The Need for Integrated, Multi-Scale Observations and Modeling to Improve Process Understanding of the Monsoon in Semi-arid Regions

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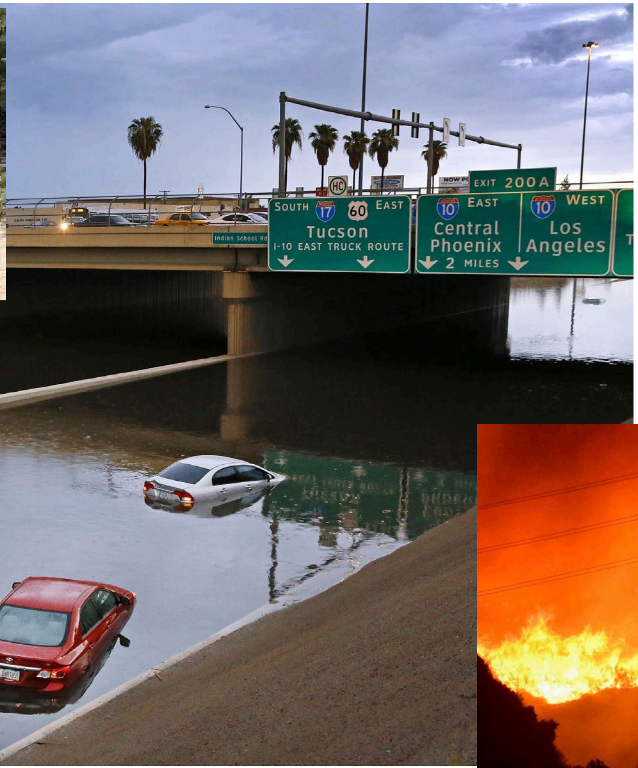
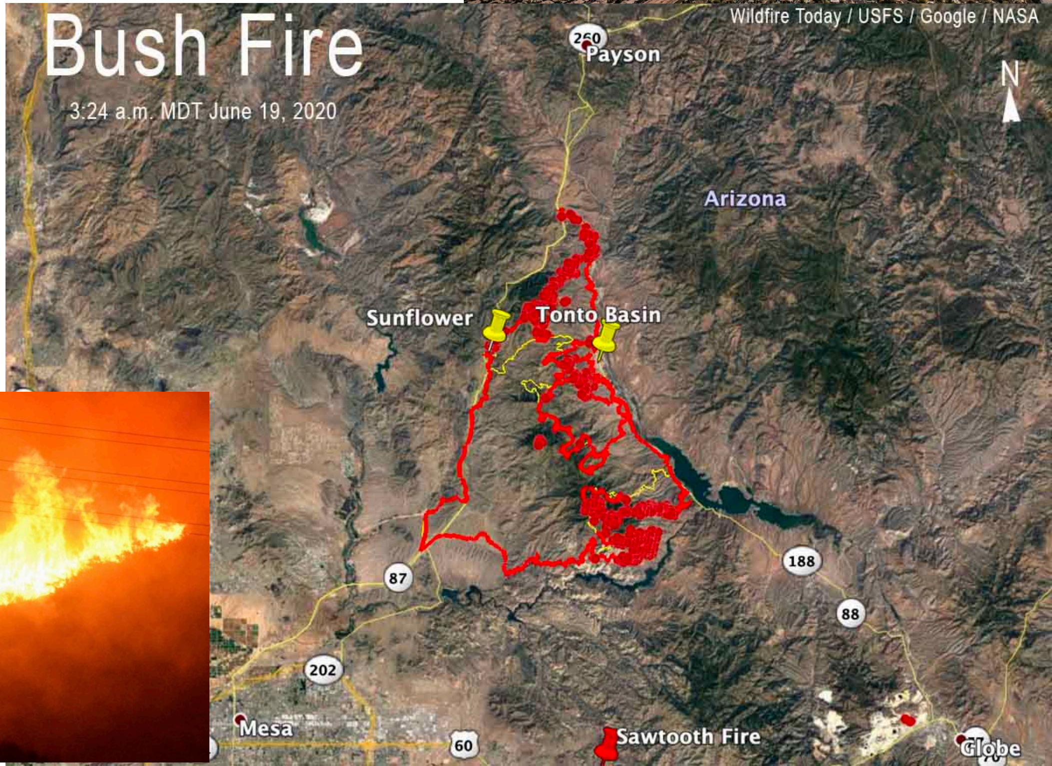
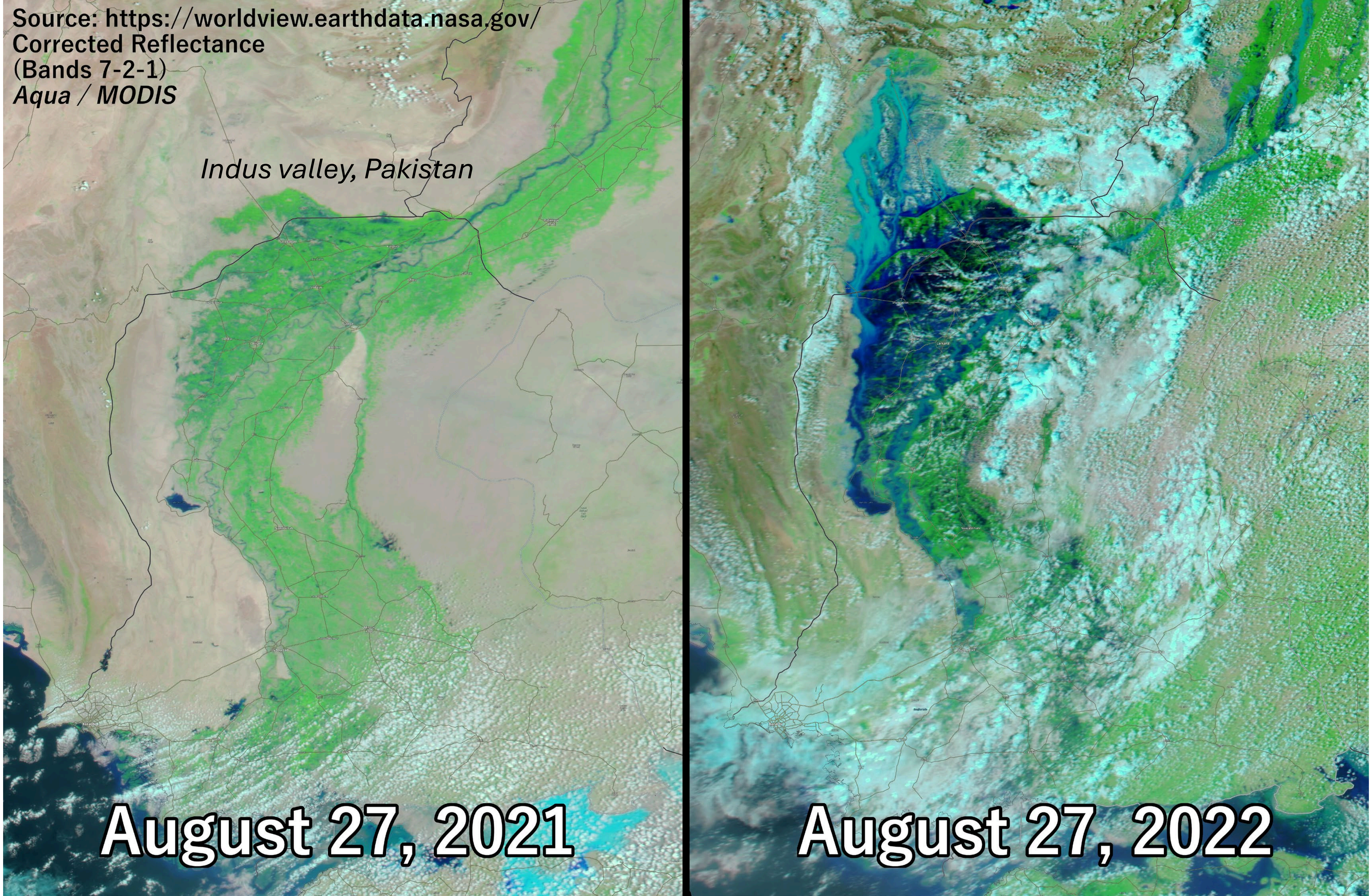
ECMWF 2nd Observational Campaigns Workshop, 3 July 2026

Big picture: extreme weather

- The “monsoon season” can bring hazardous weather to semi-arid regions: flash flooding, lightning-initiated wildfires, and dust storms impact property, infrastructure, and human lives.
  - e.g., Arizona suffered more than $3 billion in losses due to extreme weather between 2010-2016, 96% of which was from thunderstorms, wildfires, and flash floods

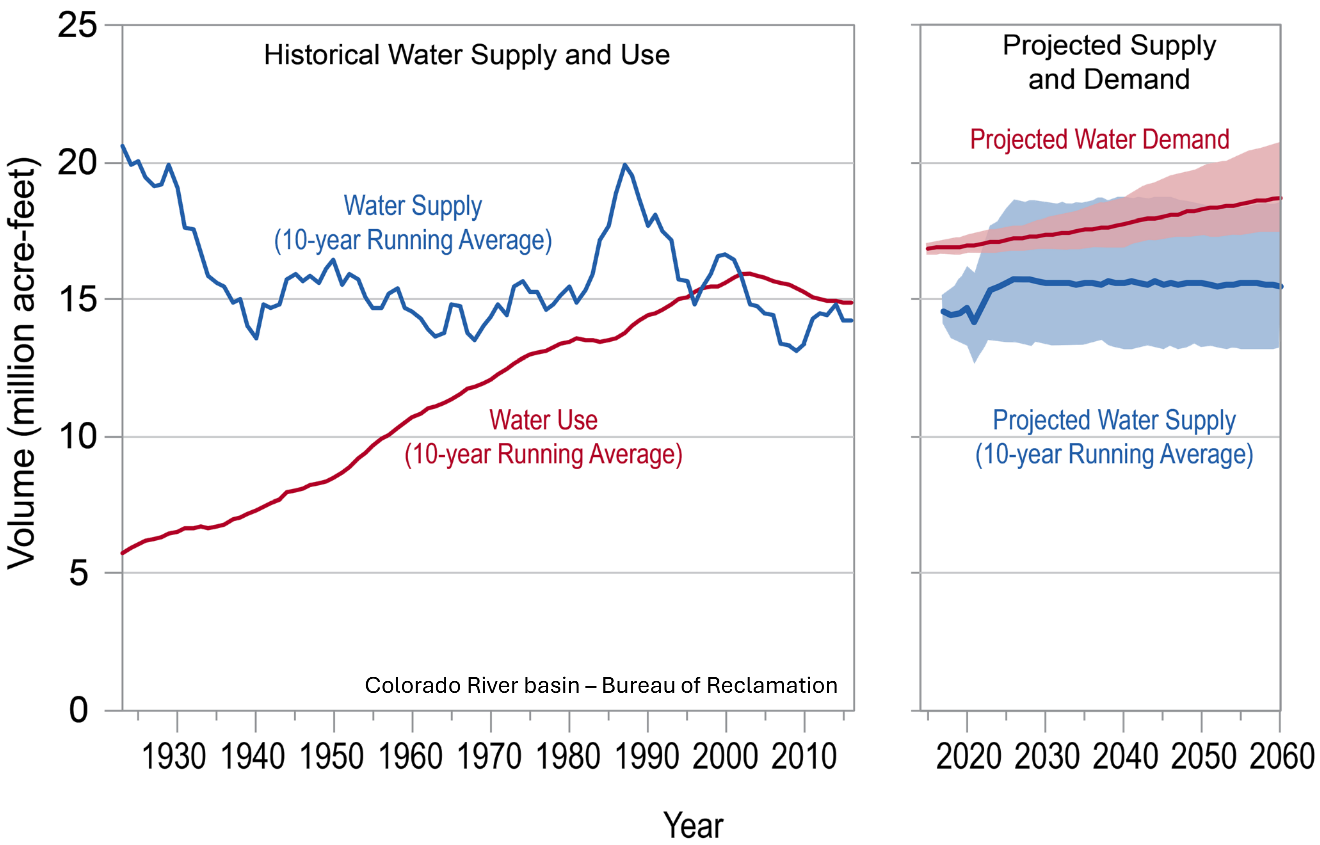





Source: https://worldview.earthdata.nasa.gov/
Corrected Reflectance
(Bands 7-2-1)
Aqua / MODIS
Indus valley, Pakistan
August 27, 2021
August 27, 2022

Big picture: water resources

- Semi-arid regions are experiencing increasingly severe heat waves, especially before the onset of the monsoon.
- In the US, there is a growing need for sustainable hydrological management in the **Colorado river basin** in an increasingly arid environment.

