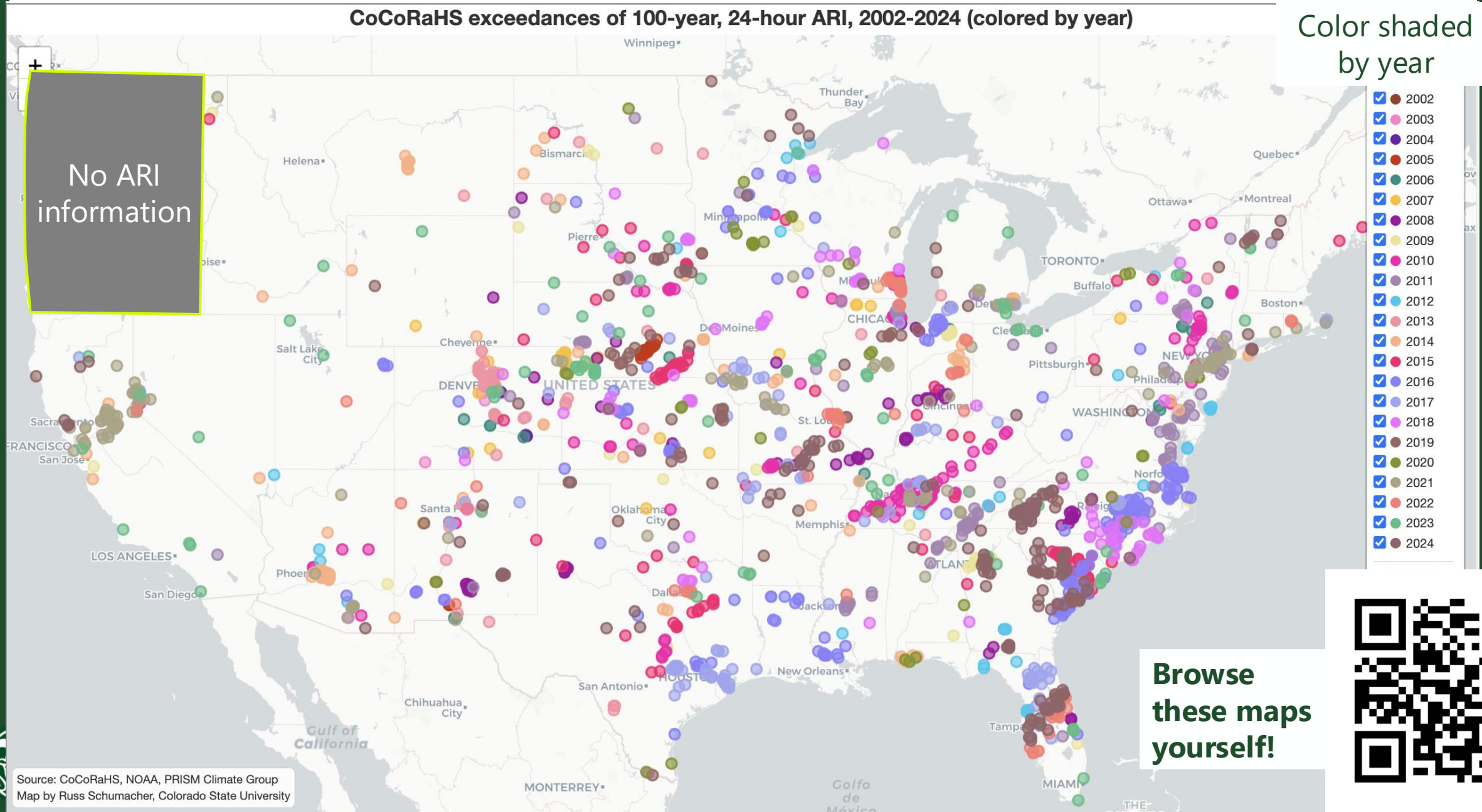
Points exceeding the 1% annual exceedance probability ("100-year rainfall"), 24 hours, 2002-2024 NOAA Stage IV analysis (gauge + radar), periods ending 1200 UTC



Points exceeding the 0.1% annual exceedance probability ("1000-year rainfall"), 24 hours, 2002-2024
NOAA Stage IV analysis (gauge + radar), periods ending 1200 UTC

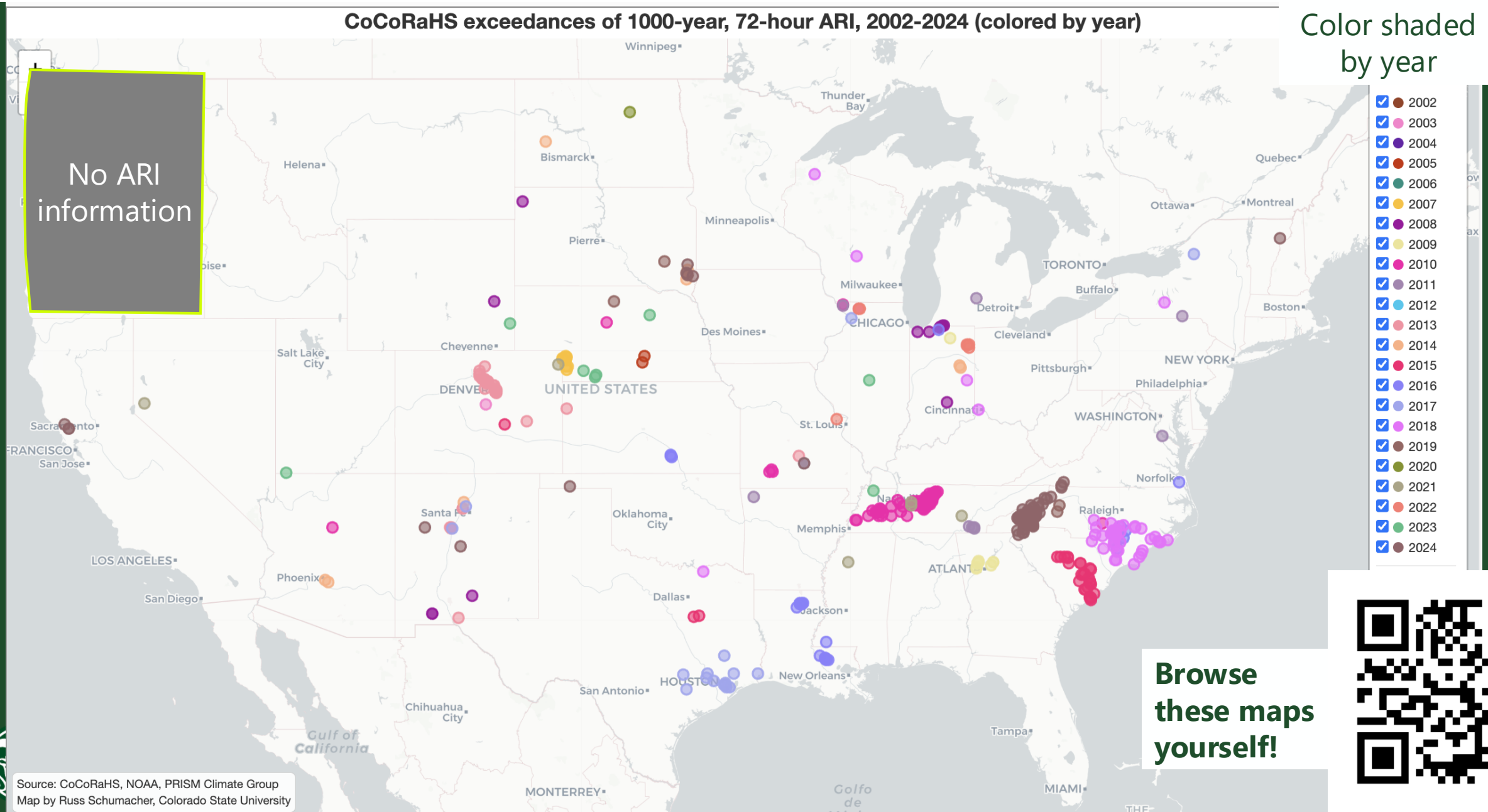


Points exceeding the 1% annual exceedance probability ("100-year rainfall"), 24 hours, 2002-2024 CoCoRaHS gauge observations, periods ending 1200 UTC



Browse these maps yourself!

