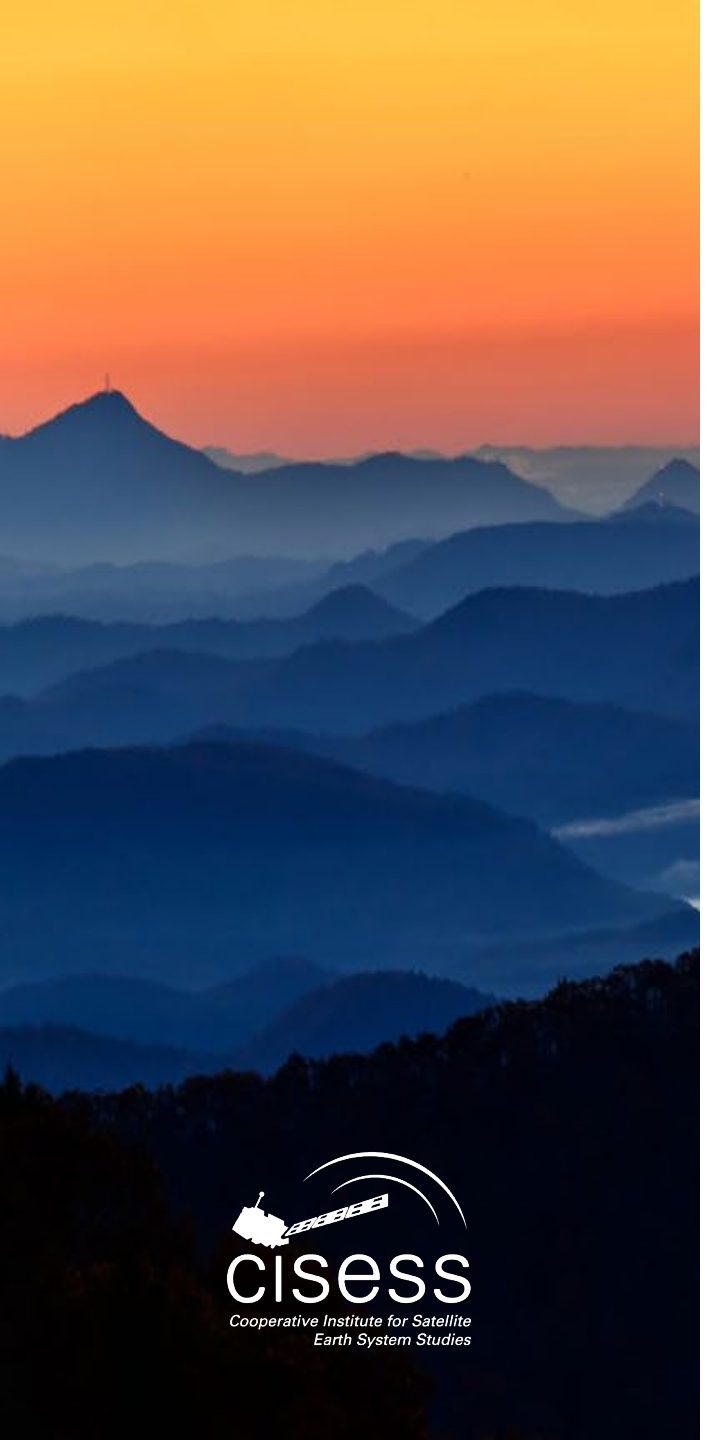

Extreme rainfall from tropical cyclones in the Appalachians: Lessons learned from Hurricane Helene (2024)

Kenneth E. Kunkel

North Carolina State University
North Carolina Institute for Climate Studies
Asheville, NC

November 4, 2025

NC STATE UNIVERSITY

NCICS

NOAA

HELENE – Anatomy of a Killer

- 108 fatalities in NC alone
- $60 Billion in damage in NC alone, for example:
- 74,000 homes damaged: of those ~9,000 severely damaged or destroyed
- Catastrophic damage to infrastructure, for example, Asheville water system severely damaged: 100,000 people had no running water for 19 days and no potable running water for 53 days
- In addition to being without water, I lost power for 15 days, cable/internet and cell service for 18 days
- More than 2,000 landslides-one of worst events in U.S. history according to U.S Geological Survey

View of Creek Next to my Subdivision

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Flooding Creek After Helene

Video link

One person lost their life in this creek about a half mile upstream from this point

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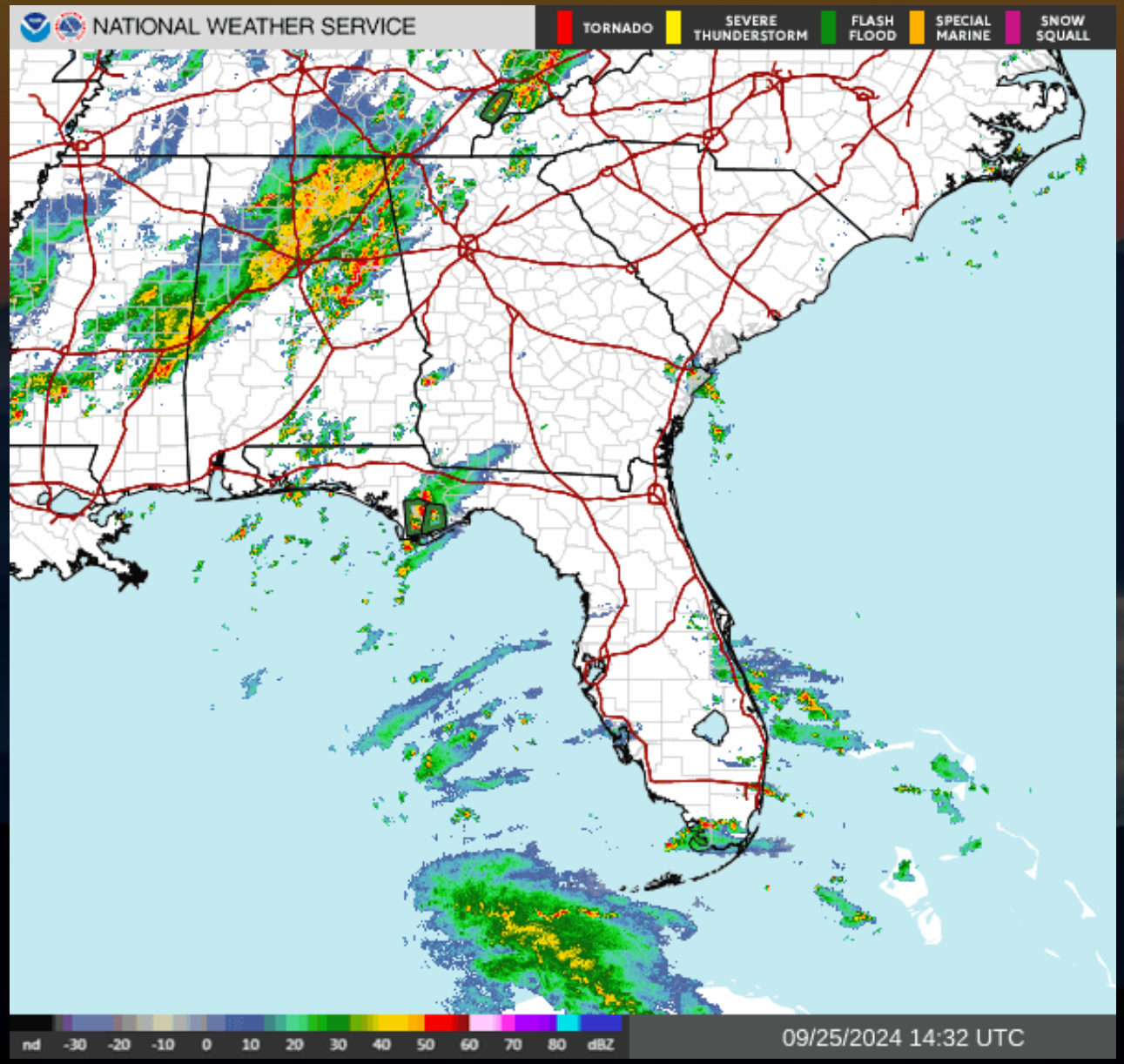

NWS radar loop, Sept. 25-27, 2024

Asheville, NC is circled, underneath Tornado at the top.