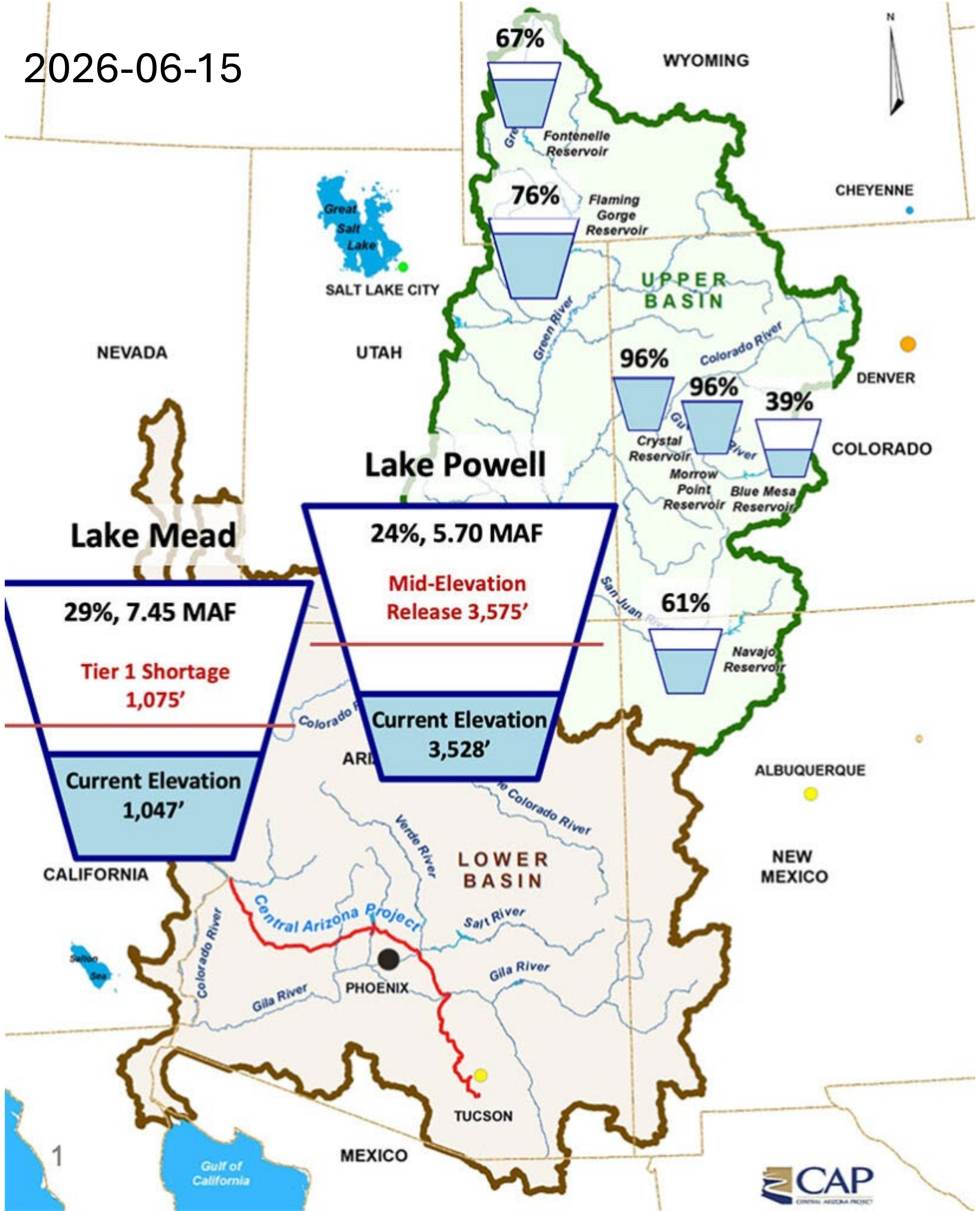


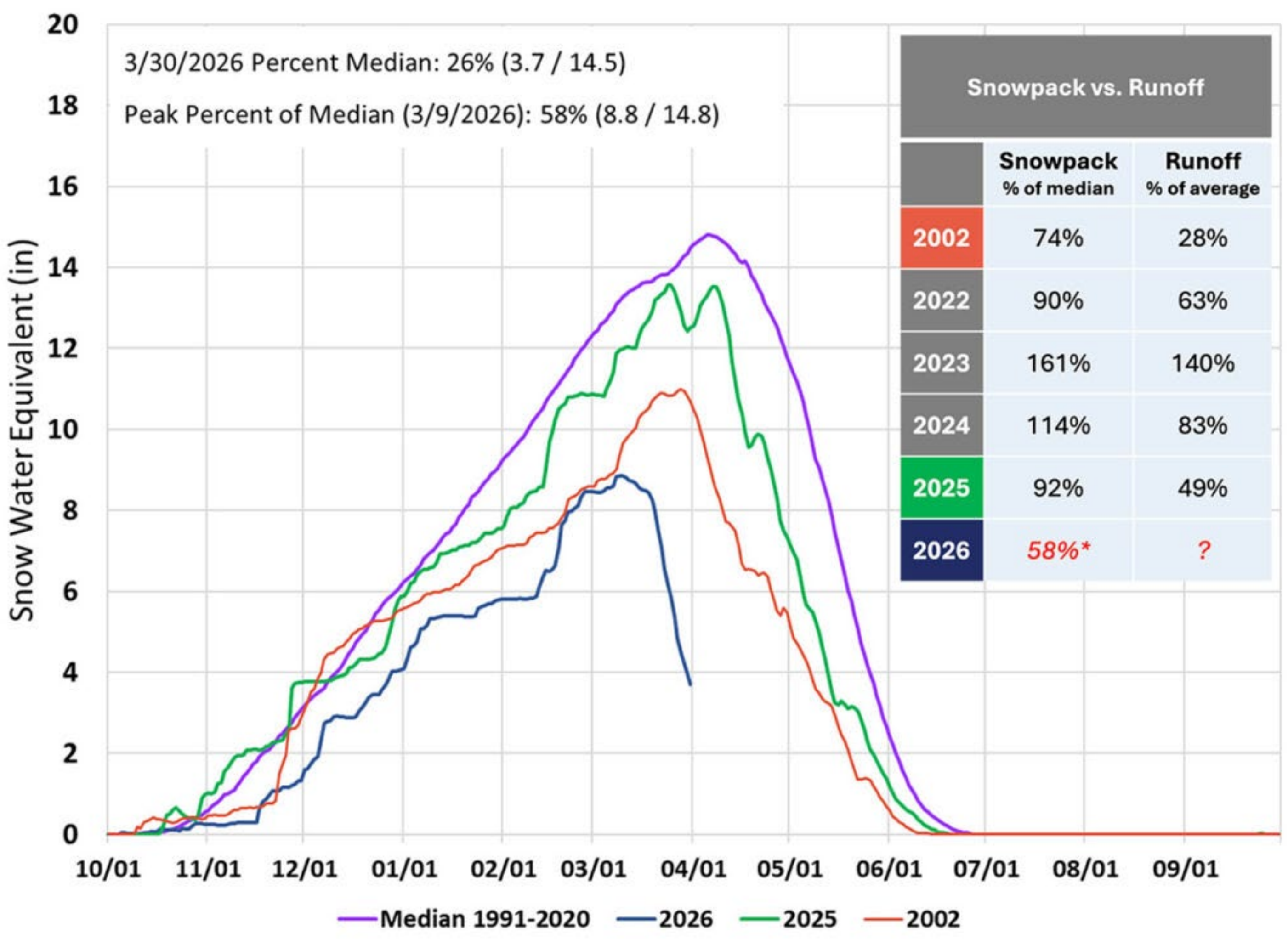
Colorado River basin – Bureau of Reclamation

Ted Roosevelt Dam – Salt River Project

Big picture: water resources

2026-06-15

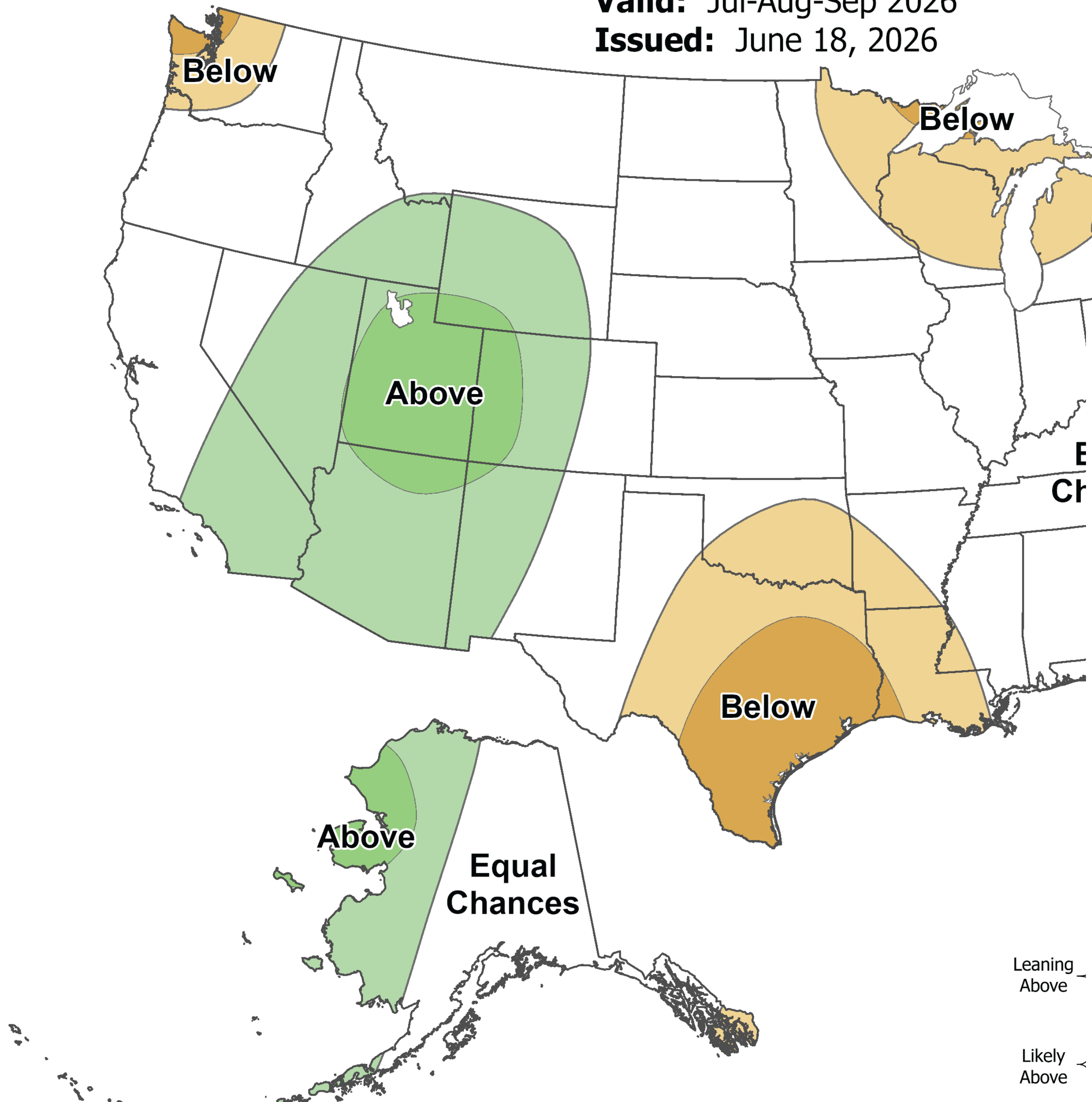




https://www.cap-az.com/colorado-river-conditions-dashboard/

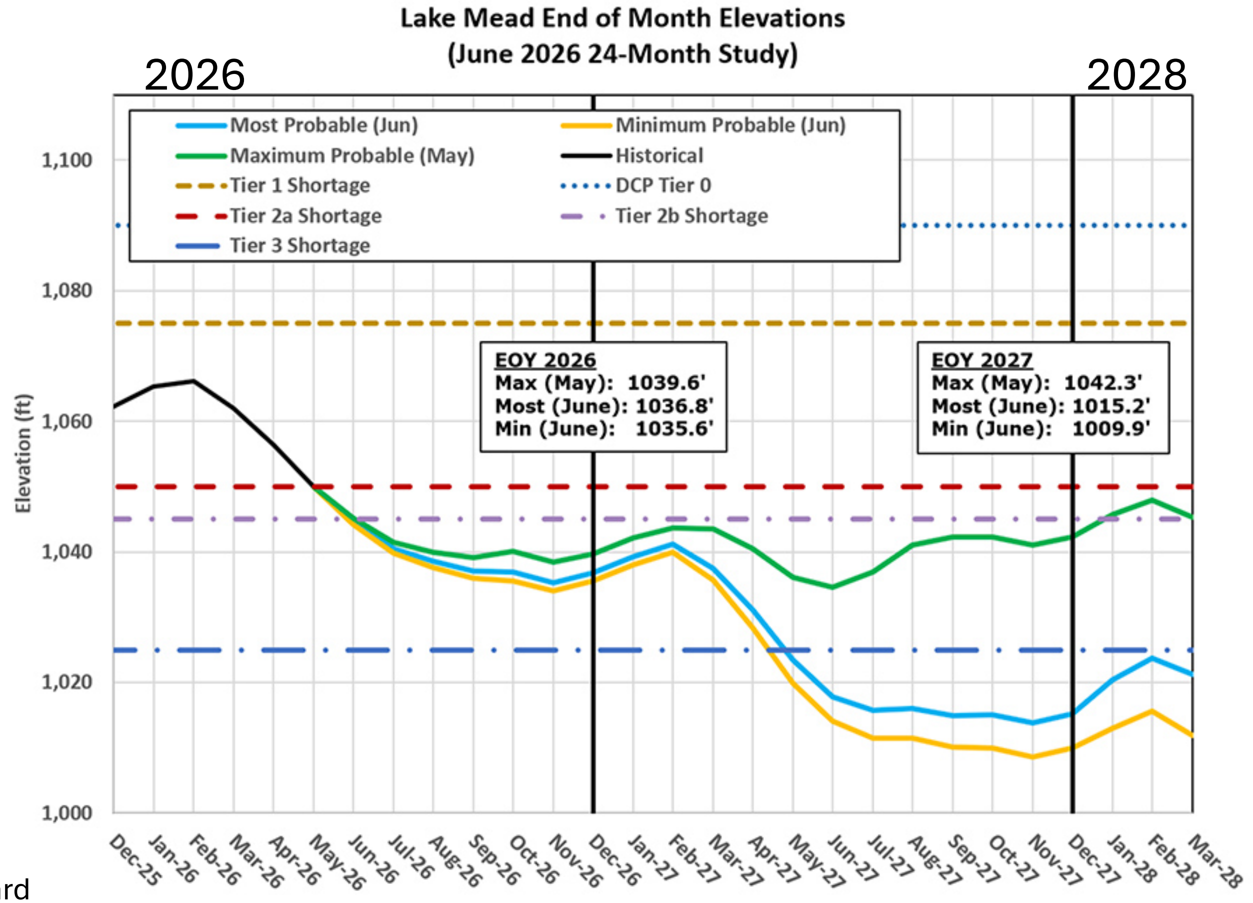
Seasonal Precipitation Outlook

Valid: Jul-Aug-Sep 2026
Issued: June 18, 2026



https://wwa.colorado.edu/resources/intermountain-west-dashboard

https://www.cap-az.com/colorado-river-conditions-dashboard/

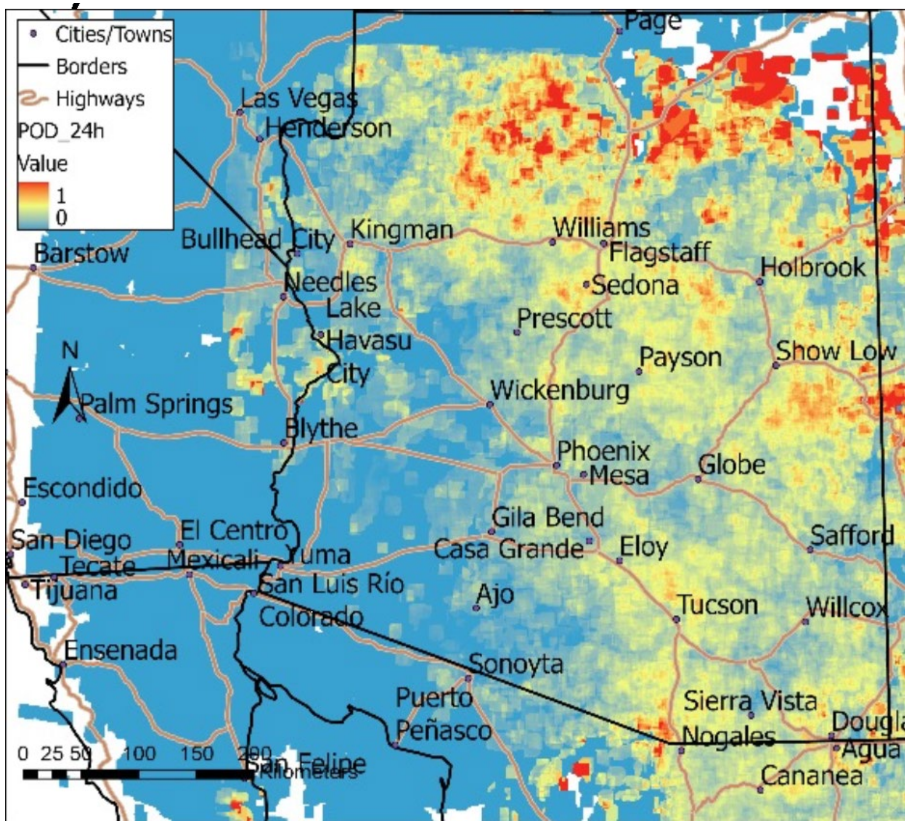


The challenge

- *There is a critical need for better predictability of monsoonal precipitation at a range of time scales from hours to decades.*

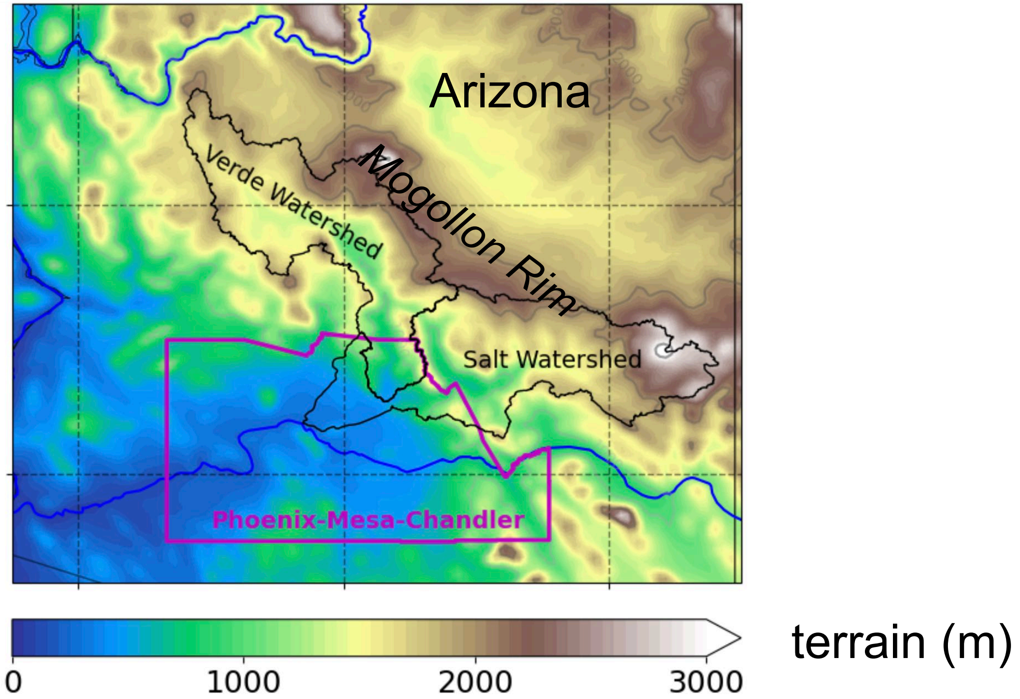
Weather predictability challenge

Convection-permitting regional atmospheric models are challenged to represent the intensity, timing, and location of deep convection during the *North American Monsoon*.