Points exceeding the 0.1% annual exceedance probability ("1000-year rainfall"), 72 hours, 2002-2024 CoCoRaHS gauge observations, periods ending 1200 UTC



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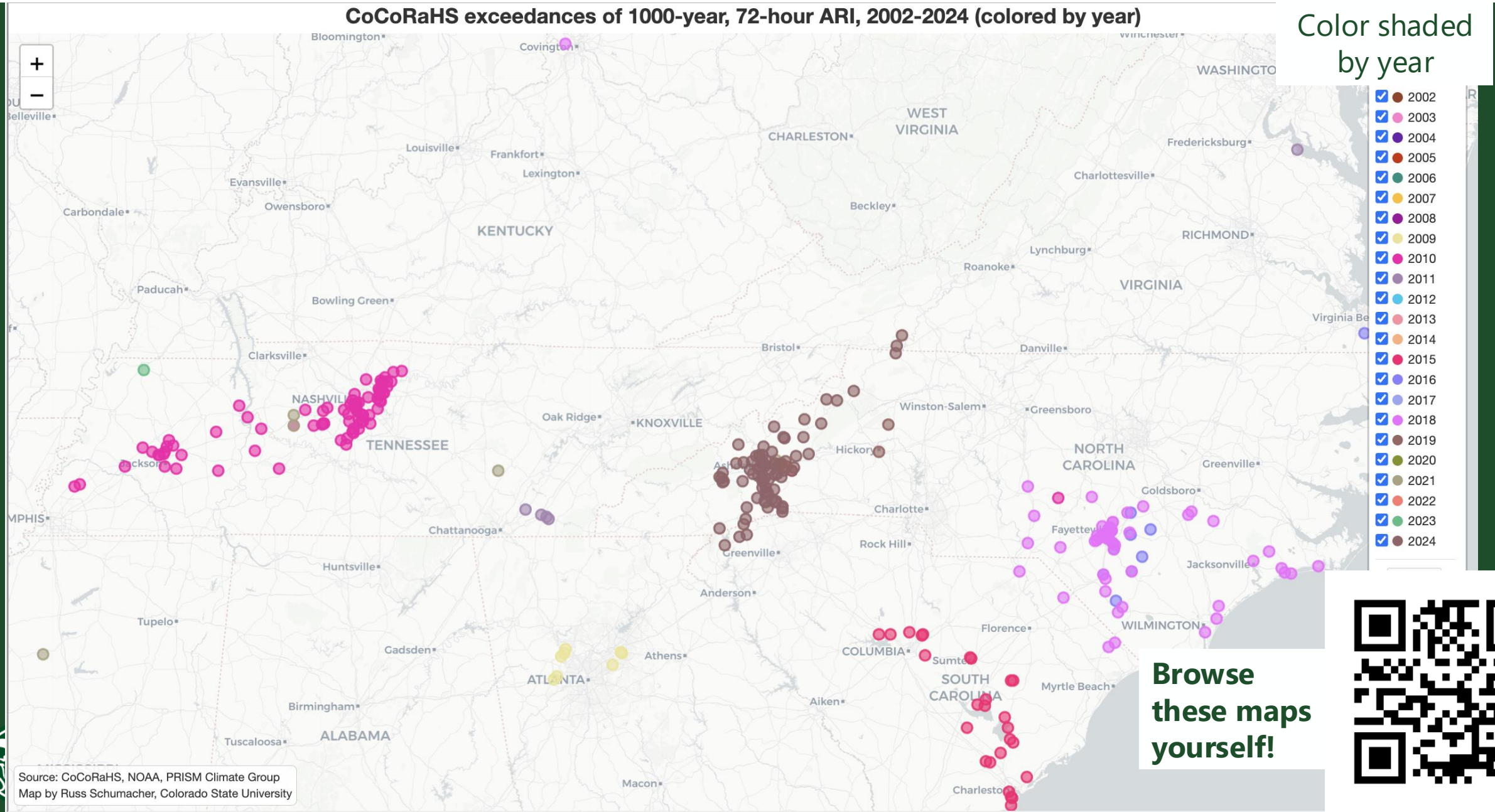