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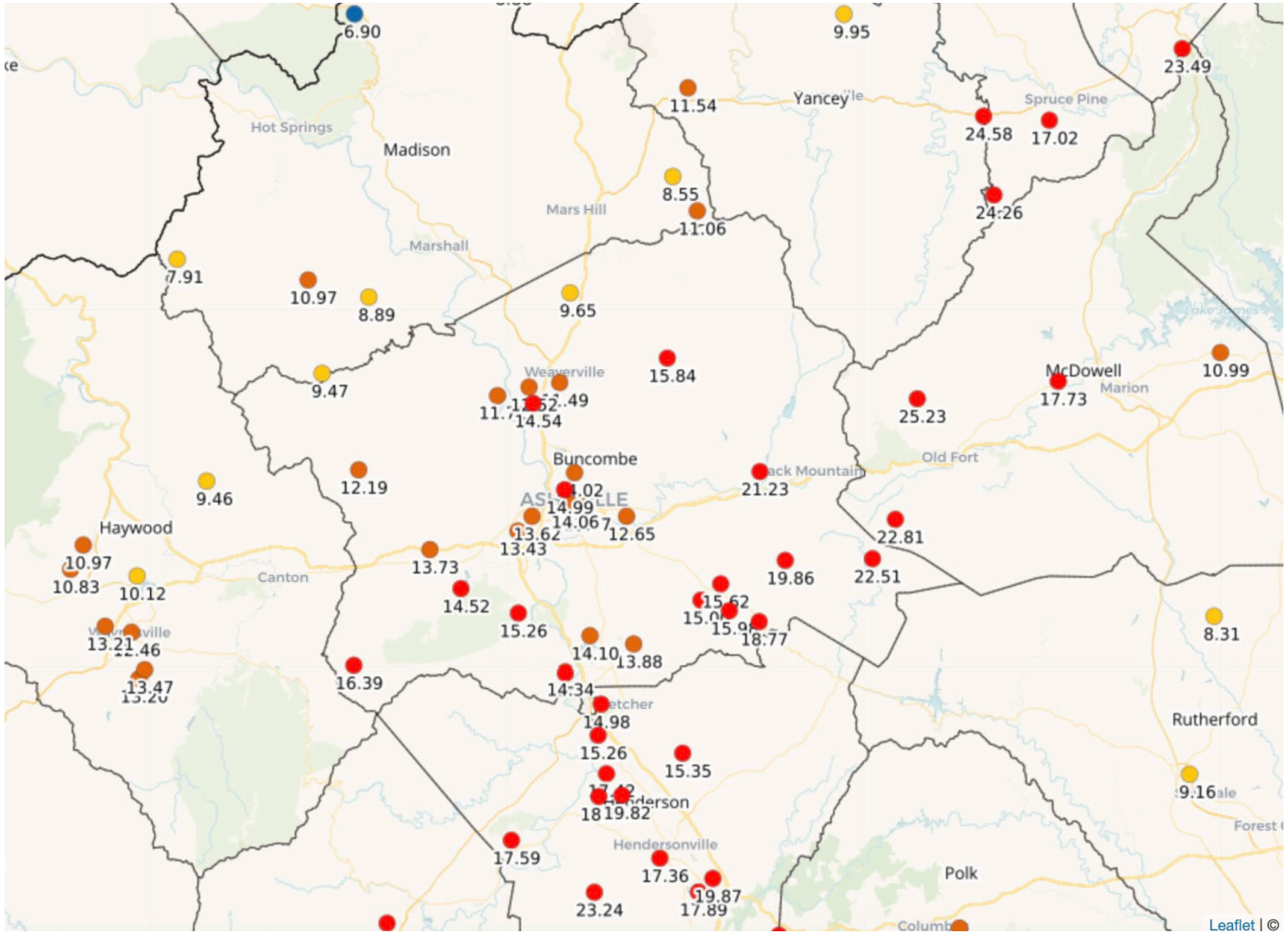
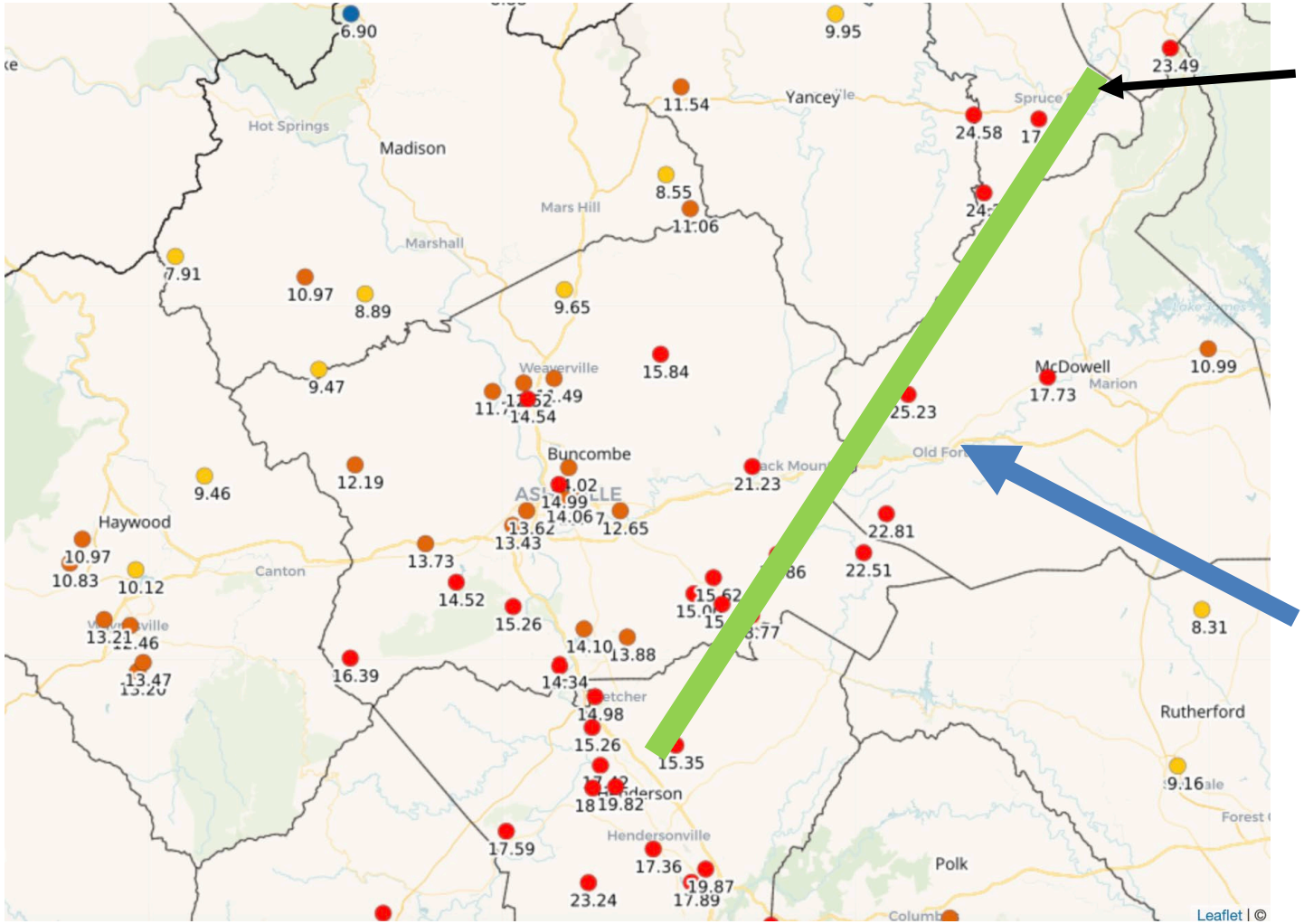
Selected Helene statistics

- 3-day rainfall totals: Busick (31 inches), Mt Mitchell (24 inches), Bear Wallow Mountain (20 inches), my house (15.6 inches, >1000 year return interval)
- High end tropical storm intensity when it reached NC
- Stalled front caused excessive rainfall before Helene's arrival
- All time record flood levels on French Broad River (previous record in 1916) and Swannanoa River (previous record in 1791)

