HRRR Analysis and Prediction of Regional Conditions Associated with Flash Floods Across Southern Utah

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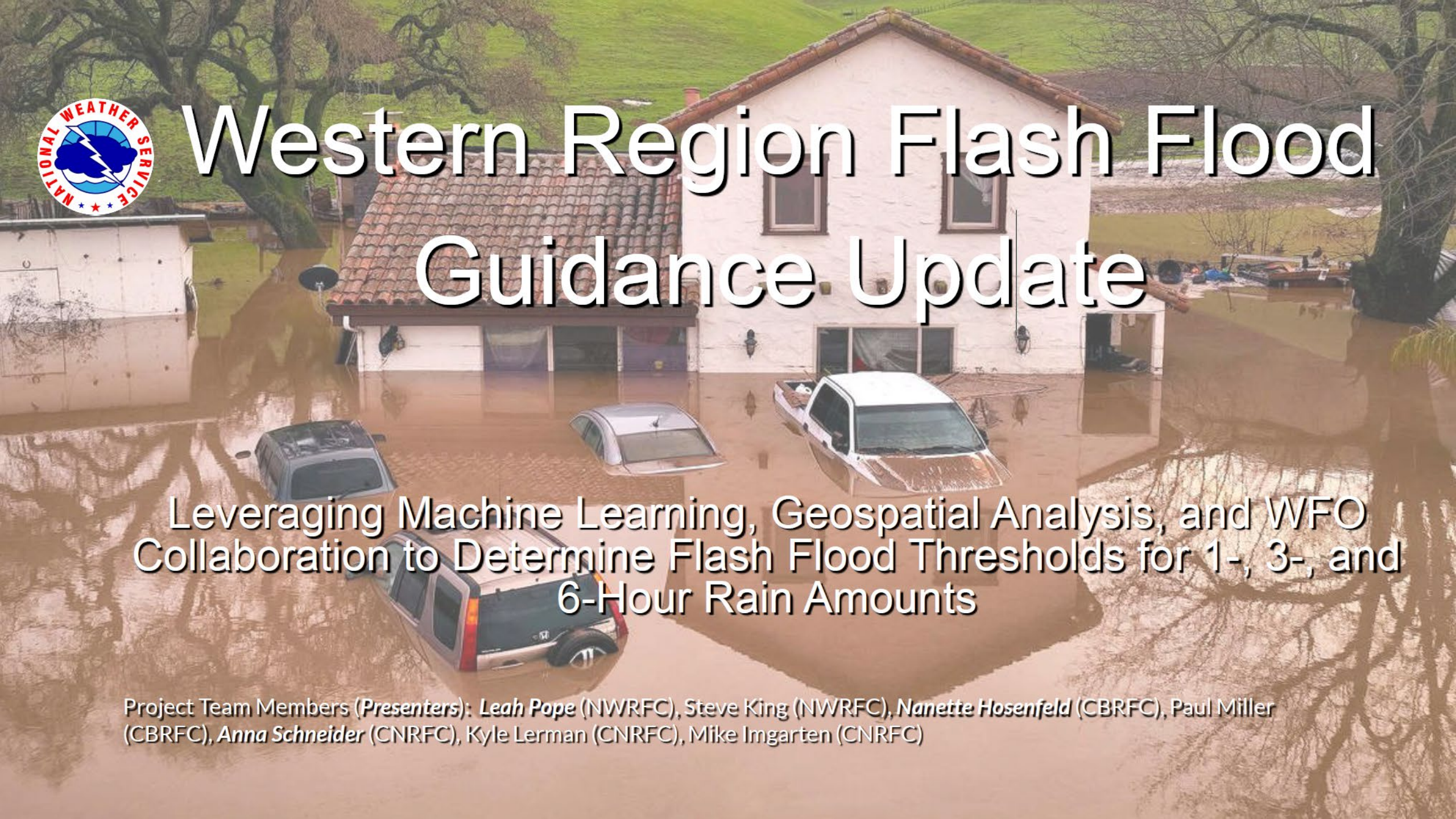
Acknowledge: NWS SLC WFO staff: David Church, Glen Merrill, Mike Seaman, & Darren Van Cleave
NWS CBRFC: Nanette Hosenfeld

Grand Staircase Escalante National Monument



Western Region Flash Flood Guidance Update

Leveraging Machine Learning, Geospatial Analysis, and WFO Collaboration to Determine Flash Flood Thresholds for 1-, 3-, and 6-Hour Rain Amounts

Project Team Members (***Presenters***): ***Leah Pope*** (NWRFC), Steve King (NWRFC), ***Nanette Hosenfeld*** (CBRFC), Paul Miller (CBRFC), ***Anna Schneider*** (CNRFC), Kyle Lerman (CNRFC), Mike Imgarten (CNRFC)

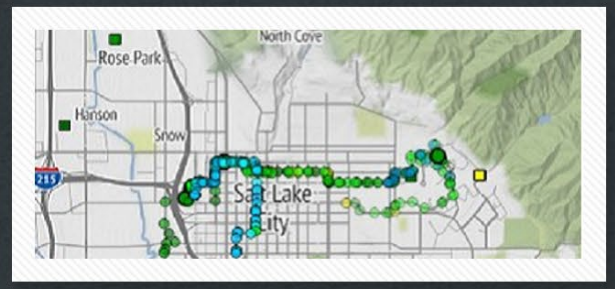
Mountain Meteorology Group
Department of Atmospheric Sciences
University of Utah
John Horel, Jim Steenburgh, Court Strong

NWS collaborations over the years funded by NWS Programs (CSTAR)

- 2002 Olympic Weather Support
- MesoWest/National Mesonet Program
- Early RTMA development
- Advanced capabilities and expanded use of ensemble-based probabilistic quantitative precipitation forecasts by field offices and in the National Blend of Models
- Advanced data fusion and data analytical techniques to assess hazardous atmospheric conditions from observations and numerical forecasts
- Developed techniques to improve downscaling of forecast or analyzed precipitation in complex terrain based on orographic precipitation gradients
- Validated cool-season snowfall forecasts across western U.S.

Horel Research Group https://horel.chpc.utah.edu

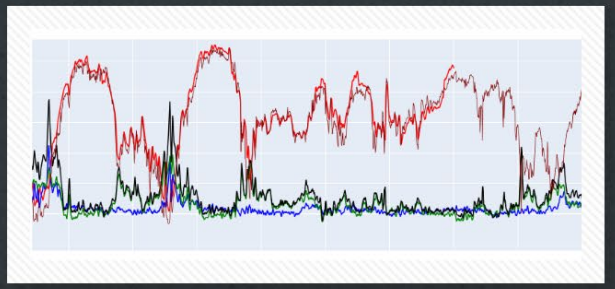
MesoWest



Air Quality

MEOP

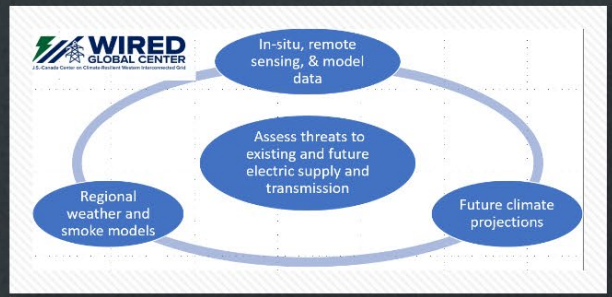
Great Salt Lake Research



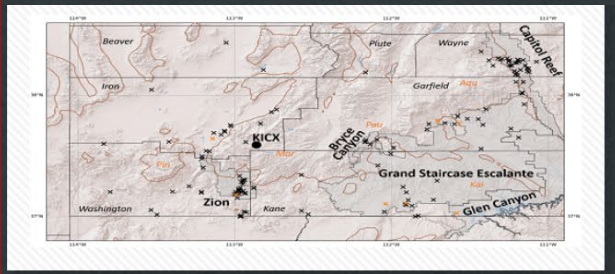
2024 Ozone Campaign

Alaska Fire and Fuels (AKFF)

Great Lakes Fire and Fuel (GLFF)



WIRED



Monsoon Research

UUNET

Mountain Meteorology Lab (MTMET)

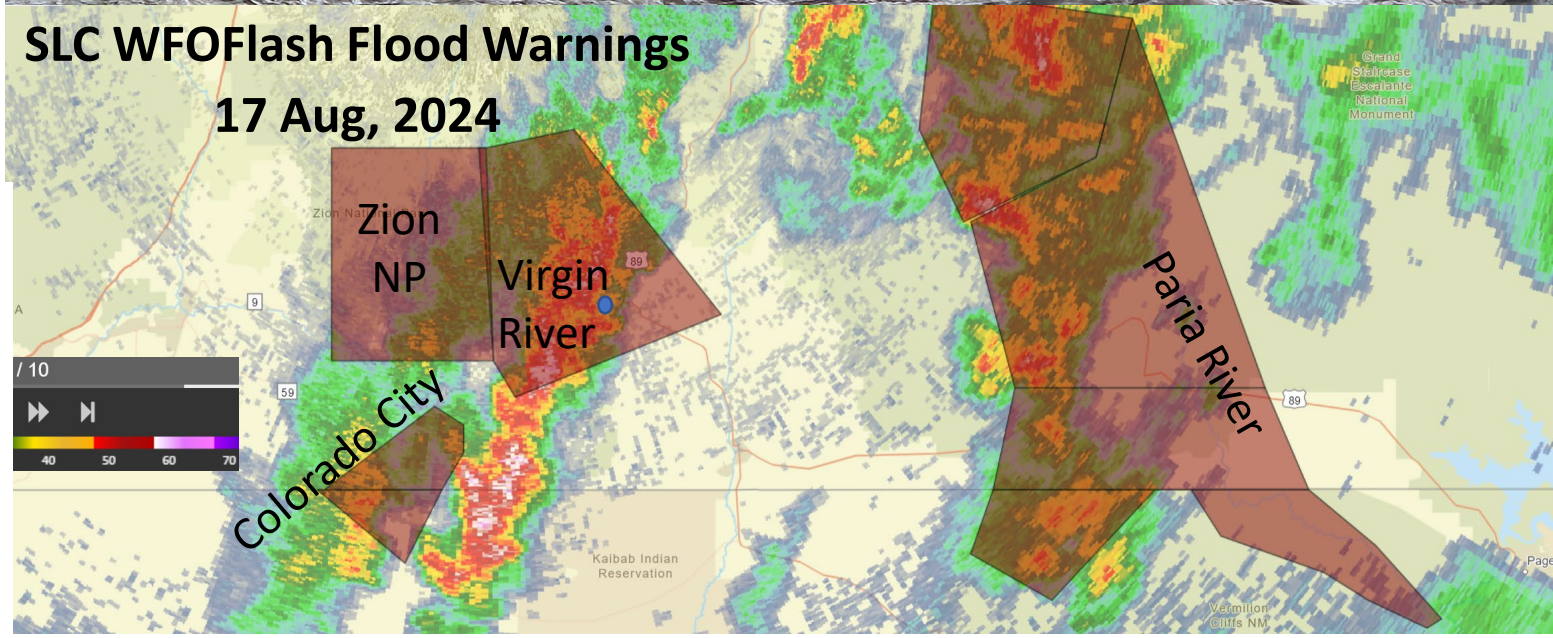
Red Butte Canyon

21 June, 2024

Clothing and UTV found in search for couple missing in Moab flood

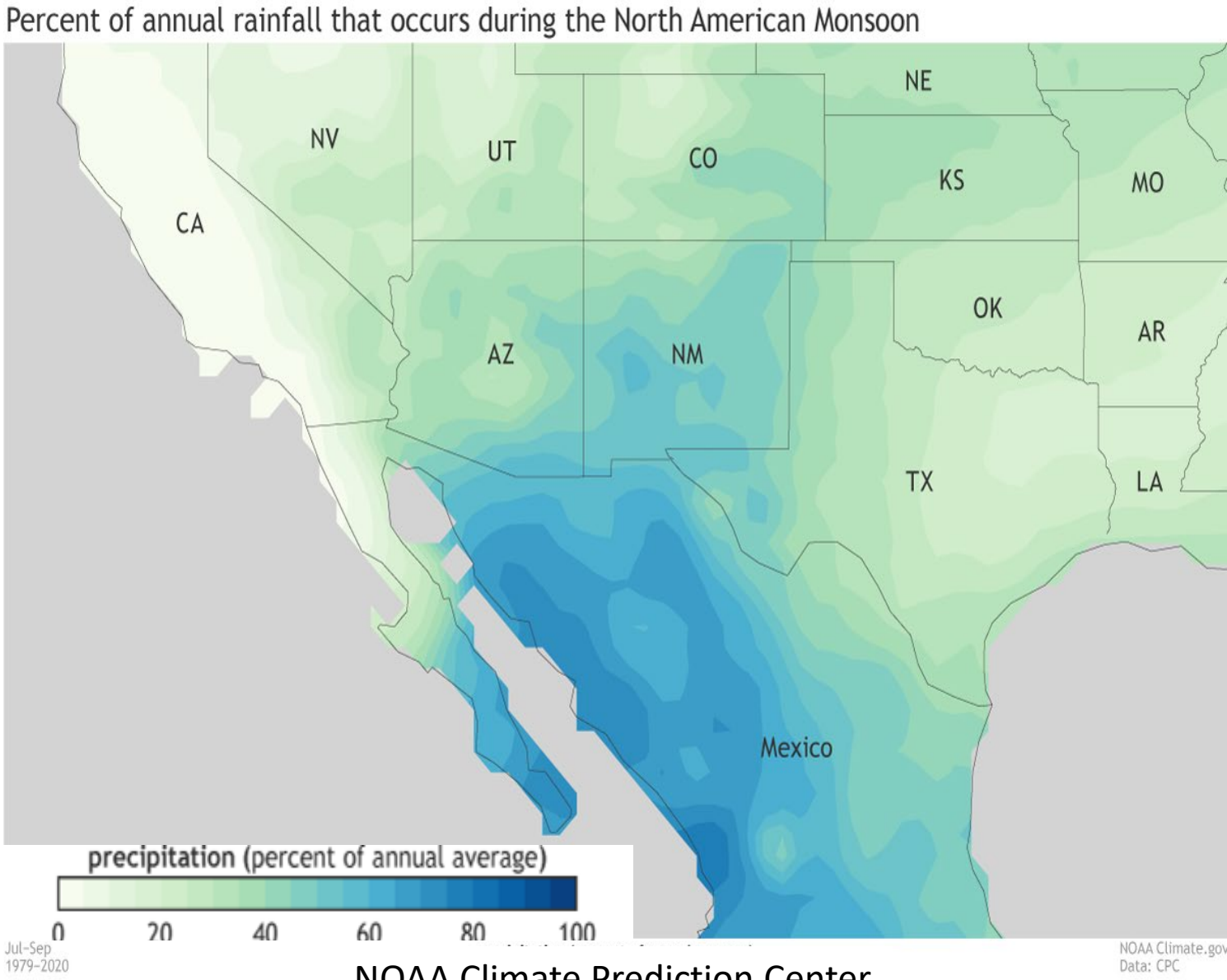
Searchers find men's pants, ladies jacket downstream; search will end at noon due to flood warning

Search teams looking for a Texas couple that's been missing for six days following an intense storm and widespread flooding June 21 have recovered a pair of men's pants, with keys and wallet inside them, and a woman's rain jacket, downstream from where their off-highway vehicle was found on the rugged Steel Bender Trail.



