A Tour of SAIL Science Accomplishments and a Preview of Ongoing and Upcoming SAIL Research

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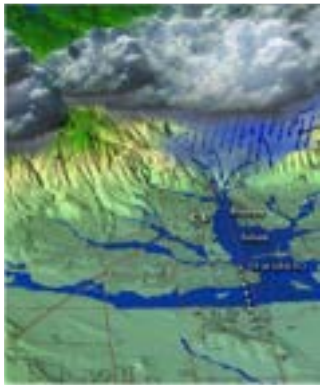
With contributions from many, many others



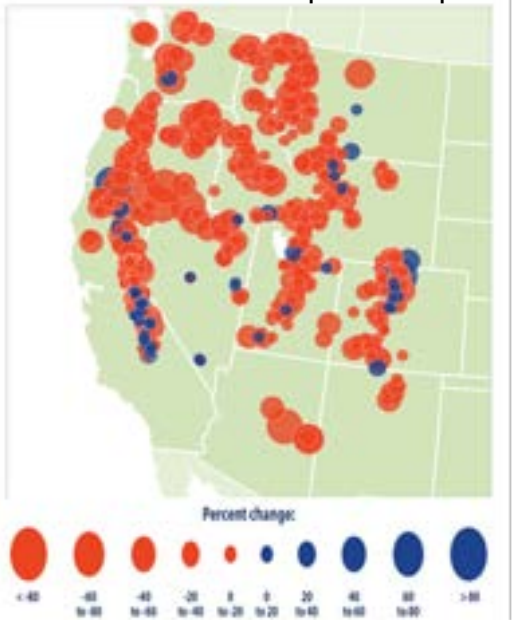
This work was supported by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research and the Atmospheric System Research under U.S. Department of Energy Contract No. DE-AC02-05CH11231.

Outline

- ❑ The changing face of water in the West to motivate SAIL
- ❑ What SAIL measured
- ❑ What we have learned from the SAIL data so far
- ❑ Summary and next steps

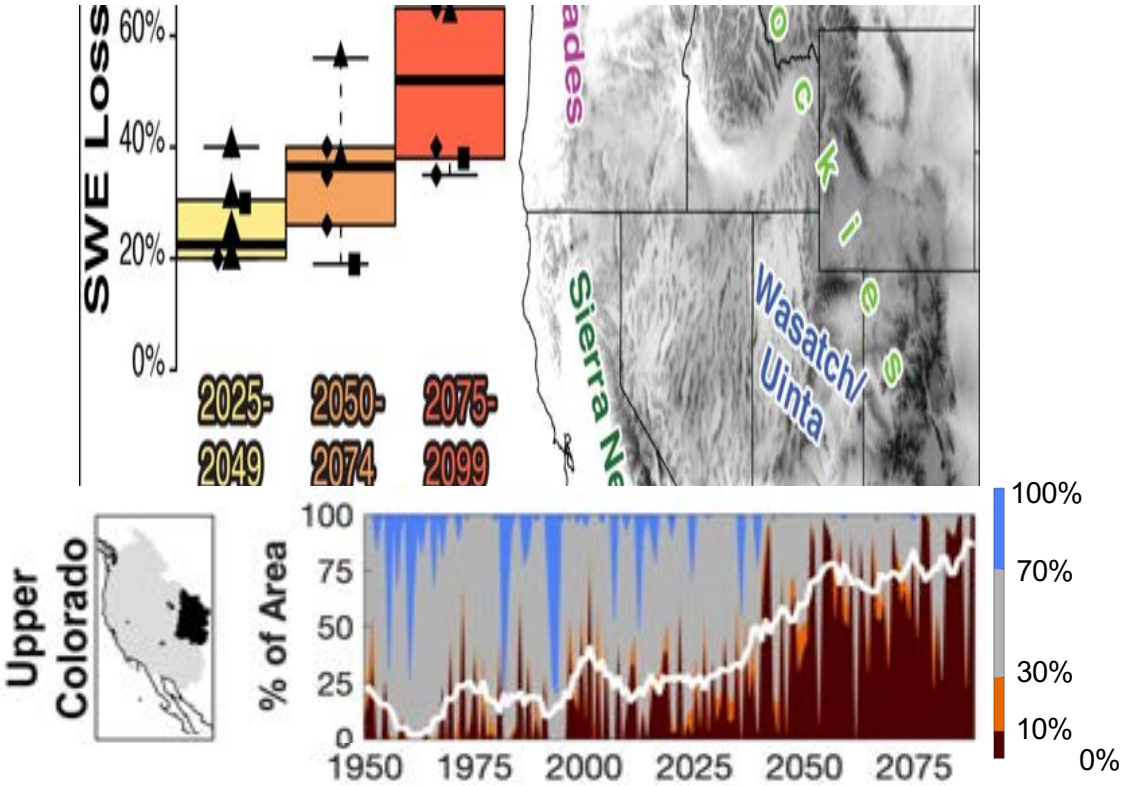
The Colorado River Watershed is changing