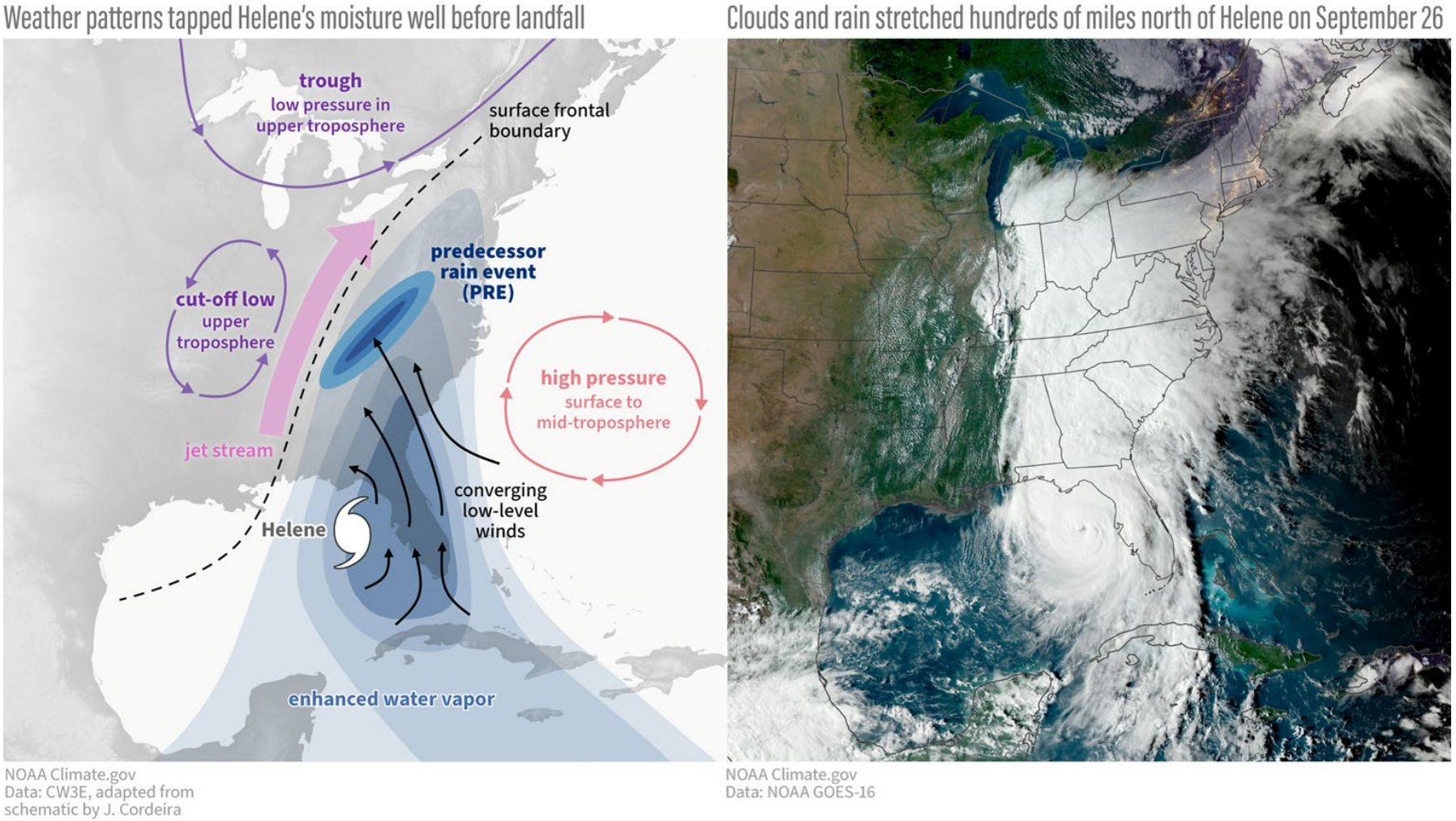
Western NC Helene Rainfall-CoCoRaHS



Western NC Helene Rainfall-CoCoRaHS

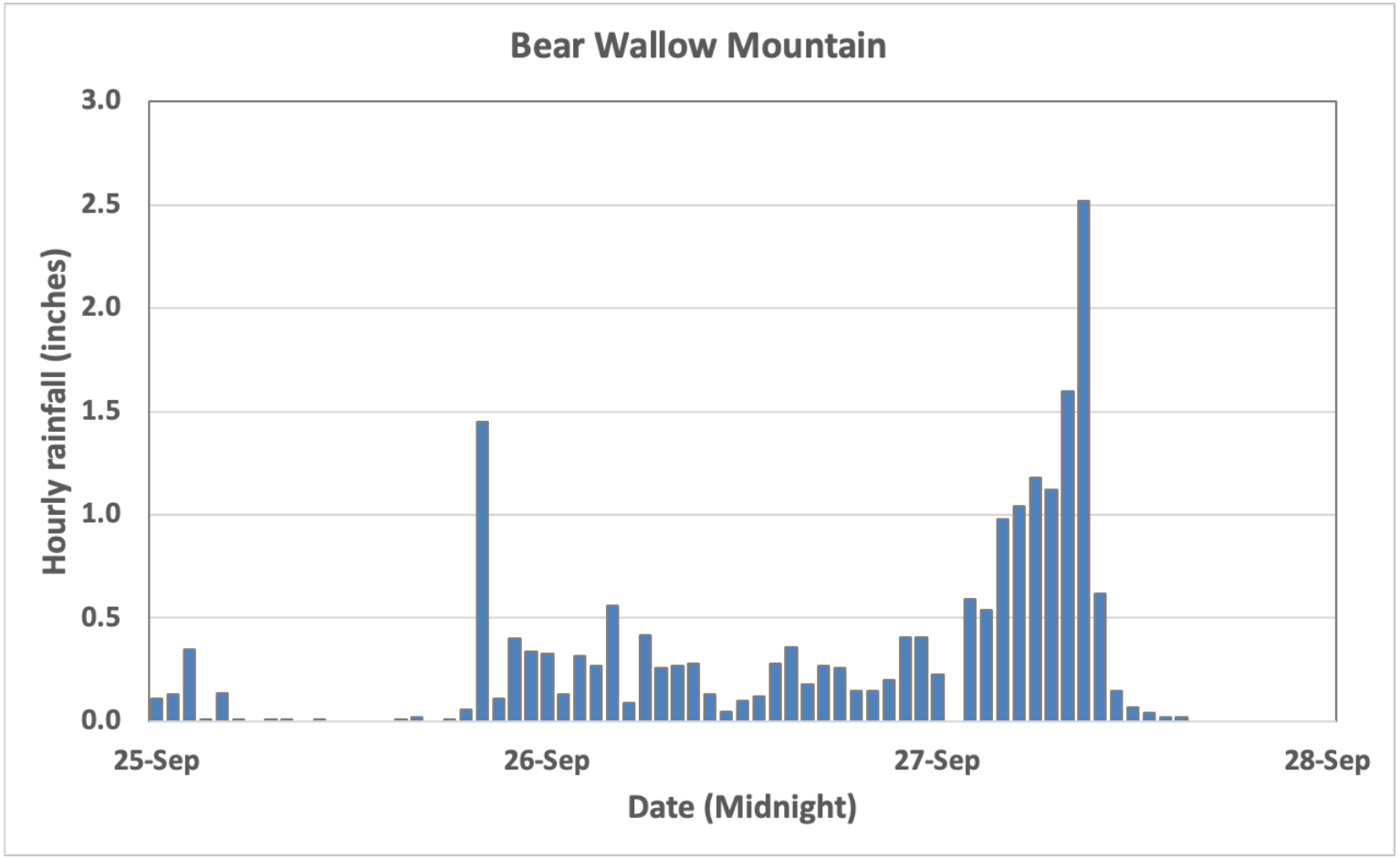


Predecessor Rain Event (PRE)