North American Monsoon

- Responsible for frequent intense convection along Mexican cordillera and over southwestern U.S. mountain ranges
- Northern monsoon extension into southern Utah leads to potential for flash floods from June to September
- Southern Utah:
  - ~300,000 permanent residents
  - > 10 million visits annually to national parks, monuments, and recreation areas



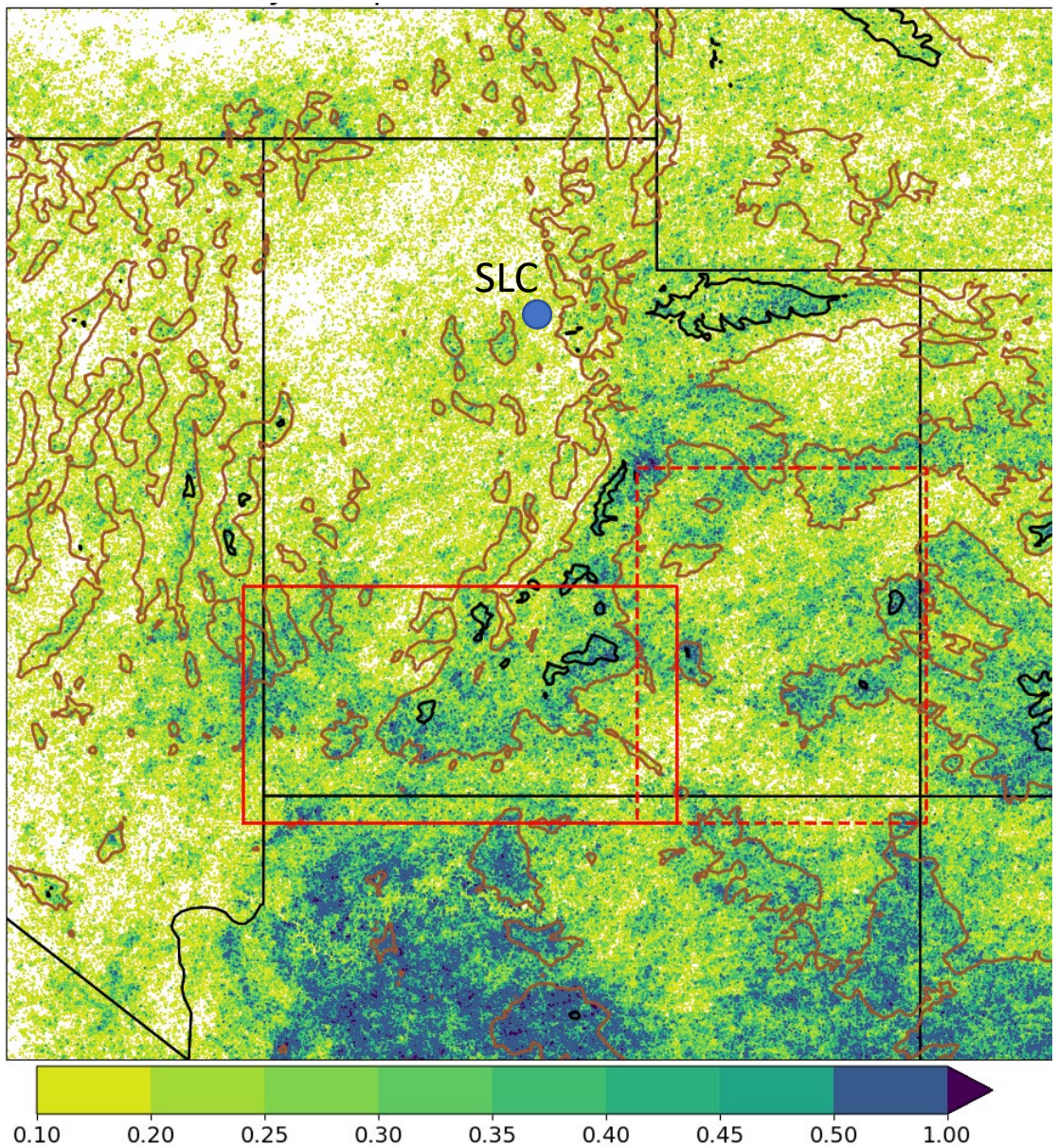
NOAA Climate Prediction Center

Flash Flood Factors

- Mesoscale: Lift, instability, moisture, wind shear
- Convective scale: Rainfall location, duration, and intensity
- Terrain: Soil type, basin hydrology, channeling

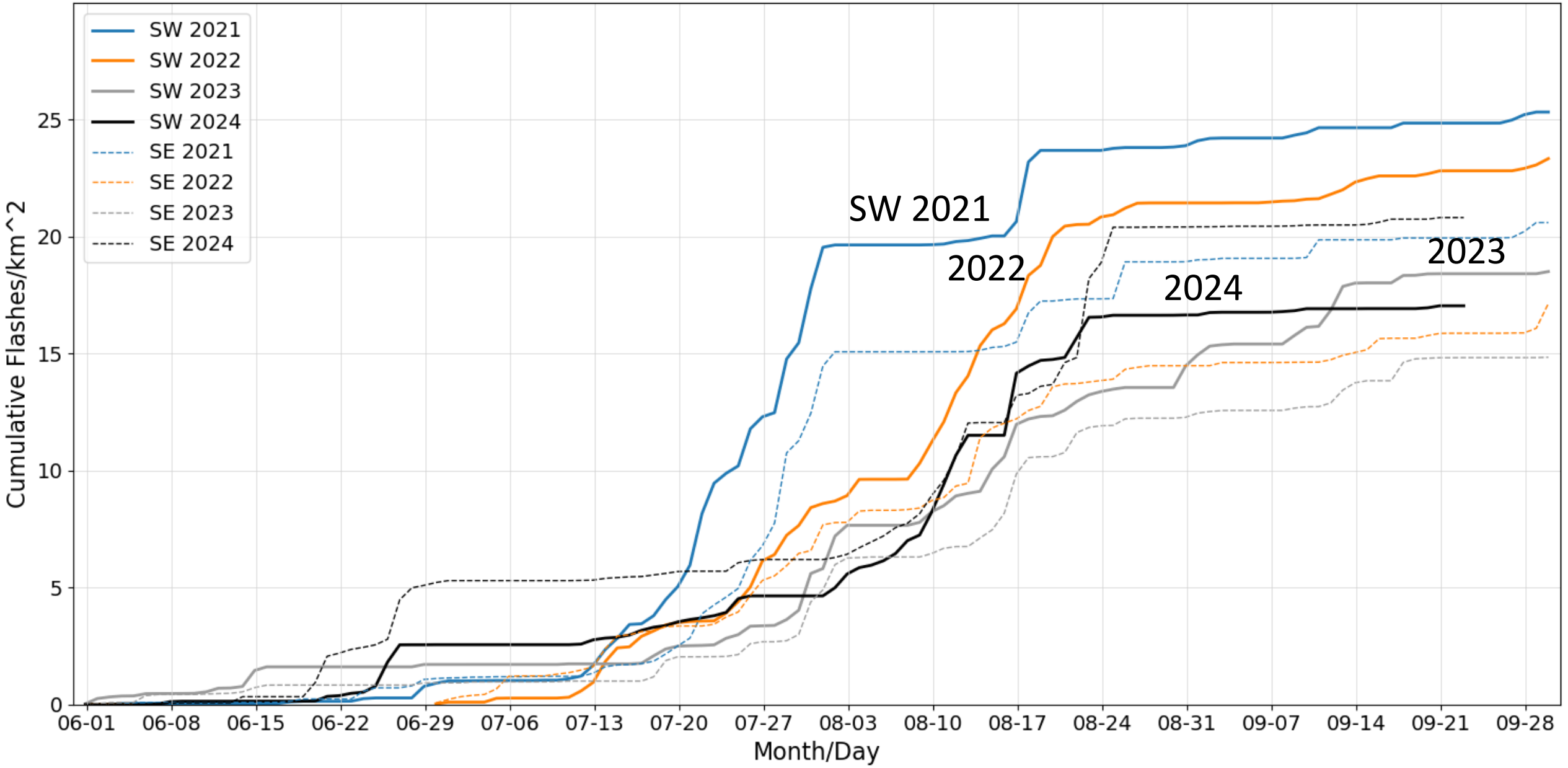
- *Flash energy density (FED) product from Multi-Radar Multi-Sensor (MRMS) system based on National Lightning Detection Network (NLDN)*
- *FED: average number of cloud-to-ground flashes per km^2 per day during the 4 seasons*

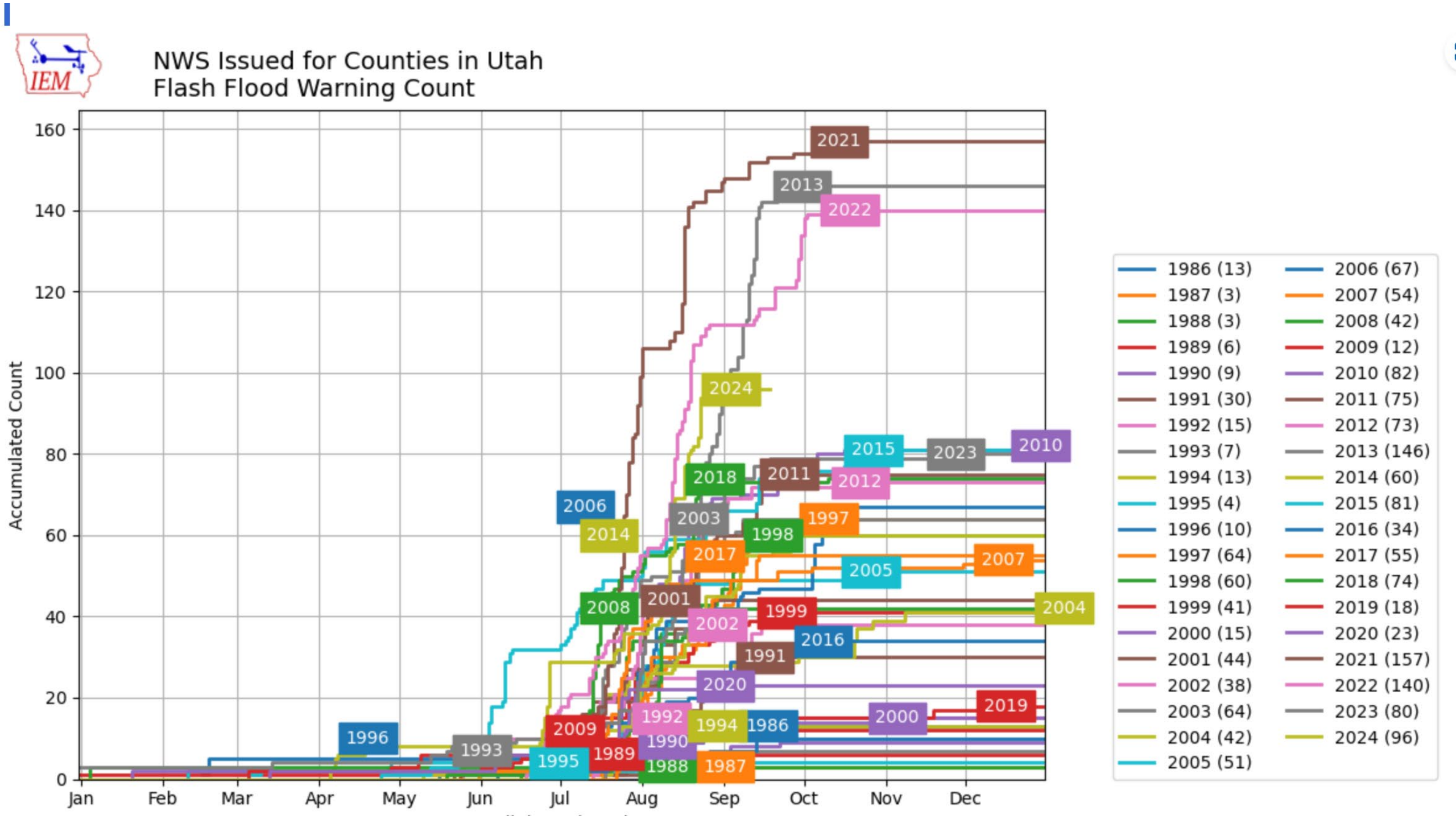
Lightning during June-September 2021-2024



Flash Energy Density: Flashes per day per km^2

SW and SE Utah Seasonal Accumulation of Lightning FED 2021-2024



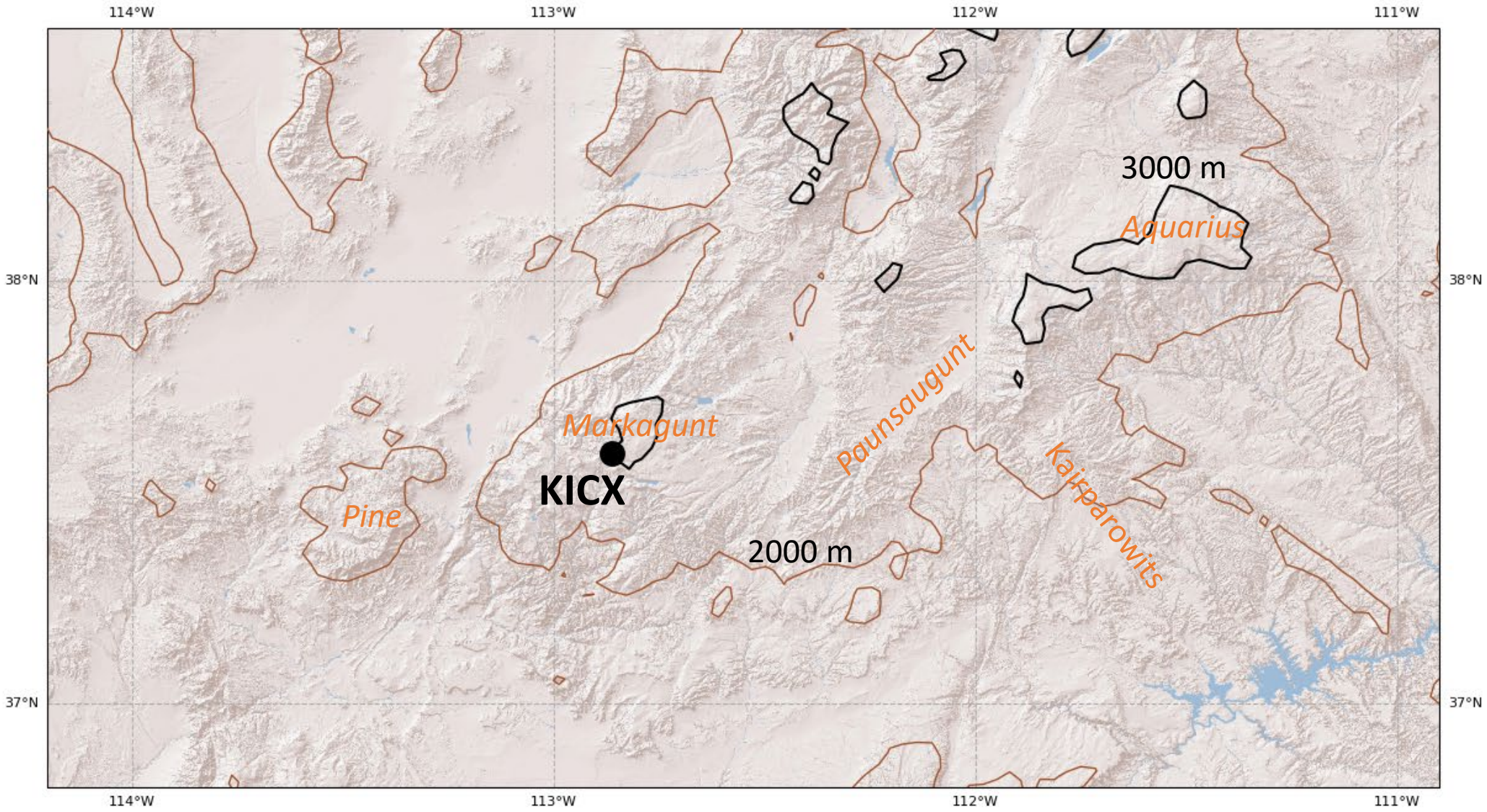

NWS Issued for Counties in Utah
Flash Flood Warning Count
Accumulated Count
0
20
40
60
80
100
120
140
160
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
1986 (13)
1987 (3)
1988 (3)
1989 (6)
1990 (9)
1991 (30)
1992 (15)
1993 (7)
1994 (13)
1995 (4)
1996 (10)
1997 (64)
1998 (60)
1999 (41)
2000 (15)
2001 (44)
2002 (38)
2003 (64)
2004 (42)
2005 (51)
2006 (67)
2007 (54)
2008 (42)
2009 (12)
2010 (82)
2011 (75)
2012 (73)
2013 (146)
2014 (60)
2015 (81)
2016 (34)
2017 (55)
2018 (74)
2019 (18)
2020 (23)
2021 (157)
2022 (140)
2023 (80)
2024 (96)