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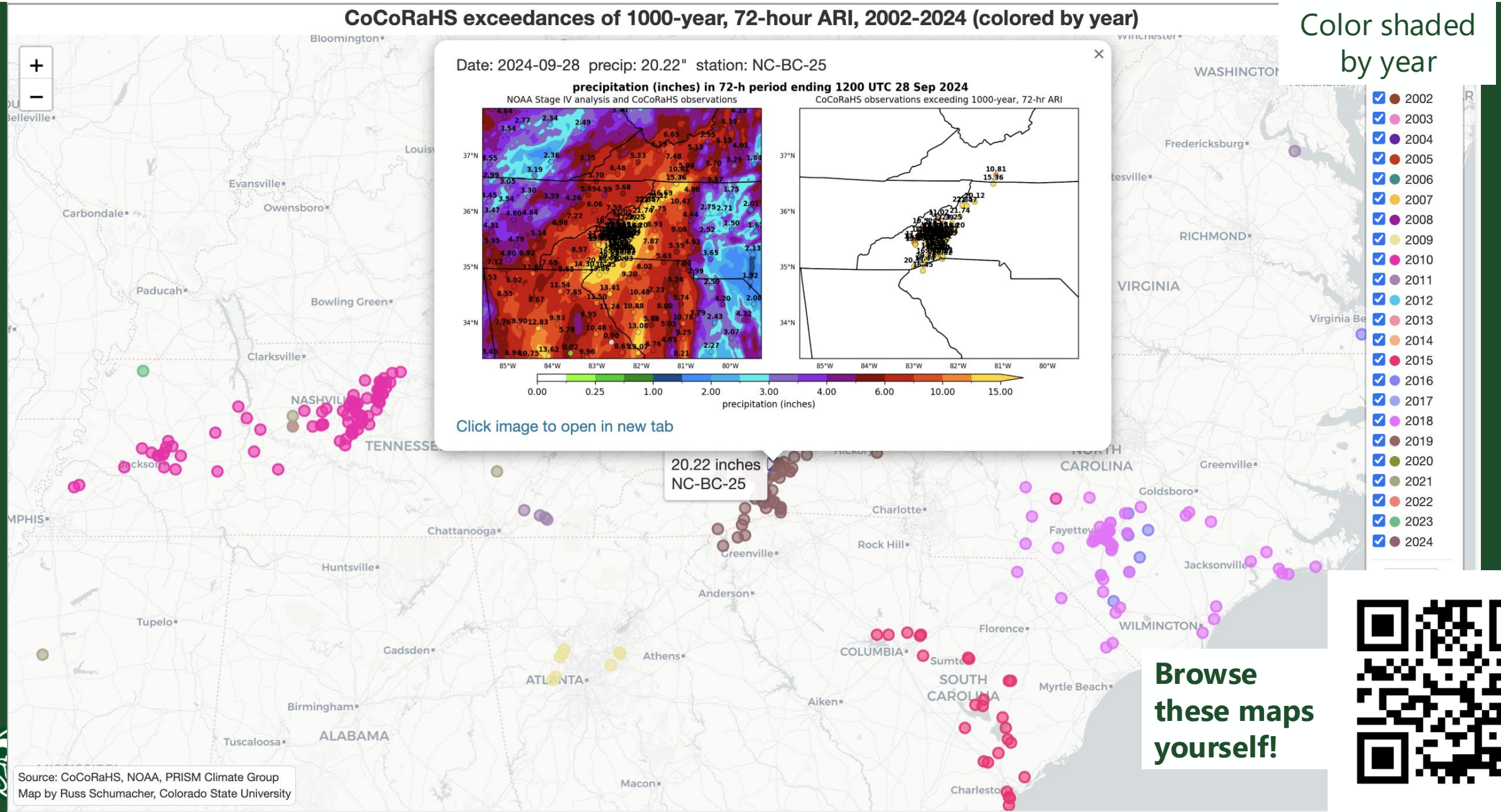
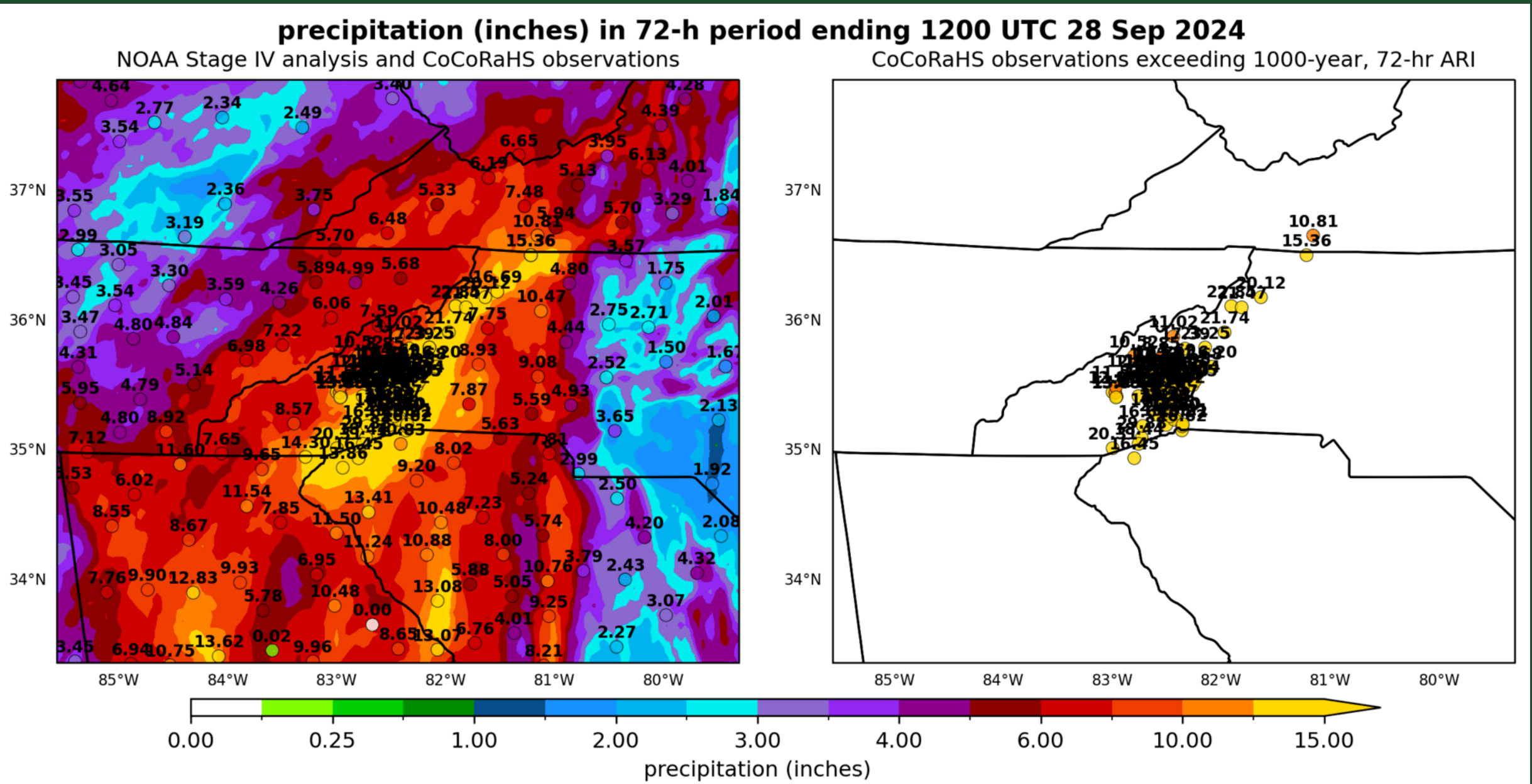
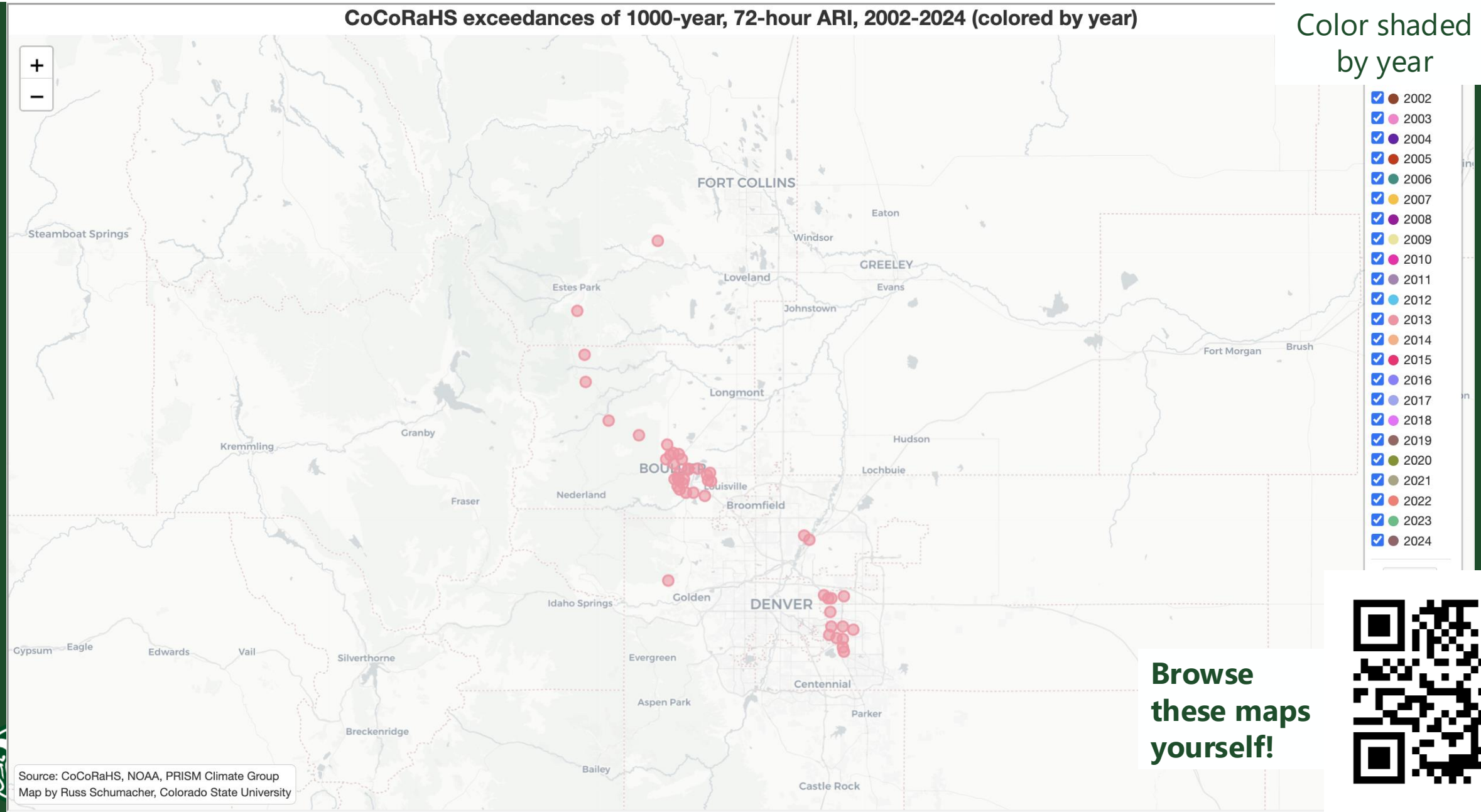
Points exceeding the 0.1% annual exceedance probability ("1000-year rainfall"), 72 hours, 2002-2024 CoCoRaHS gauge observations, periods ending 1200 UTC




precipitation (inches) in 72-h period ending 1200 UTC 28 Sep 2024
NOAA Stage IV analysis and CoCoRaHS observations
CoCoRaHS observations exceeding 1000-year, 72-hr ARI
37°N
36°N
35°N
34°N
85°W
84°W
83°W
82°W
81°W
80°W
0.00
0.25
1.00
2.00
3.00
4.00
6.00
10.00
15.00
precipitation (inches)

Points exceeding the 0.1% annual exceedance probability ("1000-year rainfall"), 72 hours, 2002-2024 CoCoRaHS gauge observations, periods ending 1200 UTC



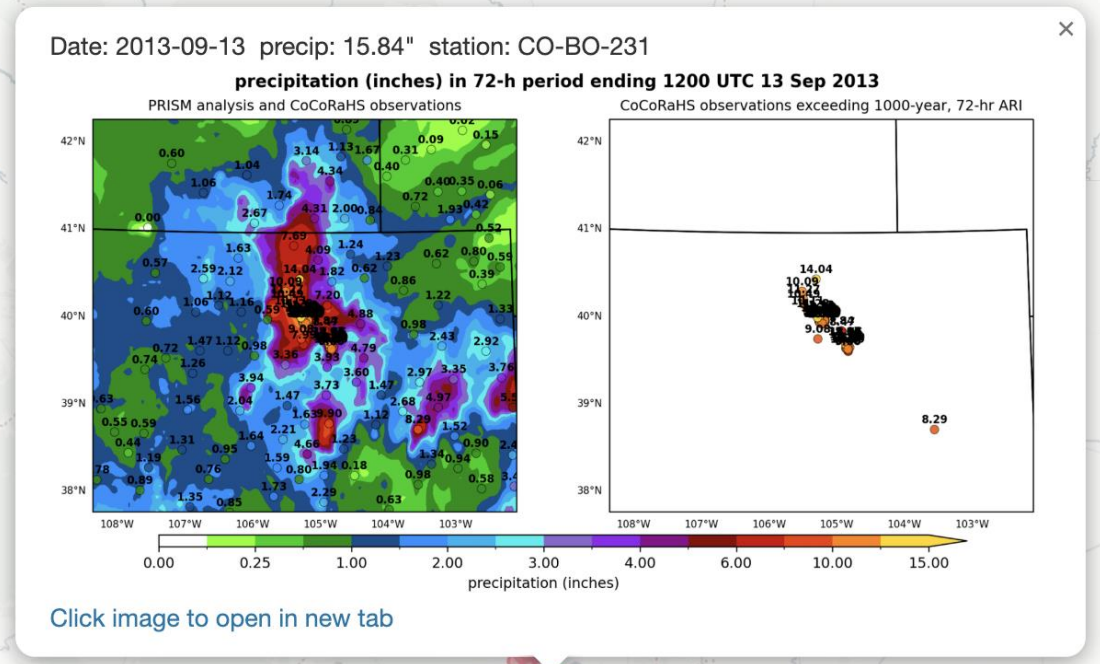
Color shaded by year

Browse these maps yourself!