Source: Climate.gov

Bear Wallow Mountain Rainfall: Anatomy of a Killer



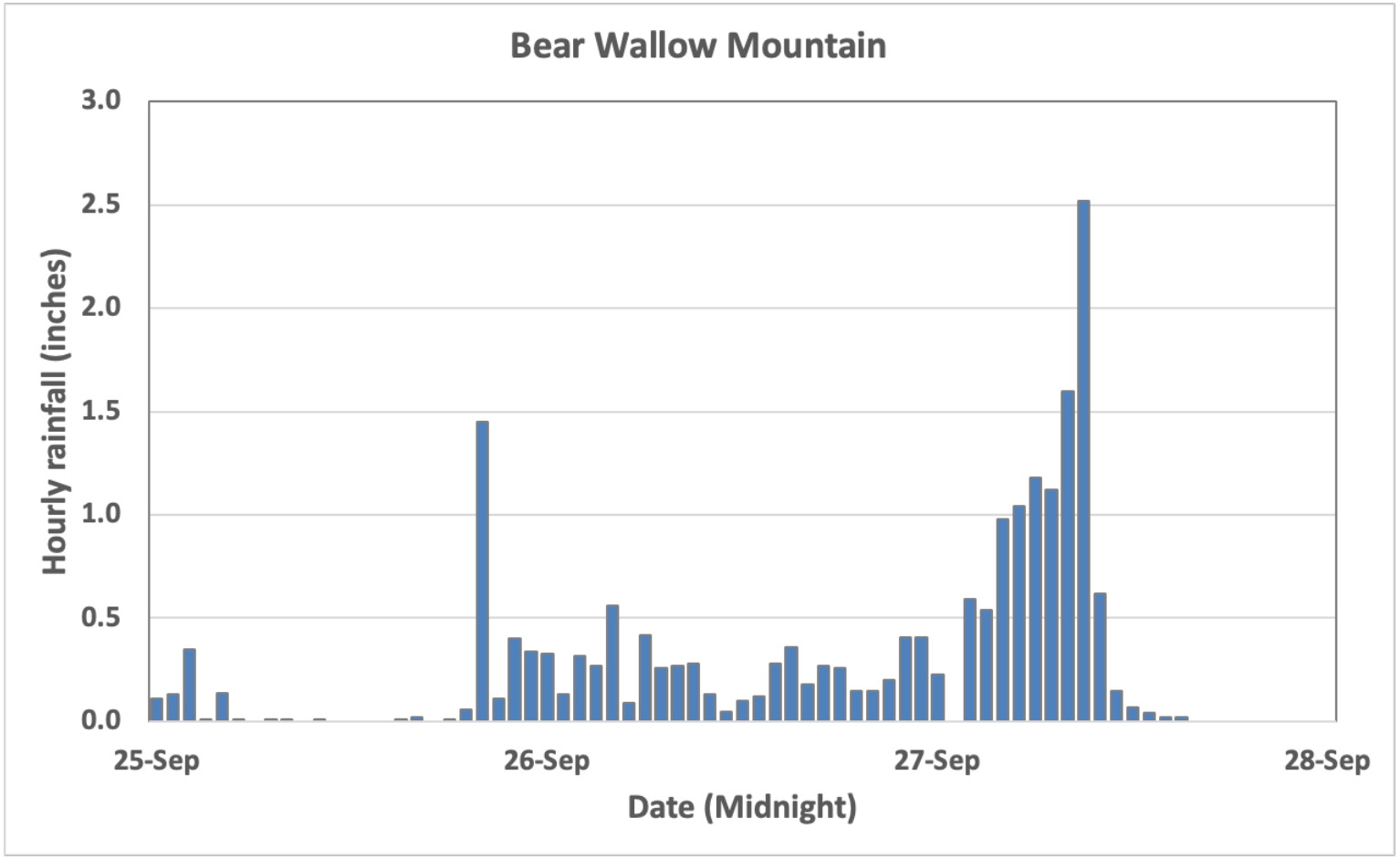
9.4 inches during 36 hours prior to Helene

10.5 inches in 12 hrs after Helene arrival

5 inches between 6 am and 9 am on Sep. 27 (after 14 inches had already fallen)

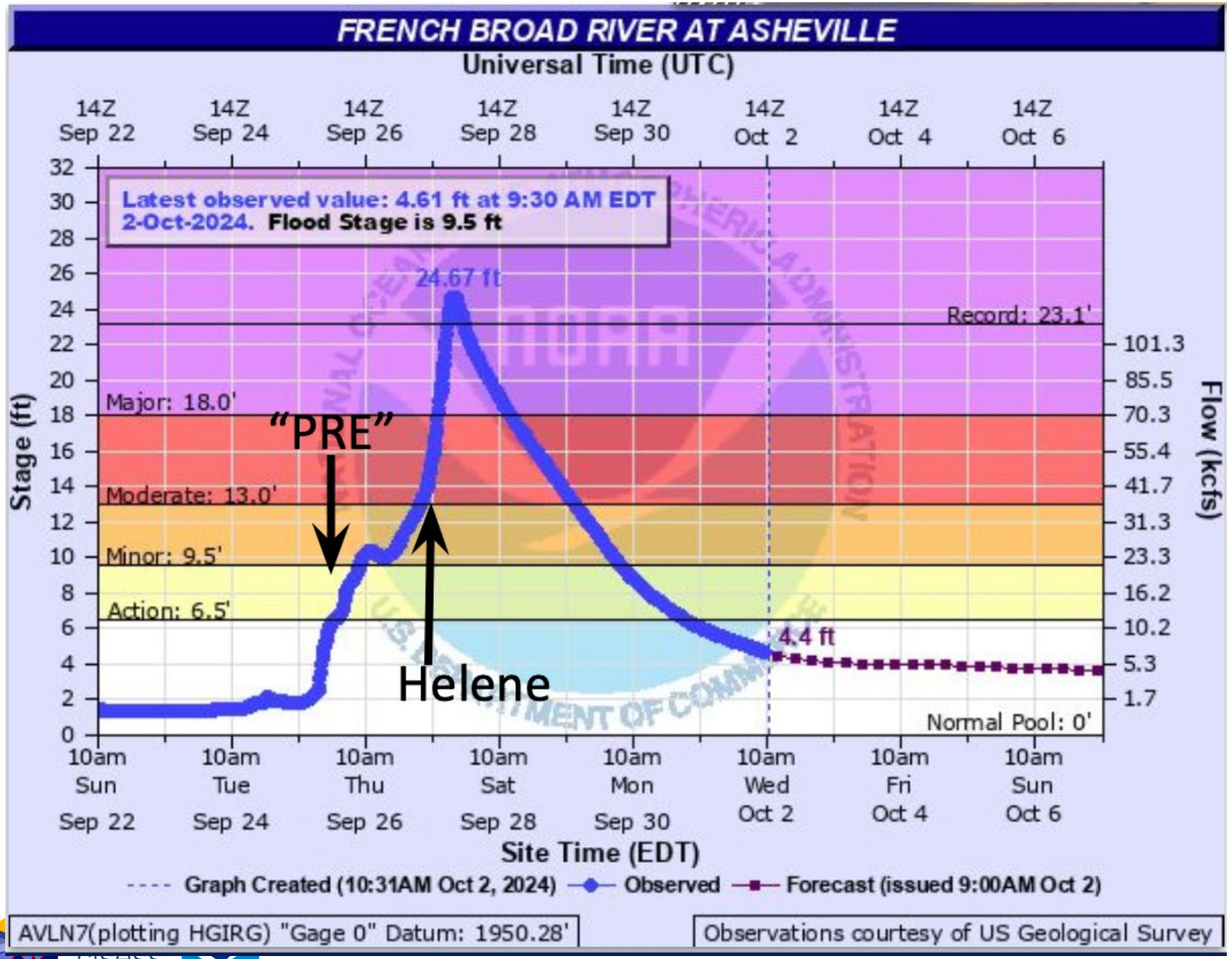
Data courtesy of the North Carolina State Climate Office

Bear Wallow Mountain Rainfall: Anatomy of a Killer



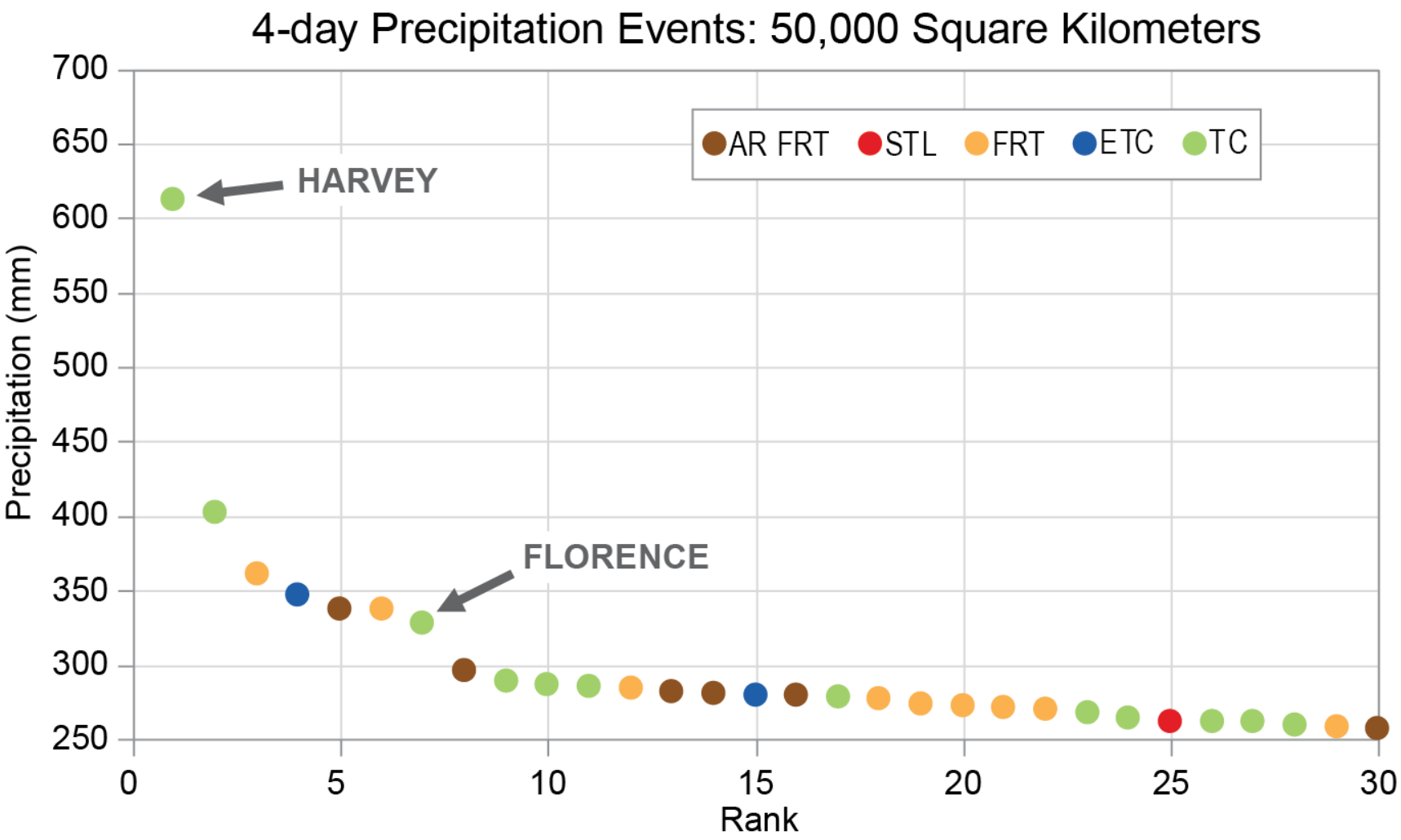
Tragic Landslides near my home (13 lives lost)