Selected flash flood research in southern Utah

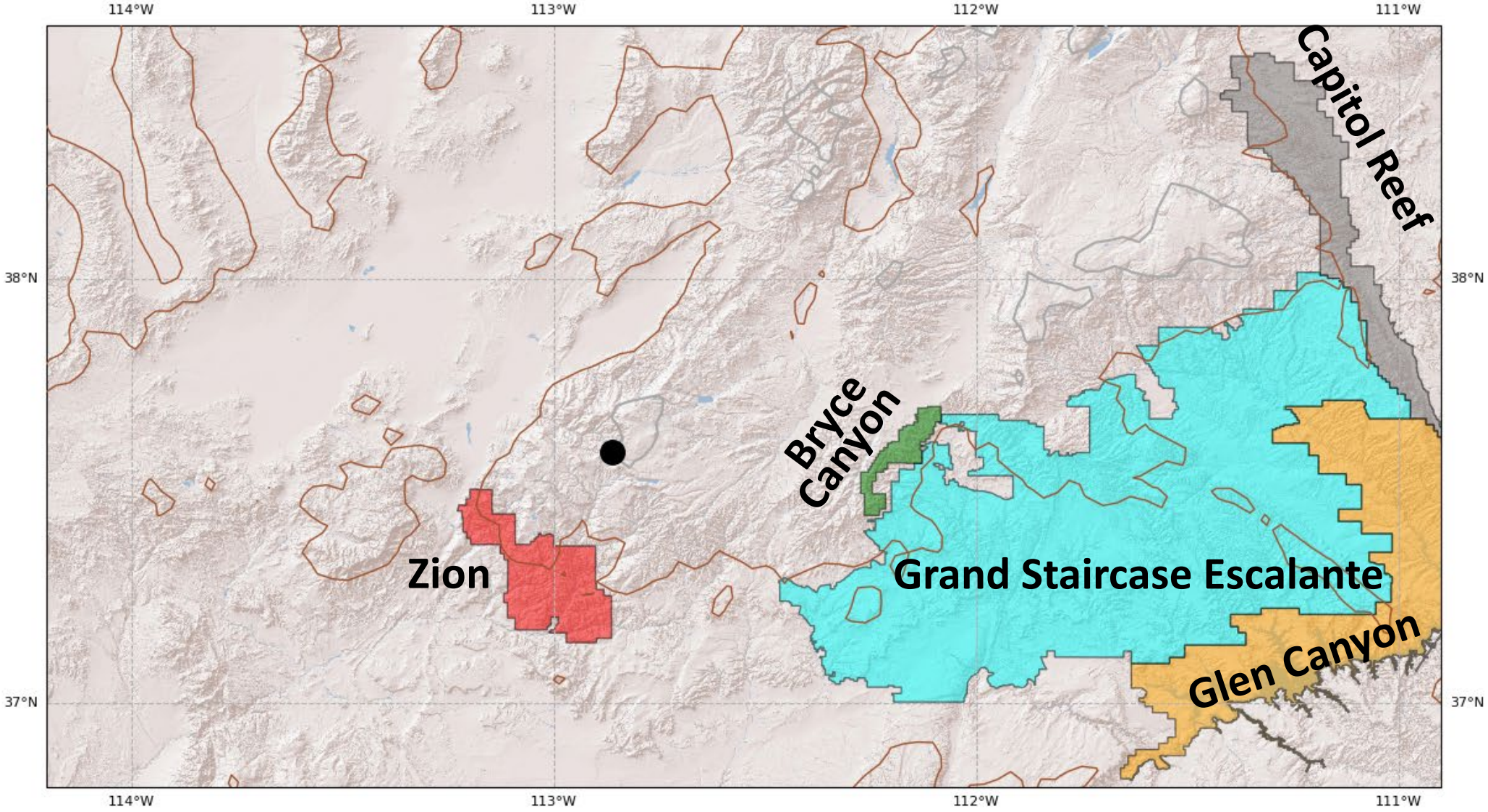
- 2005-present
  - SLC WFO developed and implemented Flash Flood Potential forecasts for national parks
  - Seaman, M., D. Church, and J. Cunningham, 2024: Leveraging probabilistic high resolution model guidance to improve flash flood forecasting across southern Utah

    https://ams.confex.com/ams/104ANNUAL/meetingapp.cgi/Paper/430507.
- 24 year lightning climatology and case studies including 2015 event
  - Smith et al., 2019: The Paroxysmal precipitation of the desert: Flash floods in the southwestern United States. *Water Resources Research* *10.1029/2019WR025480*
- 2021-2023 monsoon seasons
  - Horel, John and James Powell, 2024: Analysis and prediction of summer rainfall over southwestern Utah. *Wea. Forecasting. https://doi.org/10.1175/WAF-D-24-0018.1*
- 2024 monsoon season
  - Auston McDonald, REALM Research Experience for Undergraduates
  - Sherlyn Hilton, Professional Science Masters

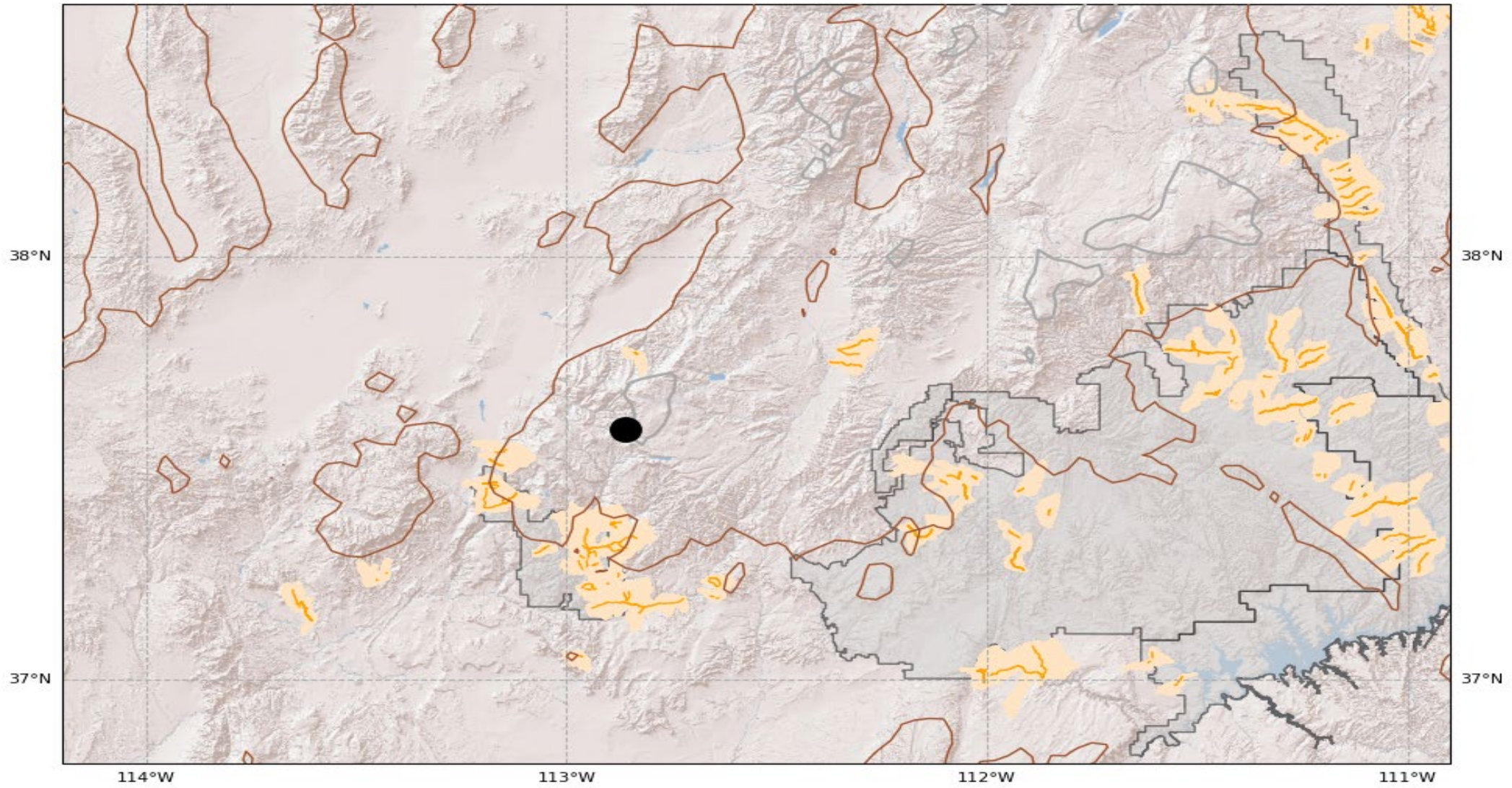
Terrain Features of Southwestern Utah



National Parks, Monuments, Recreation Areas



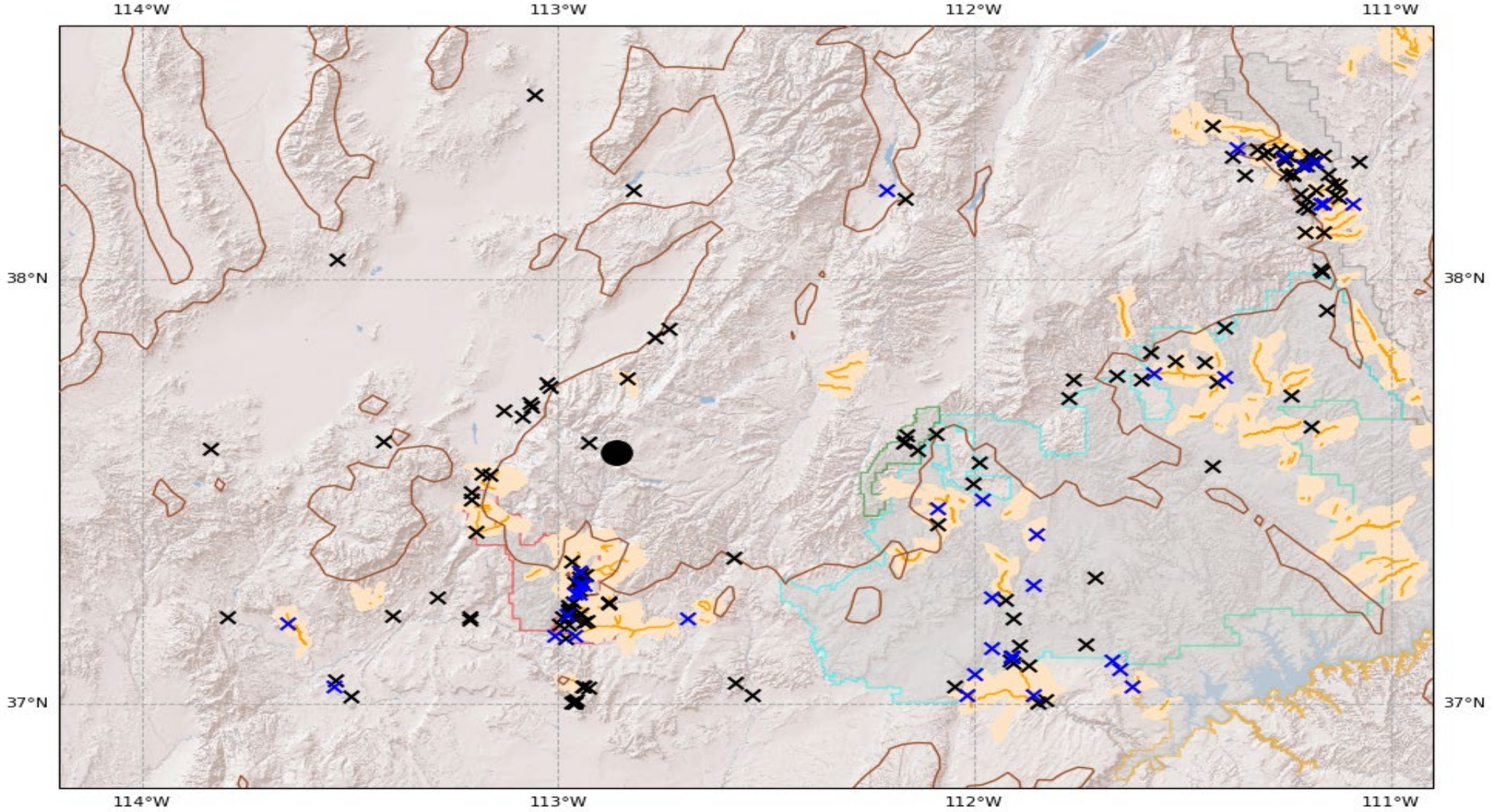
Slot Canyon: narrow channel with depth-to-width ratios > 10:1



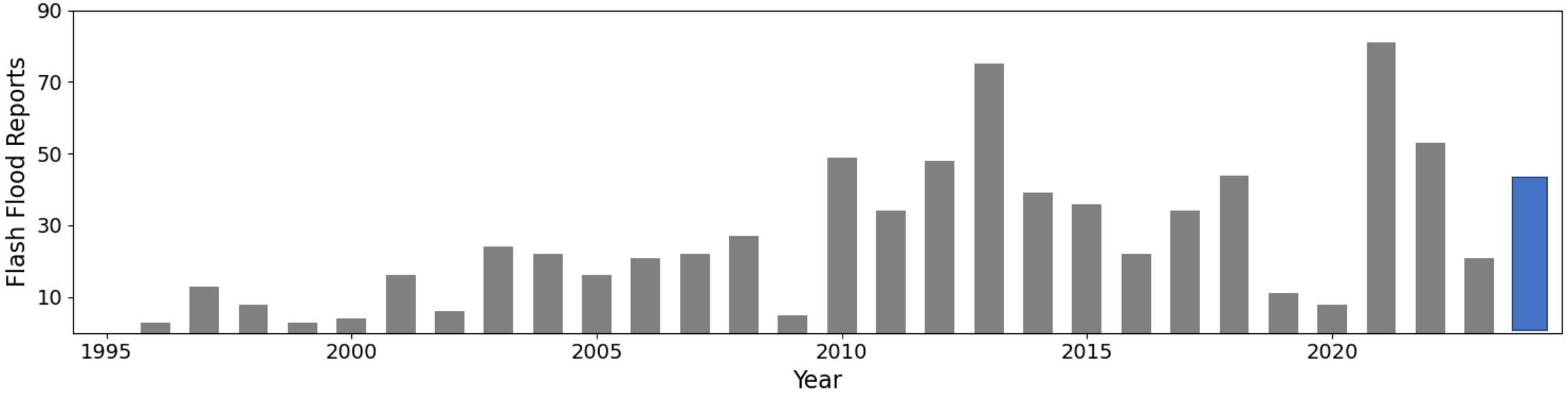
Slot canyon routes and slot canyon basins from Mike Seaman, SLC WFO

Flash Flood Reports 2021-2024

2021-2023
2024



Flash flood reports in southwestern Utah



Flash flood reports in the seven-county region of southwestern Utah

The Narrows Hike
Zion National Park

- Access to the Narrows closed when SLC WFO issues Flash Flood Warning
- Reopen Narrows when flows return below 120 cfs
- Flash Flood Potential Ranking intended to inform visitors of risk

Flash Flood Potential Rating

- Issued by SLC WFO for chance of flash flood in national parks, monuments, and recreation areas of southern Utah

Flash Flood Potential Rating
National Weather Service Salt Lake City UT
235 AM MDT Thu Jun 20 2024

Flash Flood Potential Rating for Southern Utah

	...TODAY...	...FRIDAY...
Arches National Park	Possible	Probable
Bryce Canyon National Park	Not Expected	Possible
Canyonlands National Park	Possible	Probable
Capitol Reef National Park	Possible	Probable
Glen Canyon National Rec Area	Possible	Probable
Grand Staircase-Escalante East	Possible	Probable
Grand Staircase-Escalante West	Possible	Probable
Natural Bridges NM	Possible	Probable
Grand Gulch	Possible	Probable
San Rafael Swell	Possible	Probable
Zion National Park	Not Expected	Possible

****

Definitions:

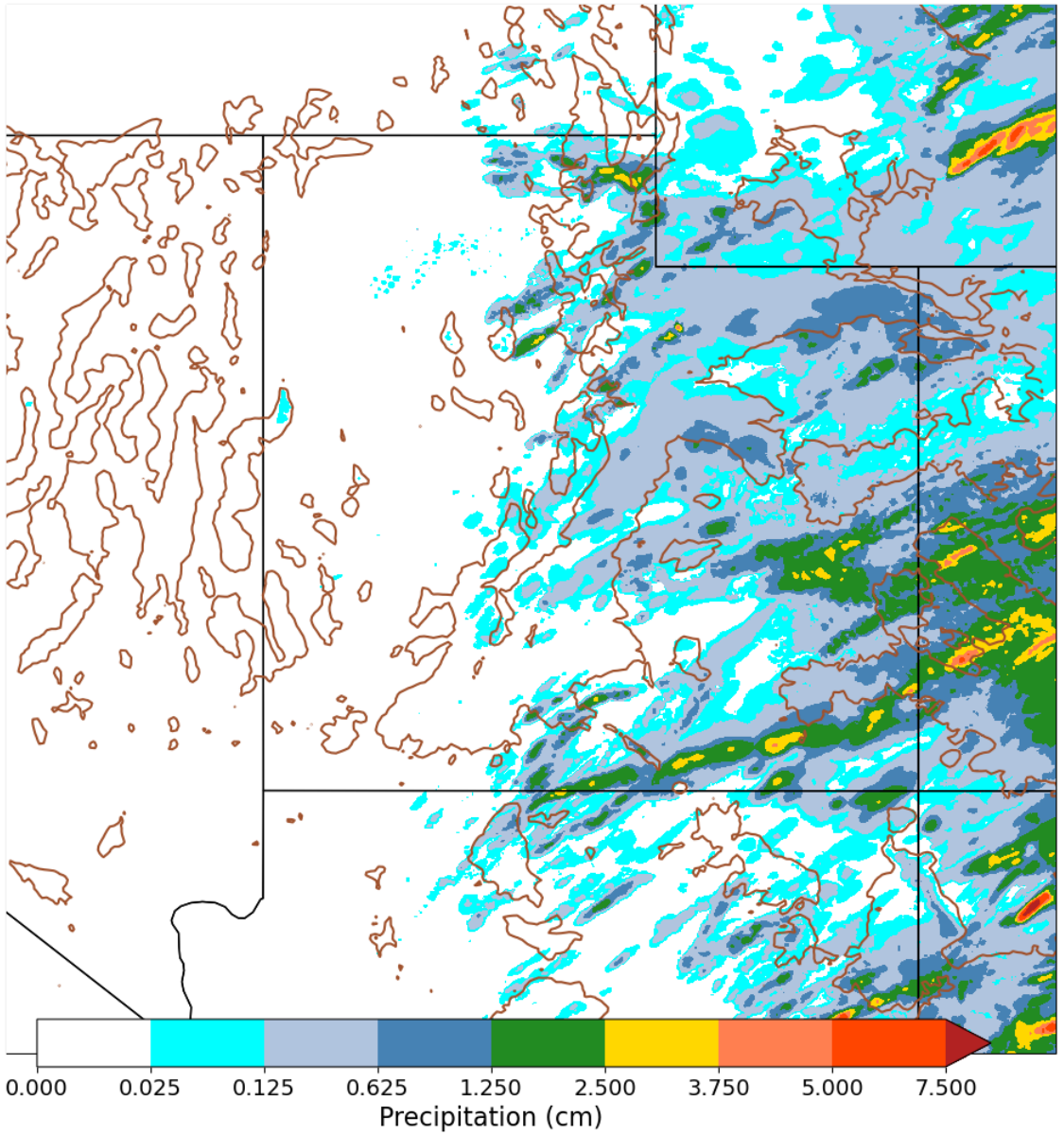
Not Expected: Flash flooding is not expected.