Points exceeding the 0.1% annual exceedance probability ("1000-year rainfall"), 72 hours, 2002-2024 CoCoRaHS gauge observations, periods ending 1200 UTC

CoCoRaHS exceedances of 1000-year, 72-hour ARI, 2002-2024 (colored by year)

Color shaded by year



2002
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2022
2023
2024

Steamboat Springs
Kremmling
Fraser
Nederland
Lochbuie
Broomfield
Fort Morgan
Brush
Idaho Springs
Golden
DENVER
Centennial
Parker
Evergreen
Aspen Park
Silverthorne
Breckenridge
Gypsum
Eagle
Edwards
Vail
Bailey
Castle Rock

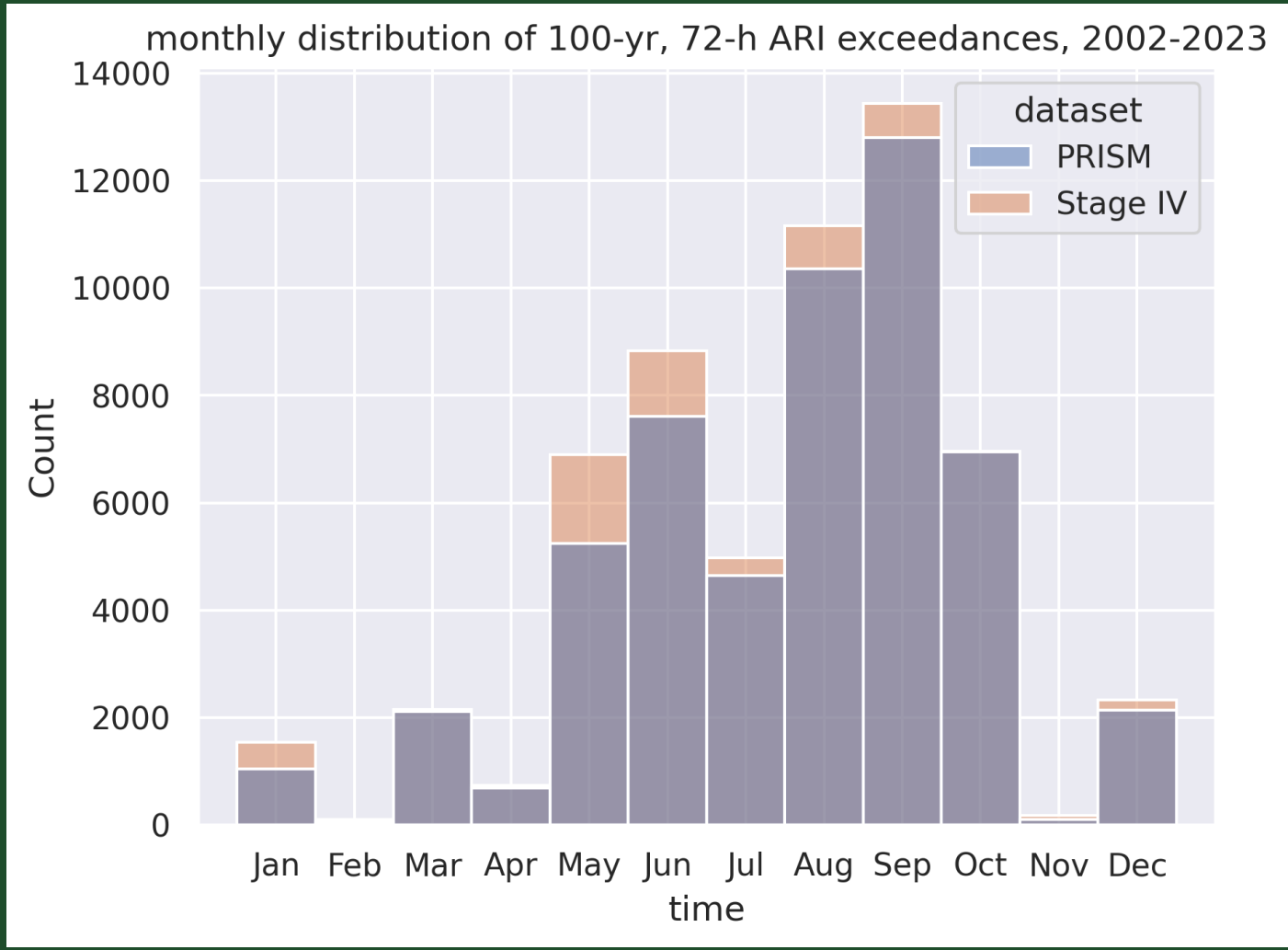
Browse these maps yourself!

Source: CoCoRaHS, NOAA, PRISM Climate Group
Map by Russ Schumacher, Colorado State University

Monthly distributions of 100-year, 72-h ARI exceedances

Stage IV vs. PRISM, 2002-2023
100-year, 72-h ARI

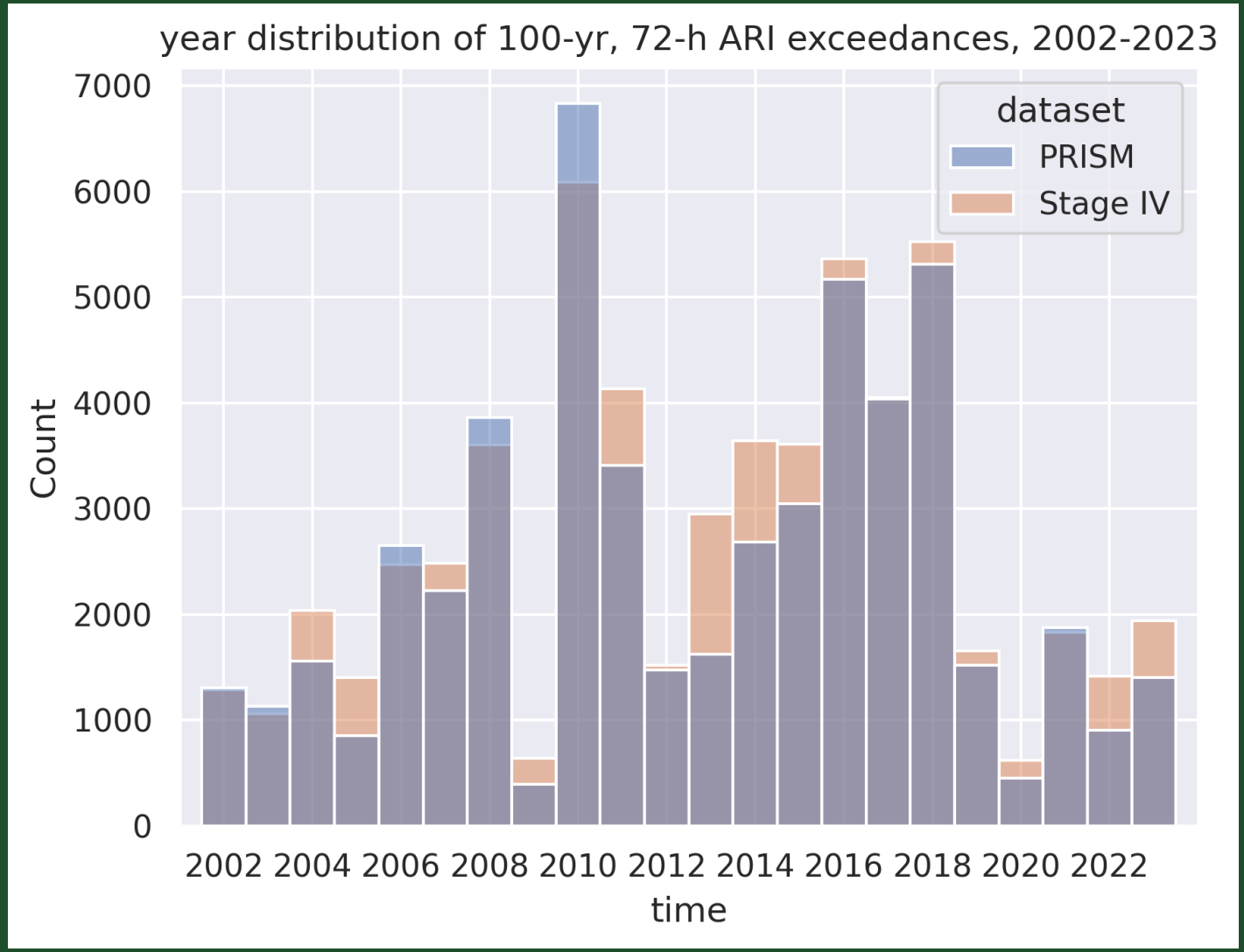
- Maximum in August-September, especially associated with tropical cyclones