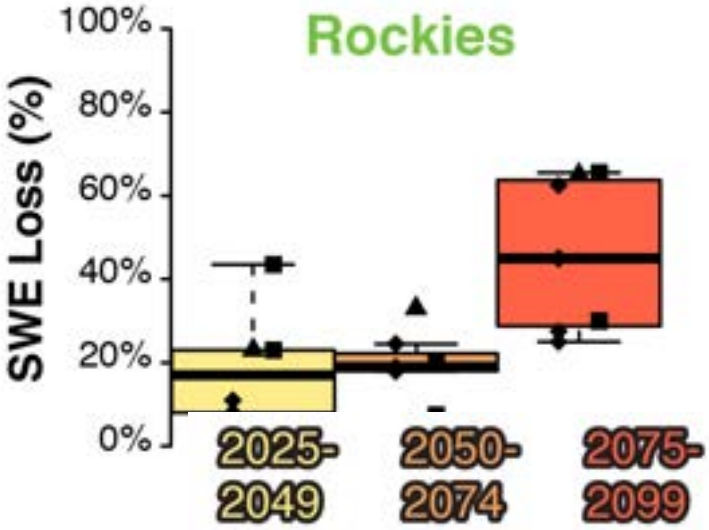
1955-2016 trends in April Snowpack



Mote and Sharp, 2016

Projections of the water availability in the West





This is a big range!

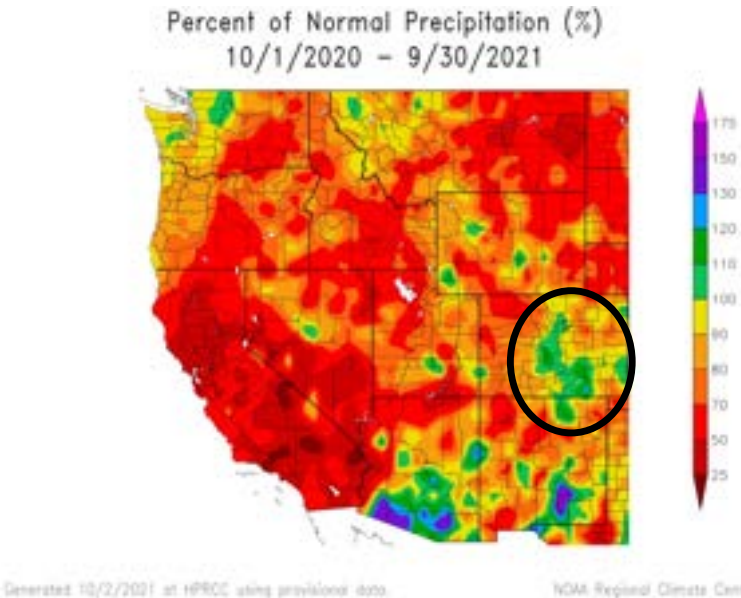
Siirila-Woodburn et al, Nature Reviews, 2021