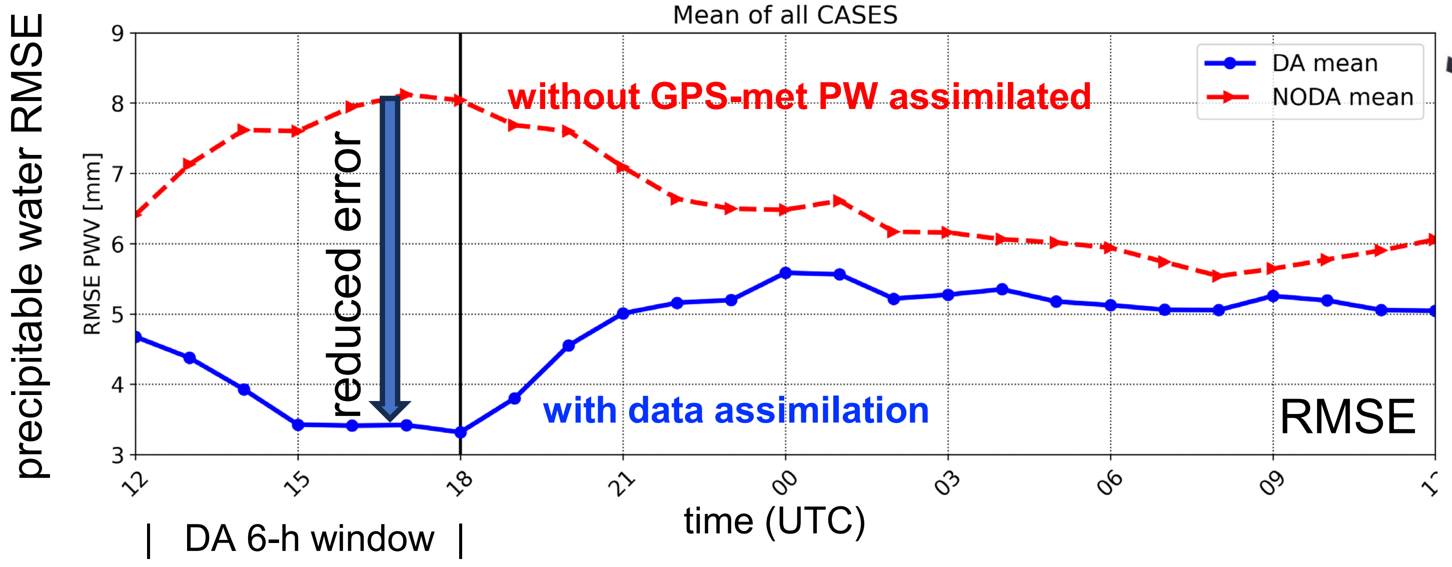
***Probability of Detection of 24-h predicted precipitation exceeding 10 mm** from the 1.5-km UA-WRF prediction system as verified against MRMS (Multi Radar–Multi Sensor) precipitation analysis for 1 June – 30 Sept 2021.*

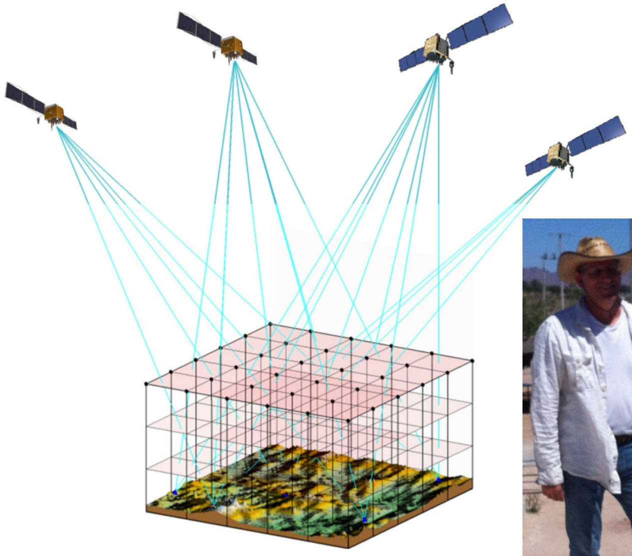
State of the art weather prediction models fail to properly capture the growth and subsequent propagation of thunderstorms off the mountains in Arizona.

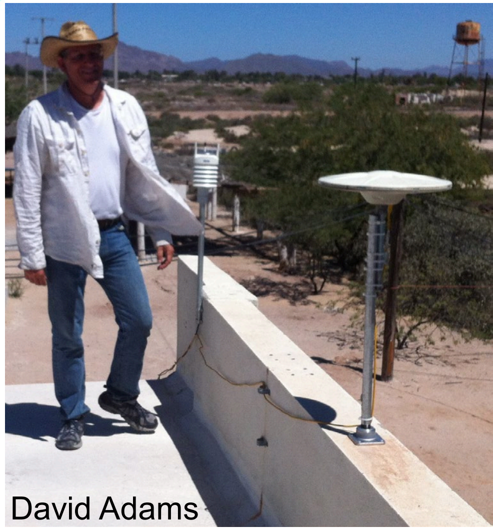


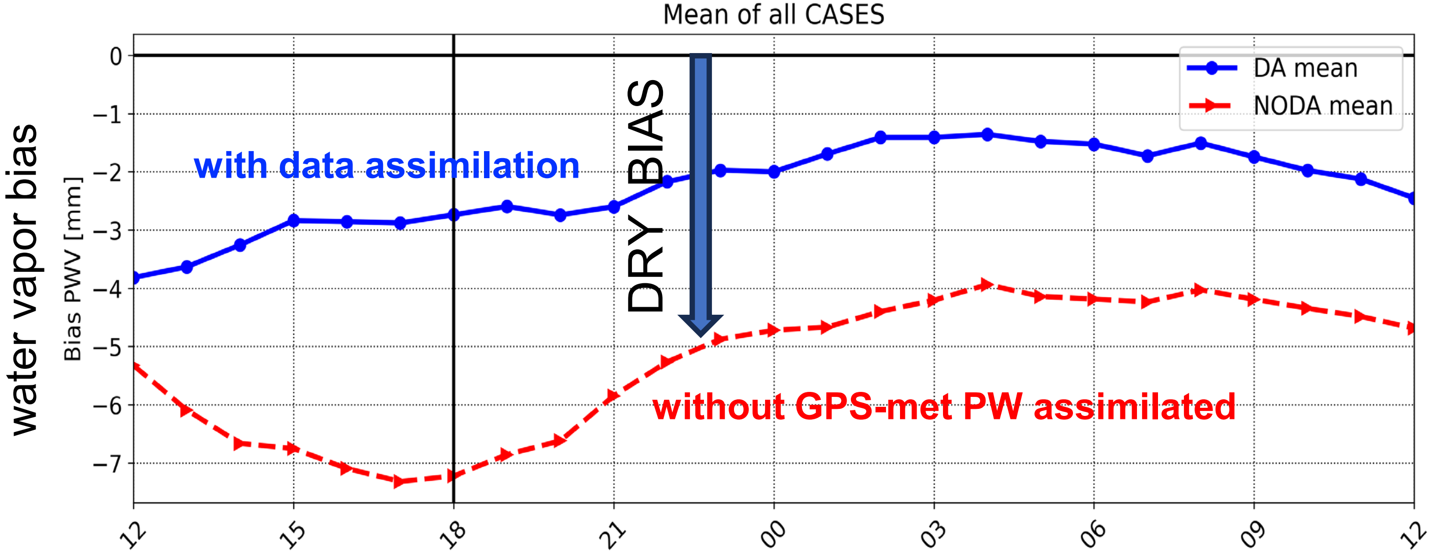
Forecasts of monsoon precipitation is very sensitive to water vapor measurements

two months simulated with 40-member ensemble EnKF forecast system using Thompson microphysics (courtesy: Bayu Risanto)







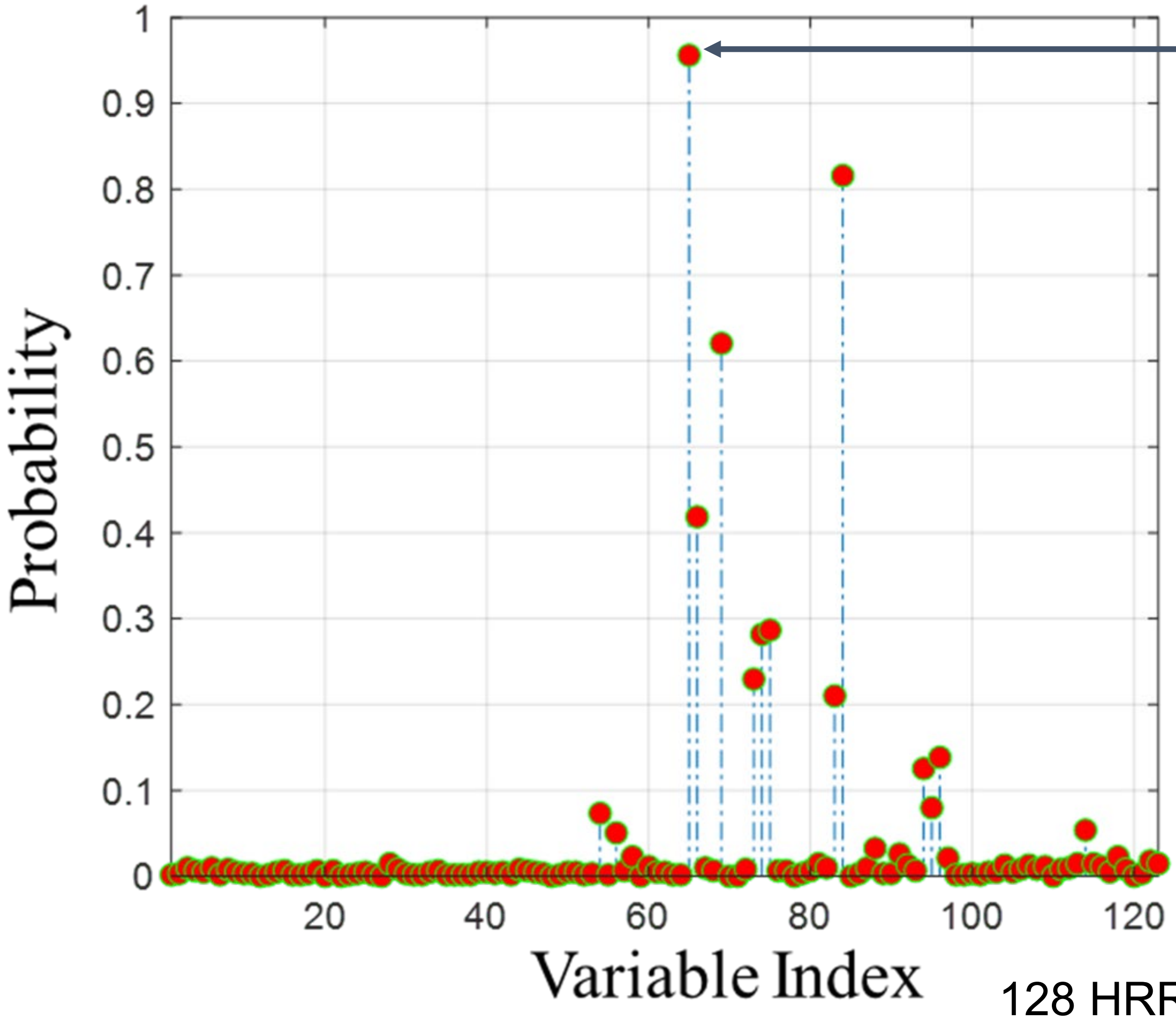


A small demonstration network of GPS-met receivers was installed in summer 2022. They measure column water vapor.

- Models – including the HRRR shown here (NODA) - have a pronounced dry bias problem.
- GPS-met water vapor data assimilation alleviated this bias problem in this 24-case sample.

Risanto et al. 2025

North American Monsoon precipitation causality



Surface Moisture Availability

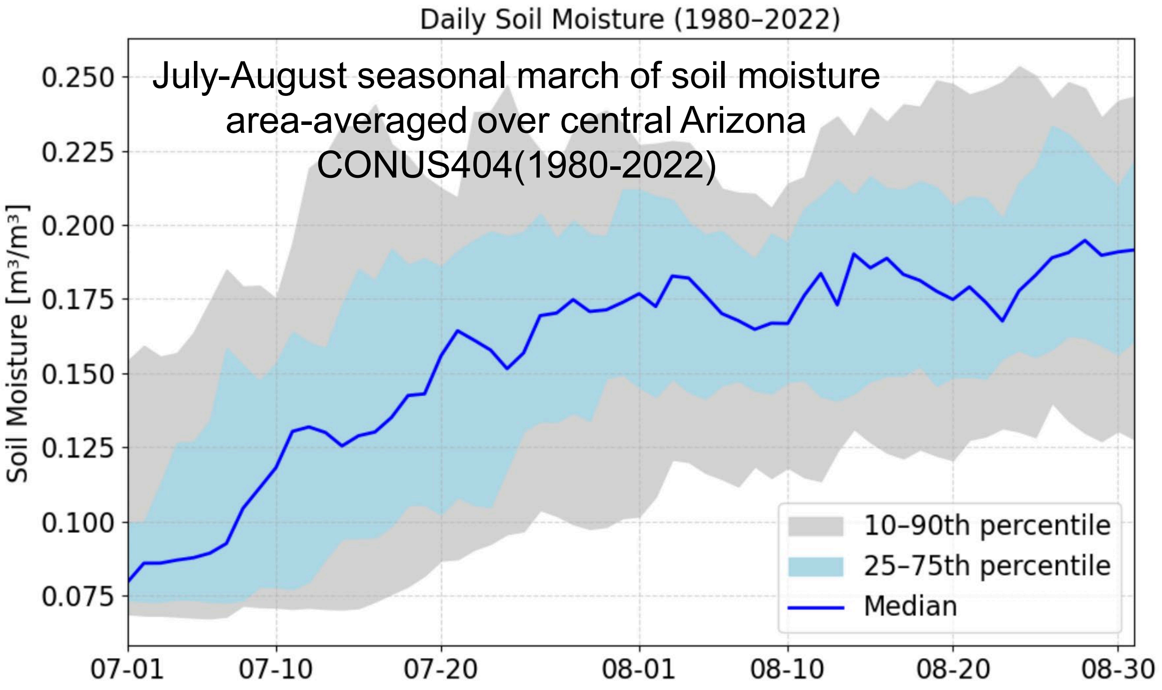
The probability of the variable being a causal factor is computed by dividing number of time a variable selected by ER over the total number of SP. The selected variables with a probability higher than 0.25 are as follows:

- MSTAV: Moisture Availability [%]: 0 m underground (anal.)
- REFC: Composite reflectivity [dB]: entire atmosphere (anal.)
- DZDT: Vertical Velocity (Geometric) [m/s]: 0.5-0.8 sigma layer (anal.)
- WIND: Wind Speed [m/s]:10 m above ground (0-1 hour max fcst)
- CAPE: Convective Avail. Potential Energy [J/kg]: surface (1 hour fcst)
- MAXUVV: Hourly Maximum of Upward Vertical Velocity [m/s]: 400-1000 mb above ground (0-1 hour max fcst)

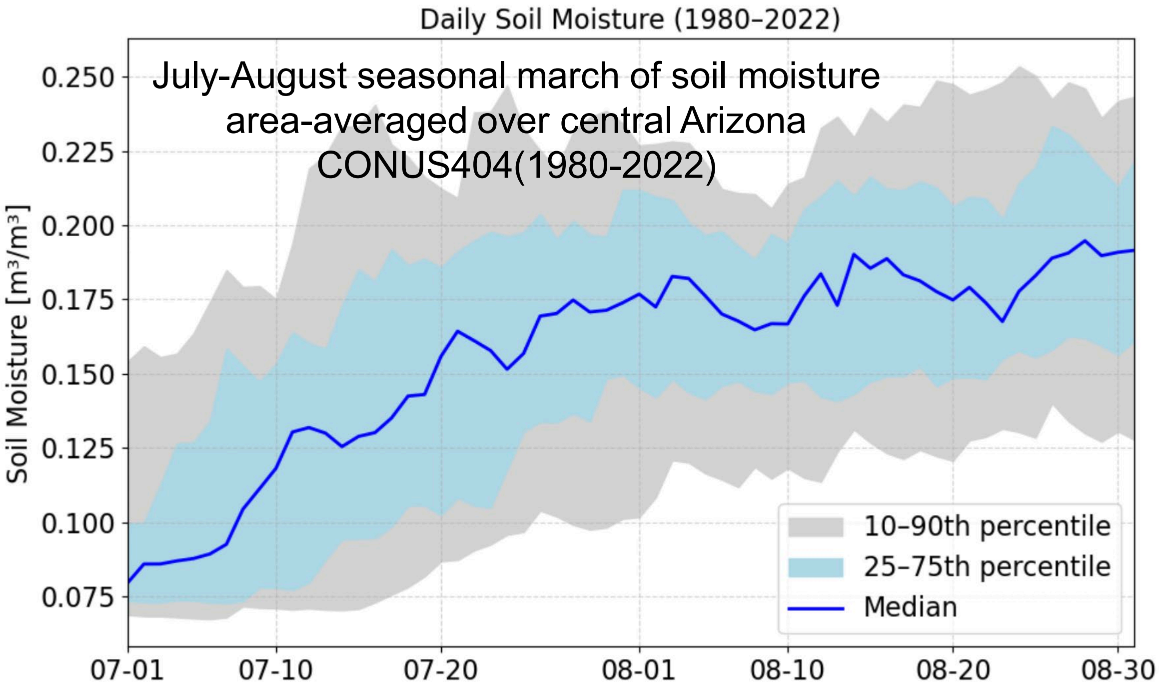
Based on 4 monsoon seasons:
MRMS Rainrate Data (2018-21)