Yearly distributions of 100-year, 72-h ARI exceedances

Stage IV vs. PRISM, 2002-2023
100-year, 72-h ARI

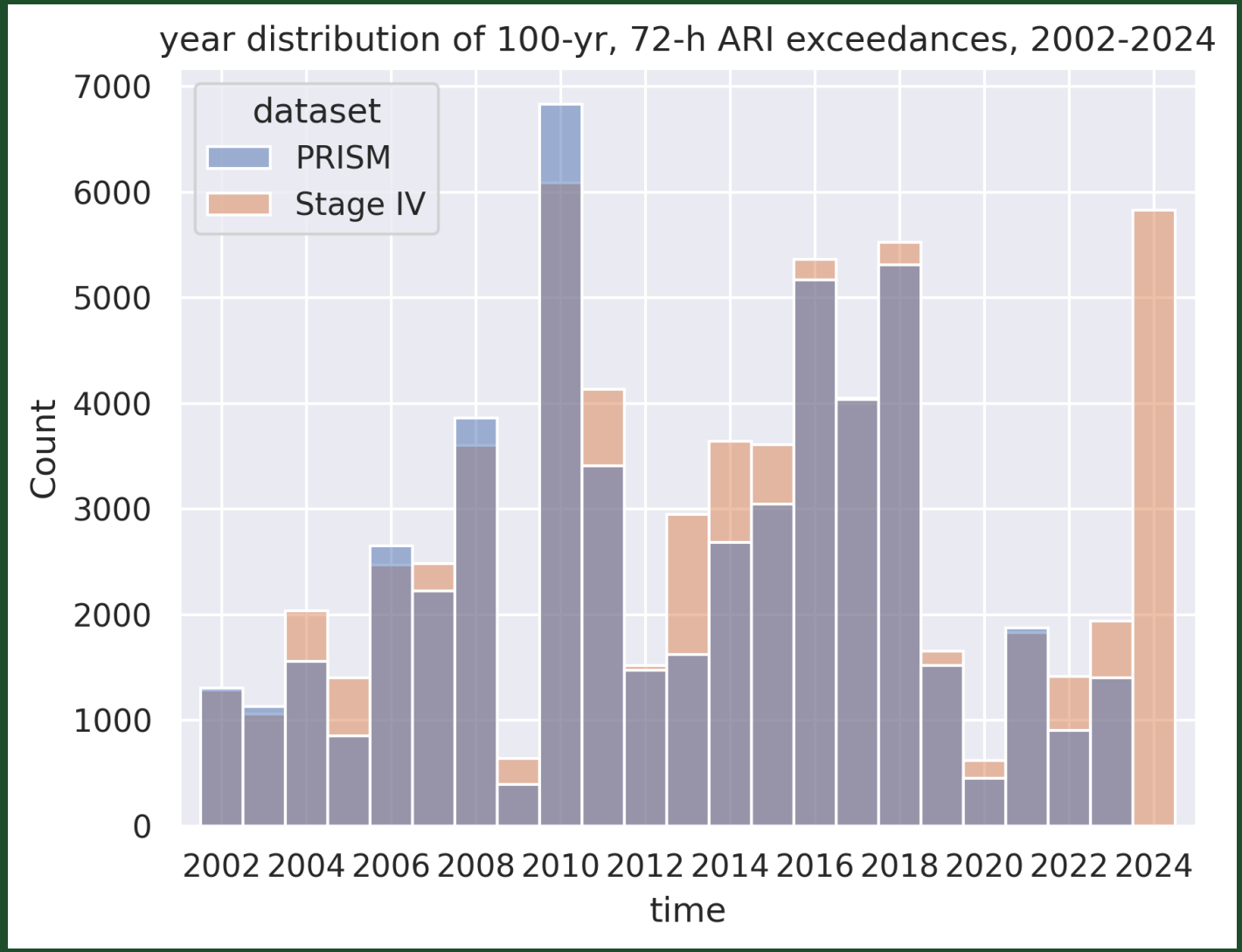
- Change over time is driven mainly by a few big events per year (or not) rather than a clear trend
  - 2010: Tennessee
  - 2018: Florence
  - etc…



Yearly distributions of 100-year, 72-h ARI exceedances

Stage IV vs. PRISM, 2002-2024
100-year, 72-h ARI

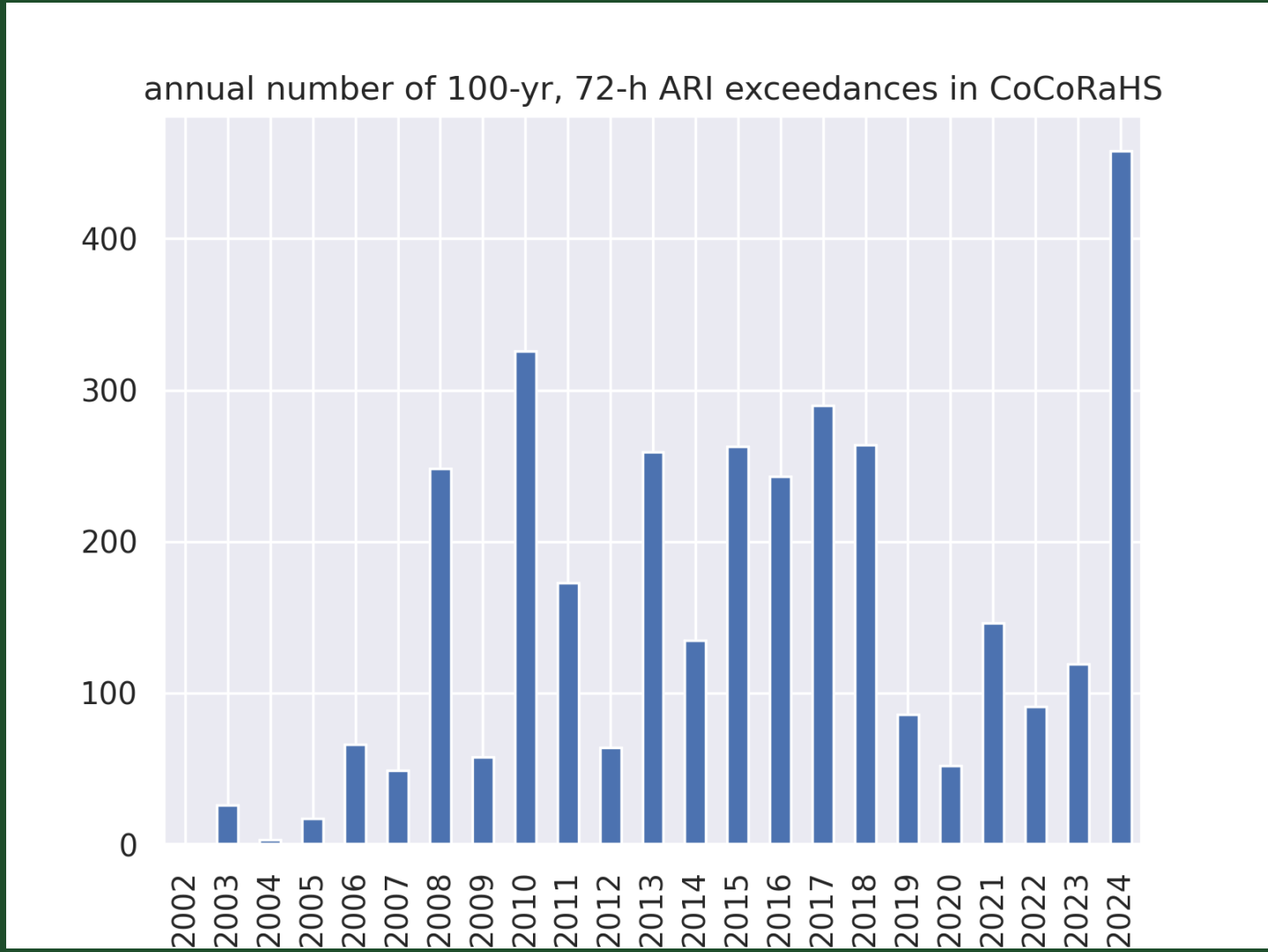
- 2024 was one of the biggest years for extreme rainfall in the CONUS no matter how you look at it
- Helene (September) and South Dakota/Minnesota (June) were major events over a large scale



Yearly distributions of 100-year, 72-h ARI exceedances

CoCoRaHS, 2002-2024
100-year, 72-h ARI

- 2024 had the most CoCoRaHS observations of extreme rainfall over 2-3 day durations



Which events rank at the top for exceedances of the 100-year, 72-h ARI? (2002-2023/24)