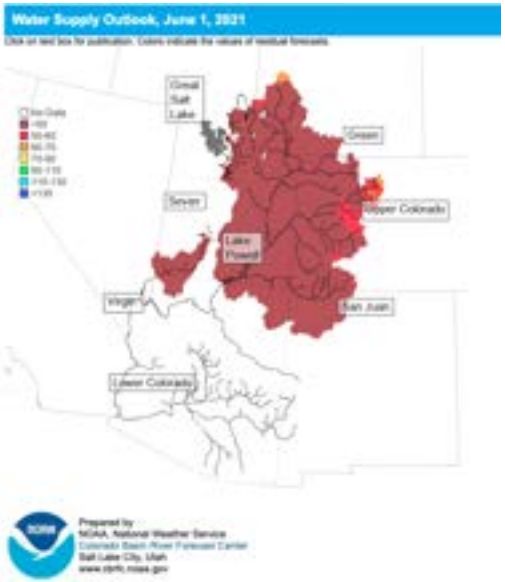
The Mystery of the Missing Water

The 2021 Drought Emergency was a wake-up call, not just for water management, but for the science too.

The emergency occurred in a year of slightly-below-normal precipitation, with potential to directly impact hydropower generation.

Where did that water go?!?!





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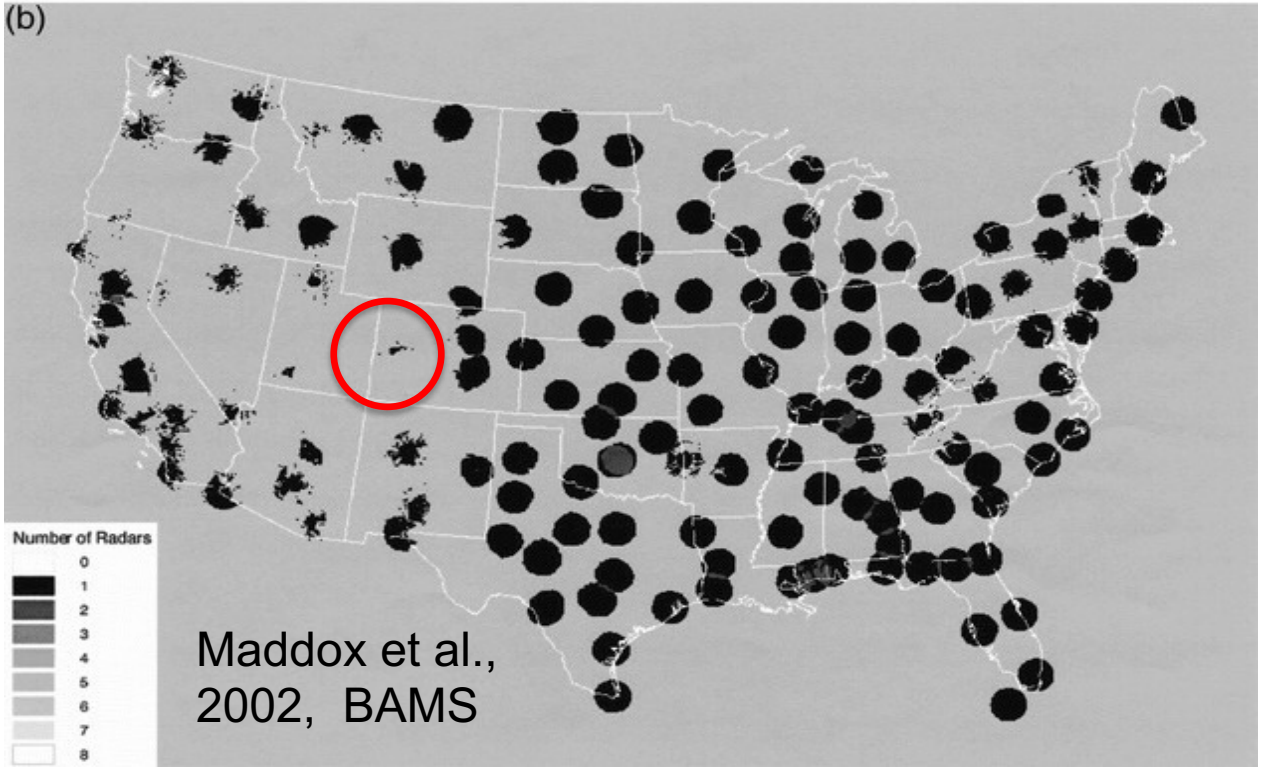
Let’s Go Where the Water Is …