Possible: Some slot canyons, dry washes, and small streams may experience flash flooding.

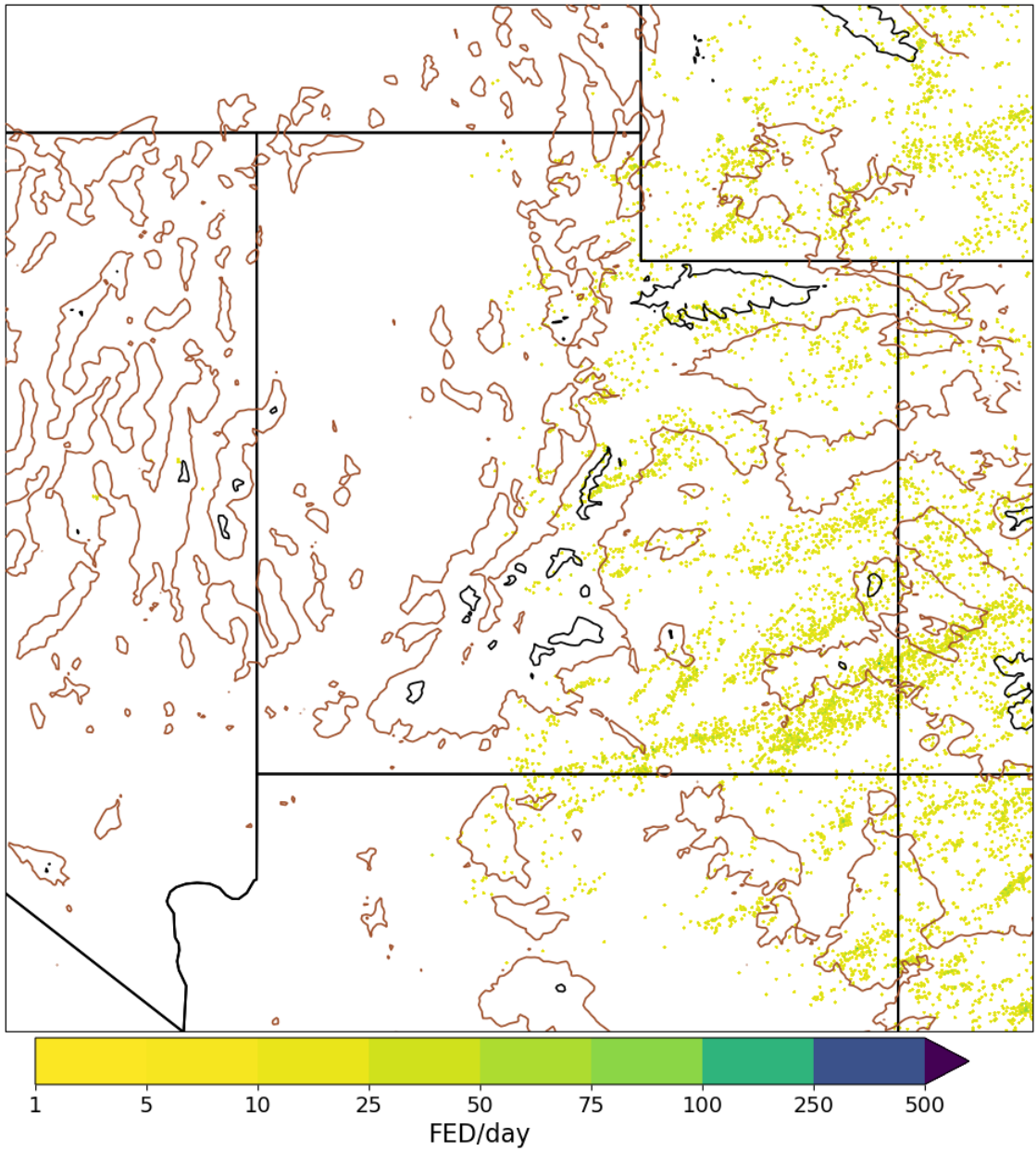
Probable: Some slot canyons, dry washes, and small streams are expected to experience flash flooding.

Expected: Many slot canyons, dry washes, and small streams are expected to experience flash flooding.

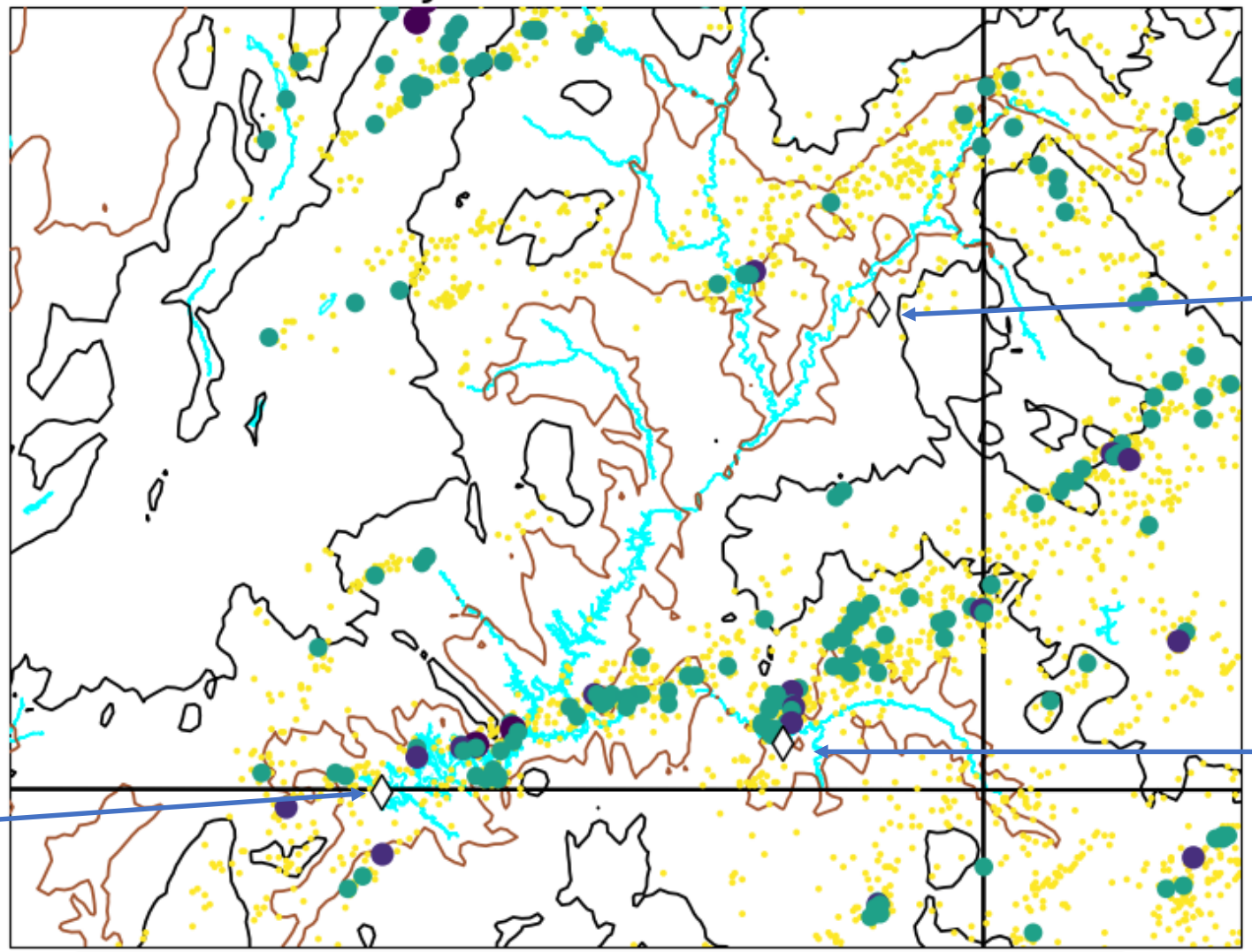
Multi-Radar Multi-Sensor (MRMS) Precipitation
21 June 2024 LT Total (cm)



MRMS NLDN Flash Energy Density (FED)
21 June 2024 LT (Flashes km^{-2} day^{-1})



MRMS NLDN Flash Extent Density
1700 UTC 21 June 2024 - 0200 UTC 22 2024



30 40 50 60 70 80 90 100

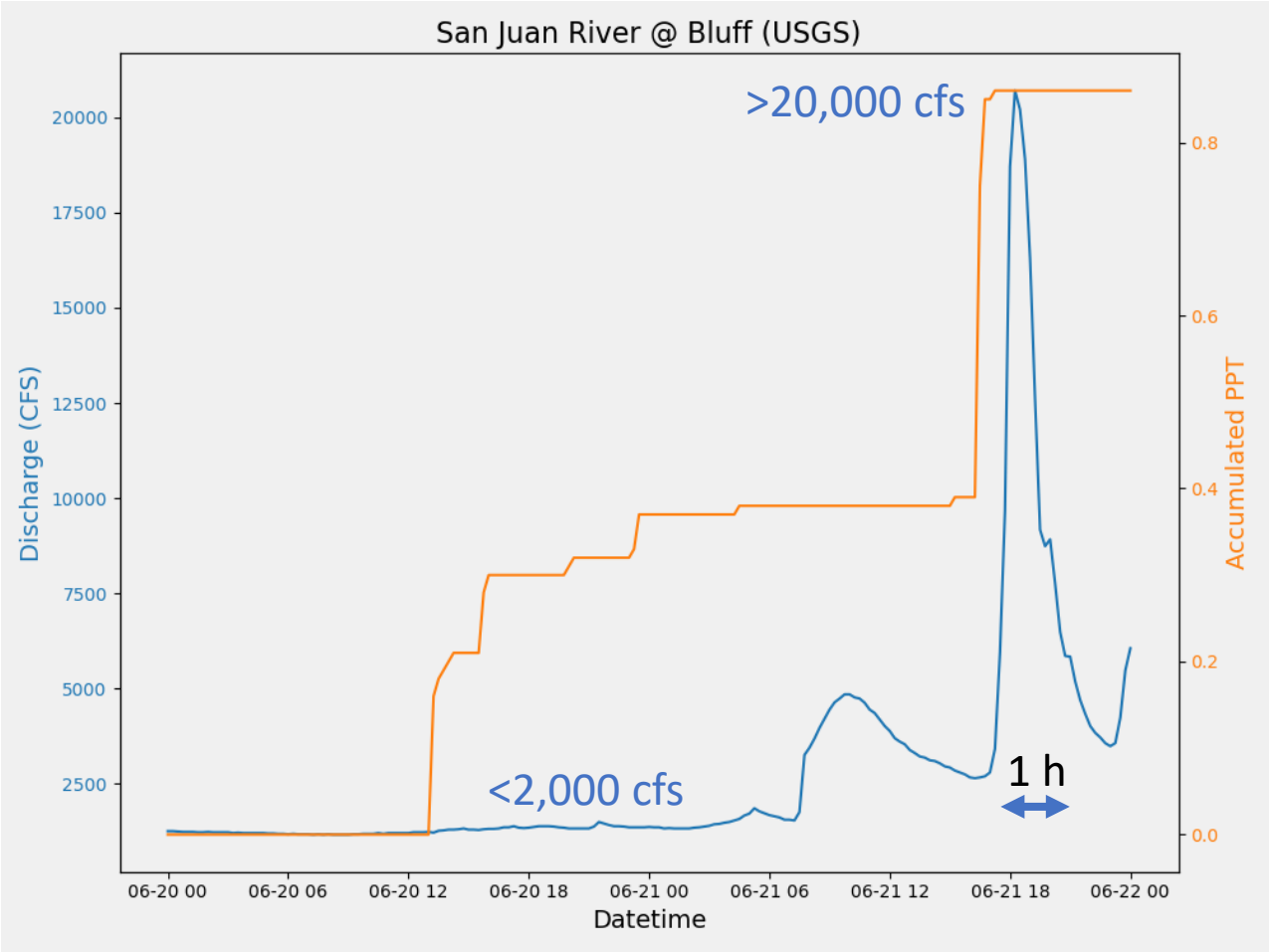
Estimate of total CG flashes km^{-2} during 9 h period

Moab
5:45-6:15 PM
~1 in
flash flooding

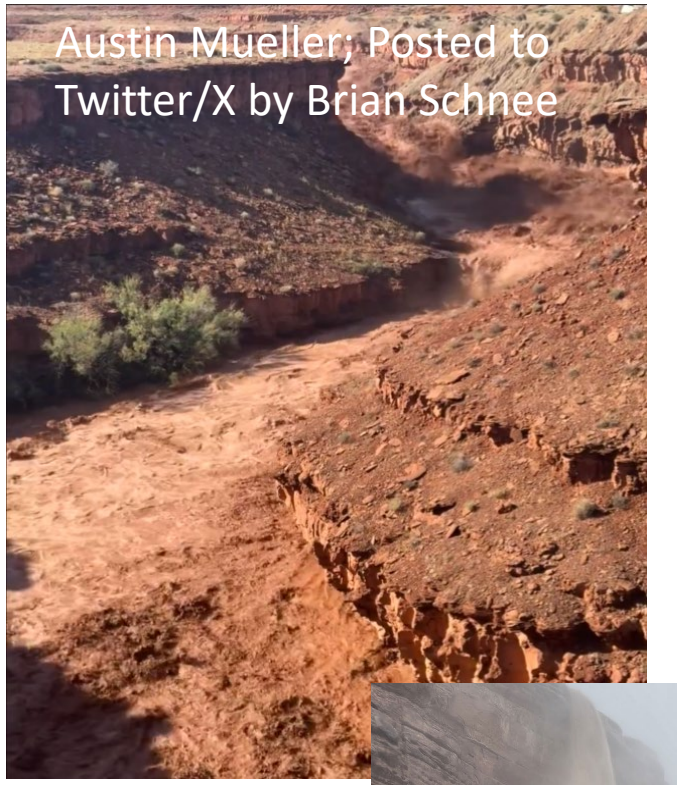
Bluff
4:30-5:30 PM
1 in+
San Juan River
flash flood

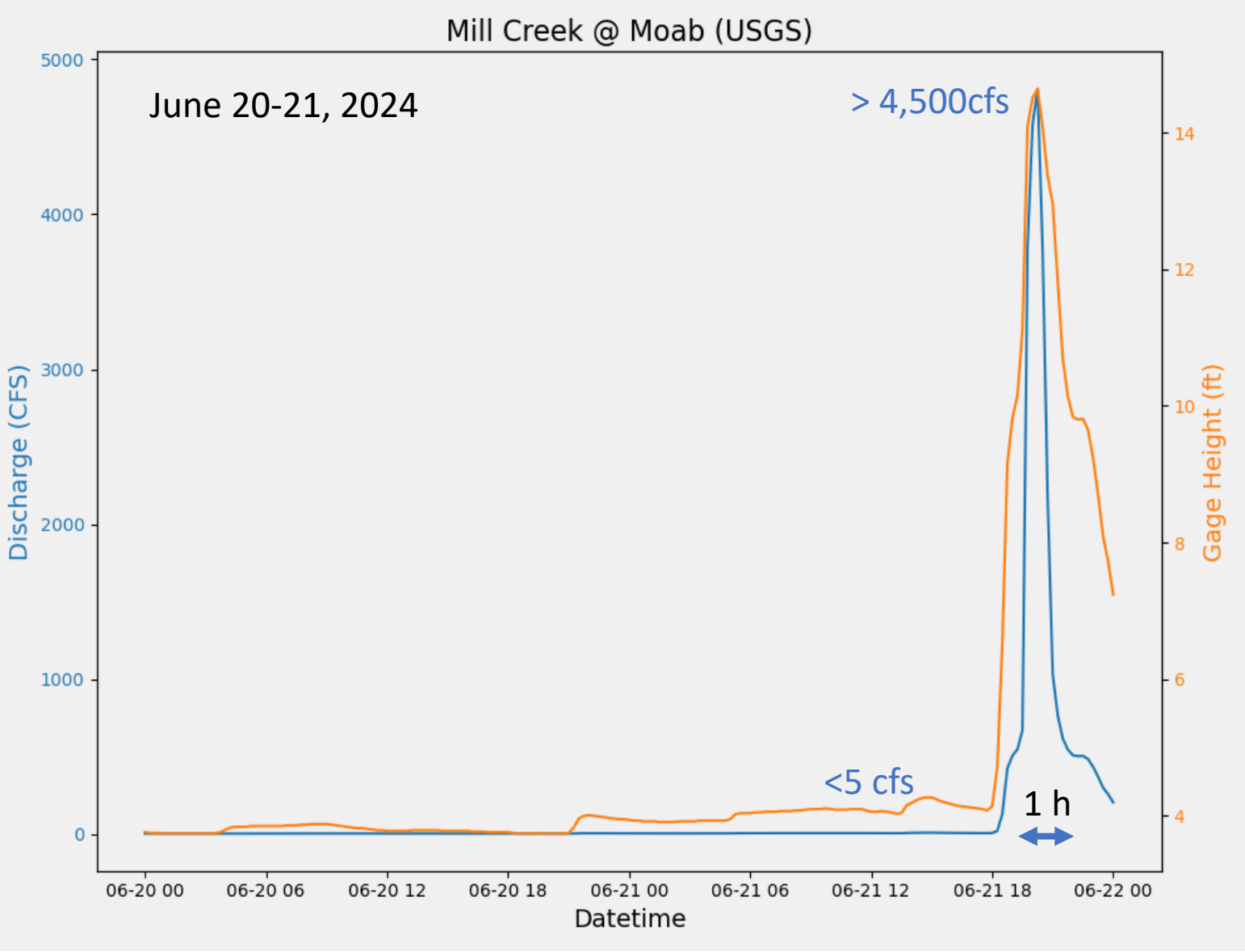
Lake Powell
1:30-2:00 PM
1-2 in hail
Boat capsized