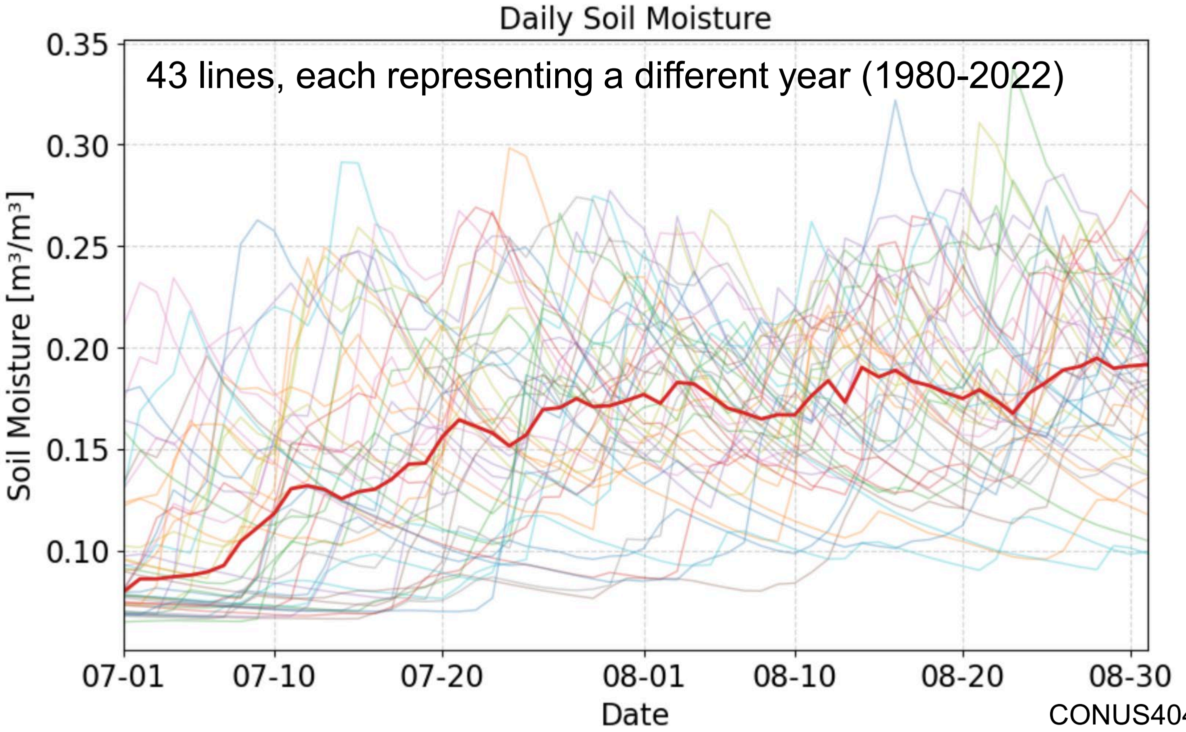
128 HRRR model output fields

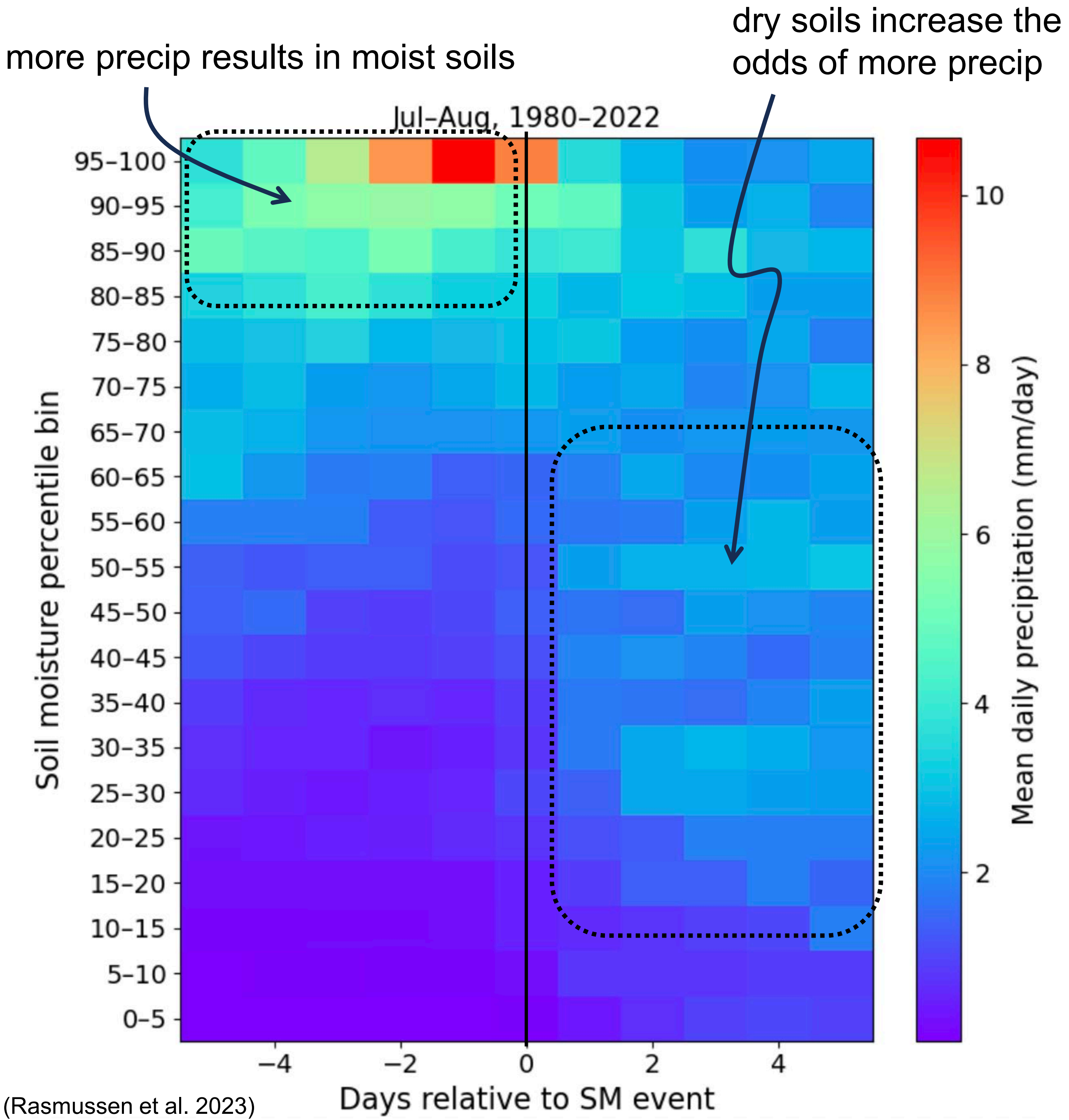
(Shroeder et al. 2024)



CONUS404 (Rasmussen et al. 2023)



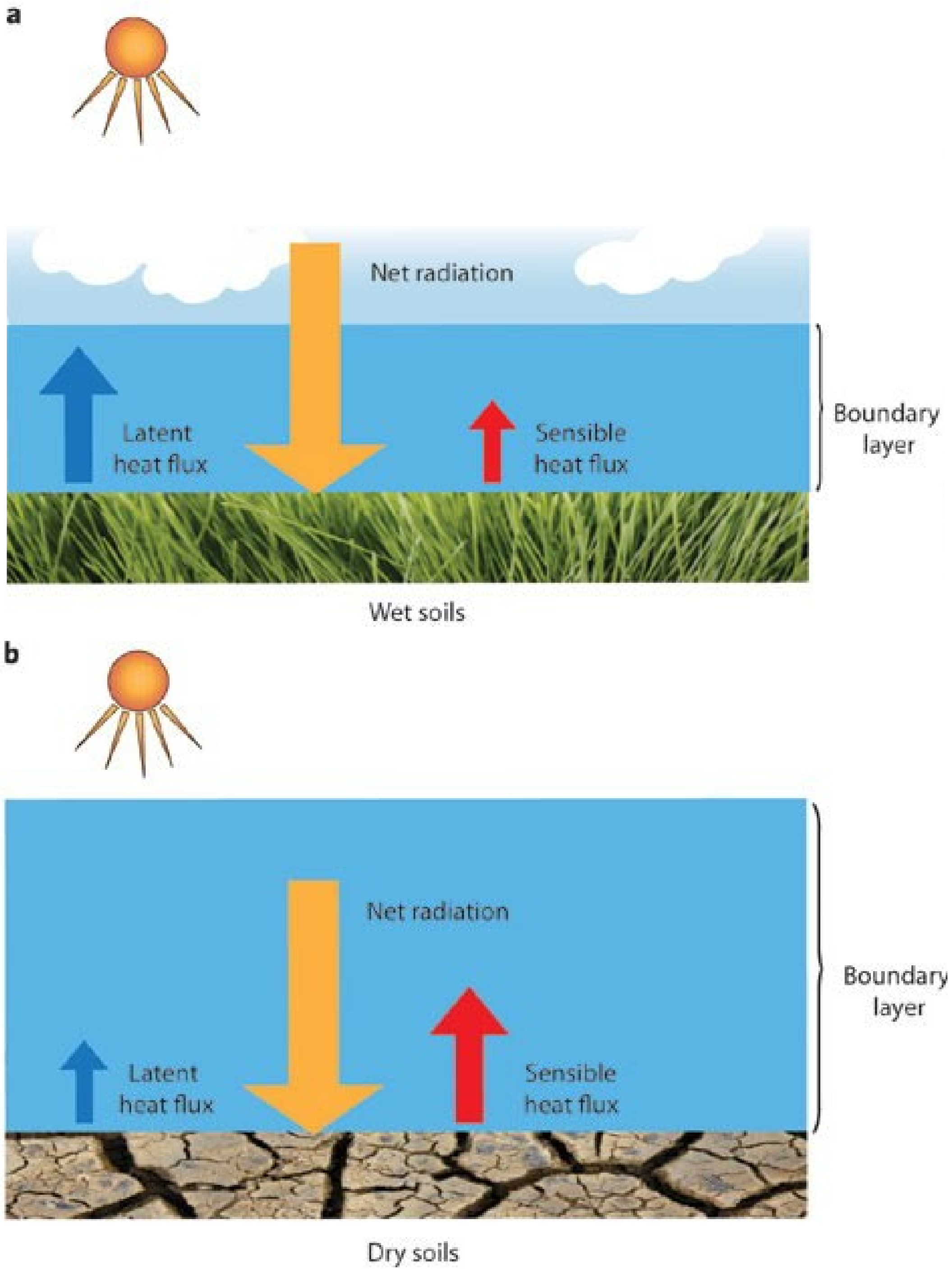


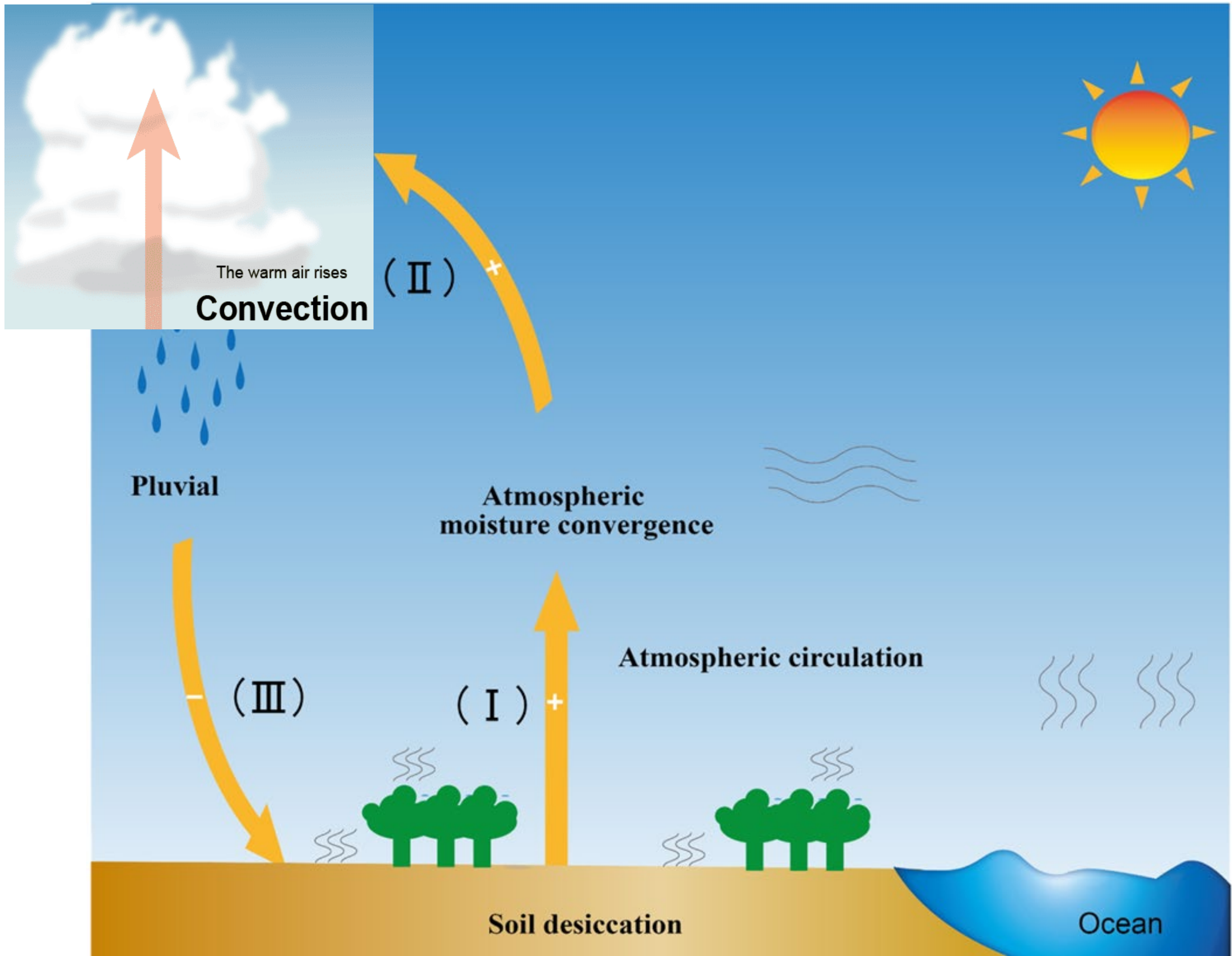


CONUS404 (Rasmussen et al. 2023)

soil moisture – moisture convergence - precipitation **feedback**

moisture sources are *remote*.



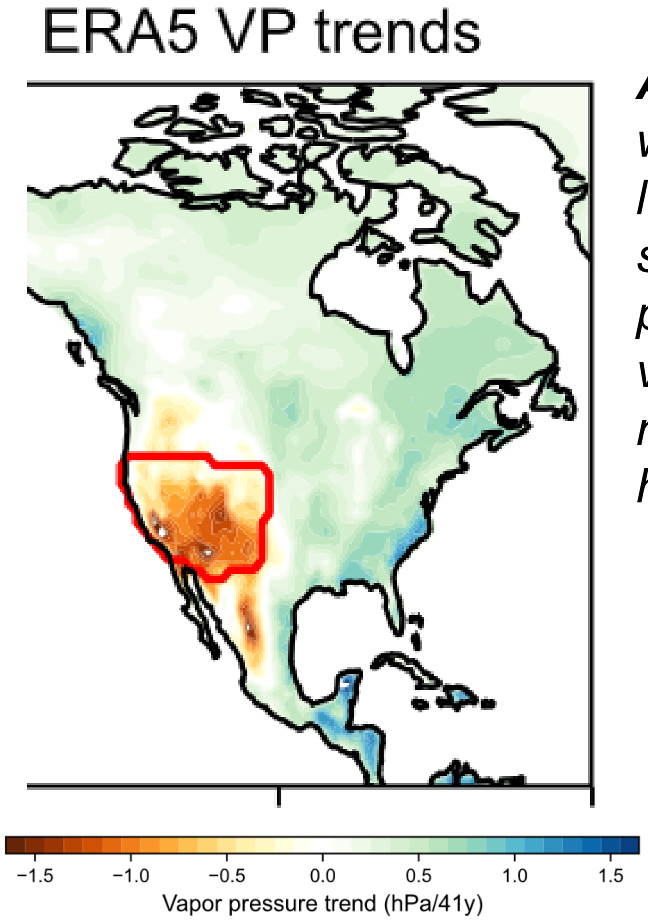


Climate predictability challenge

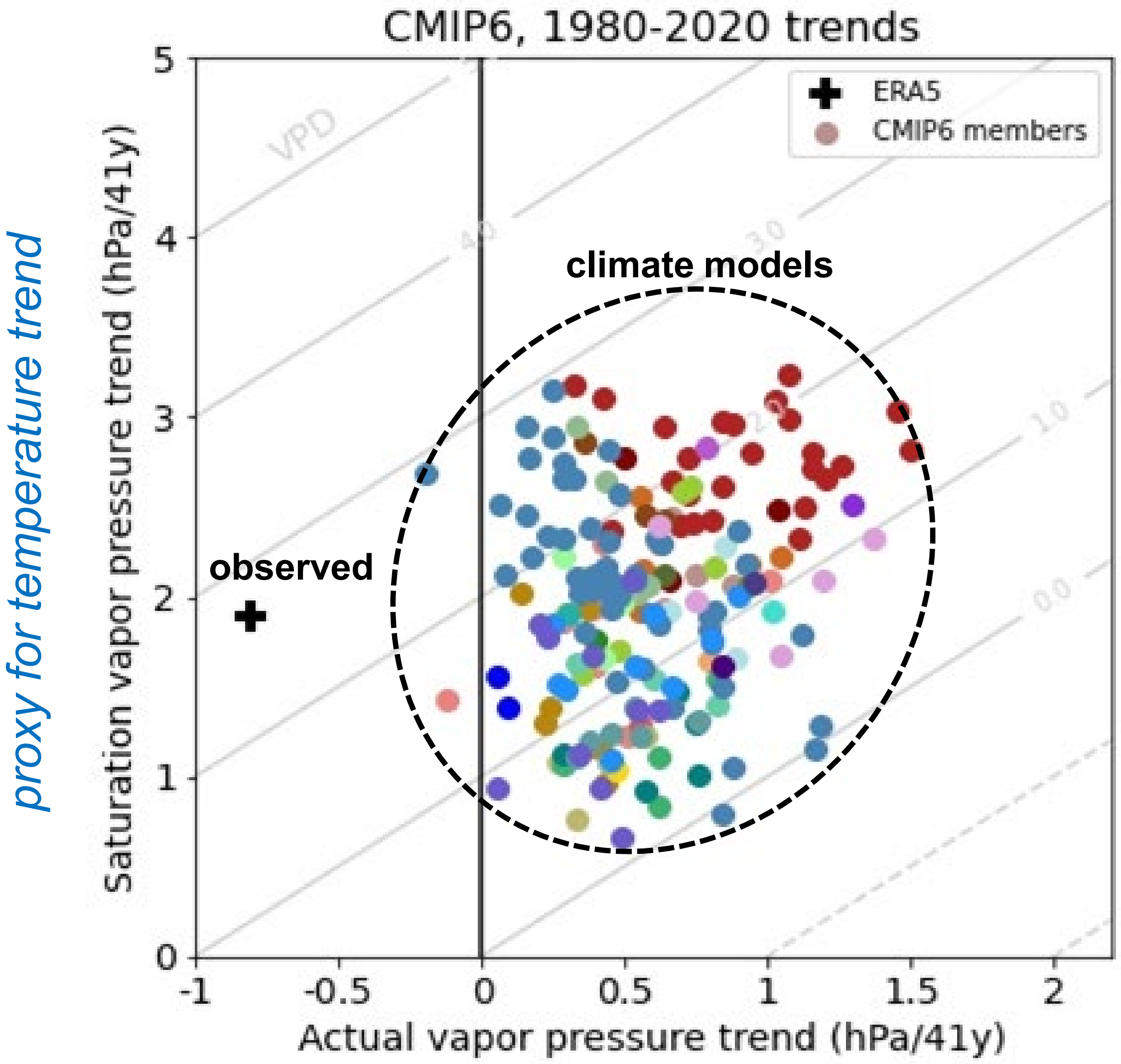
Southwestern US has been drying the last 4 decades.