But That's Not Always so Easy …



But That's Not Always so Easy …

Photo Credit: billy barr (2021)

But That's Not Always so Easy …

Photo Credit: Ryan Currier (2021)

SAIL Science Objectives

The Surface Atmosphere Integrated Field Laboratory (SAIL) Campaign deployed the AMF2 near Crested Butte, Colorado from 9/21 to 6/23 to study atmosphere-hydrology connections including:

1. Precipitation: how and how much.
2. Winds: sublimation and snow redistribution.
3. Aerosols: surface and atmosphere radiative impacts
4. Aerosols: interactions with precipitation.
5. Surface fluxes: controls on the surface energy and mass balance.

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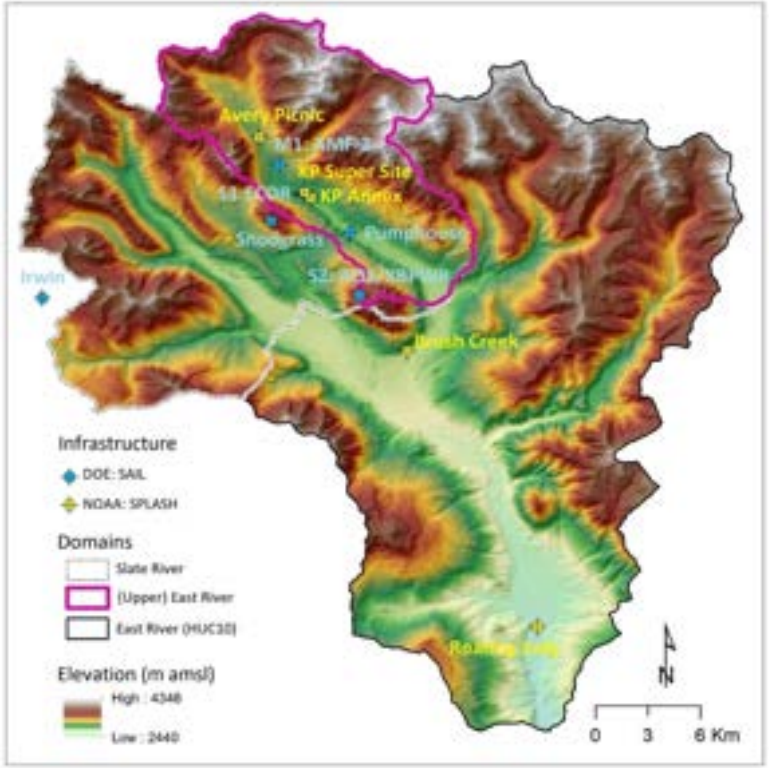