San Juan River
June 20-21, 2024



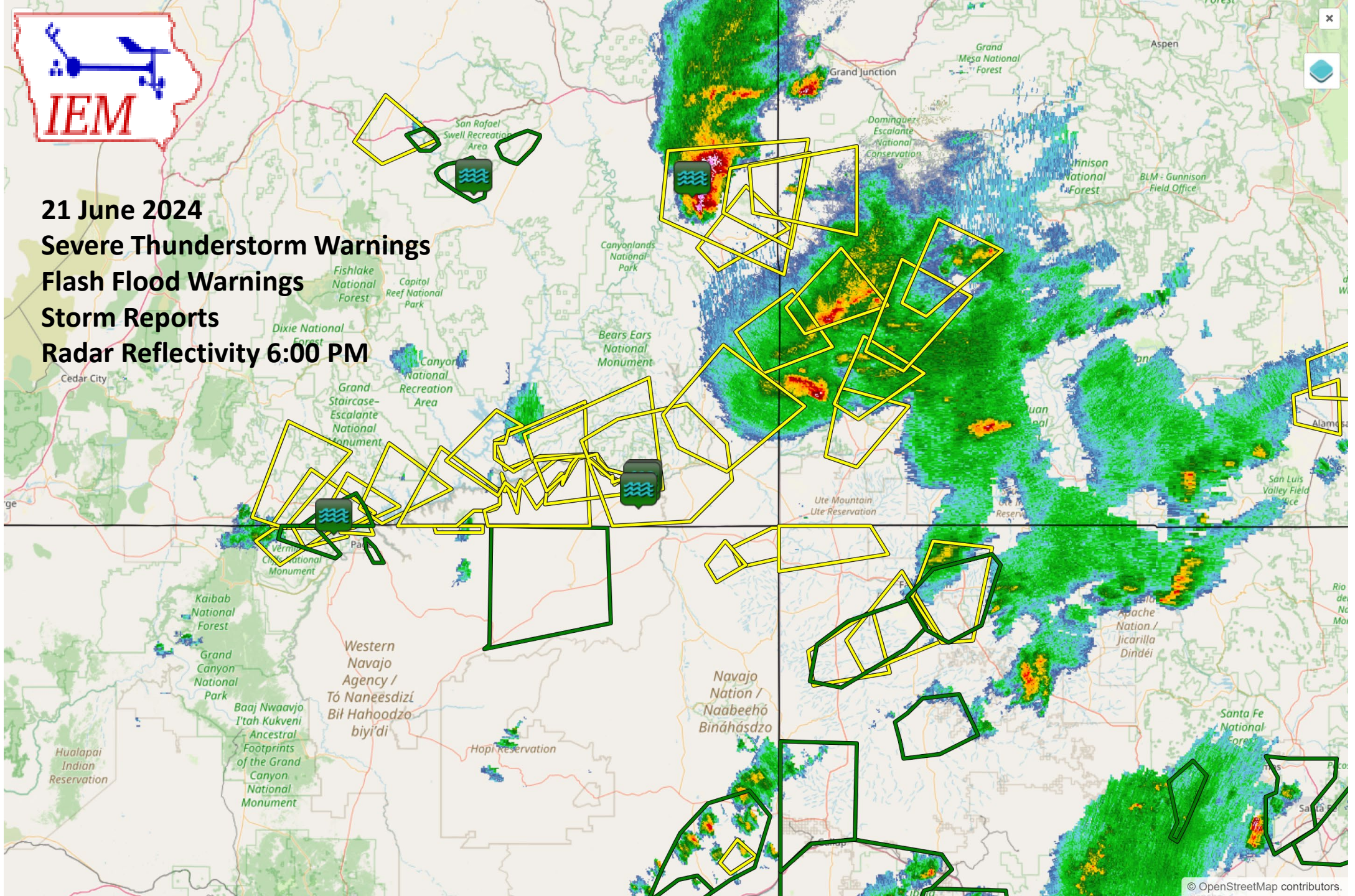
San Juan River





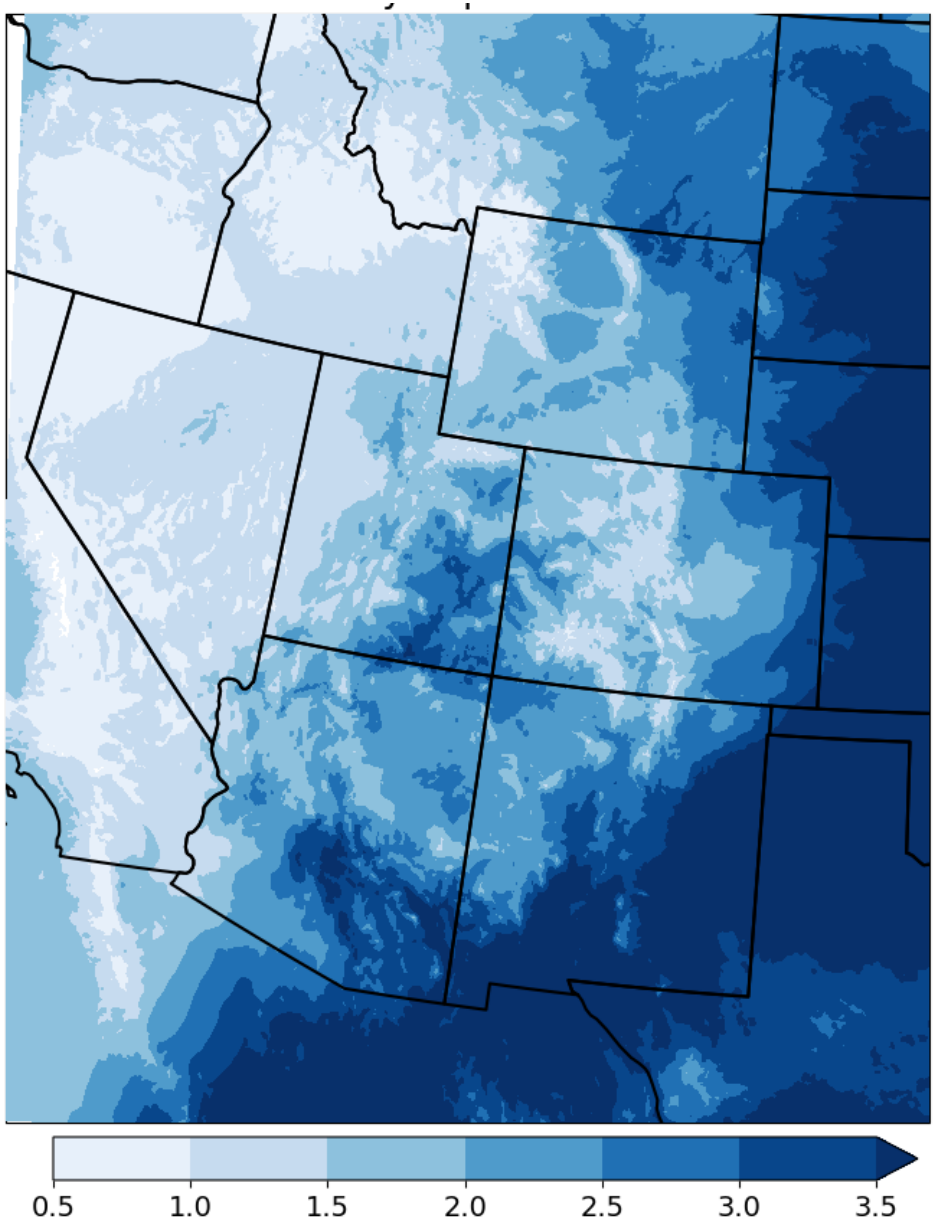
2 fatalities in Mill Creek

20 hikers rescued in Grandstaff Canyon

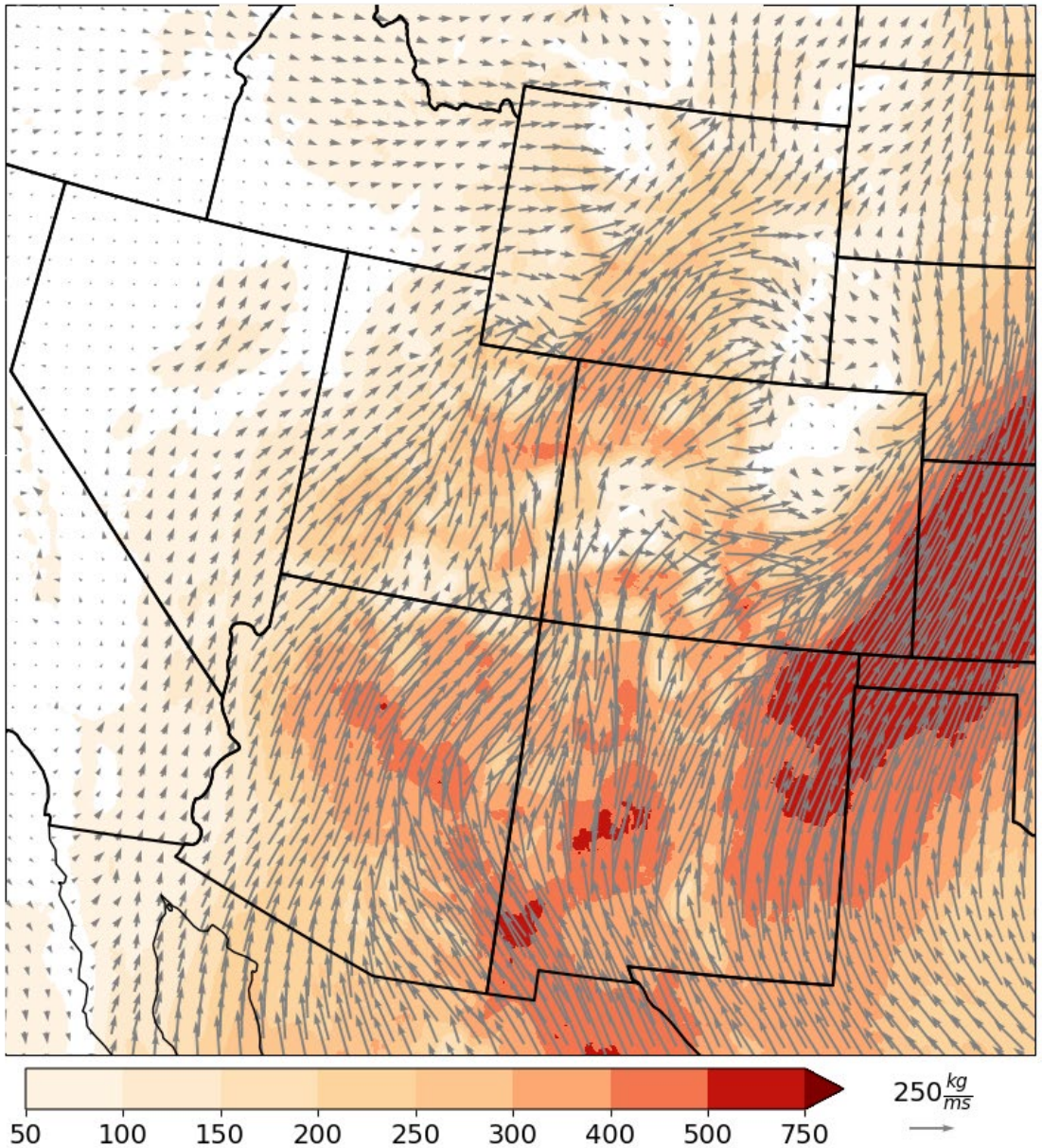

IEM
21 June 2024
Severe Thunderstorm Warnings
Flash Flood Warnings
Storm Reports
Radar Reflectivity 6:00 PM
Grand Junction
Aspen
Grand Mesa National Forest
Dominguez Escalante National Conservation
Gunnison National Forest
BLM - Gunnison Field Office
San Rafael Swell Recreation Area
Canyonlands National Park
Fishlake National Forest
Capitol Reef National Park
Dixie National Forest
Bears Ears National Monument
Cedar City
Grand Staircase-Escalante National Monument
Canyon National Recreation Area
Ute Mountain Ute Reservation
San Luis Valley Field
Kaibab National Forest
Grand Canyon National Park
Western Navajo Agency / Tó Naneesdizí Bił Hahoodzo biyi'di
Navajo Nation / Naabeehó Binahásdzo
Hopi Reservation
Hualapai Indian Reservation
Baaj Nwaavjo I'tah Kukveni - Ancestral Footprints of the Grand Canyon National Monument
Apache Nation / Jicarilla Dindéi
Santa Fe National Forest
© OpenStreetMap contributors.

High Resolution Rapid Refresh (HRRR) Analyses for 18-21 UTC 21 June 2024

Precipitable Water (cm)



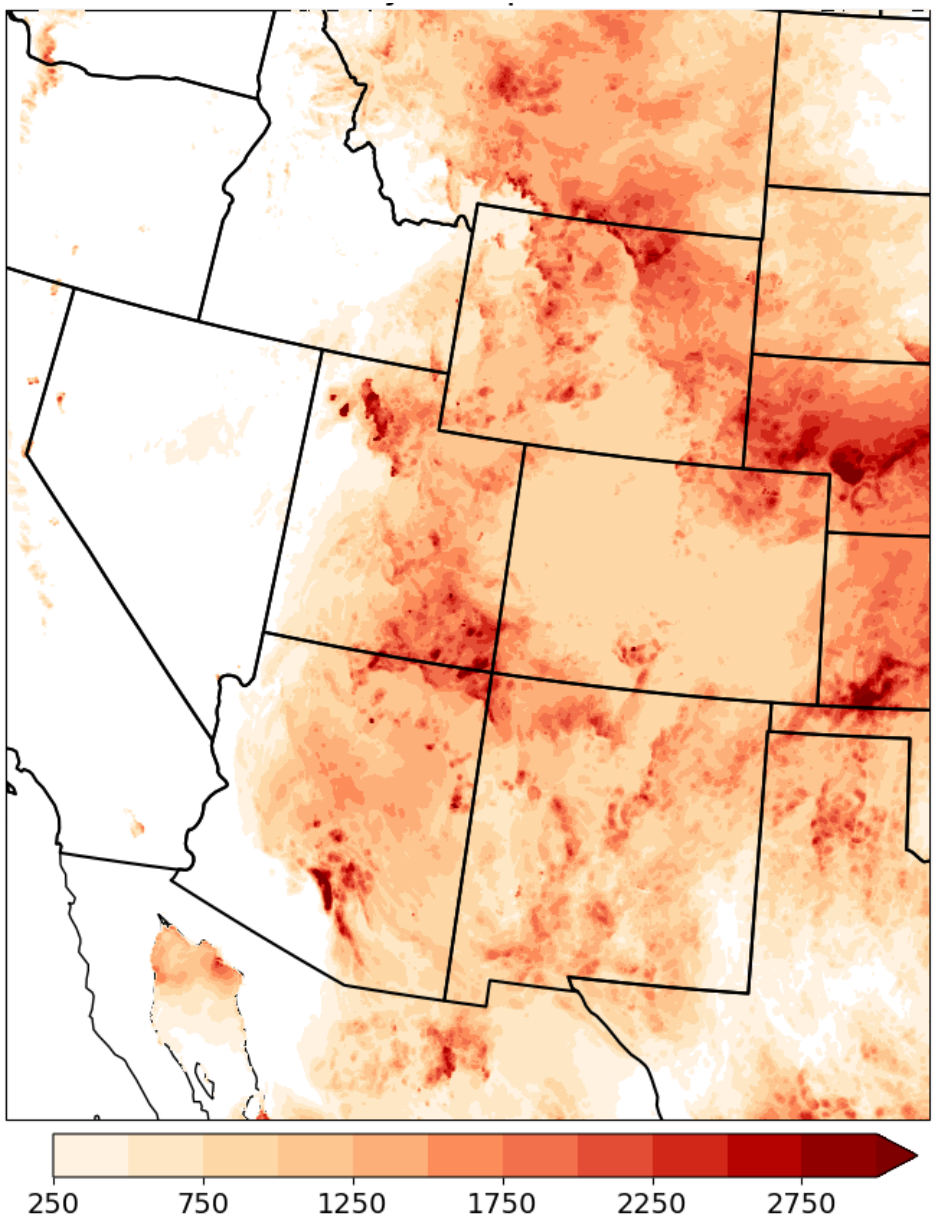
(Sfc- 500 hPa Integrated Vapor Transport (kg m^{-1} s^{-1})