None of the CMIP6 climate models capture this.

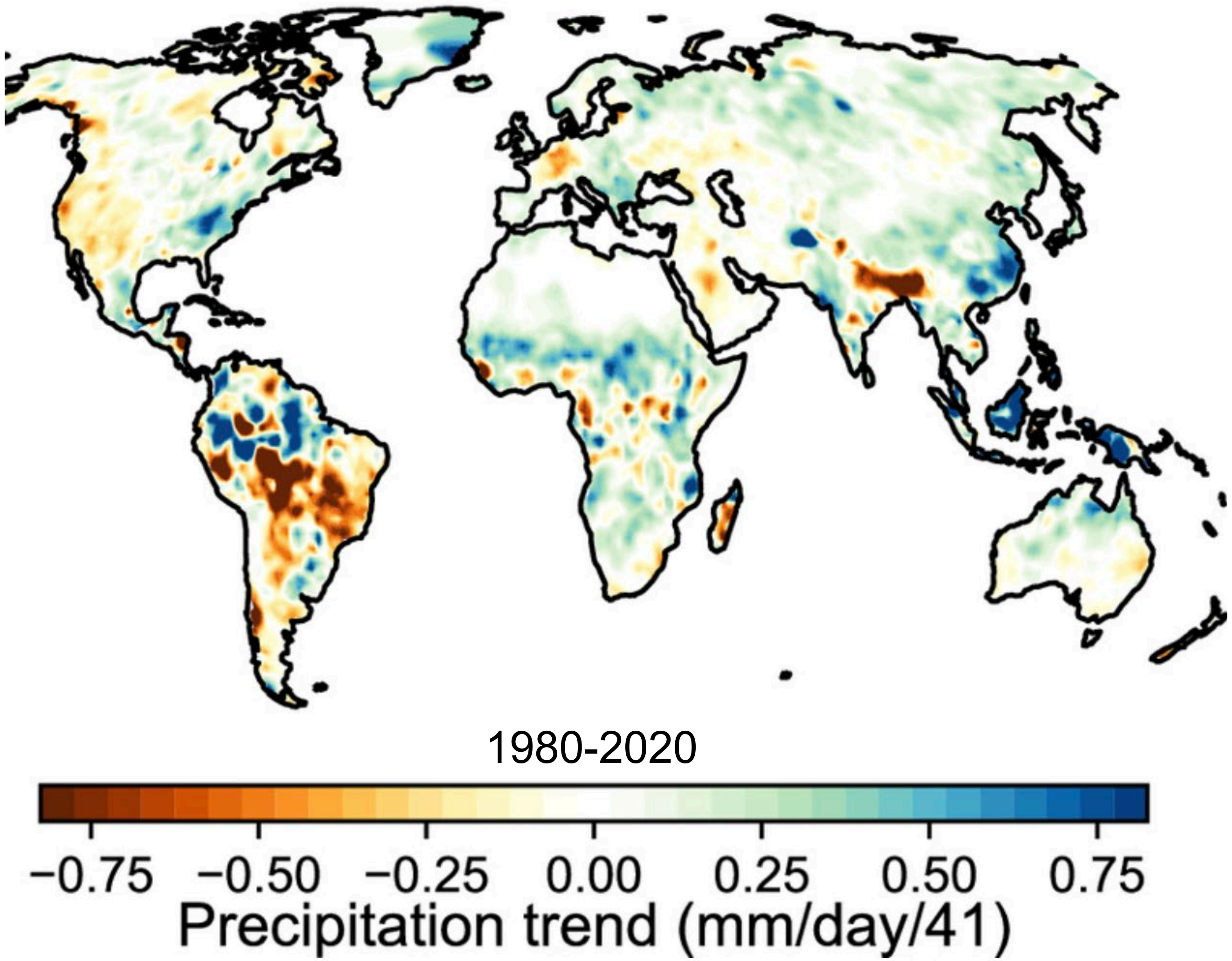
NCAR | Community Earth System Model



All *CMIP6 models disagree with observations over the last 4 decades in the southwestern US. They all predict an increase in water vapor during the NAM, and more precipitation. It didn't happen.*

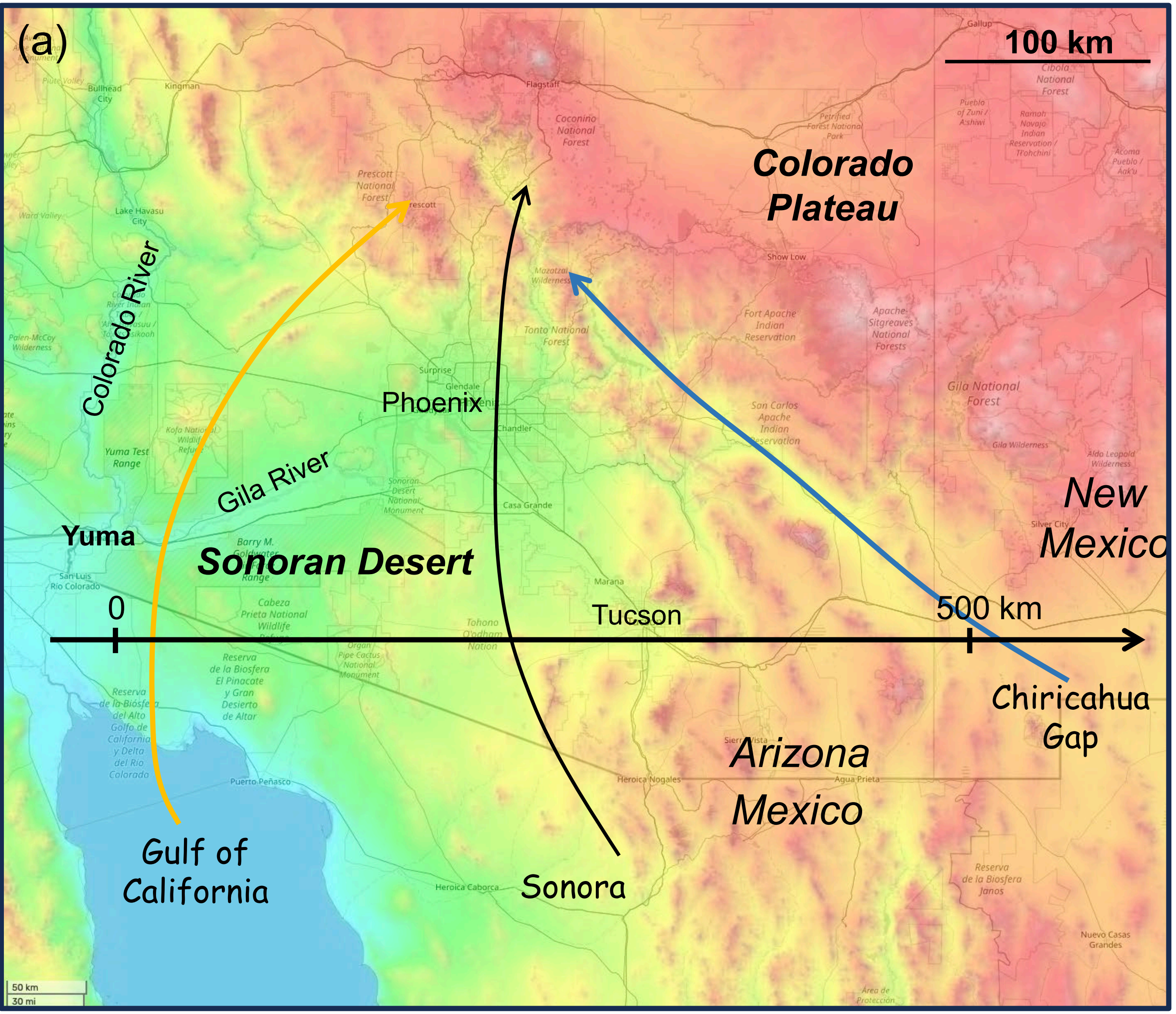


Simpson et al. (2024) https://doi.org/10.1073/pnas.2302480120

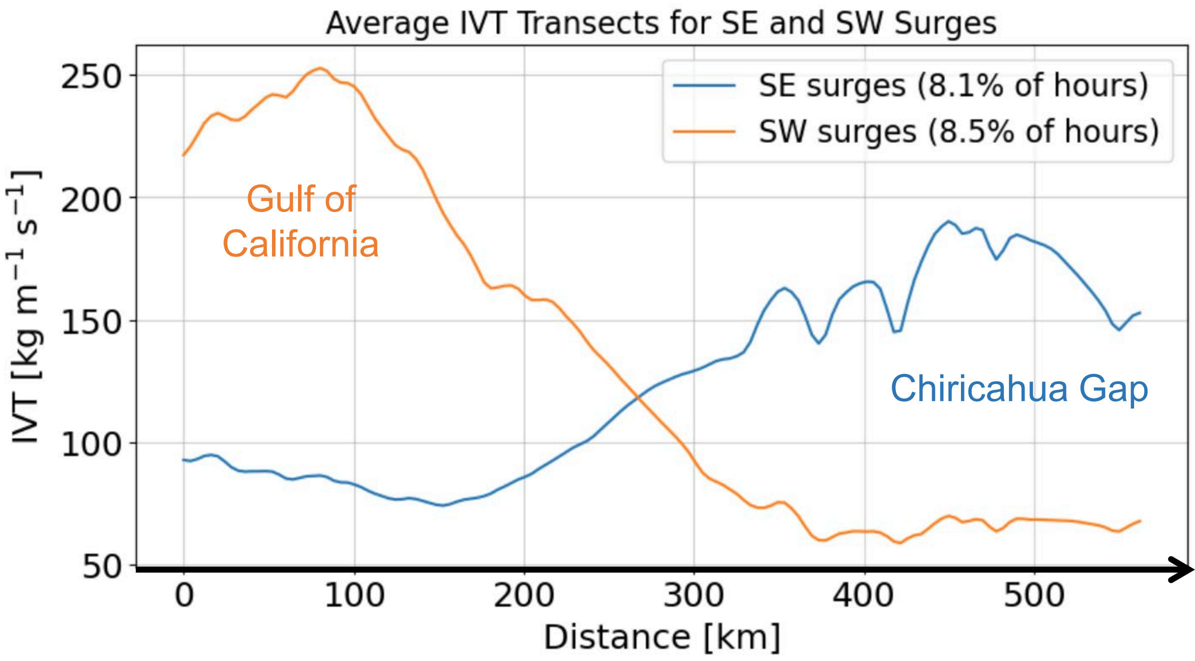


[Simpson et al. 2024]