PRISM

Event	# of points	
2010-05-03	2074	Tennessee
2018-09-17	1901	Florence
2016-03-11	1577	LA/AR
2015-10-05	1567	S. Carolina
2014-08-25	1561	Montana
2016-10-09	1268	Matthew
2008-09-15	1229	Ike & PRE
2017-08-29	1095	Harvey
2006-06-28	1085	Mid-Atlantic

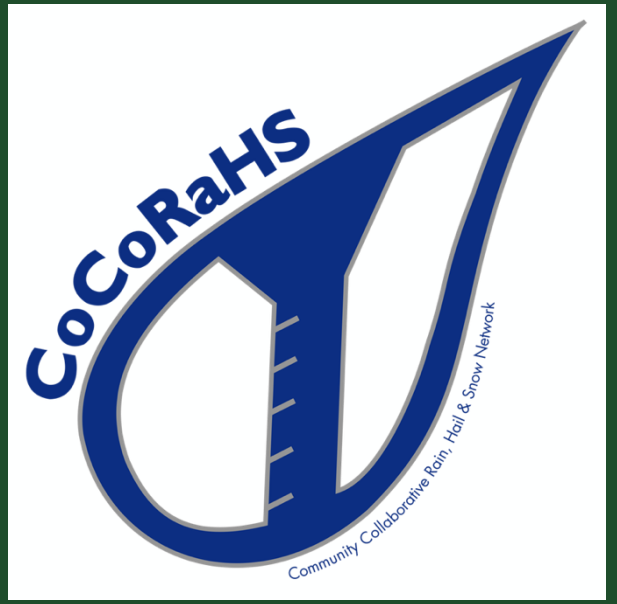
Stage IV

Event	# of points	
2014-08-25	1858	Montana
2018-09-17	1821	Florence
2010-05-03	1607	Tennessee
2016-03-11	1502	LA/AR
2015-10-05	1491	S. Carolina
2016-10-09	1290	Matthew
2024-09-28	**1205**	Helene
2008-09-15	1176	Ike & PRE
2018-09-16	1147	Florence

Which events rank at the top for exceedances of the 100-year, 72-h ARI?

CoCoRaHS

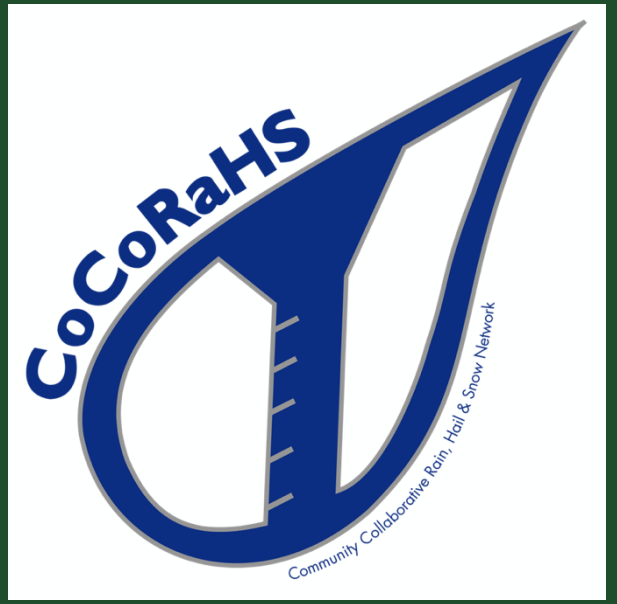
Event	# of points	
2010-05-03	147	Tennessee
2013-09-13	146	Colorado
2024-09-28	130	Helene
2008-09-15	118	Ike & PRE
2015-10-05	111	S. Carolina
2024-09-27	100	Helene
2017-08-28	89	Harvey



Which events rank at the top for exceedances of the 1000-year, 72-h ARI?

CoCoRaHS

Event	# of points	
2010-05-03	77	Tennessee
2024-09-28	66	Helene
2013-09-13	49	Colorado
2018-09-17	40	Florence
2015-10-05	21	S. Carolina
2016-10-09	10	Matthew
2017-08-29	8	Harvey



Several CoCoRaHS volunteers have observed multiple 100-year rainstorms

- NC-BC-115, near Black Mountain east of Asheville, has recorded 4, and two were in the same month!
  - September 26, 2015; September 17, 2018 (Florence); September 30, 2018; September 27, 2024 (Helene)
- Four observers have recorded three
  - MO-SN-2, MO-FSA-001, TN-DV-108, TN-HM-2

- This may speak to the need for the NOAA Atlas 15 update
- **But CoCoRaHS volunteers are meaningfully contributing to the observation and understanding of extreme rainfall!**

And a few CoCoRaHS volunteers have observed multiple 1000-year events!

In 2024:

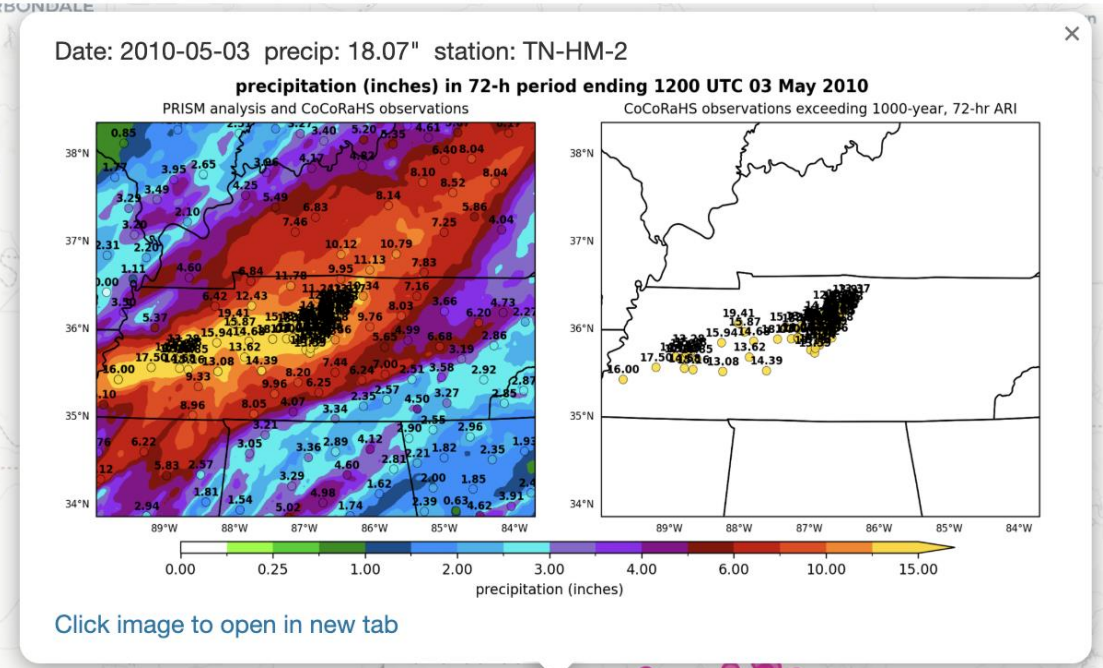
- NC-BC-76 and NC-BC-115 in the mountains east of Asheville
  - Past events were September 2015 and June 2019, and then Helene
- SD-LN-12 and SD-LN-19, near Sioux Falls
  - June 2014 and June 2024

- This may speak to the need for the NOAA Atlas 15 update
- **But CoCoRaHS volunteers are meaningfully contributing to the observation and understanding of extreme rainfall!**

Points exceeding the 0.1% annual exceedance probability ("1000-year rainfall"), 72 hours, 2002-2024 CoCoRaHS gauge observations, periods ending 1200 UTC

CoCoRaHS exceedances of 1000-year, 72-hour ARI, 2002-2024 (colored by year)

Color shaded by year



18.07 inches
TN-HM-2

Cape Girardeau
POPLAR BLUFF
JONESBORO
JACKSON
MEMPHIS
Southaven
Florence
HUNTSVILLE
Columbia
Cookeville
MURFREESBORO
TENNESSEE

2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

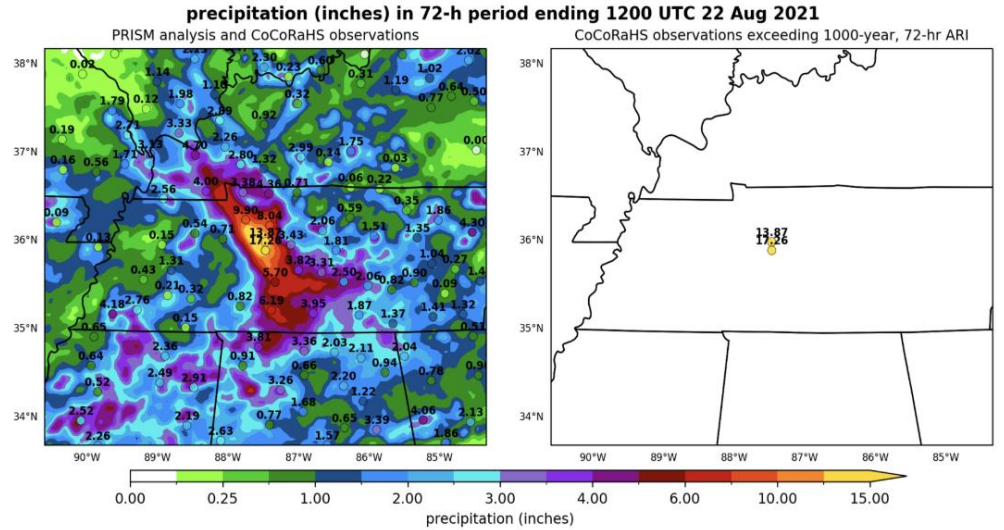
Browse these maps yourself!