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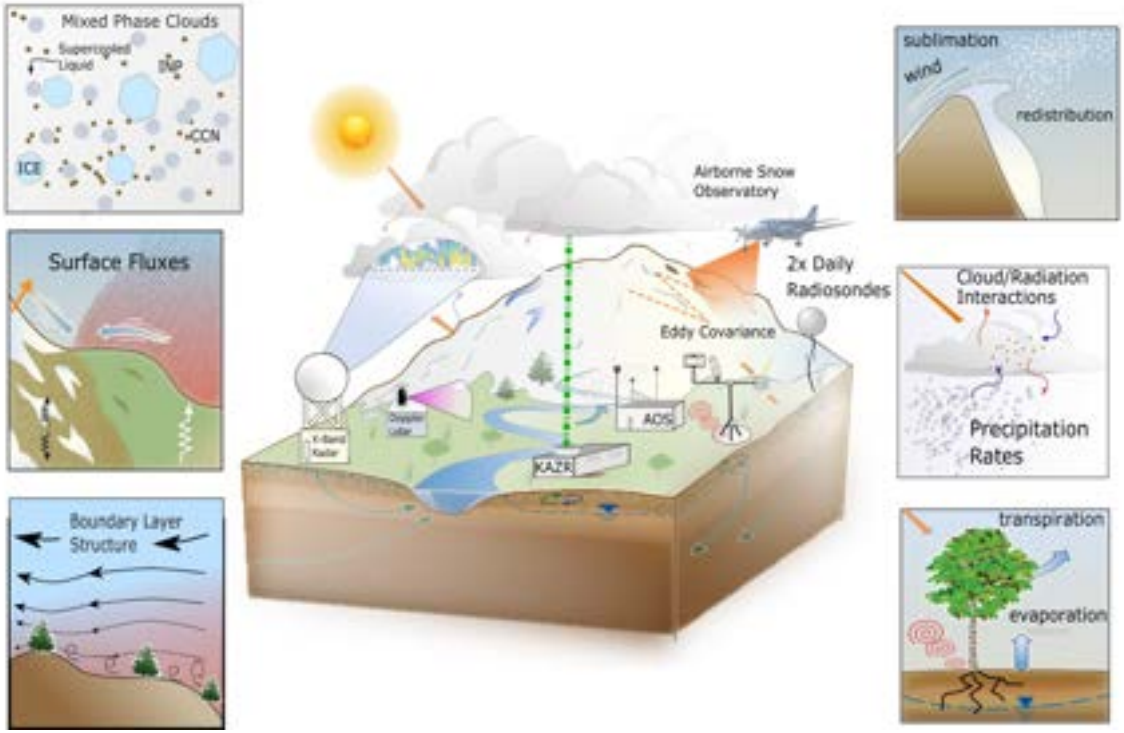