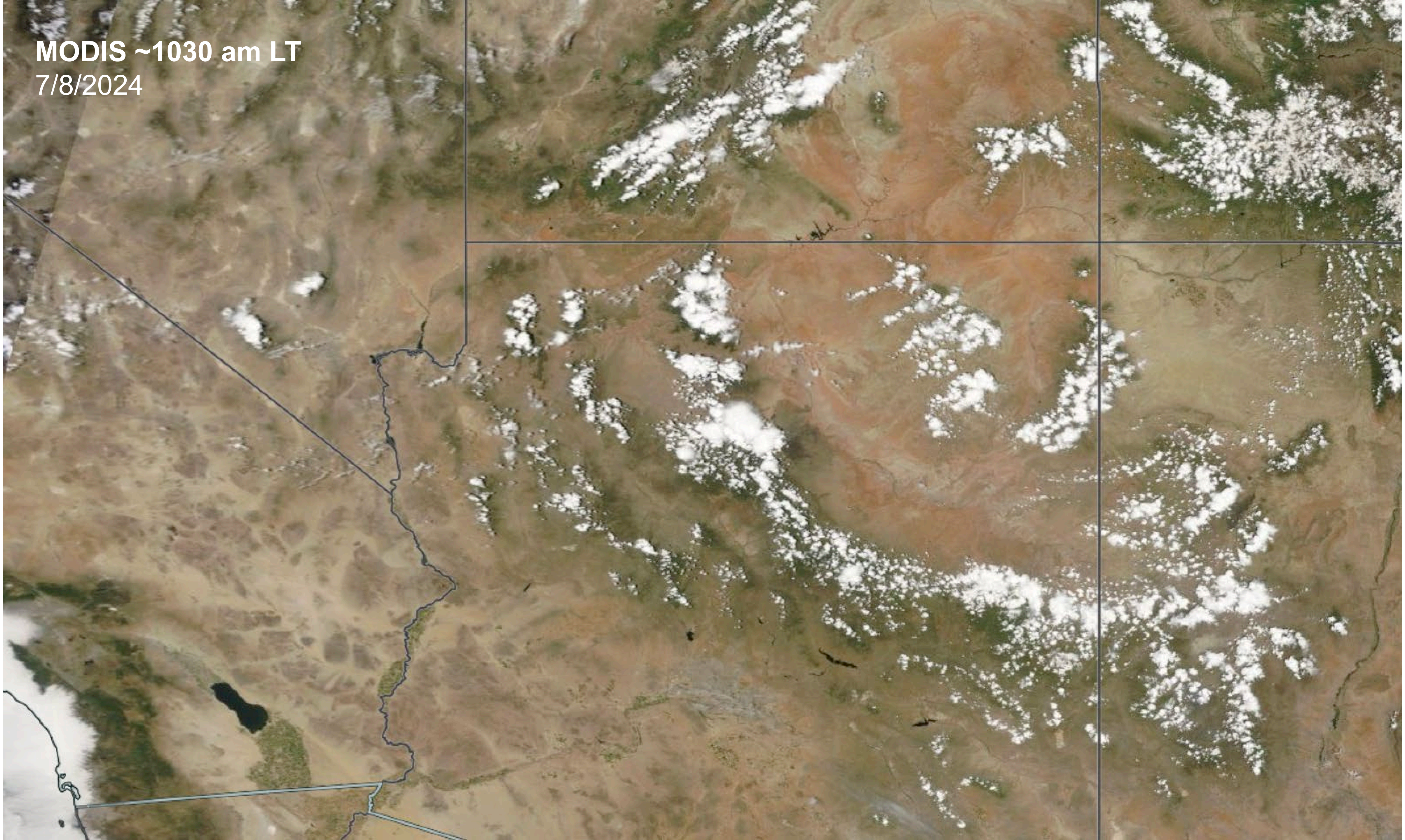
water vapor transport - moisture surges



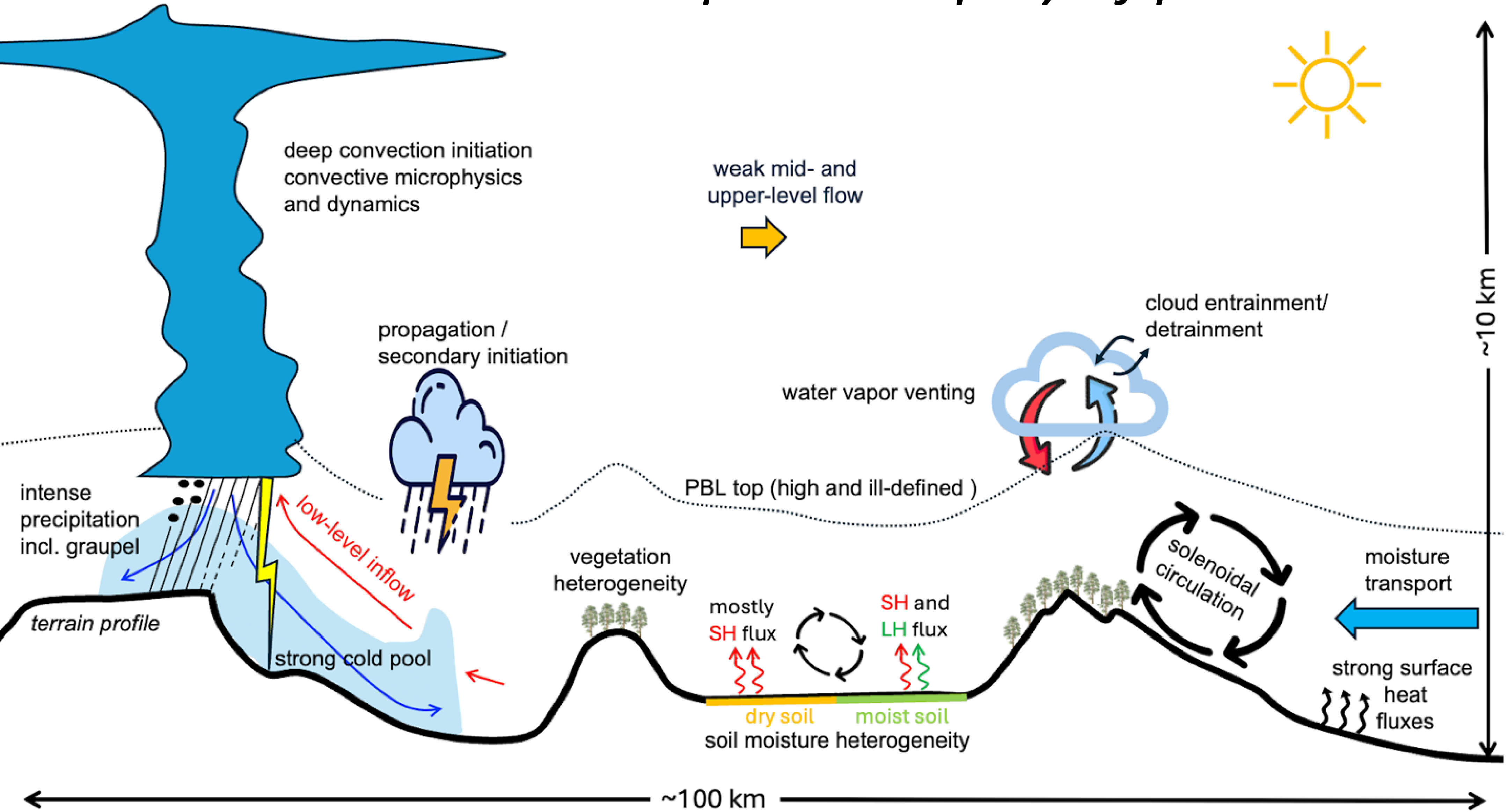
integrated vapor transport (IVT)



source: CONUS404 data JA 1980-2022

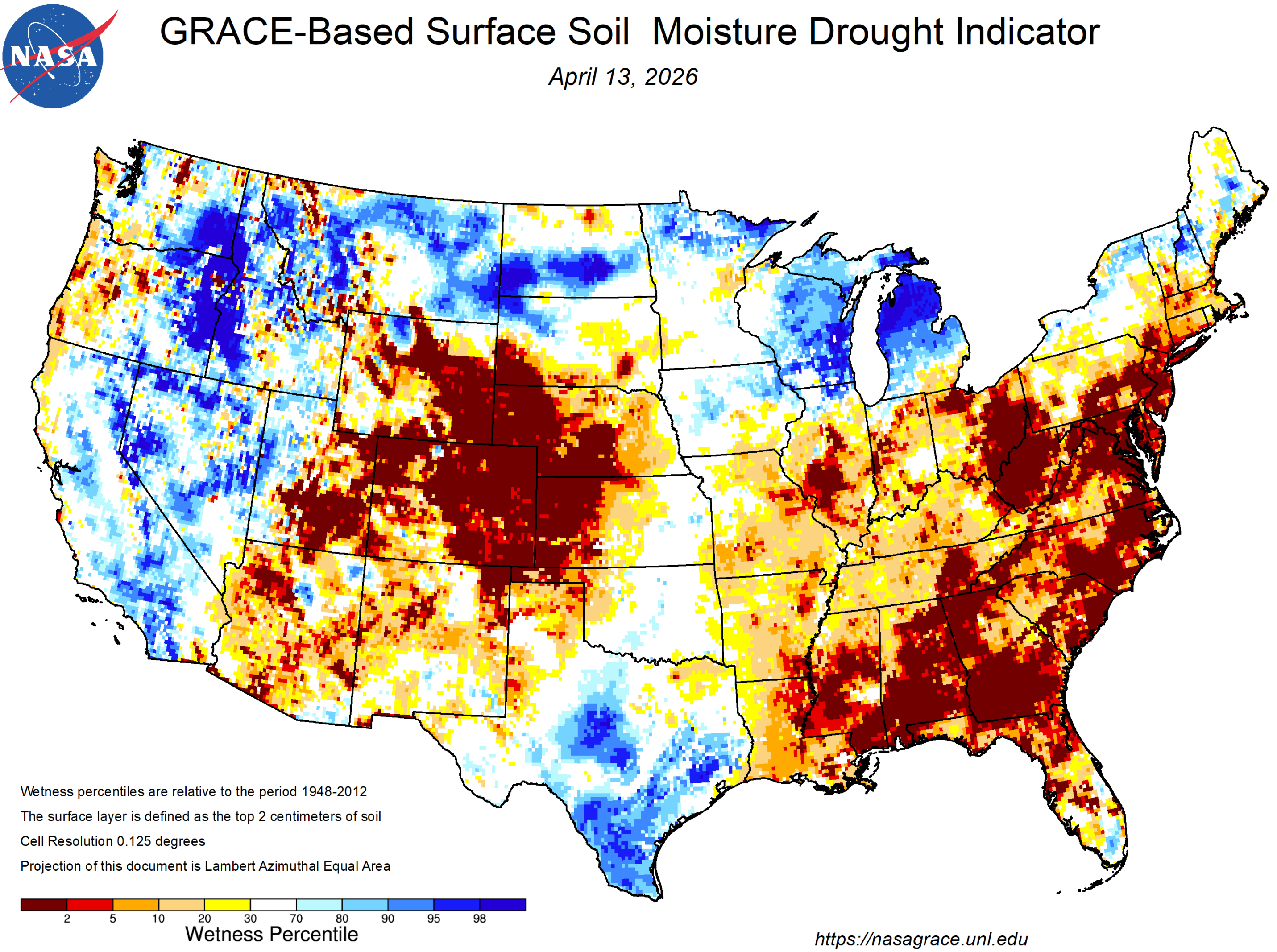

MODIS ~1030 am LT
7/8/2024

The root cause of poor predictability of the Southwest monsoon lies in a complex interplay of processes



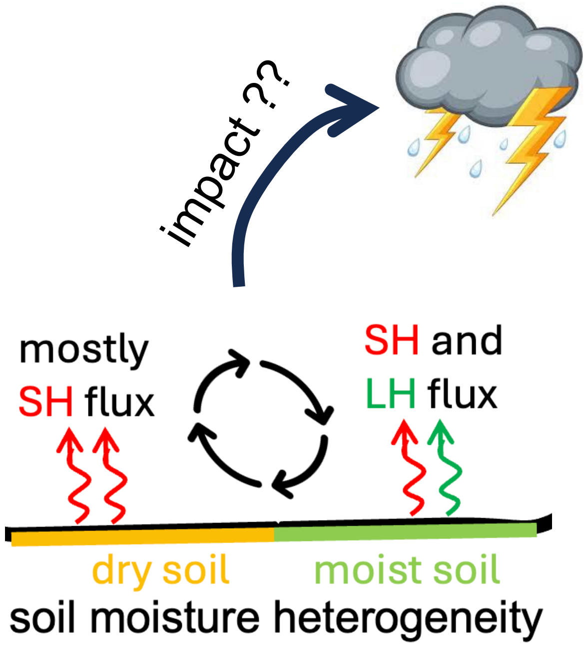
What measurements are missing yet impactful?

Soil moisture



soil moisture measurement from space
- gravitational anomalies (GRACE)
- active: L-band SAR (NISAR)
- passive microwave (SMAP / SMOS)

(accuracy is limited by sparse measurements, uncertainty of satellite measurements, and poor predictability of precip and ET)



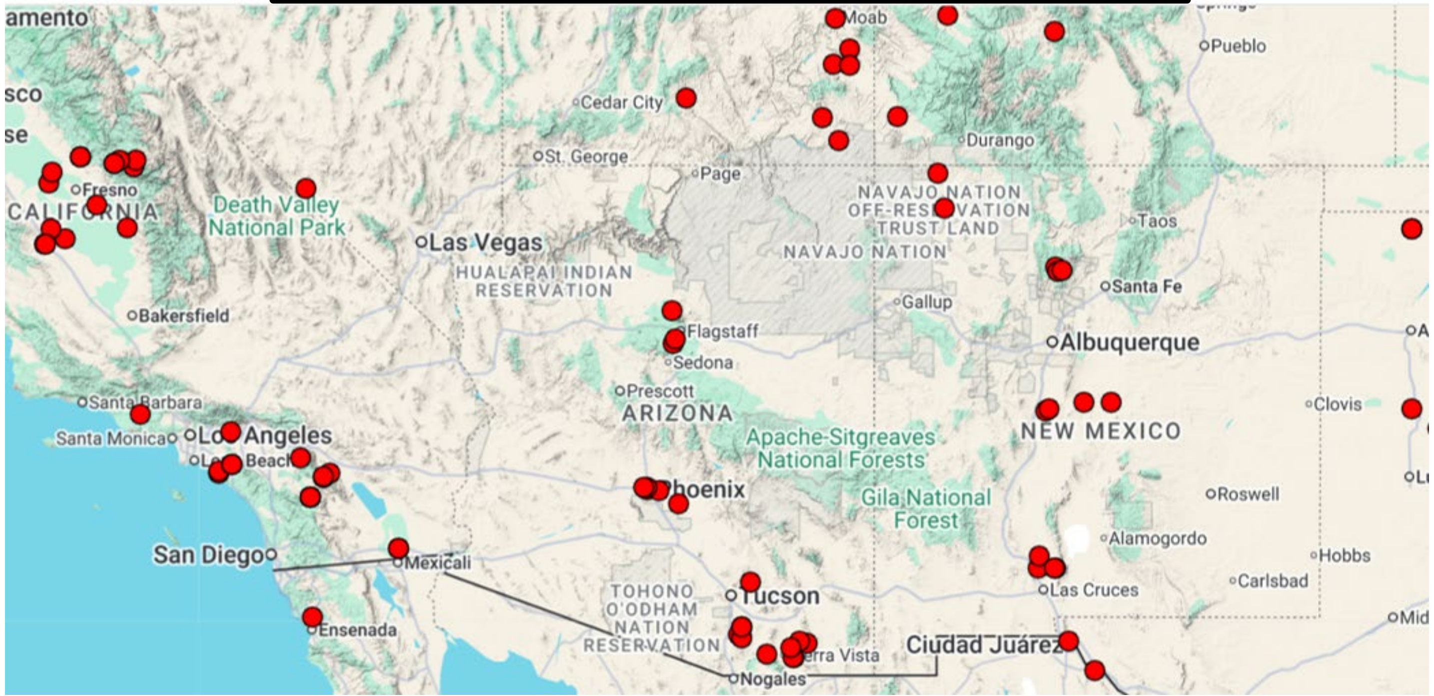
SH: sensible heat flux
LH: latent heat flux

What critical measurements are missing yet impactful?

Surface energy balance

There are only a few long-term sites (>10 years)
of ET / surface energy balance data.
Most have a short-term record.

Current Ameriflux tower network

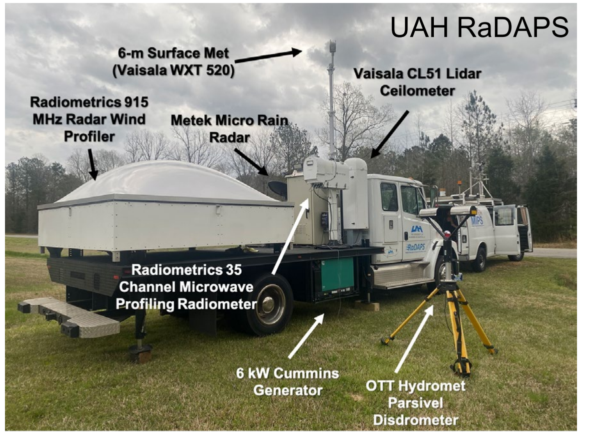


What critical measurements are missing yet impactful?

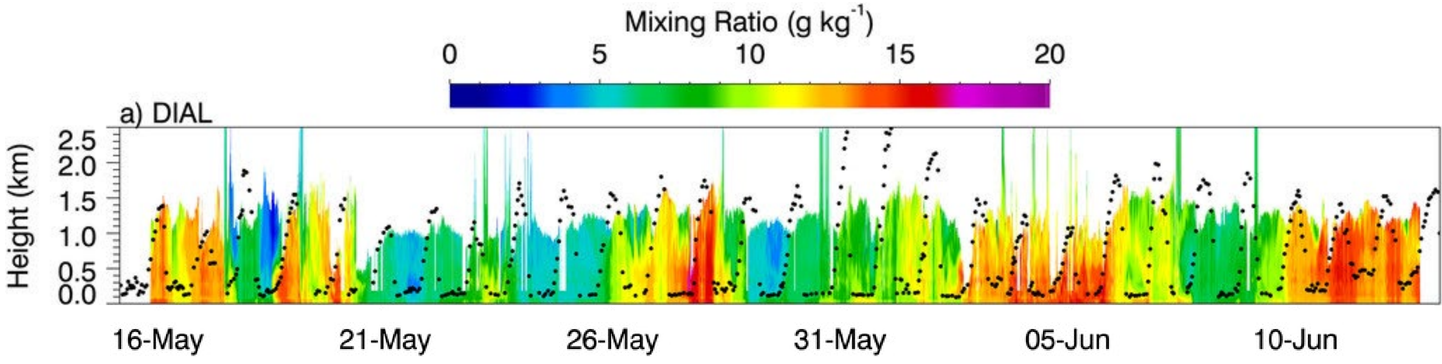
Water vapor + wind profiling

Moisture surge monitoring requires measurements of water vapor and its transport.

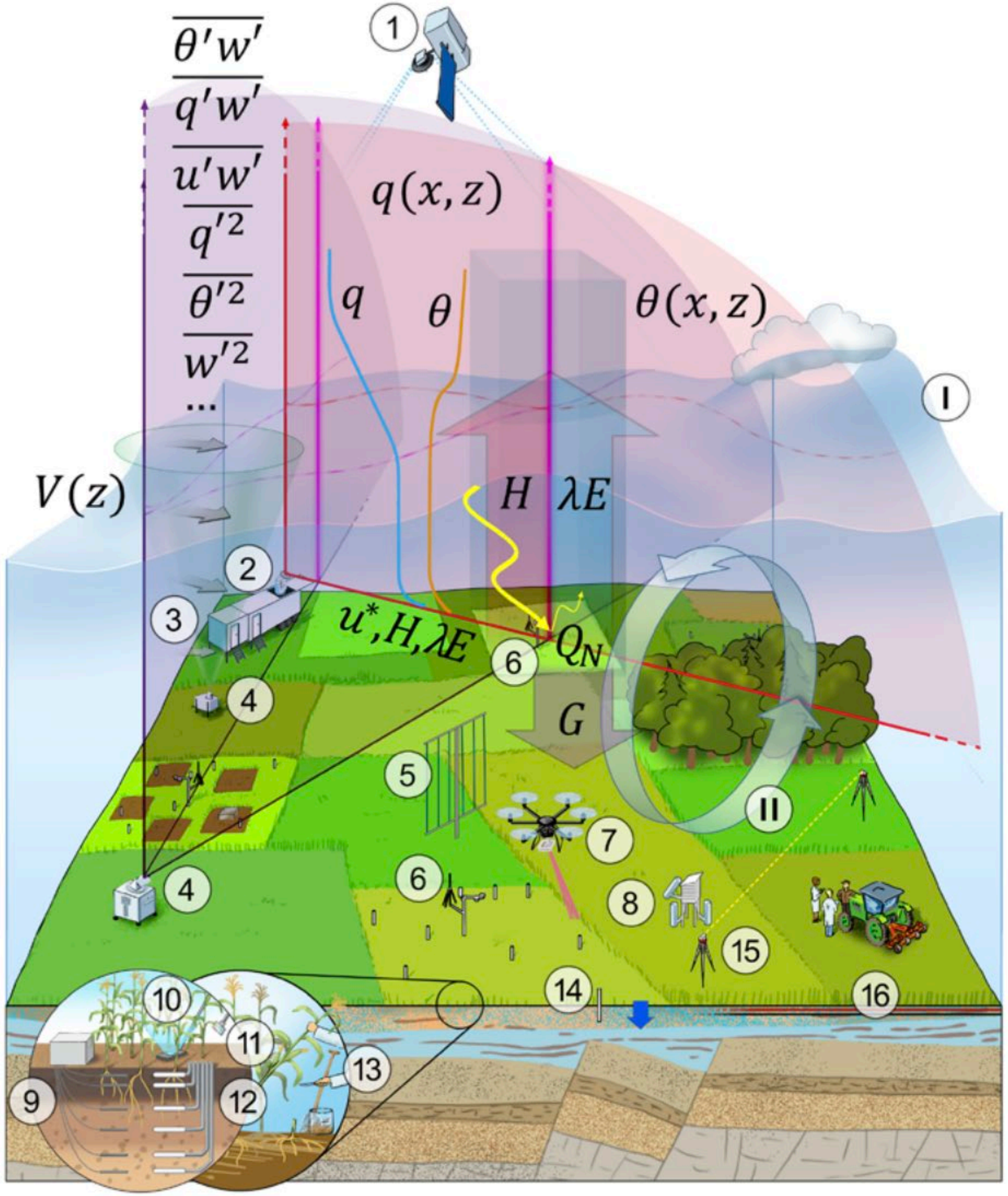
- GPS-PW
- MPD or AERI
- 915 MHz radar wind profiler (RWP)