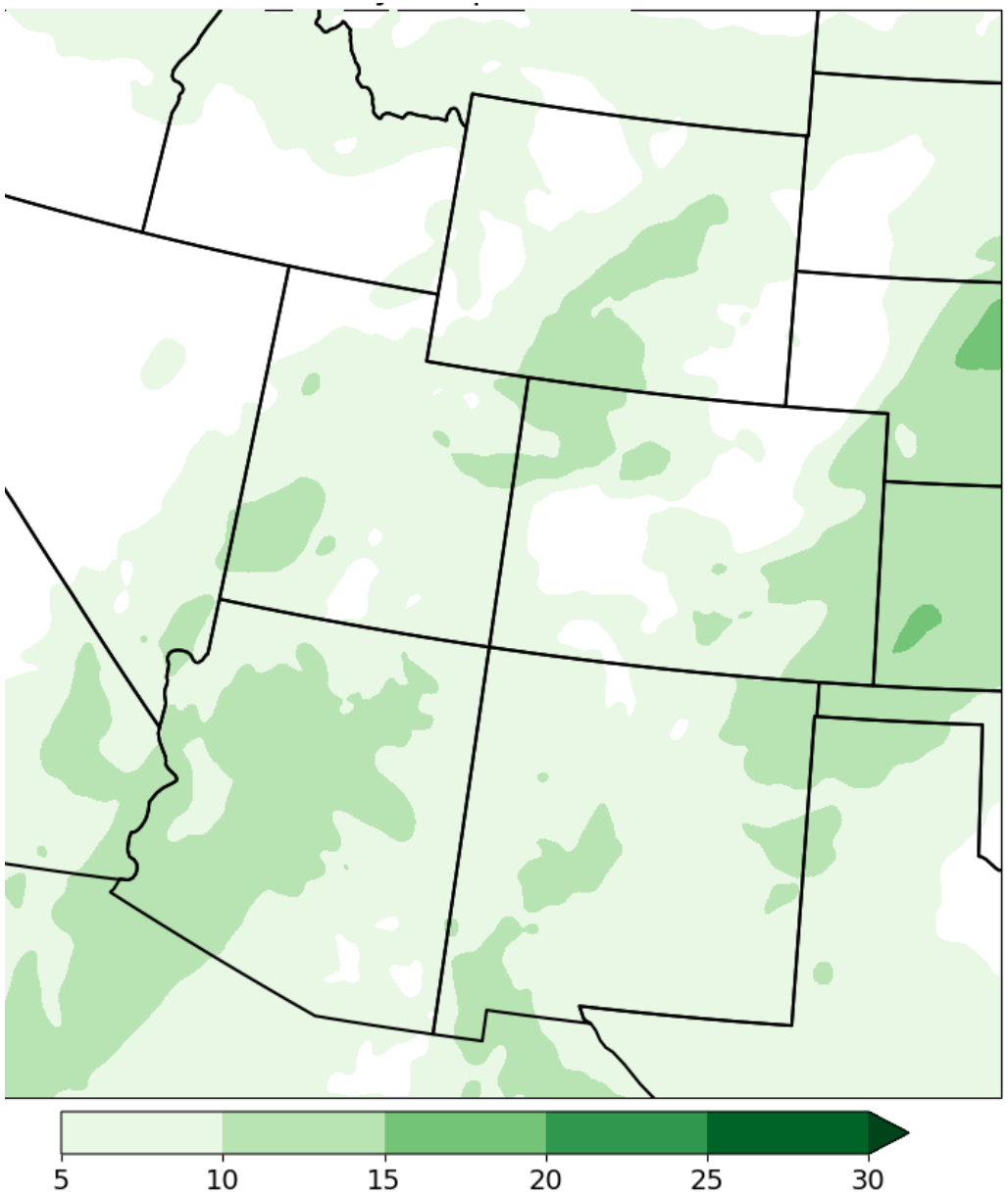
Arising from remnants of tropical storm Alberto

High Resolution Rapid Refresh (HRRR) Analyses for 18-21 UTC 21 June 2024

Maximum CAPE (J kg^{-1})



700 hPa Wind Speed (m s^{-1})



Horel and Powell (2024; *WAF*)

Hypothesis: forecasts of high precipitable water (PWAT) and convective available potential energy (CAPE) from HRRR averaged across southwest Utah may identify days likely to experience unusually high rainfall amounts across region

- *No expectation that HRRR forecasts at lead times of 13-18 h will indicate where intense rainfall may fall or flash floods may occur*

Approach

- HRRR NCEP model runs available every hour for contiguous U.S. at 3 km resolution during 2021-2023 summers
- Forecasts available every hour at lead times from F01-F18
- Create 12 member Time Lagged Ensemble (TLE) from 3 initialization times [21-23 MDT] for later period when convection initiating [1200–1500 MDT]
- Use bias correction and Random Forecast classification approaches to test hypothesis

Horel and Powell (2024; *WAF*)

- **Hypothesis:** forecasts of high precipitable water (PWAT) and convective available potential energy (CAPE) from High Resolution Rapid Refresh (HRRR) averaged across southwest Utah may identify days likely to experience unusually high rainfall amounts across region
- *No expectation that HRRR forecasts at lead times of 13-18 will indicate where intense rainfall may fall or flash floods may occur*
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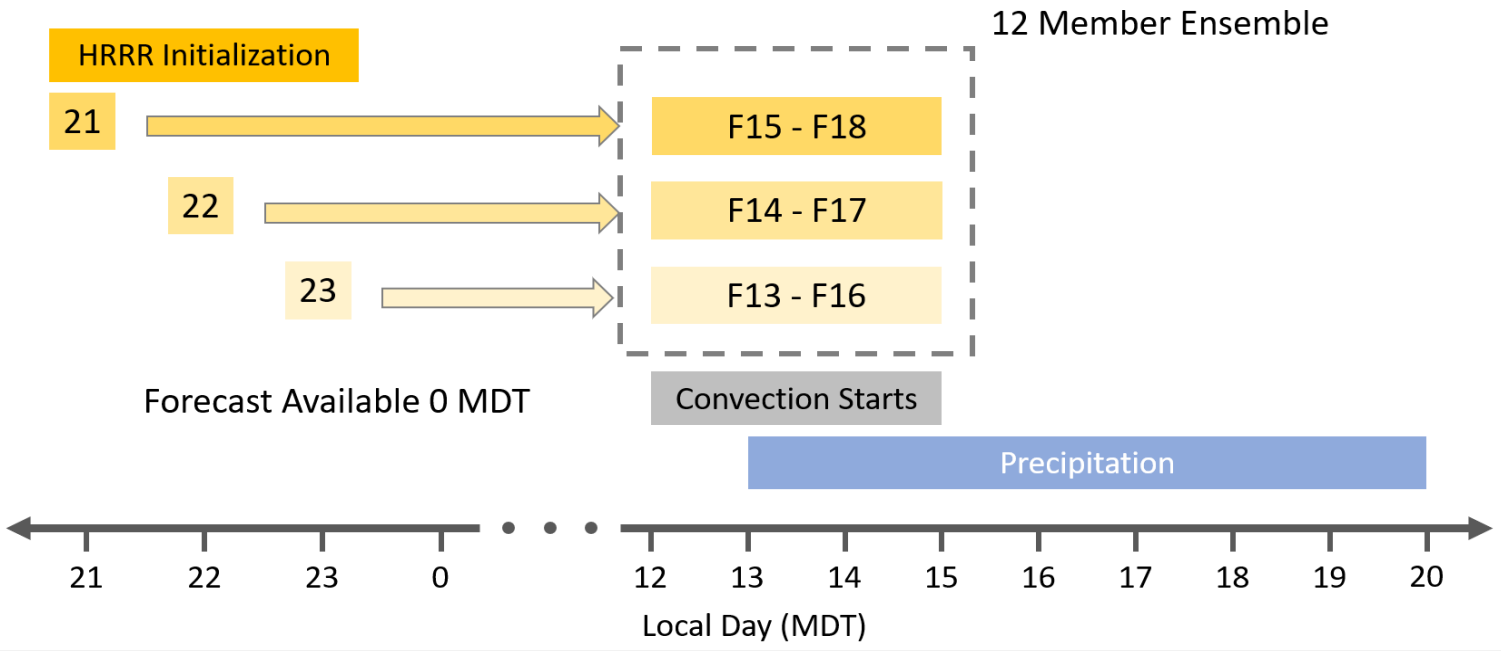
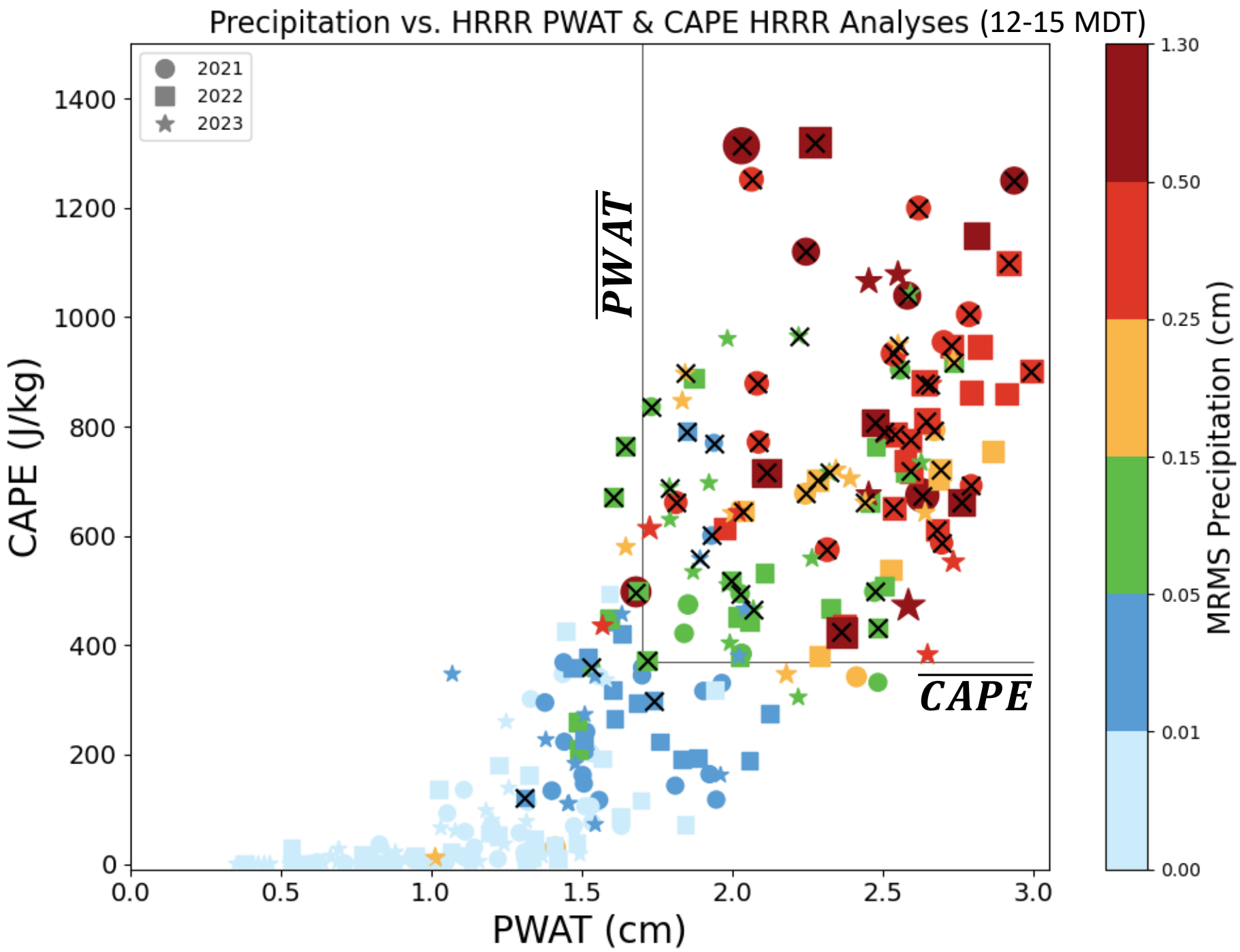
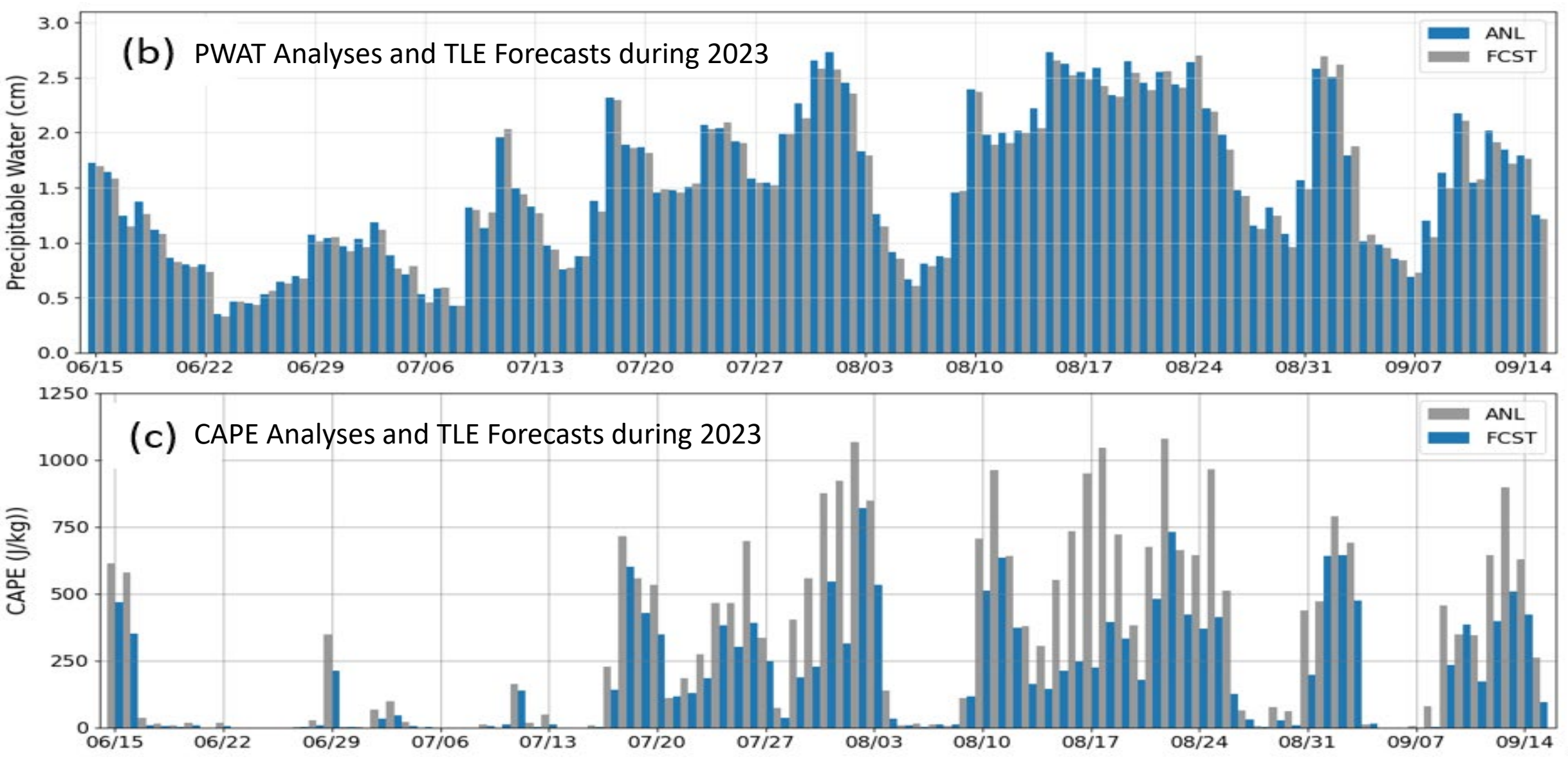


Horel and Powell
(*WAF* 2024)

PWAT, CAPE, Rainfall averaged over SW Utah

- Higher Rainfall over SW Utah when CAPE and PWAT above 3-yr (2021-2023) means
- Nearly all days with flash flood reports occur when CAPE and PWAT above 3-yr means & higher areally averaged rainfall




(b) PWAT Analyses and TLE Forecasts during 2023
Precipitable Water (cm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ANL
FCST
06/15
06/22
06/29
07/06
07/13
07/20
07/27
08/03
08/10
08/17
08/24
08/31
09/07
09/14
(c) CAPE Analyses and TLE Forecasts during 2023
CAPE (J/kg))
1250
1000
750
500
250
0
ANL
FCST
06/15
06/22
06/29
07/06
07/13
07/20
07/27
08/03
08/10
08/17
08/24
08/31
09/07
09/14