Data courtesy of the North Carolina State Climate Office



Source: NOAA National Weather Service, Greenville/Spartanburg

Hurricanes Harvey/Florence Analysis

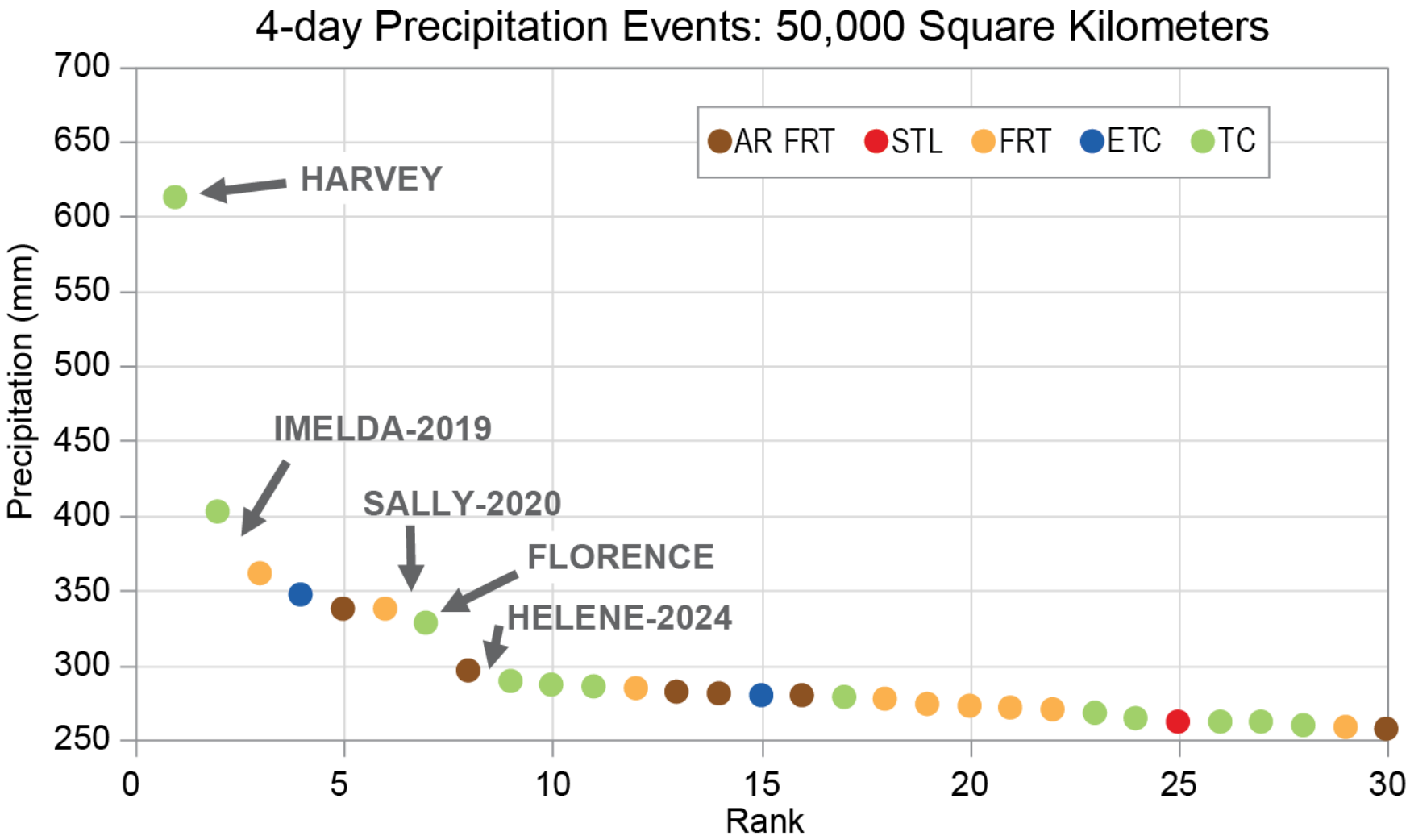


Kunkel, K.E. and S.M. Champion, 2019: An assessment of rainfall from Hurricanes Harvey and Florence relative to other extremely wet storms in the United States. *Geophys. Res. Lett.*, **46**, 13,500–13,506. https://doi.org/10.1029/2019GL085034