Precipitation, Clouds, Winds, Aerosols, Radiation, Temperature, Humidity …

- Numerous datastreams collected.
- https://sail.lbl.gov/what-we-measure



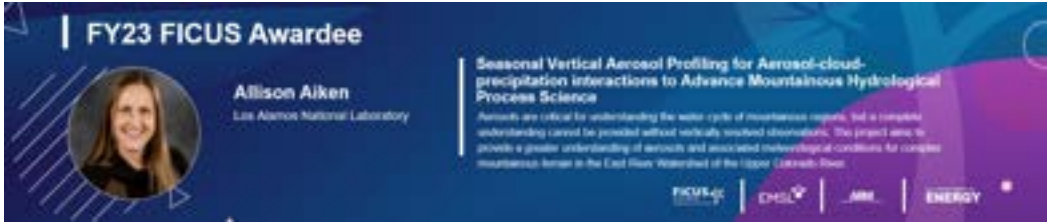




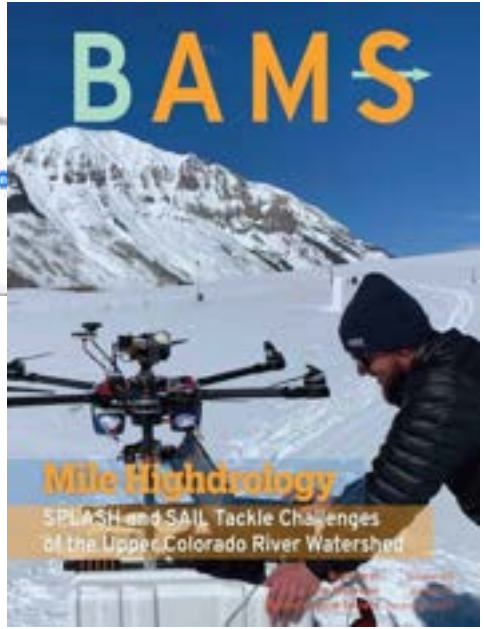
Images courtesy of ARM Flickr Account

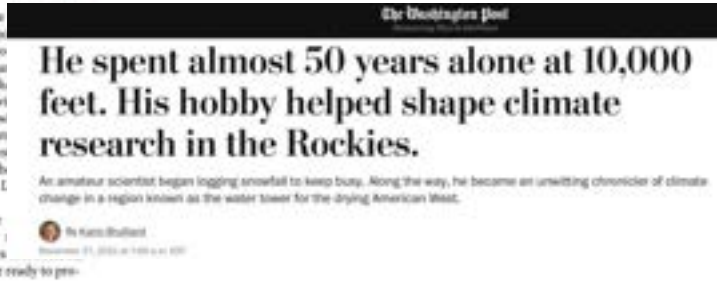
And Even More with TBS and Guest Instruments

- Seven separate TBS deployments across seasons.
- A dozen guest instruments supported.



SAIL in the news!





SAIL Team: It takes a (large) village

- The science team covers 4 National Labs, 10 universities, and 2 research centers.
- Supported by ARM Program: operations team led by LANL, significant support across Nat'l Labs
- Much larger extended community of researchers across multiple disciplines.

A Snowball Effect

- SAIL began with a close partnership with ESS's Watershed Function SFA.
- It grew to include NOAA Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology (SPLASH) and NSF Sublimation of Snow (SOS)

SAIL/SPLASH/SOS (S^3) Science Summits

CU-Boulder, November 1-3, 2023

LBNL, November 1-3, 2023

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S^3 2025: High-Water Mark for UCRB Analysis

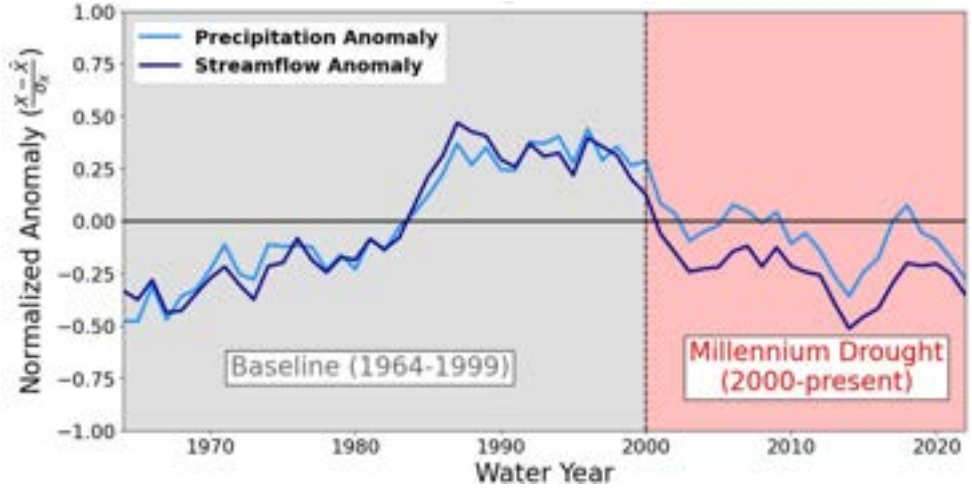
- Lots of SAIL data! https://adc.arm.gov//discovery/#/results/site_code::guc
- Lots of SPLASH data! https://zenodo.org/communities/splash/records?q=&l=list&p=1&s=10&sort=newest
- Lots of SOS data! https://data.eol.ucar.edu/master_lists/generated/sos/
- These data provide unprecedented data density for the UCRB!