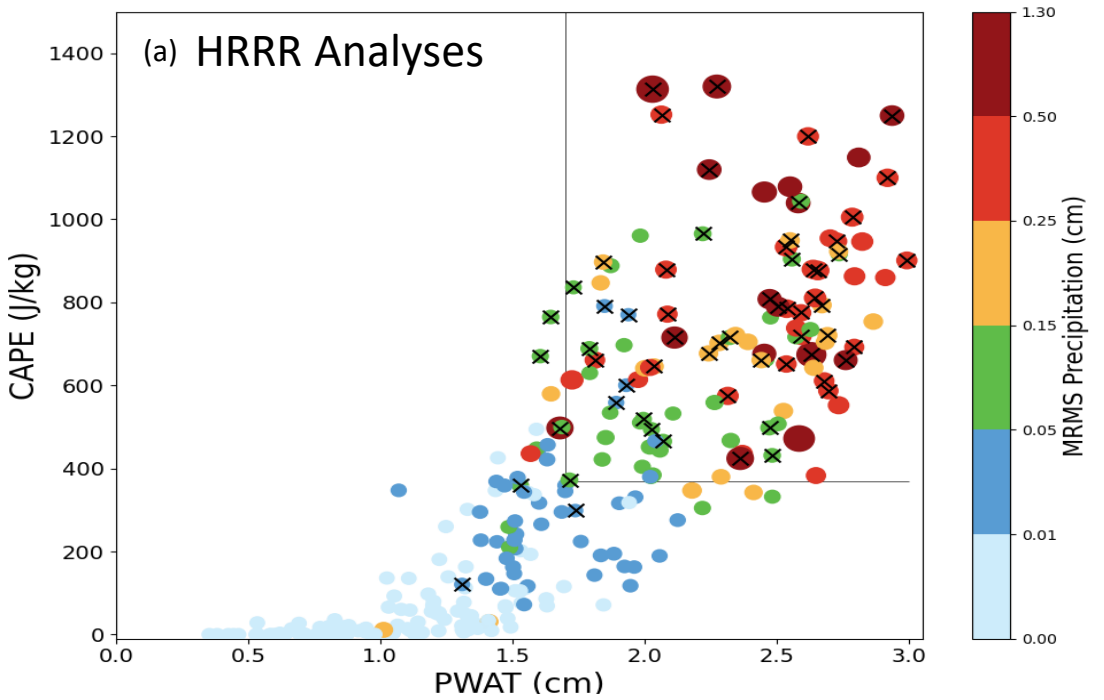
Top:

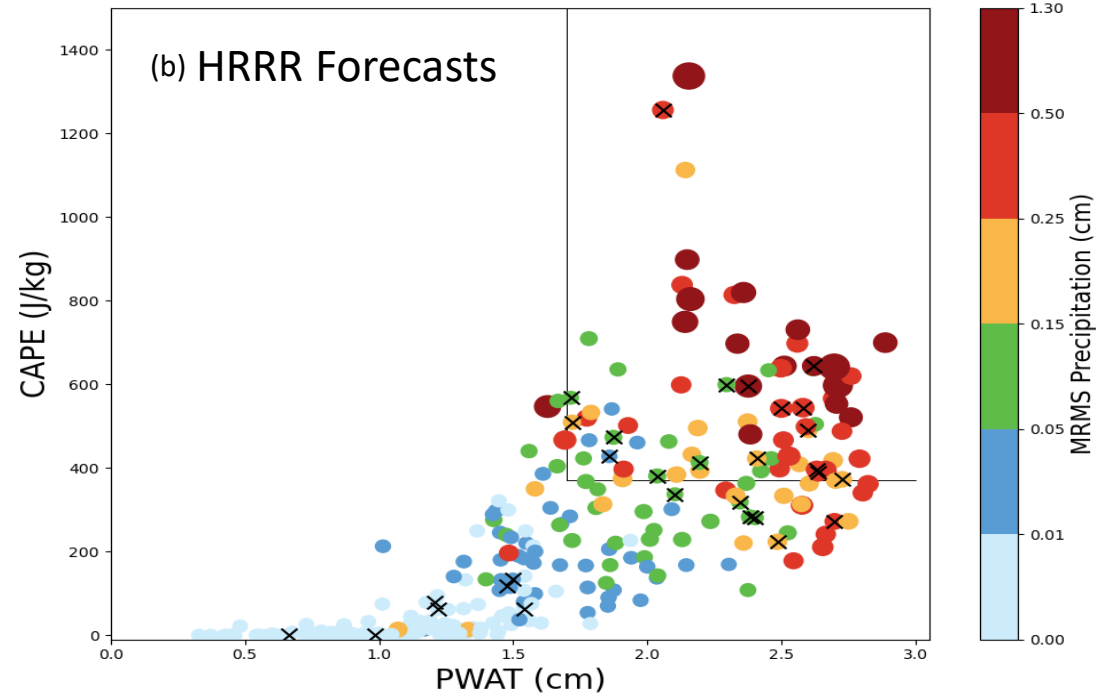
- Repeating HRRR analyses of maximum PWAT (cm) vs CAPE (J kg $^{-1}$) during 1800–2100 UTC (1200–1500 MDT) each day of the three summers averaged over southwestern Utah
- Color & size of each circle denote daily MRMS precipitation. Crosses are days with at least one flash flood report
- Solid lines highlight mean PWAT and CAPE

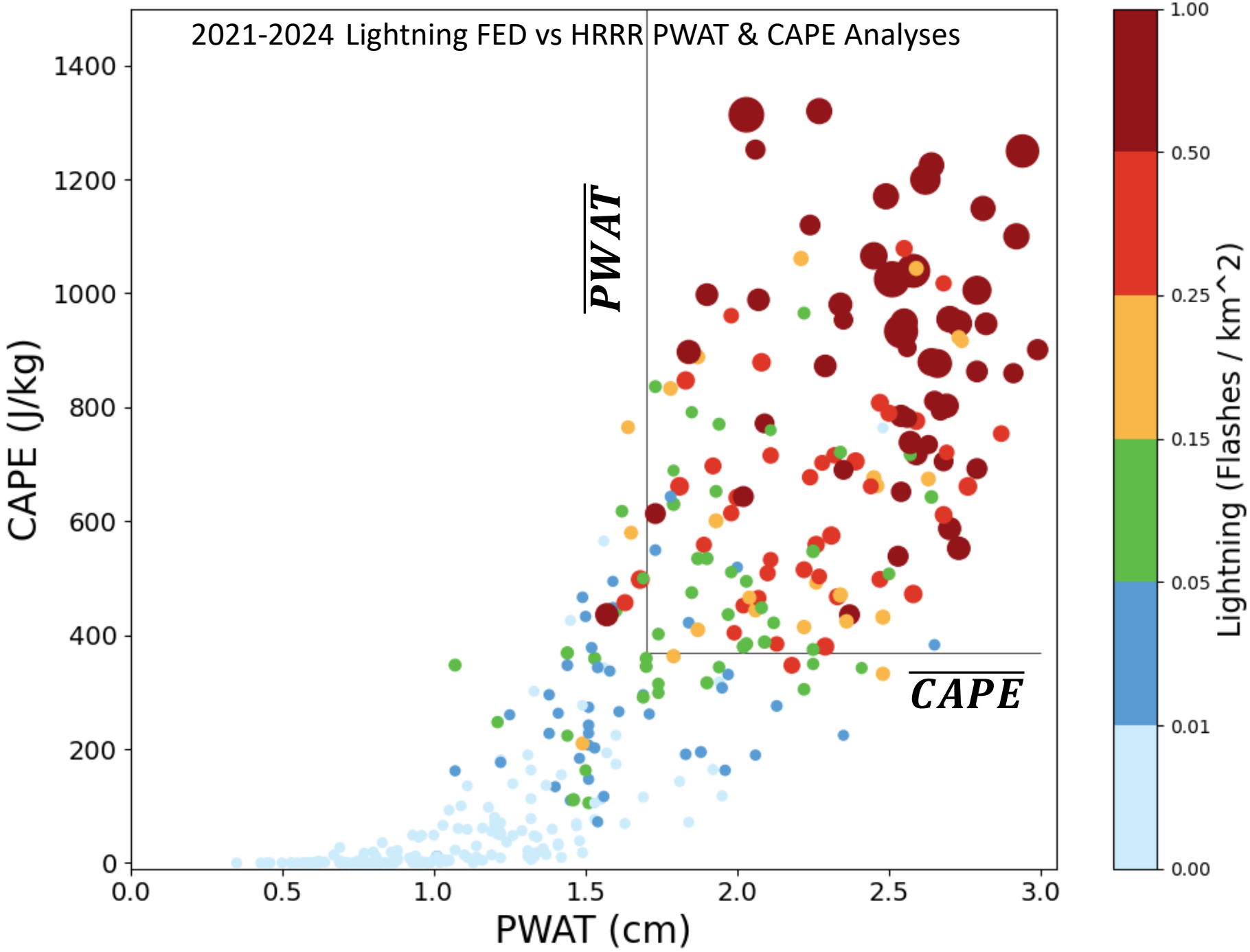
Bottom:

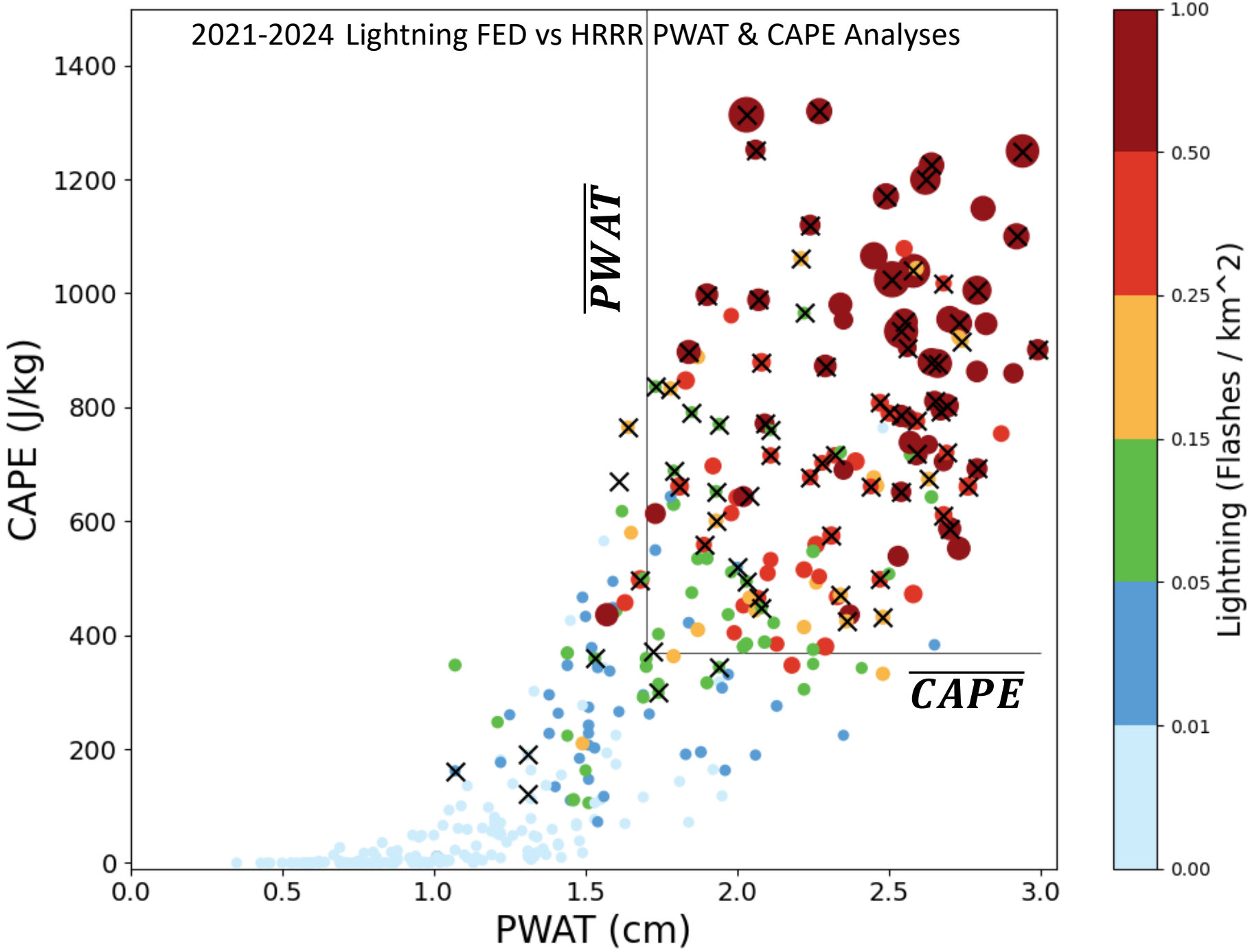
Same but for HRRR Time-Lagged Ensemble (TLE) mean forecasts of PWAT vs CAPE initialized between 0300 and 0500 UTC and valid at 1800–2100 UTC

- **TLE ensembles underestimate CAPE**
- **Reduces skill at estimating days with high rainfall, lightning, or storm reports**



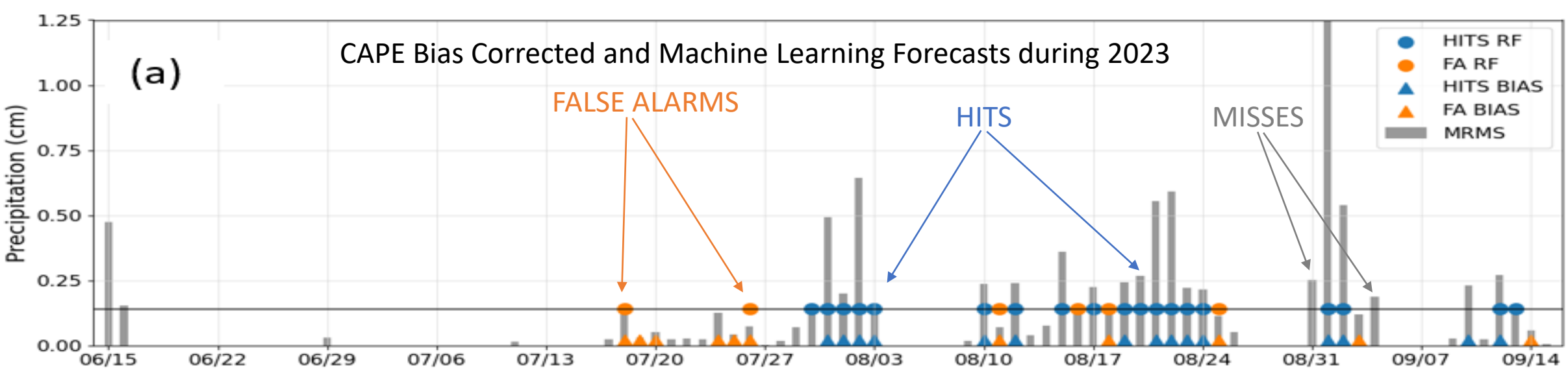



2021-2024 Lightning FED vs HRRR PWAT & CAPE Analyses
CAPE (J/kg)
PWAT (cm)
Lightning (Flashes / km^2)
$\overline{PWAT}$
$\overline{CAPE}$
0
200
400
600
800
1000
1200
1400
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.00
0.01
0.05
0.15
0.25
0.50
1.00


2021-2024 Lightning FED vs HRRR PWAT & CAPE Analyses
CAPE (J/kg)
PWAT (cm)
Lightning (Flashes / km^2)
$\overline{PWAT}$
$\overline{CAPE}$
0
200
400
600
800
1000
1200
1400
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.00
0.01
0.05
0.15
0.25
0.50
1.00

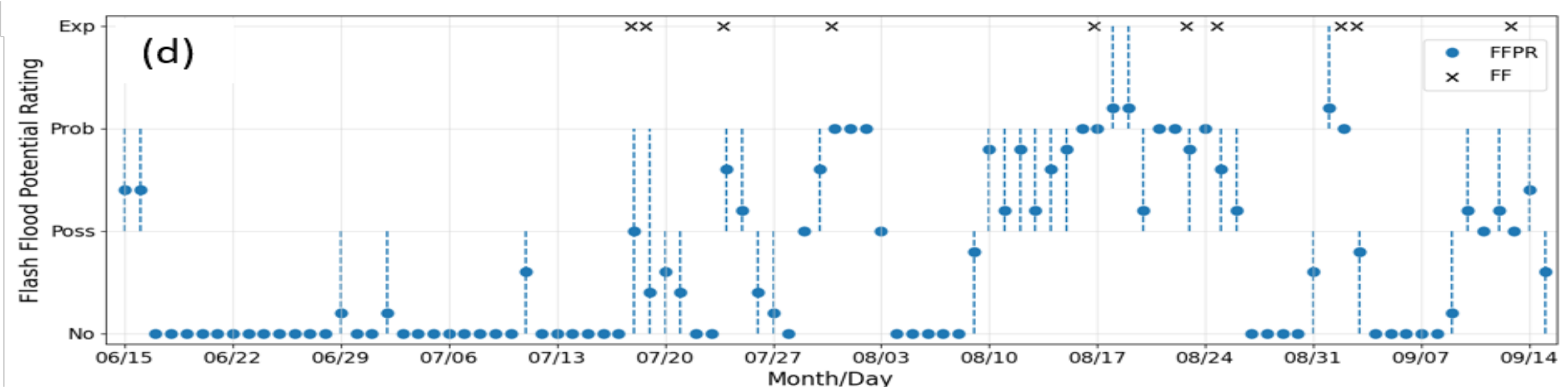
Supervised Random Forest Classification

- Arbitrary decision to target relatively rare high rainfall days (75^{th} percentile, areally averaged MRMS > 0.14 cm)
- Days subdivided randomly during 2021 and 2022 into 67% training and 33% validation datasets
- Test dataset: summer 2023
- Optimal hyperparameters varied depending on the relative sizes of training and validation datasets but limited impact on results
- Accuracy score: 0.93
- Feature importance: 53% TLE PWAT and 47% CAPE
- Handles bias of CAPE forecasts