Hurricanes Harvey/Florence Analysis

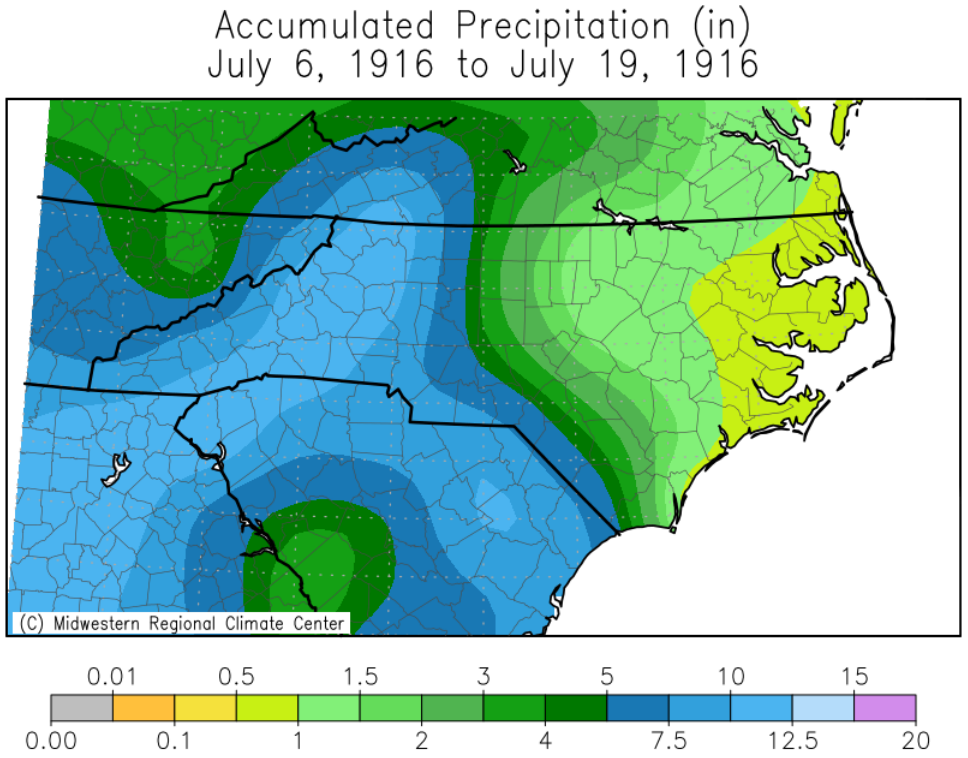
I updated the analysis to 1949–2024

Update to 2024

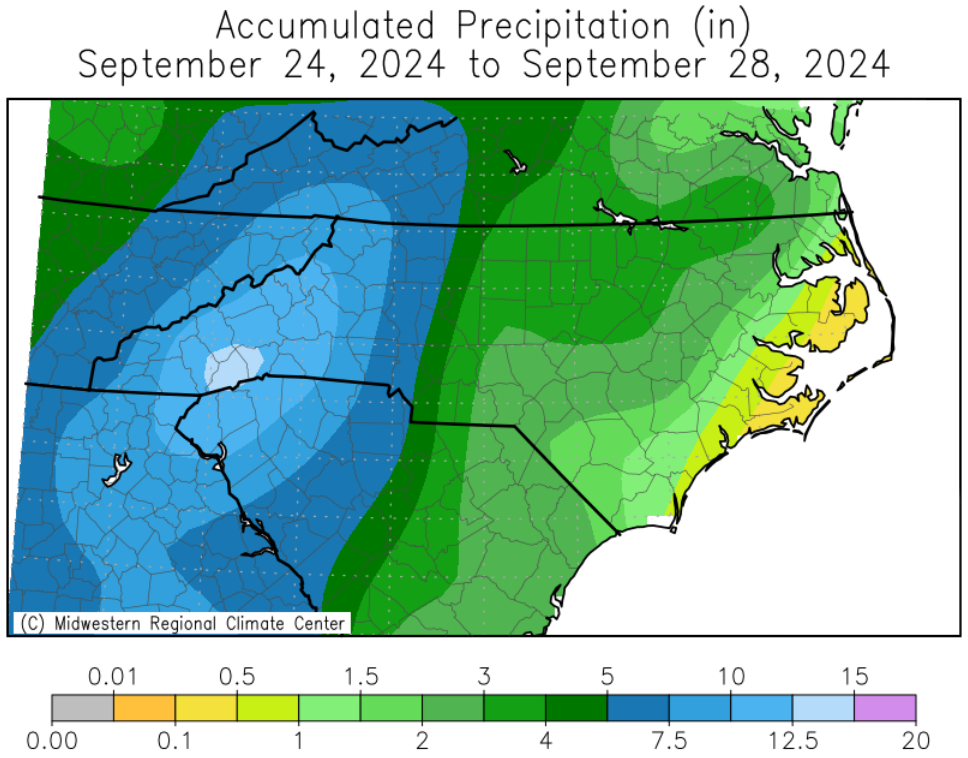


Comparison of 1916 and 2024 Rainfall Events

1916



2024



Comparison of 1916 and 2024 Rainfall Events

Highest amounts in 1916:

Altapass: 31 inches
Rockhouse: 30 inches
Highlands: 26 inches
Brevard, Banner Elk: 22 inches
Hendersonville: 20 inches

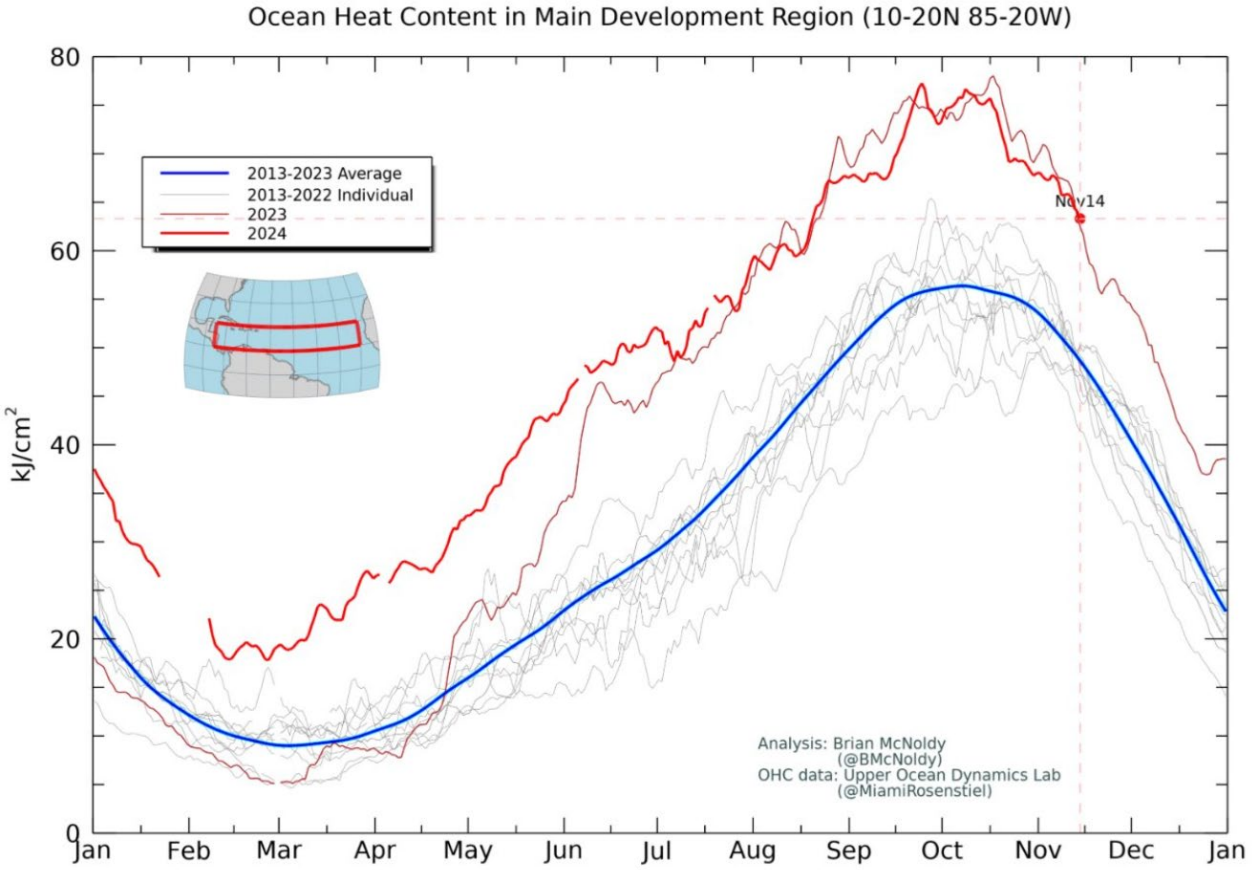
The 1916 flood was also a compound event: back-to-back TCs