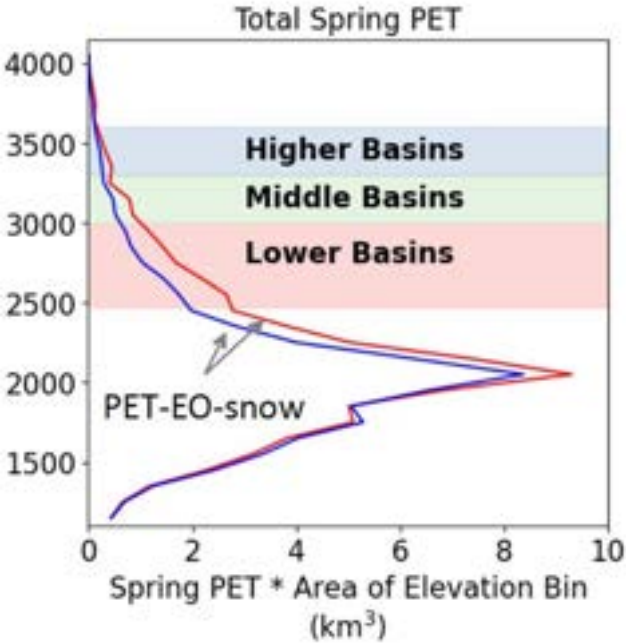
SAIL by the Numbers

Publications, Reports, Seminars, Scientific Meeting Presentations …

- 51 S^3 seminars (and counting)
- 20 publications, 36 reports (and counting)

Missing Water Mystery Solved … For Now



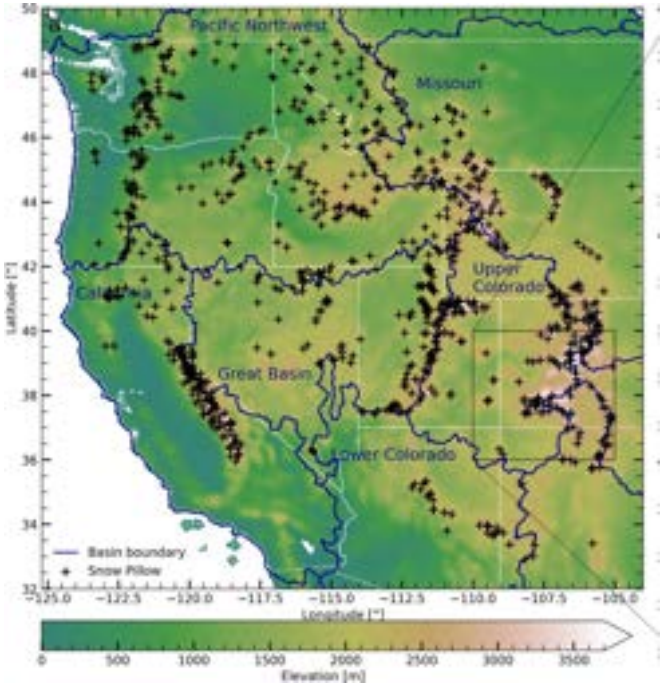


Reduced spring precipitation and potential evapotranspiration (PET) were the main culprits. Other processes may cause future reduced water resources.

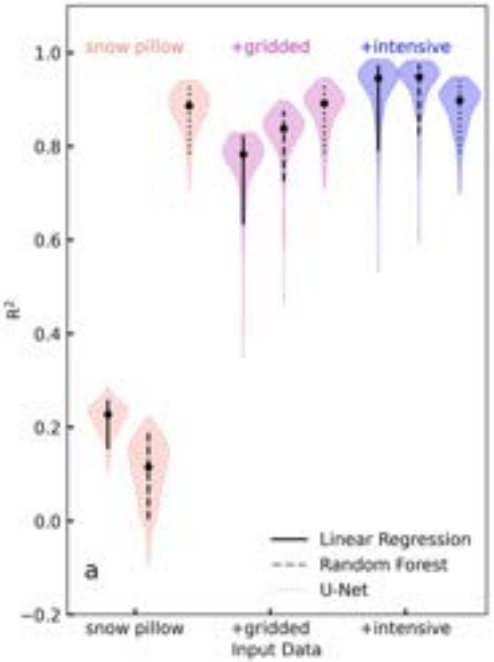
Hogan and Lundquist, (2024) *GRL*

AI for Resilient Snowpack Estimation

- The network for estimating snowpack across the Mountain West is sparse and hard to augment.
- We can use different data sources and algorithms for accurately estimating snowpack in bad snow years.
- Snowpack estimation skill will be significantly degraded without intensive data, like SAIL, and/or AI methods.