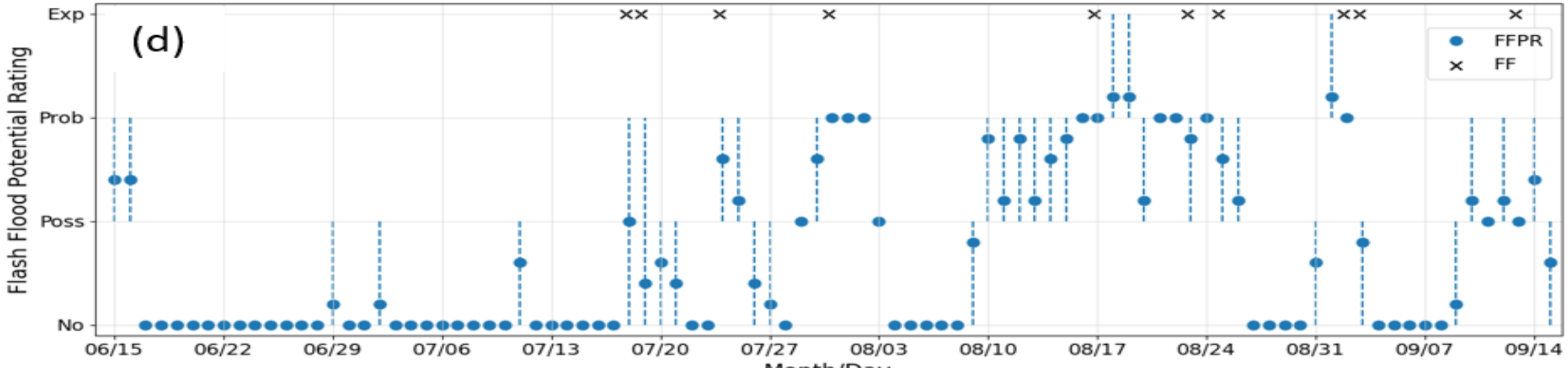
TLE forecast hits (blue) and false alarms (orange) for random forest (circles) and bias-corrected (triangles) methods to predict rainfall that exceeds 75th percentile (solid line)

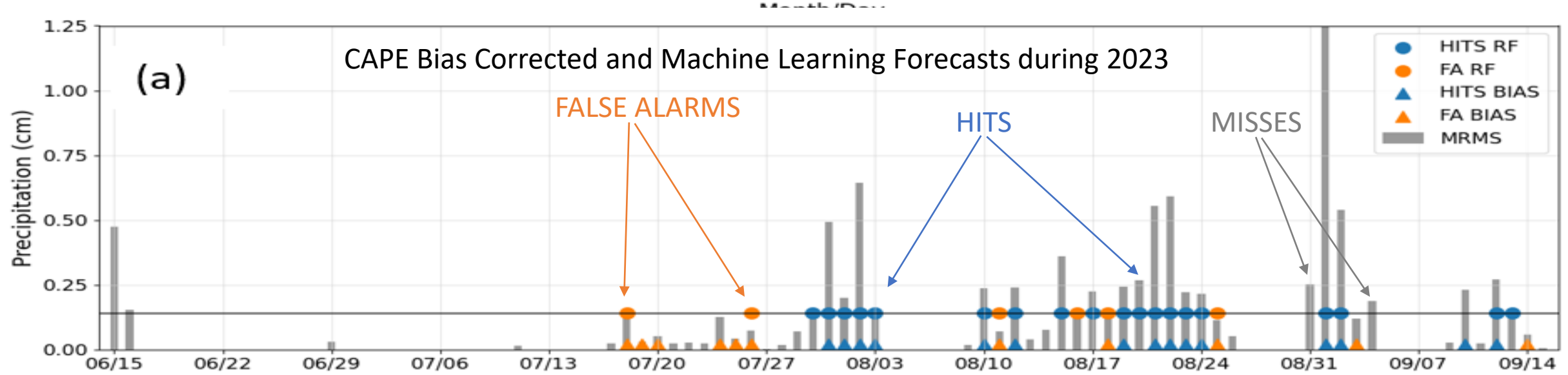
Mean (circles) and spread (dashed lines) of FFPR forecasts issued SLC WFO for 5 parks. **Crosses denote flash flood days**



SLC WFO Forecasts of Flash Flood Potential Rating (FFPR) during 2023

Mean (circles) and spread (dashed lines) of FFPR forecasts issued SLC WFO for 5 parks. **Crosses denote flash flood days**





TLE forecast hits (blue) and false alarms (orange) for random forest (circles) and bias-corrected (triangles) methods to predict rainfall that exceeds 75th percentile (solid line)

Summary and ongoing/future work

- Residents and visitors vulnerable to flash flooding near southern Utah canyons
- Horel & Powell (2024; *WAF*)
  - Time-lagged ensembles of HRRR forecasts that are 13-18 h prior to the afternoon period are useful for situational awareness of widespread rainfall after adjusting for underprediction of afternoon CAPE
  - Improved skill is possible using random forest classification relying only on PWAT and CAPE to predict excessive rainfall days
- Extend analysis across southern Nevada, southern Colorado, & northern Arizona incorporating more variables and other machine learning techniques
- Examine impacts of Flash Flood Warnings and Flash Floor Potential Rankings on visitor behavior at Zion National Park
- What is the forecast skill of hourly ensembles from Rapid Refresh Forecast System (RRFS)? Global Ensemble Forecast System (GEFS)?
- Possible participation in future Flash Flood and Intense Rainfall Experiments (FFaIR)?
- Can PWAT/CAPE in climate simulations be used as proxies to evaluate future trends in southern Utah rainfall extremes?

Questions?

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Flash Flood Videos
Havasupai. August 22, 2024: https://youtu.be/U9Gt9EAQRsk?si=dVOaljylyndnHujt

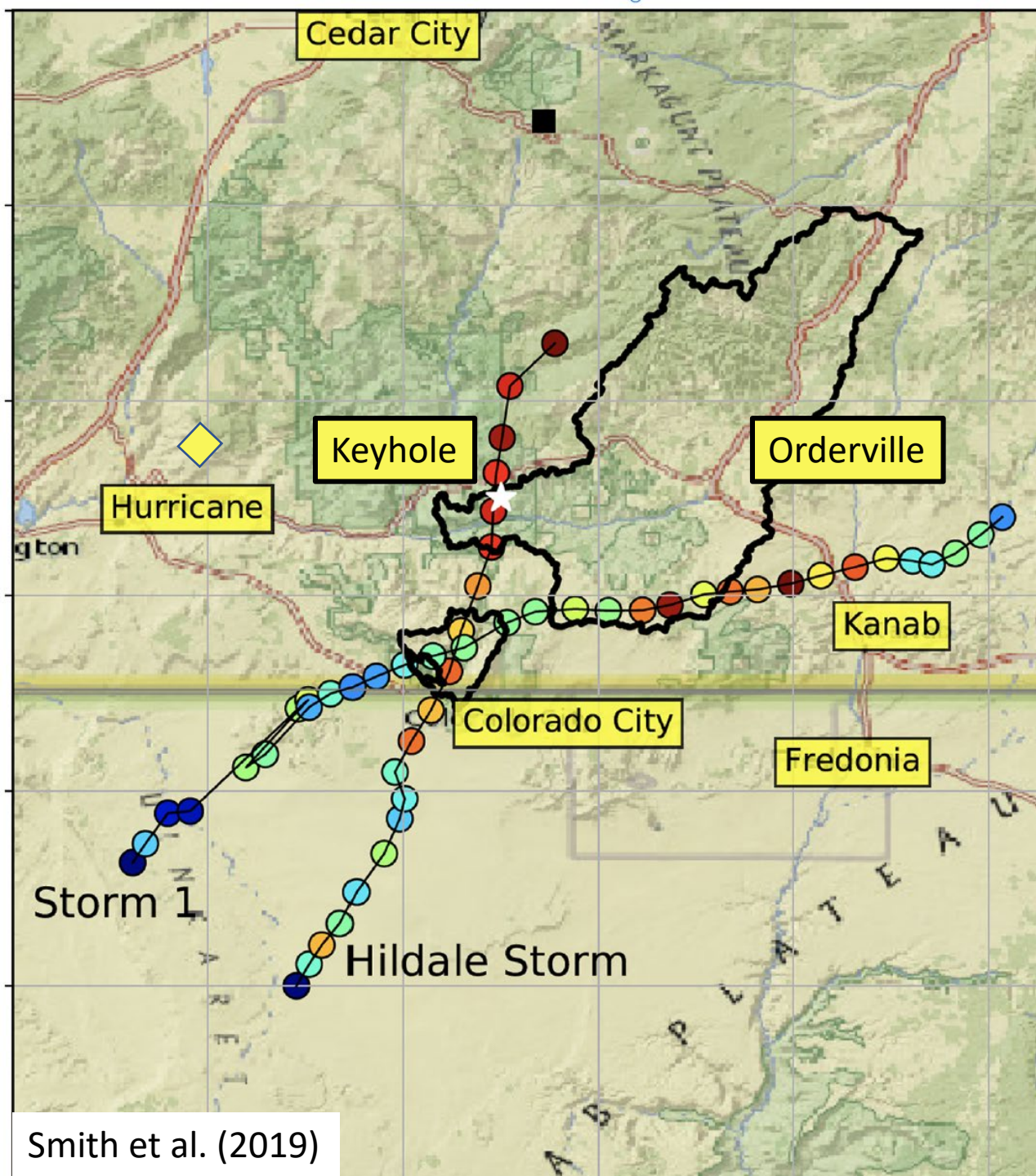
Zion Narrows. August 23, 2023: https://www.youtube.com/watch?v=rdZFUWE3WMU

Zion Narrows. August 3, 2021: https://www.youtube.com/watch?v=E5sn1ZMltak

15 September 2015

The paroxysmal precipitation of the desert: Flash floods in the southwestern United States

Smith et al. (2019) *Water Resources Research* [10.1029/2019WR025480](https://doi.org/10.1029/2019WR025480)



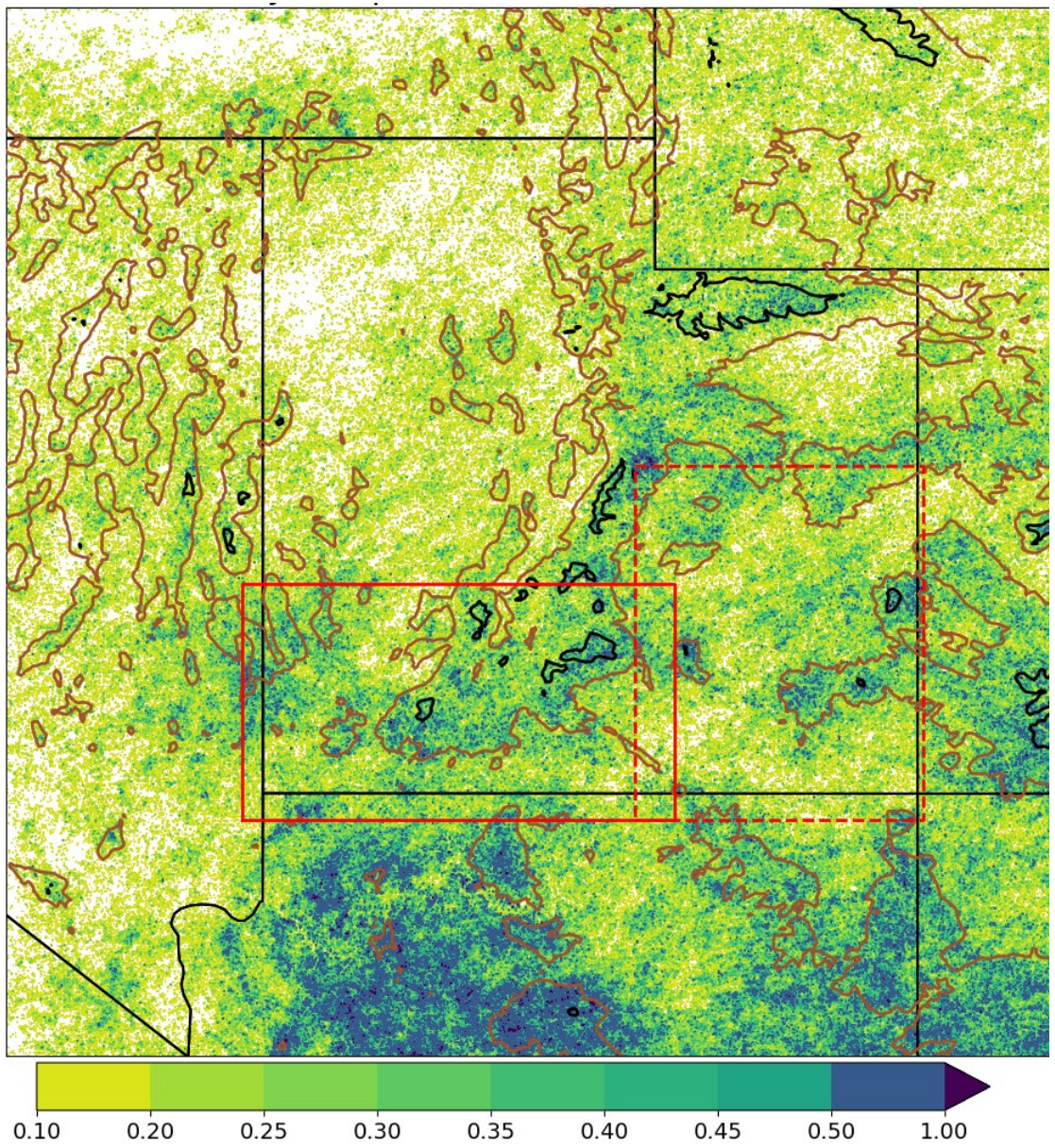
Smith et al. (2019)

14 Sept 2015

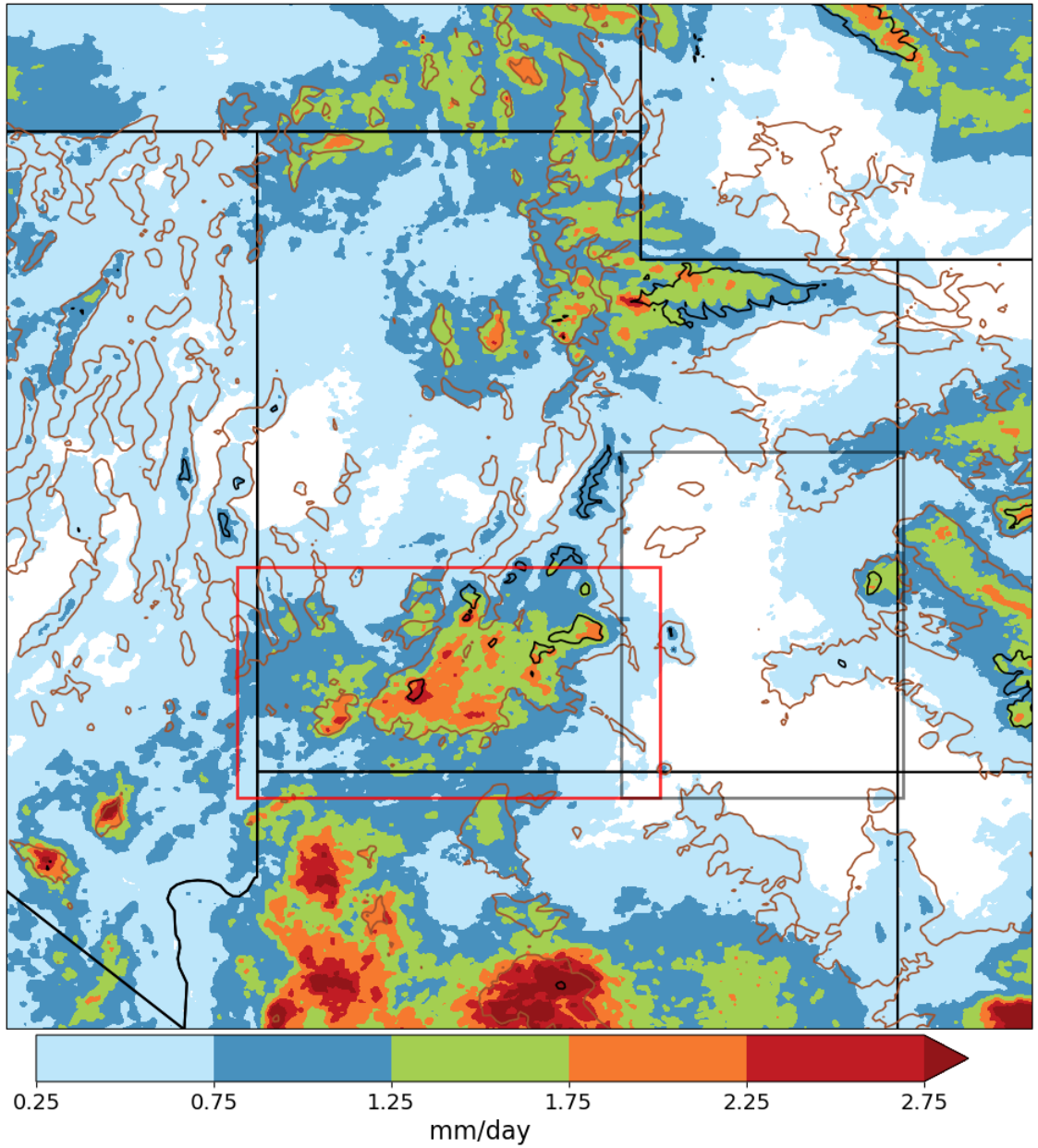
Hilldale, UT. 13 fatalities

Keyhole, ZNP:
7 fatalities

Lightning 2021-2024



MRMS Precipitation 2021-2024
Fraction:97%



MRMS Precipitation