Source: CoCoRaHS, NOAA, PRISM Climate Group
Map by Russ Schumacher, Colorado State University

Points exceeding the 0.1% annual exceedance probability ("1000-year rainfall"), 72 hours, 2002-2024 CoCoRaHS gauge observations, periods ending 1200 UTC

CoCoRaHS exceedances of 1000-year, 72-hour ARI, 2002-2024 (colored by year)

Date: 2021-08-22 precip: 17.26" station: TN-HM-2



Click image to open in new tab

Color shaded by year

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2022
2023
2024

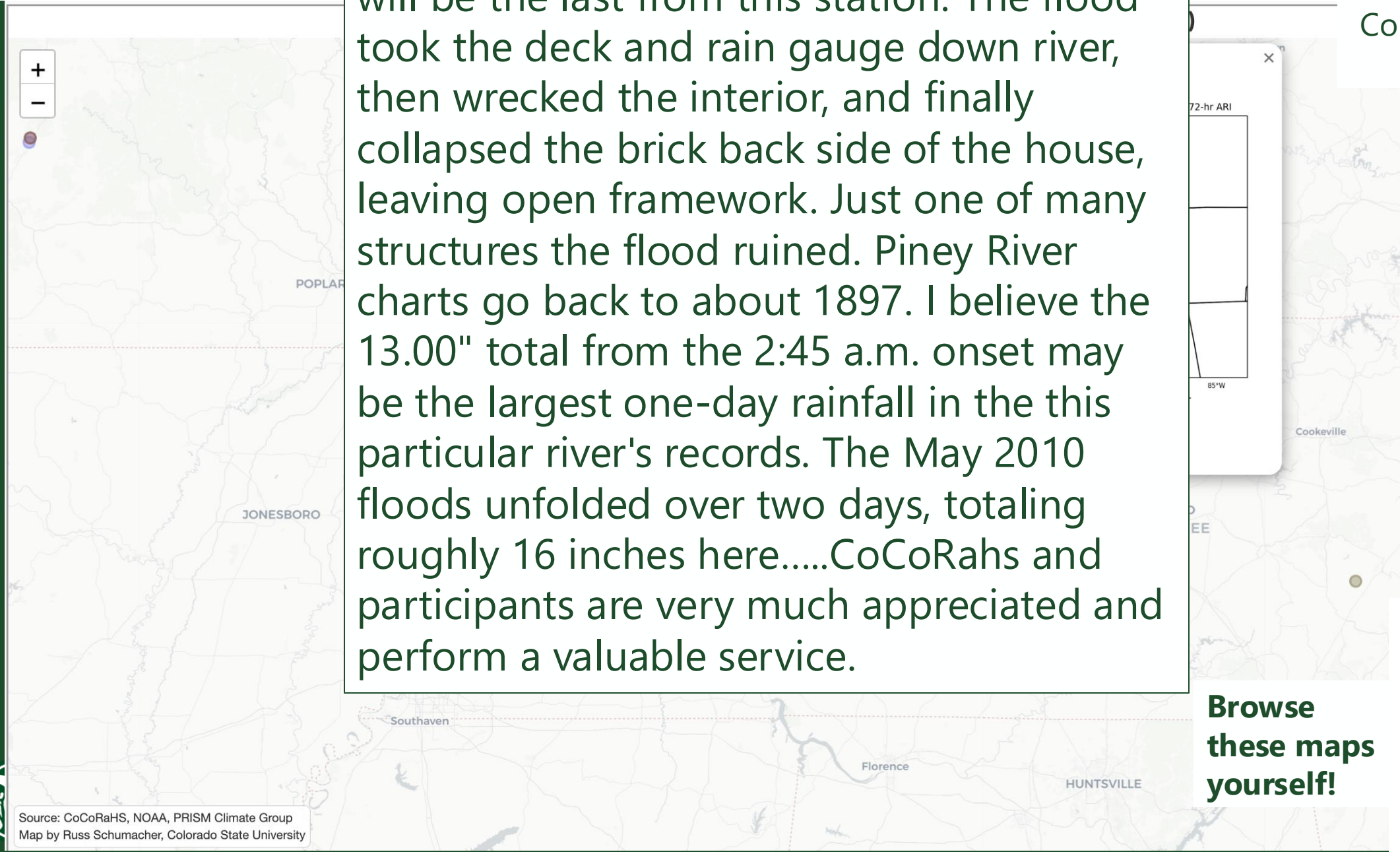
Cape Girardeau
POPLAR BLUFF
JONESBORO
JACKSON
MEMPHIS
Southaven
Florence
HUNTSVILLE
Columbia
MURFREESBORO
TENNESSEE
Cookeville

Browse these maps yourself!

Source: CoCoRaHS, NOAA, PRISM Climate Group
Map by Russ Schumacher, Colorado State University

Points exceeding the C … "), 72 hours, 2002-2024 C … TC

Unfortunately, after 5,000 plus reports this will be the last from this station. The flood took the deck and rain gauge down river, then wrecked the interior, and finally collapsed the brick back side of the house, leaving open framework. Just one of many structures the flood ruined. Piney River charts go back to about 1897. I believe the 13.00" total from the 2:45 a.m. onset may be the largest one-day rainfall in the this particular river's records. The May 2010 floods unfolded over two days, totaling roughly 16 inches here.....CoCoRahs and participants are very much appreciated and perform a valuable service.



Color shaded by year

2002
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2024

Browse these maps yourself!

What about non-stationarity and climate change?

- Everything discussed so far assumes "stationarity" – that the statistics are the same over the entire time period
- We know that the climate is warming, which increases the potential for extreme precipitation. We also know that just collecting more data will improve the estimates.
- It's clear that this should be incorporated into precipitation frequency estimation somehow, but how to best do so is a topic of active research