Comparable rainfall amounts to Helene, but the two TCs were separated by a week

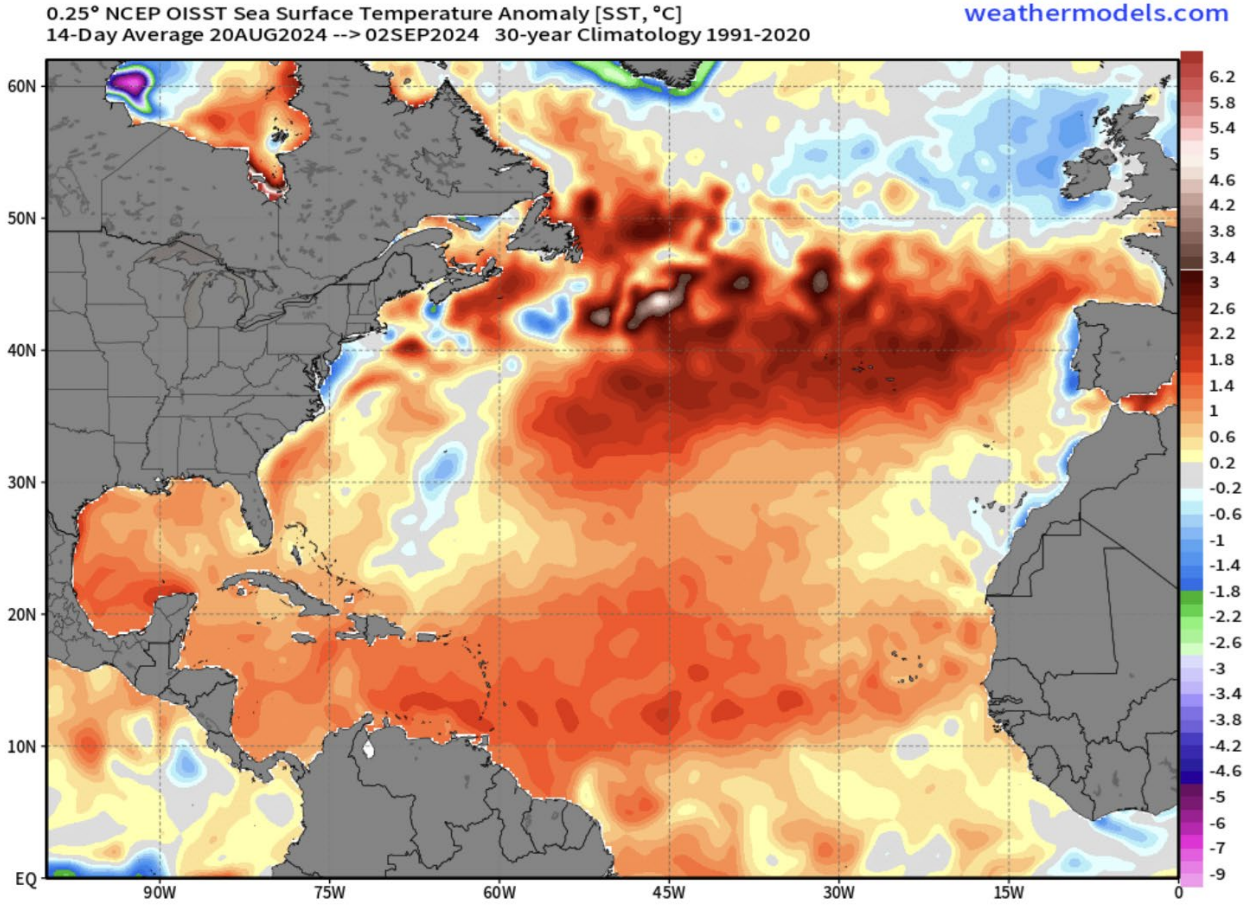
Helene rainfall vs PMP

- Nearly all rainfall fell in about a 40-hr period
- Hydrometeorological Report 51(1978) - 48-hr durations:
  - Point (10 mi^2): 43 inches (vs 31 inches at Busick)
  - 1,000 mi^2: 27 inches (lots of 20+ inch amounts, but probably short of PMP area average)
  - 5,000 mi^2: 20 inches (ditto)
  - 20,000 mi^2 : 14-15 inches (compared to 12 inches for Helene)
- Rainfall amounts along the eastern Appalachian escarpment were well in excess of 1000-yr return period (from NOAA Atlas 14), but somewhat short of PMP levels according to HMR 51