2 months of MPD water vapor profiles (Spuler et al. 2022)



GLAFO: The GEWEX Land-Atmosphere Feedback Observatory

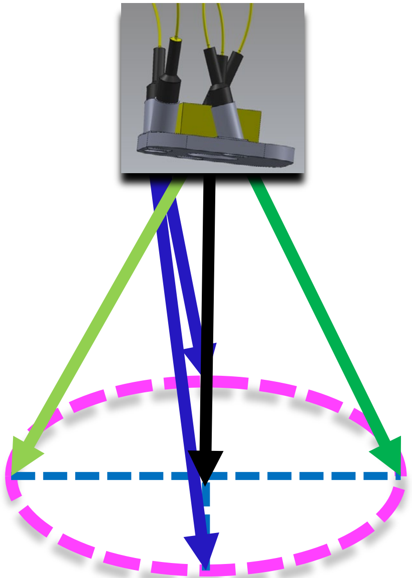


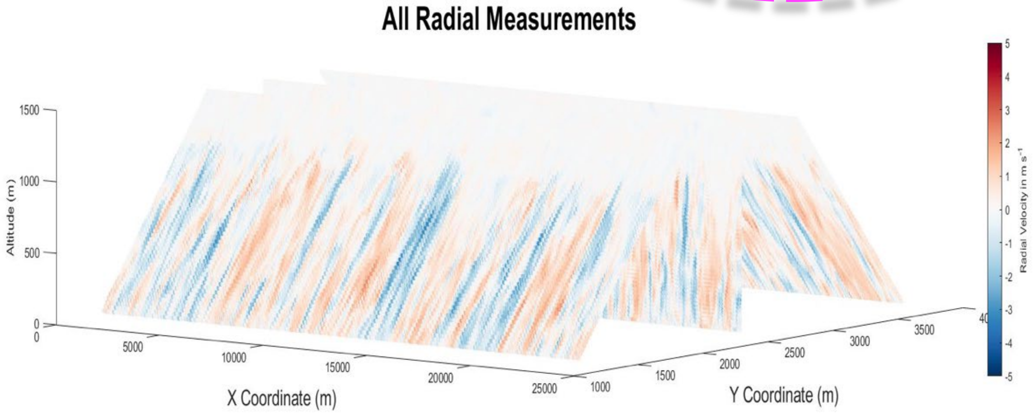
https://gewex.org
Volker Wulfmeyer

What critical measurements are missing yet impactful?

Airborne water vapor + wind profiling

Doppler lidar (3D wind profiles)

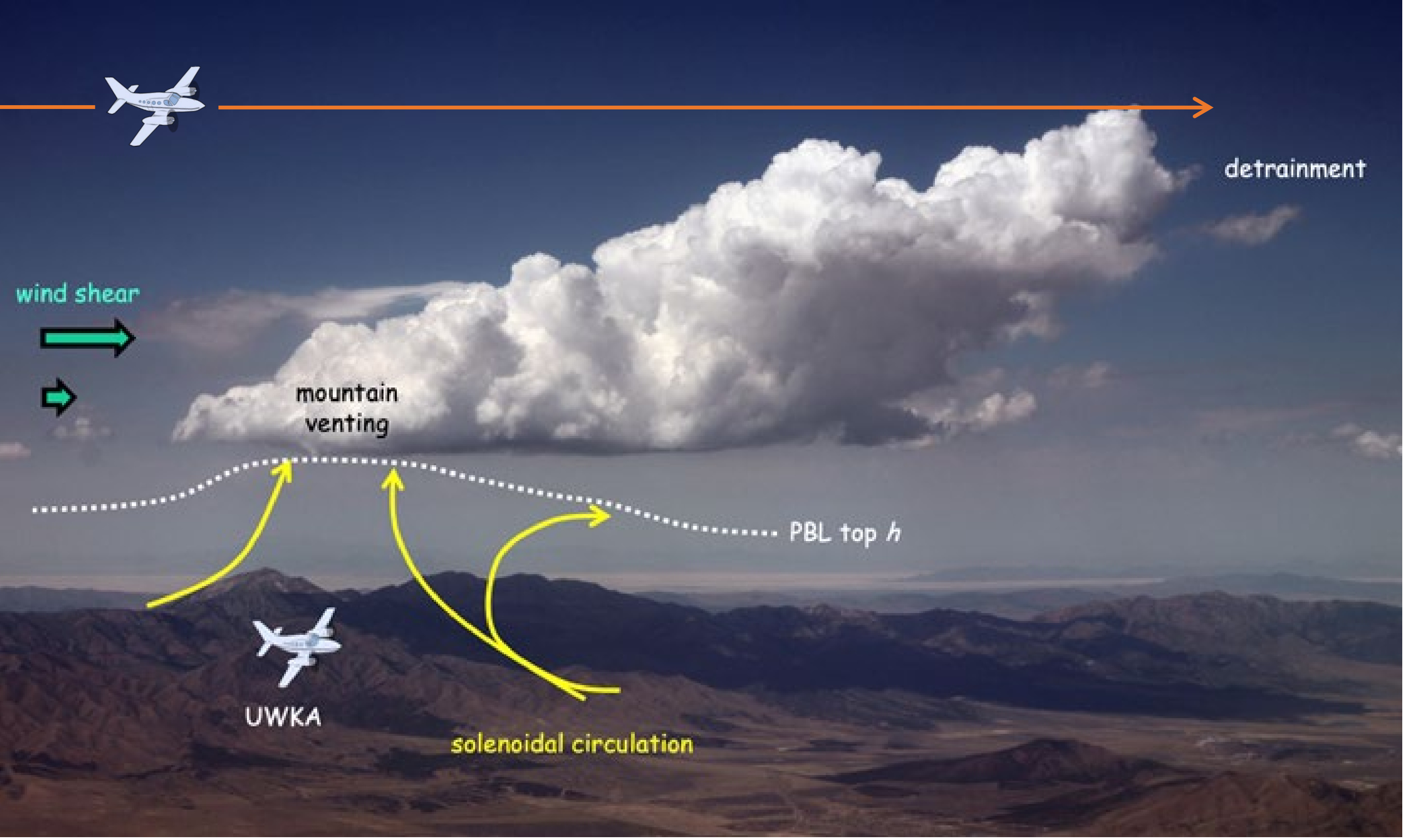




new University of Wyoming King Air

Raman lidar (water vapor)

Raman lidar water vapor estimates (Bergmaier et al. 2014)



moisture convergence:

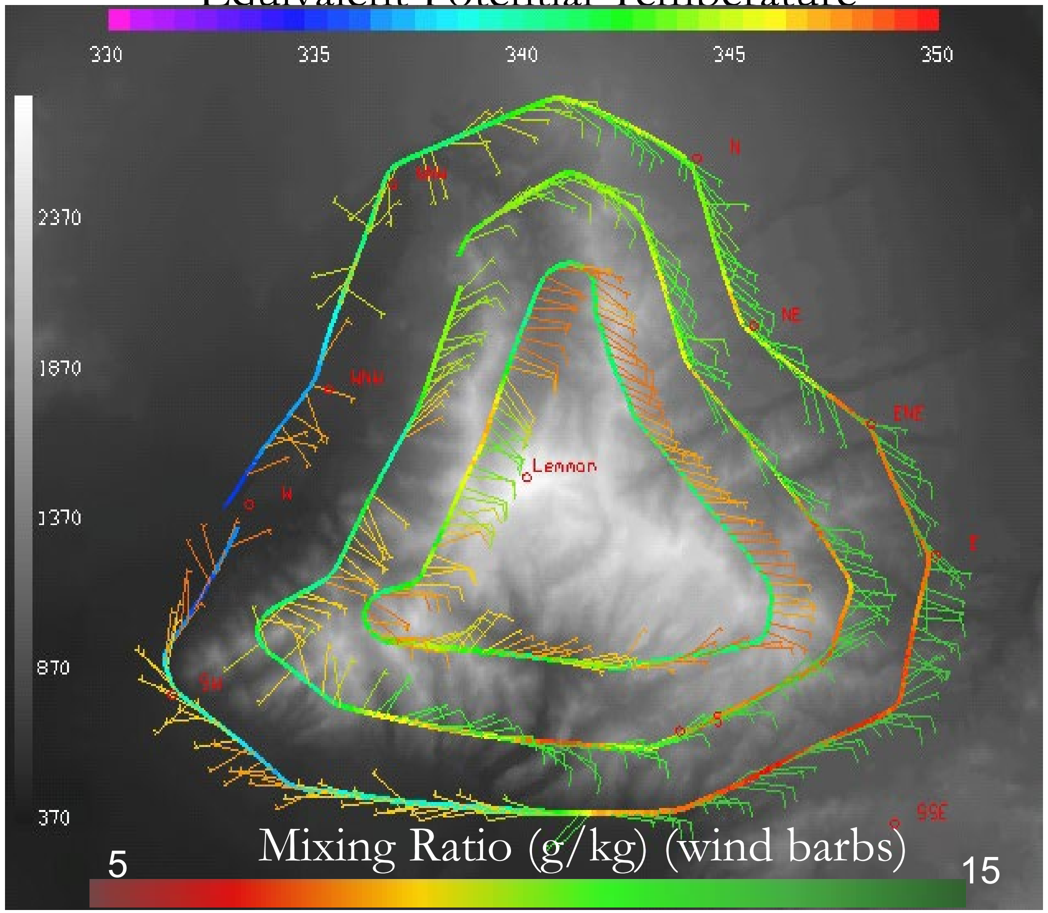
$$\oint \rho \, q \, v_n \, ds \qquad \text{kg m}^{-1}\ \text{s}^{-1}$$

specific humidity

normal wind into loop

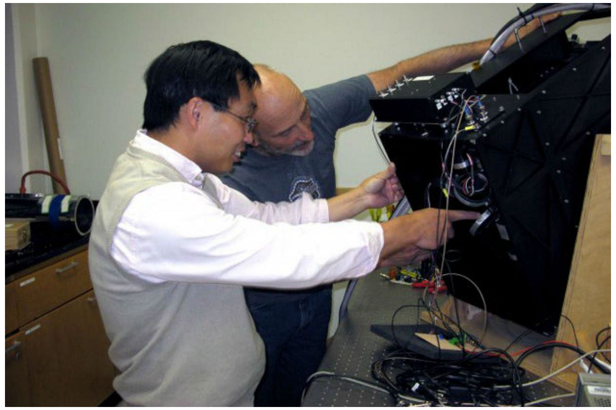
CuPIDO 8/8/2006 18:01-18:51 UTC

Equivalent Potential Temperature



ADL

MARLi

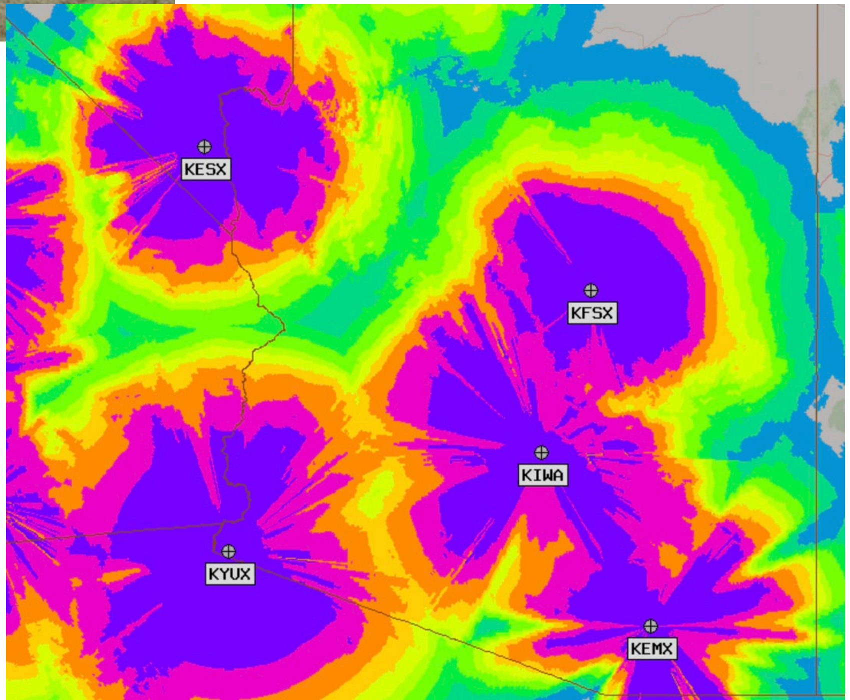


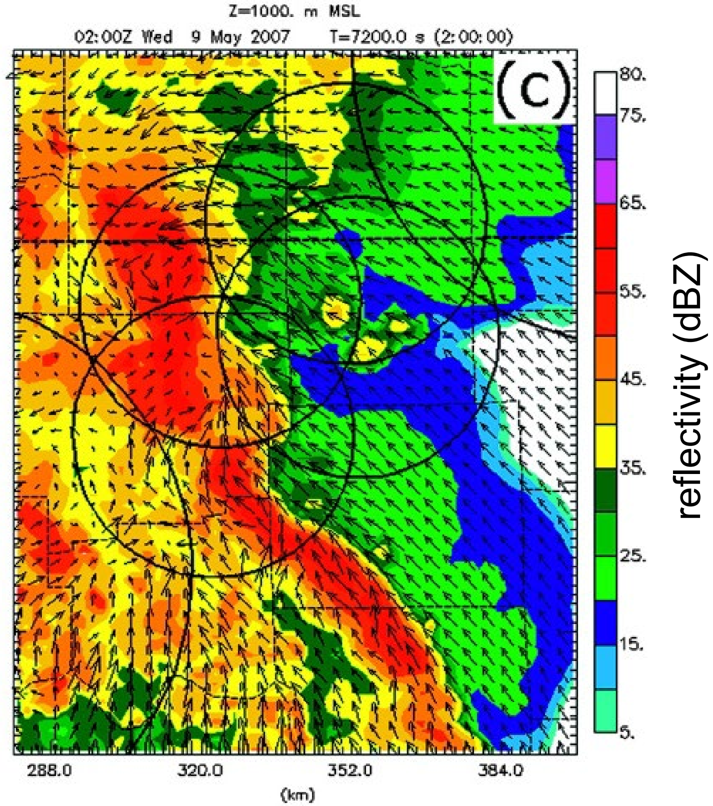
What critical measurements are missing yet impactful?