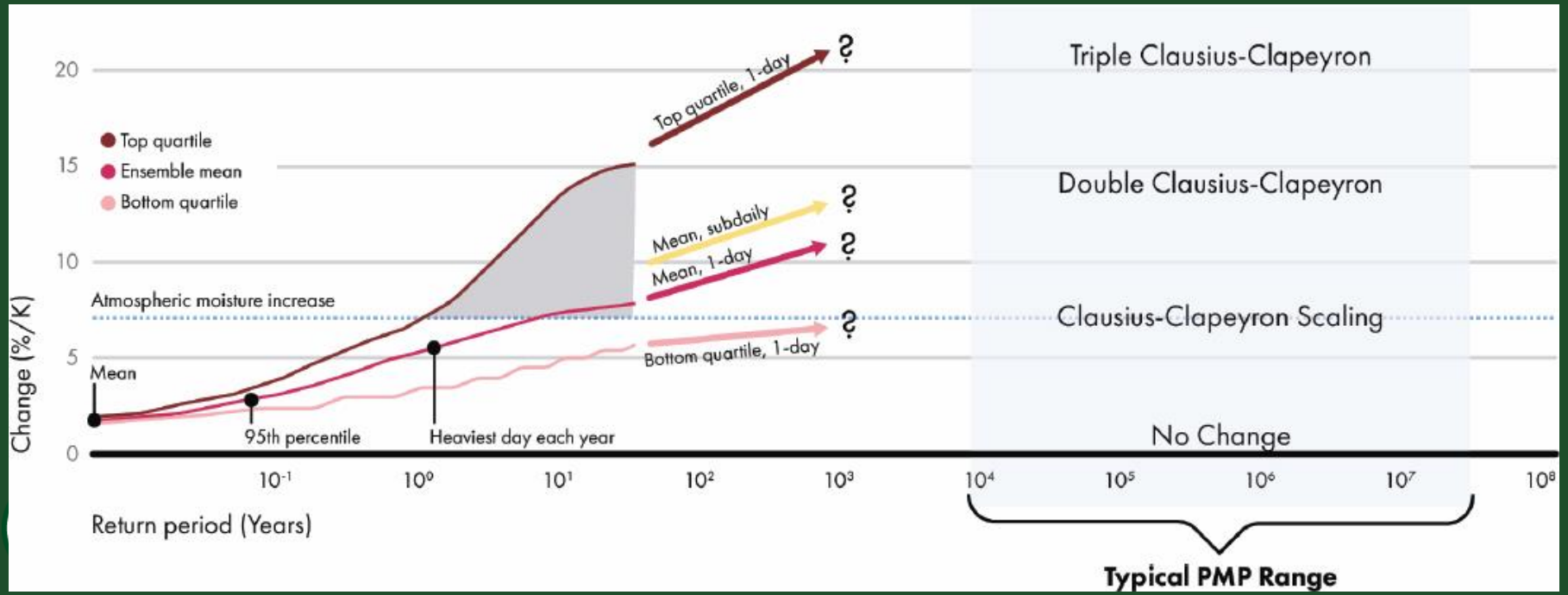
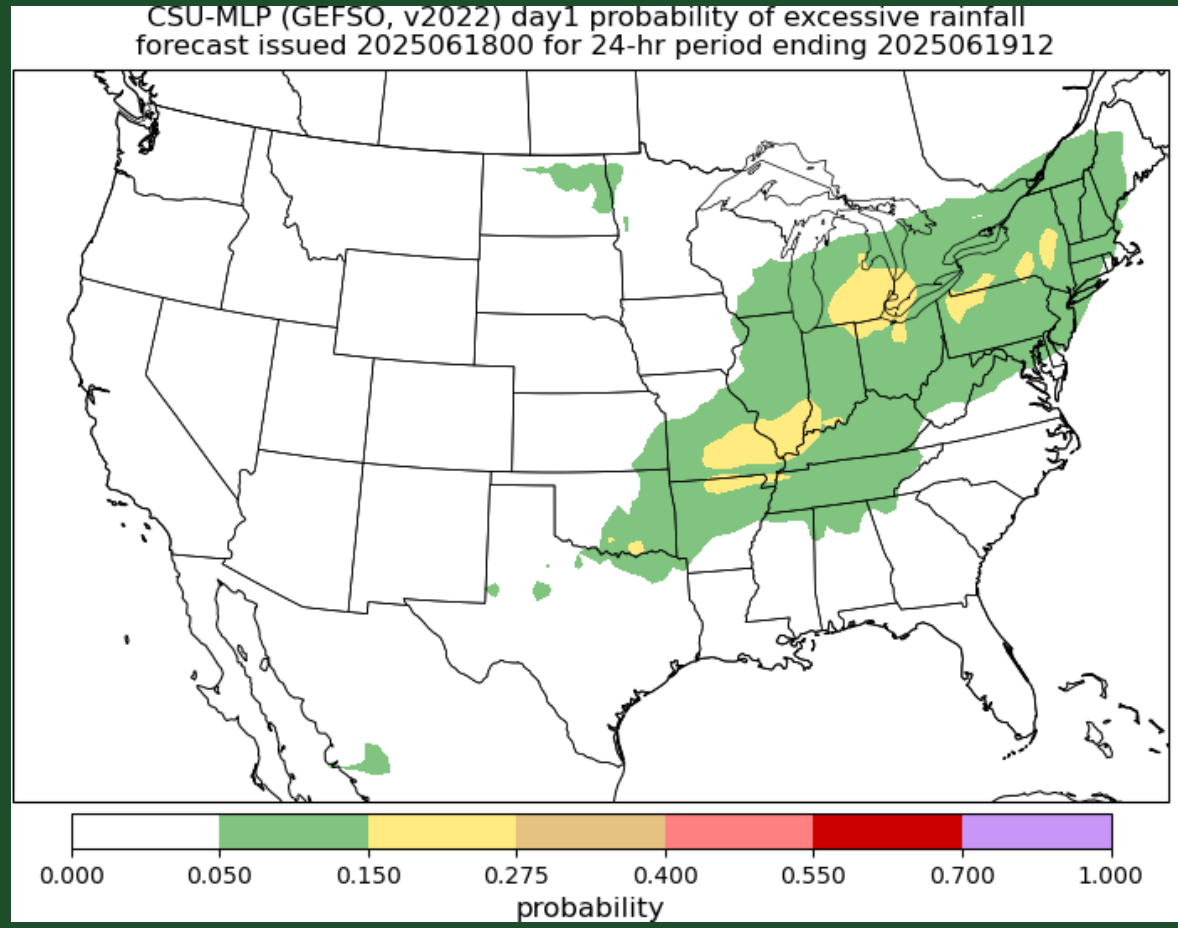
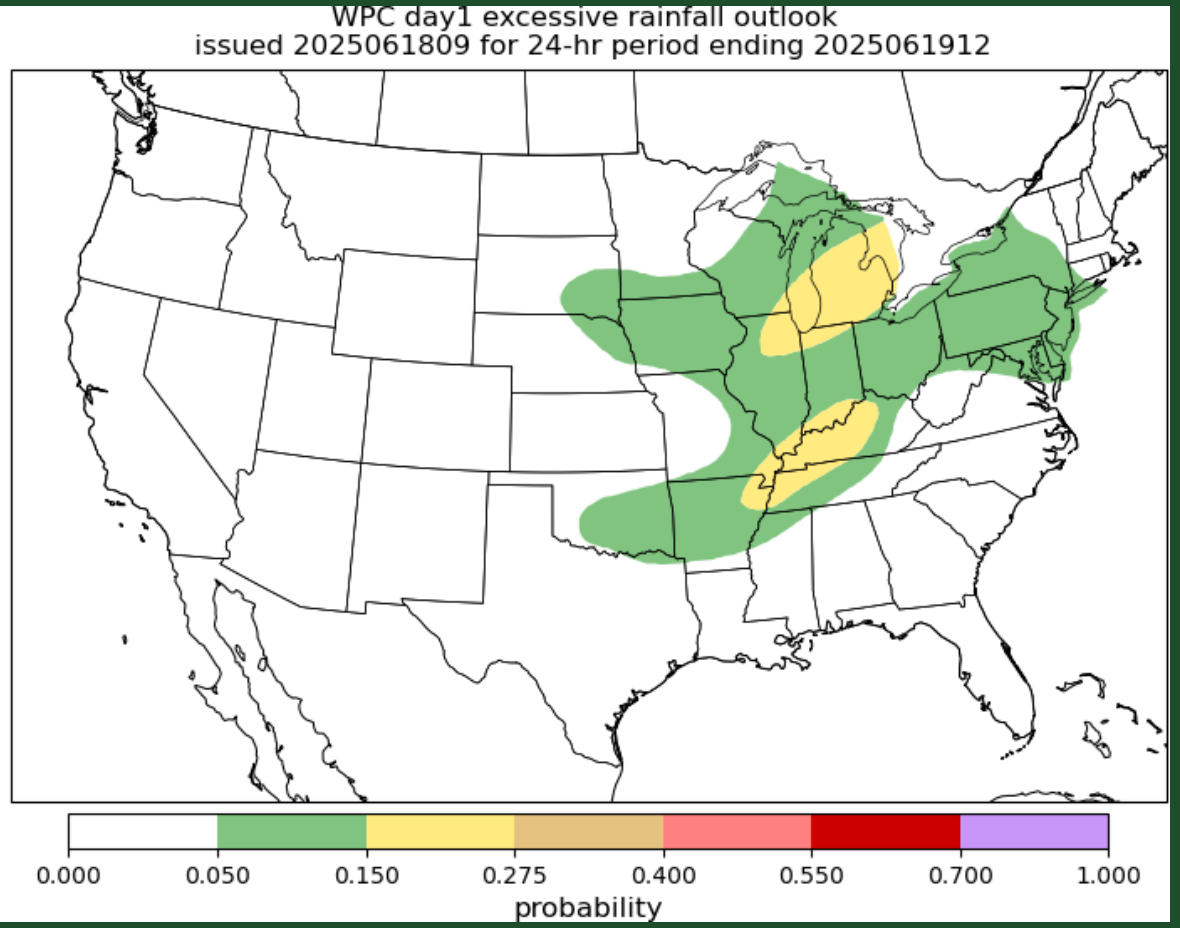


Fig. 3-4, National Academies report on Modernizing Probable Maximum Precipitation Estimation

We use average recurrence intervals in the development of forecast systems for excessive rainfall



CSU Machine Learning guidance



Weather Prediction Center Excessive Rainfall Outlook

COLORADO STATE UNIVERSITY

https://schumacher.atmos.colostate.edu/hilla/csu_mlp/

Summary and conclusion

- Return periods can be a useful concept for understanding the risk of extreme precipitation and flooding – but they are also easy to misunderstand
- A 100-year rainstorm is rare at any given location, but we expect many of them to occur *somewhere* each year
- The chance of occurrence is the same in each year, so it is possible (though unlikely) to get a 100-year storm in back-to-back years
- A 100-year rainstorm does not necessarily lead to a 100-year flood

Summary and conclusion

- **CoCoRaHS volunteers often observe these extreme events, and are meaningfully contributing to extreme precipitation research!**

Interactive maps:

Questions? Comments?
russ.schumacher@colostate.edu

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