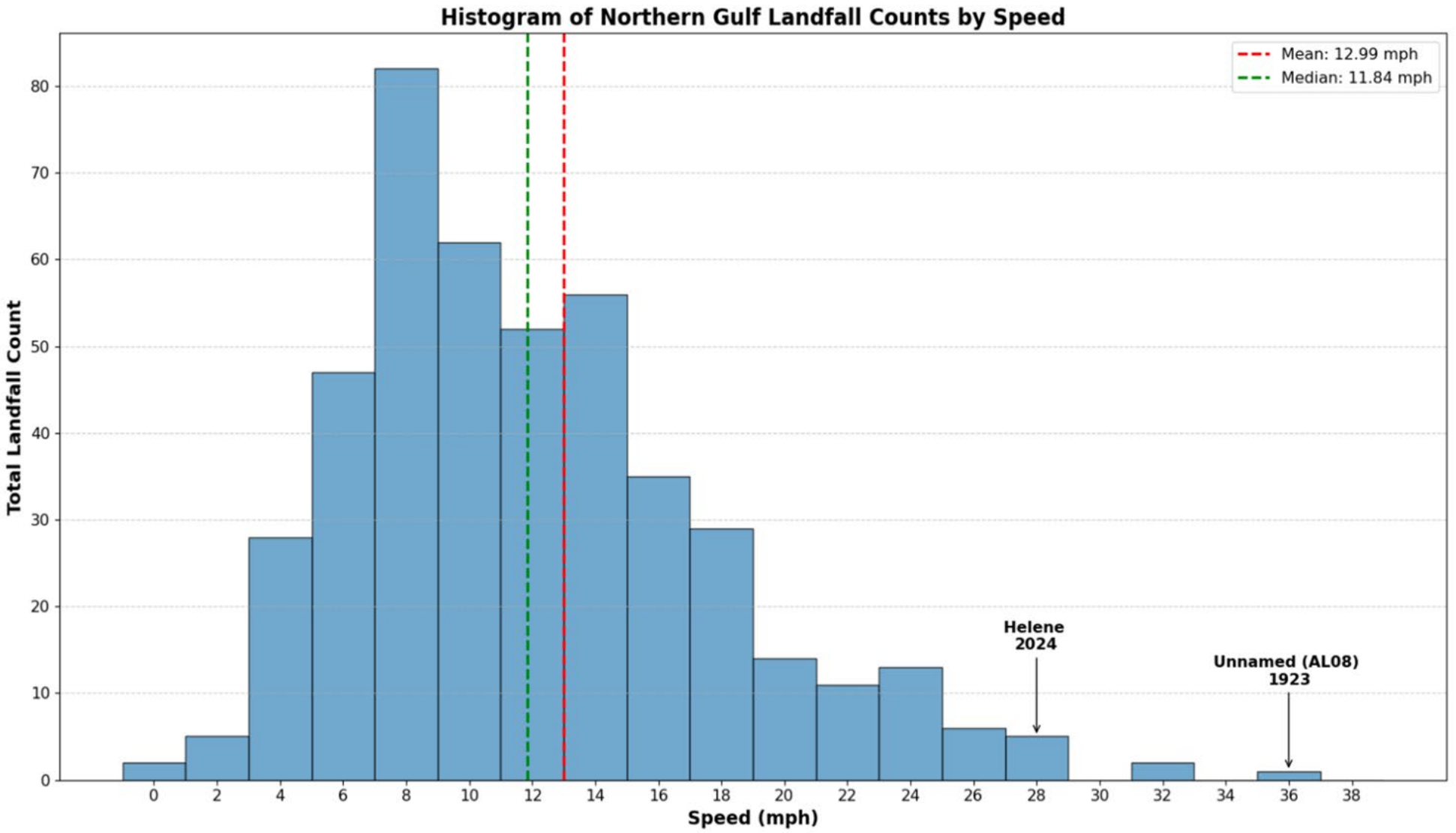
The Atlantic Was Record Hot



Source: Brian McNoldy

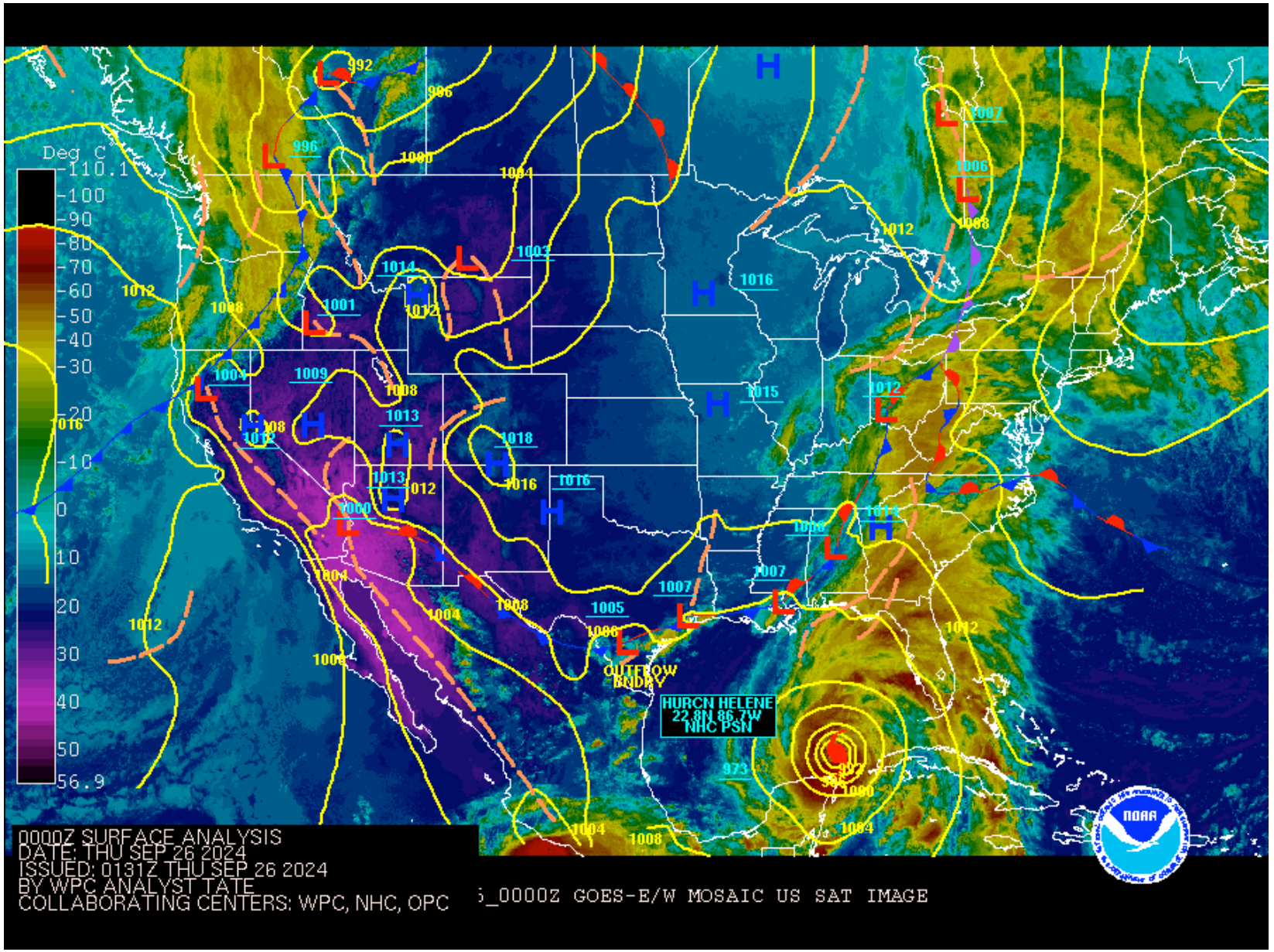


Source: WeatherModels.com

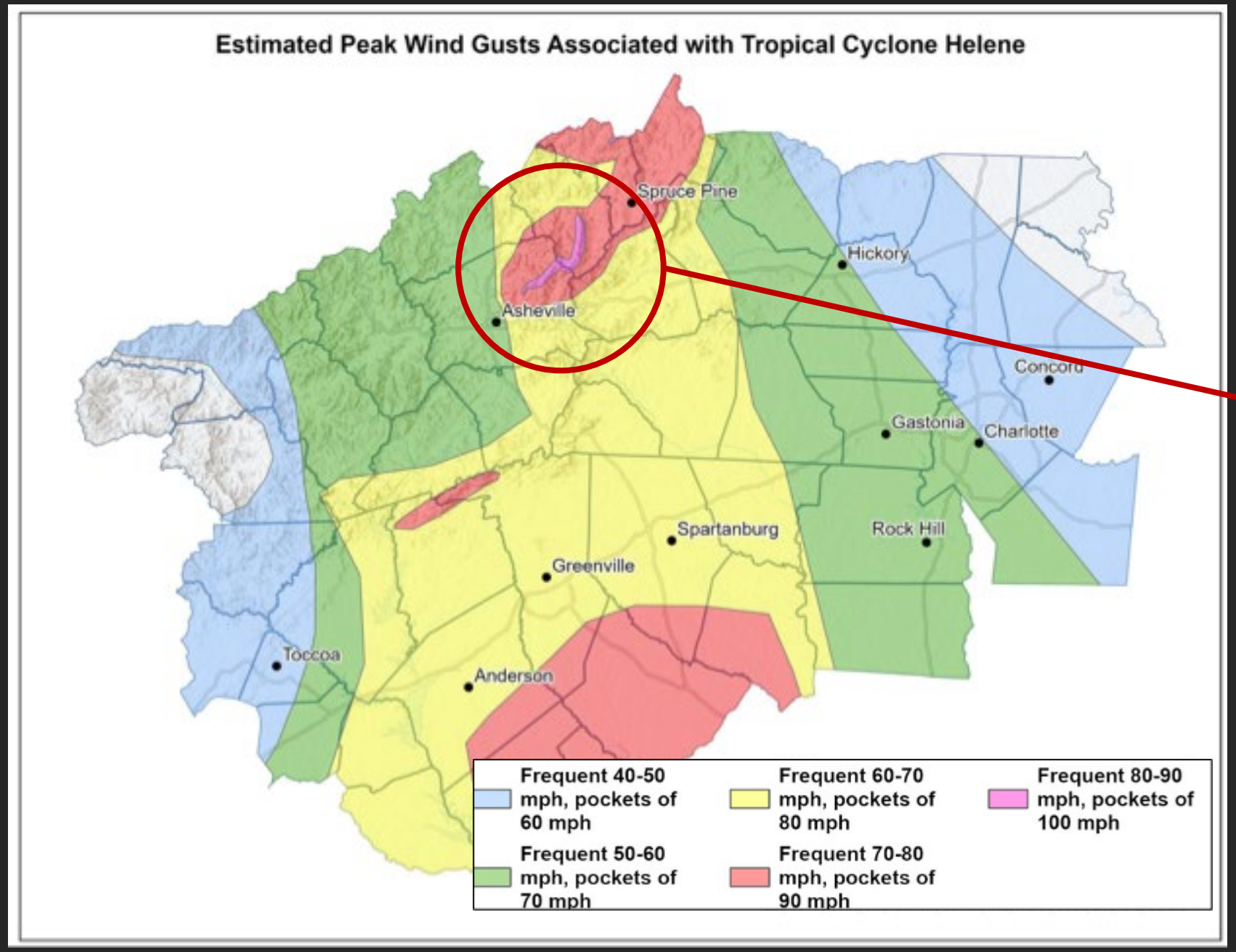


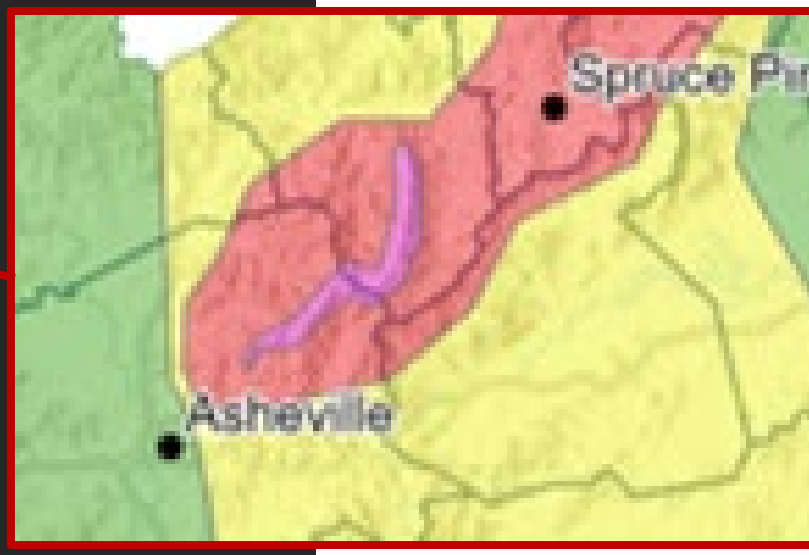
Source: NOAA National Hurricane Center

Wednesday



Source: NOAA Weather Prediction Center





No confirmed tornadoes in our region.

Source: NOAA National Weather Service, Greenville/Spartanburg

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Storm Transposition and Meteorology

- Transposition
  - Could occur anywhere along the eastern escarpment of the southern Appalachians
- How could this storm be maximized
  - There may be a more optimum balance between TC forward speed (maintain intensity) and duration (precipitation accumulation) that produces higher storm total rainfall
  - Higher TC intensity (e.g. Camille), increasing orographically-enhanced rainfall
  - Longer duration frontal precursor

Summary

- Meteorology: Compound event-stalled front followed by Helene
- Rainfall amounts were historic
  - Area-averaged multi-day rainfall was (nationally) one of the largest in last 75 years and on a par with Florence (2018)
  - Rainfall was below HMR 51 PMP values by 20-30%
- Highest rainfall rates occurred at the end of the event
  - I hypothesize that this greatly amplified the peak river stages and associated hydrologic impacts
- Need to characterize the event probability for planning decisions
  - Annual Exceedance Probability < 0.1% (according to Atlas 14)
  - We need a continuum from 0.1% (Atlas 15) to PMP
  - NASEM 2024 report recommendation for probabilistic framework

Acknowledgements

- Dr. Carl Schrek (North Carolina Institute for Climate Studies, NCSU) provided me with several of the graphics
  - He has produced a very informative Youtube video series on Helene
  - https://www.youtube.com/playlist?list=PLzWyoqOPKBiOkvxcmgKBuLiIVsQJDJo8V

- This work was partially supported by NOAA through the Cooperative Institute for Satellite Earth System Studies under Cooperative Agreement NA24NESX432C0001T101

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