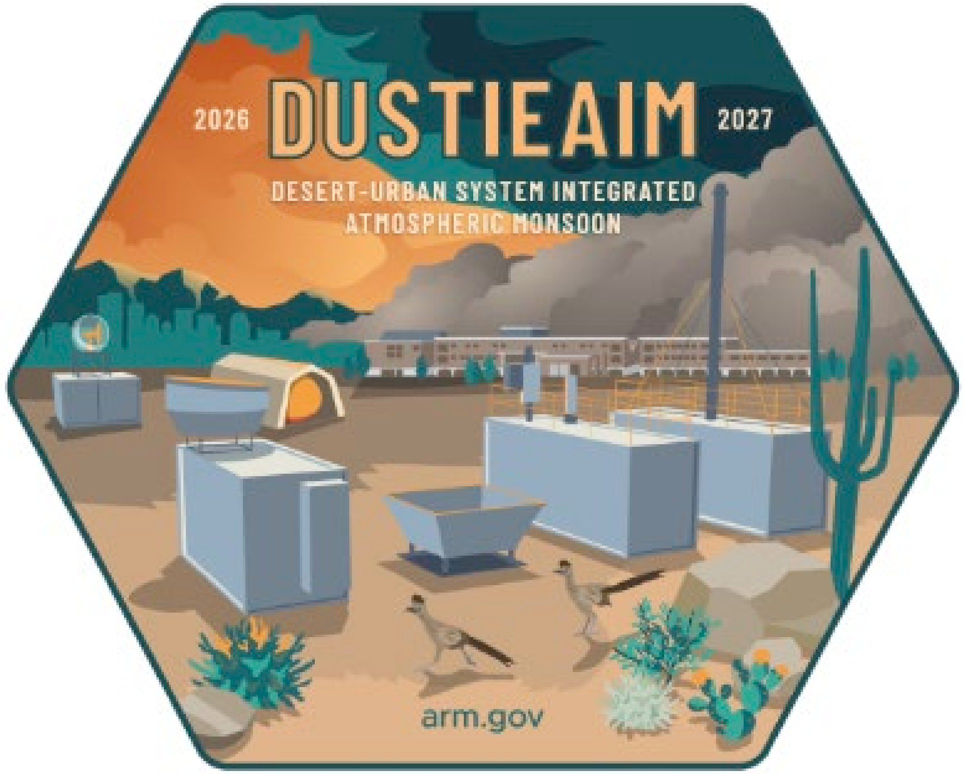
Scanning radar data

- quantitative precip estimation
- dual-Doppler synthesis
- cold pool characteristics
- dual-pol measurements (rain / graupel)

radar quality index, Arizona (https://mrms.nssl.noaa.gov/)

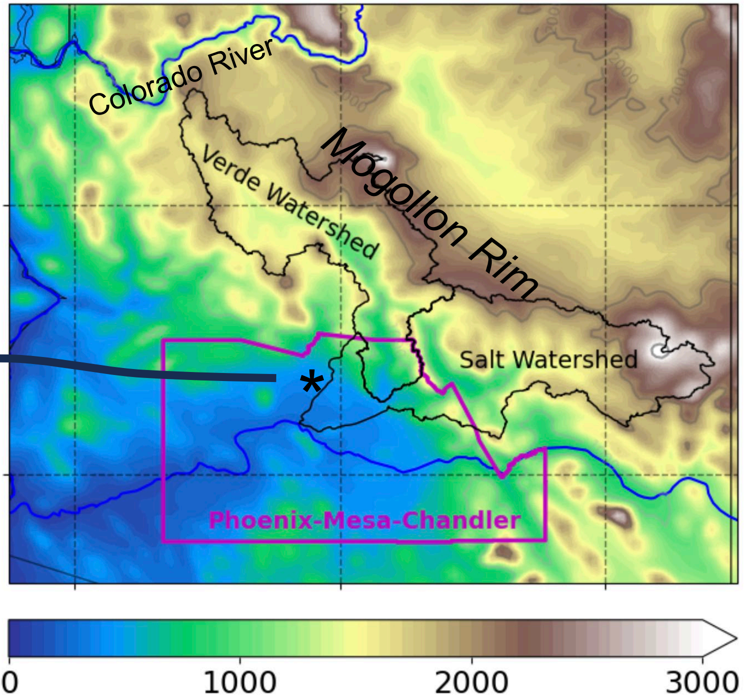




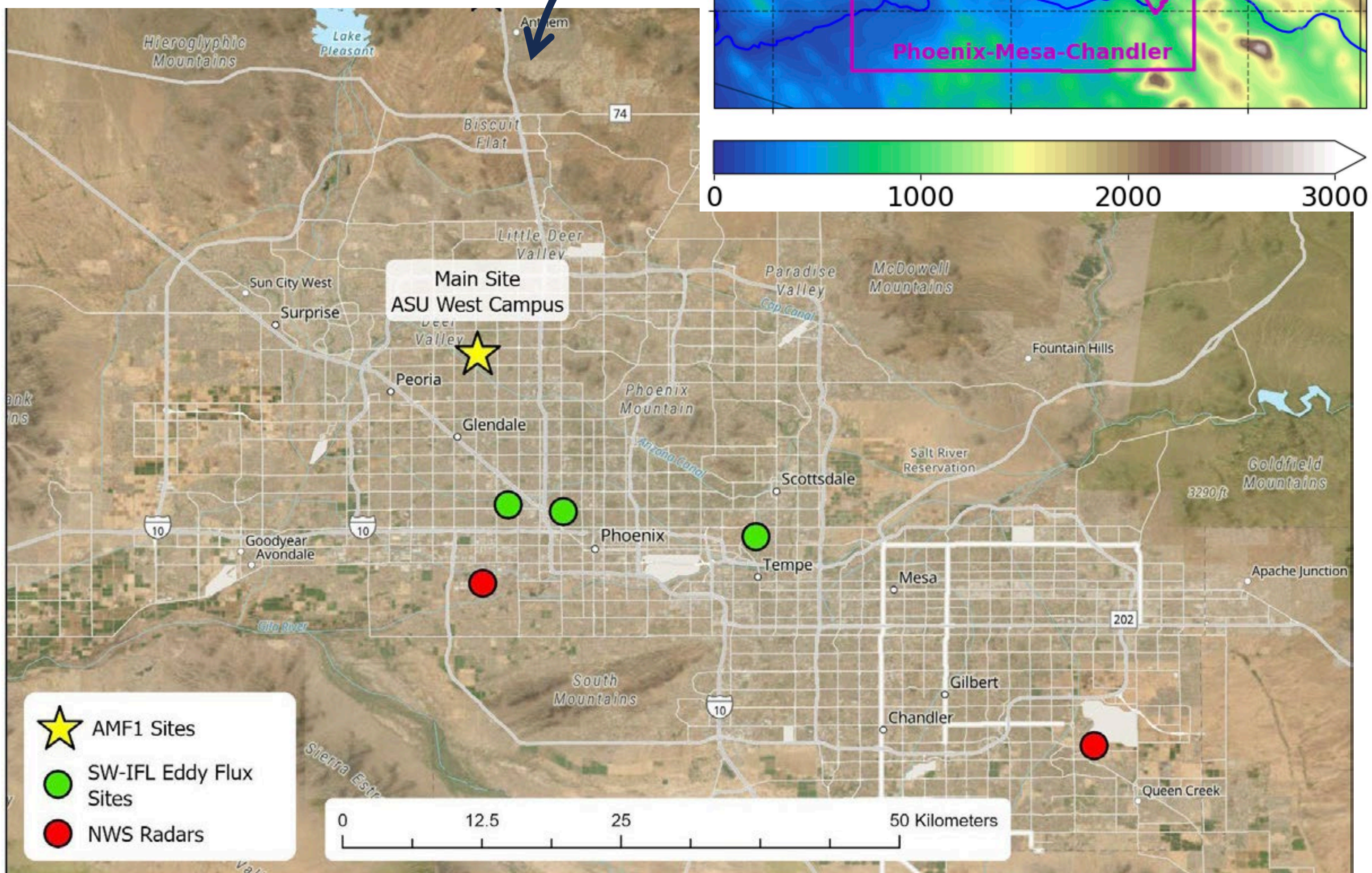


Lead: Allison Aiken, LANL
~15 June ‘26 – 30 Sept ’27
AMF1 with suite of ~50 instruments

- new scanning precip radar (C-band SAPR)
- scanning cloud radar (W-Ka-band SACR)
- water vapor profiles (DIAL and AERI)
- wind profiler (RWP)
- profiling cloud radar (KAZR)
- micropulse lidar (MPL), ceilometer
- surface energy balance (ECOR, radiation)
- soil temp and moisture profiles
- aerosol sizing, radiative properties
- aerosol chemistry, aerosol extinction profiles
- stereo-cameras



Phoenix metro



CONVECT 2027

CONvection and water Vapor Exchange in Complex Terrain

<u>Science Steering Committee</u>

Curtis James, lead PI

Steve Koch

Angela Rowe

Adriana Bailey

Jason Knievel

Stephan de Wekker

Mike Biggerstaff

Bart Geerts

<u>Collaborating institutions</u>

Embry-Riddle Aeronautical University

U. Arizona

U. Wisconsin

U. Michigan

NCAR

U. Virginia

U. Oklahoma

U. Wyoming

NSF AGS FIRP Track 3 Complex proposal
field campaign 5 June – 2 Sept 2027

© Curtis James, 2021

CONVECT aims to improve fundamental understanding of the roles of
water vapor transport,
land-atmosphere interaction,
PBL processes, and
convective feedbacks
on warm-season precipitation in a semi-arid environment.

CONVECT is about atmospheric and land surface *processes* whose linkages are poorly understood and parameterized.

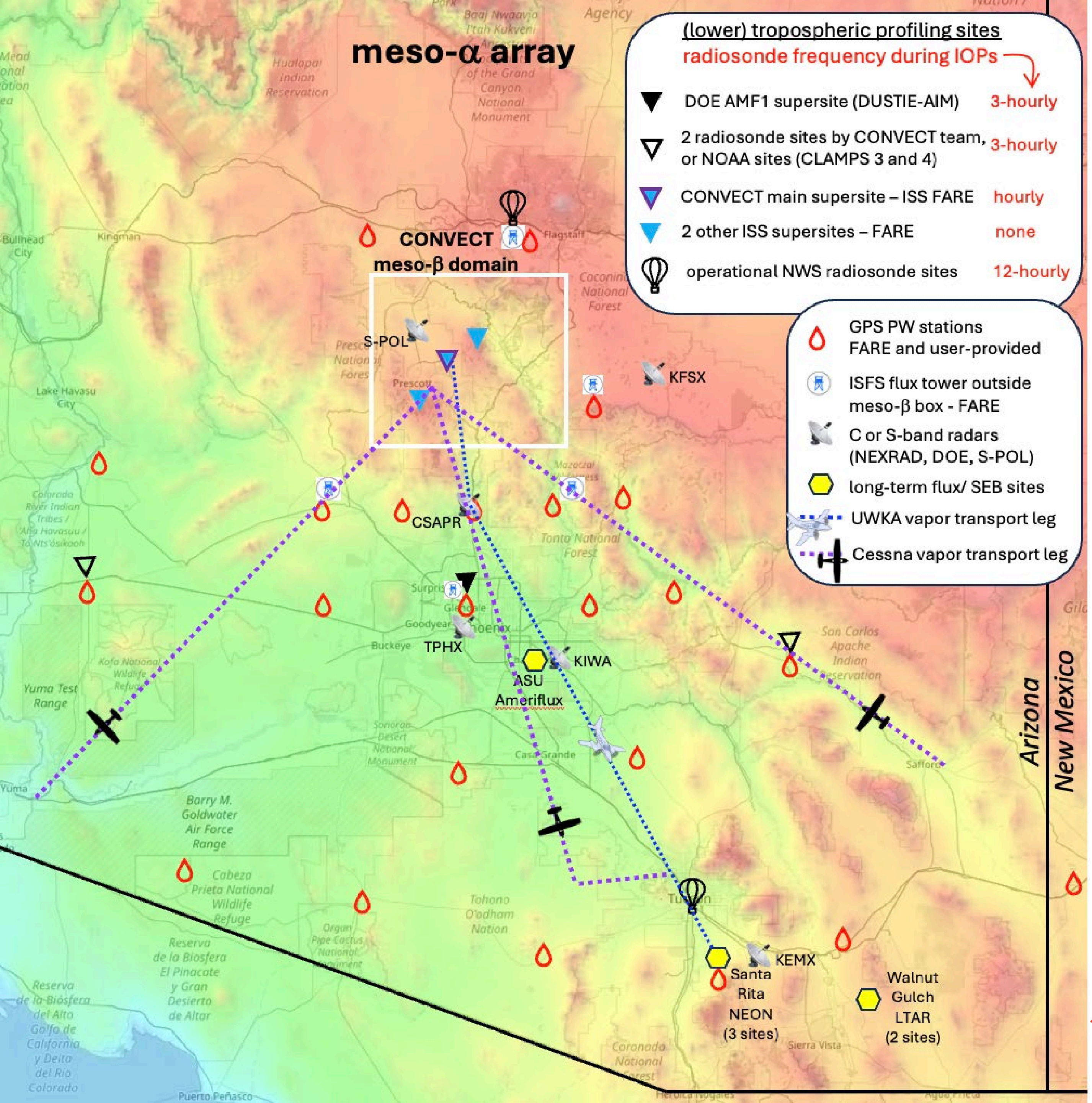
Field campaign modeling and data assimilation to improve understanding & predictability

- CONVECT will serve as a testbed for the evaluation & improvement of **land surface models**. (NCAR RAL)

- CONVECT will use state-of-the-art coupled atmosphere-land modeling that will use an **observationally-constrained, high-resolution 4DDC representation** to understand soil moisture-convection feedbacks and monsoon precipitation predictability. (NCAR RAL)

- CONVECT will be used to evaluate a new **operational convection-permitting model** (RRFS) (NOAA)

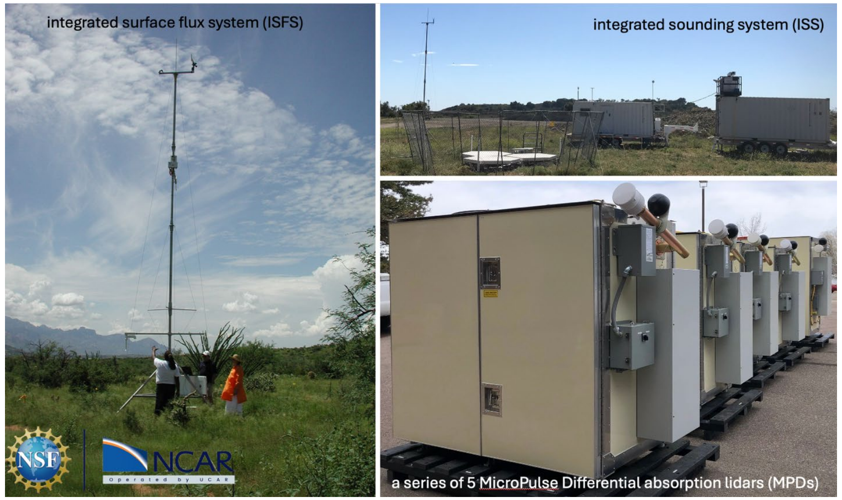
- CONVECT data will be used to evaluate CESM/ CLM to examine **S2S predictability** (NCAR CDG)



Synergies with other agencies

- **NASA Earth Science**
  - PBL DS incubation with airborne DIAL and hyperspectral microwave for temperature/humidity profiling
  - NASA ARID (Terrestrial Ecology) with SEB probes and airborne soil moisture
- **NOAA GSL**
  - CLAMPS #3 and #4
  - performance of NOAA's new CPM (RRFS)

CONVECT as a demonstration testbed for an operational Mesonet

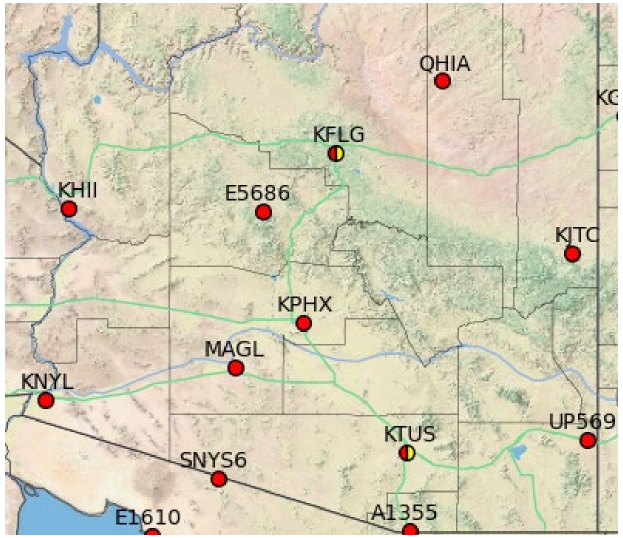


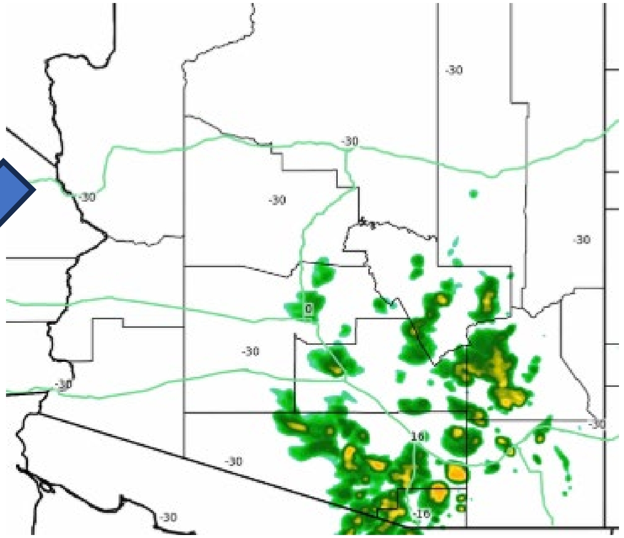
distributed network of critical observations

data assimilation

DERECHO
NSF NCAR Supercomputer

coupled land-atmosphere
numerical weather prediction model





more informed
decision making

Southwestern US Weather and Water Resilience across Timescales

a UCAR PACUR-funded workshop

https://water-climate.engin.umich.edu/sw/

18-19 November 2026
AZ Institute for Resilience, University of Arizona

Who?
Utility companies, water managers
field campaign planners
modelers – LES to S2S

Topics:
Stakeholder needs
weather and water predictability across timescales
cool season: snowpack, ARs, and groundwater recharge
hot season: wildfires and convective downbursts, droughts and flashfloods

Take-aways

- The roles of water vapor transport, land-atmosphere interaction, PBL processes, and convective feedbacks on warm-season precipitation in **semi-arid environments** are poorly understood, due to an historical lack of suitable measurements.

- This limits **predictability of hazardous weather and long-term sustainability of water resources**.

- There is a **need for integrated measurements** serving as a testbed for model evaluation and an operational mesonet.