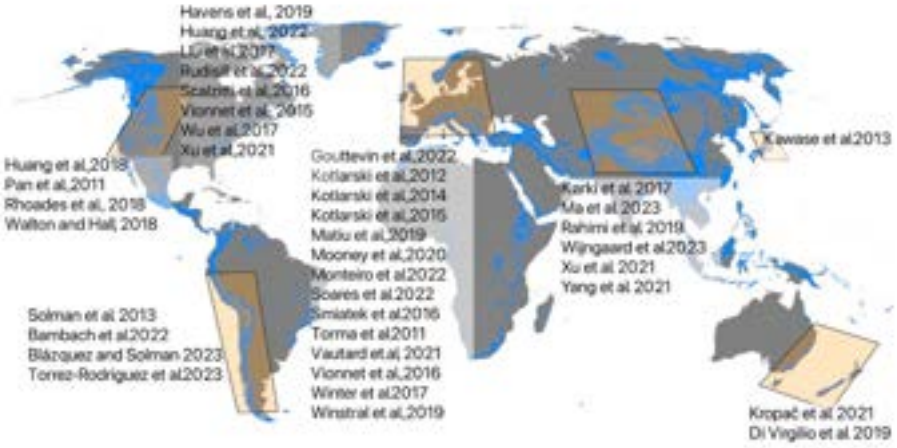
Current in situ snowpack measurement network



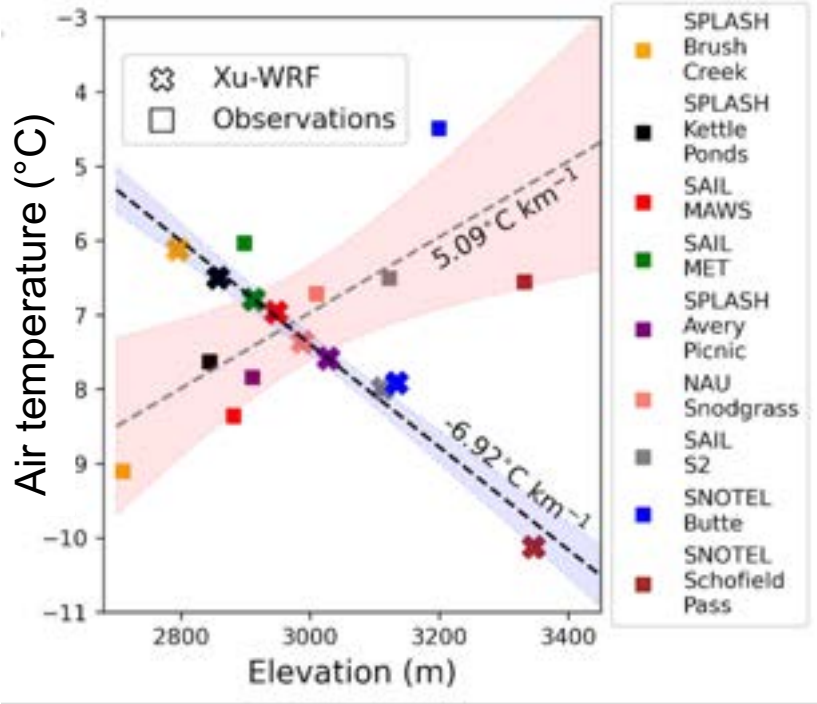
Snowpack estimation skill in the 21st Century using three levels of obs. information and data algorithms.

Cowherd et al. (2024) *Nat Comm Earth and Env.*

Pervasive Cold Biases in Surface Temperature



Pervasive T2m cold biases in atmospheric process models over mountainous regions exist. SAIL data identified the multiple underlying causes of this bias.

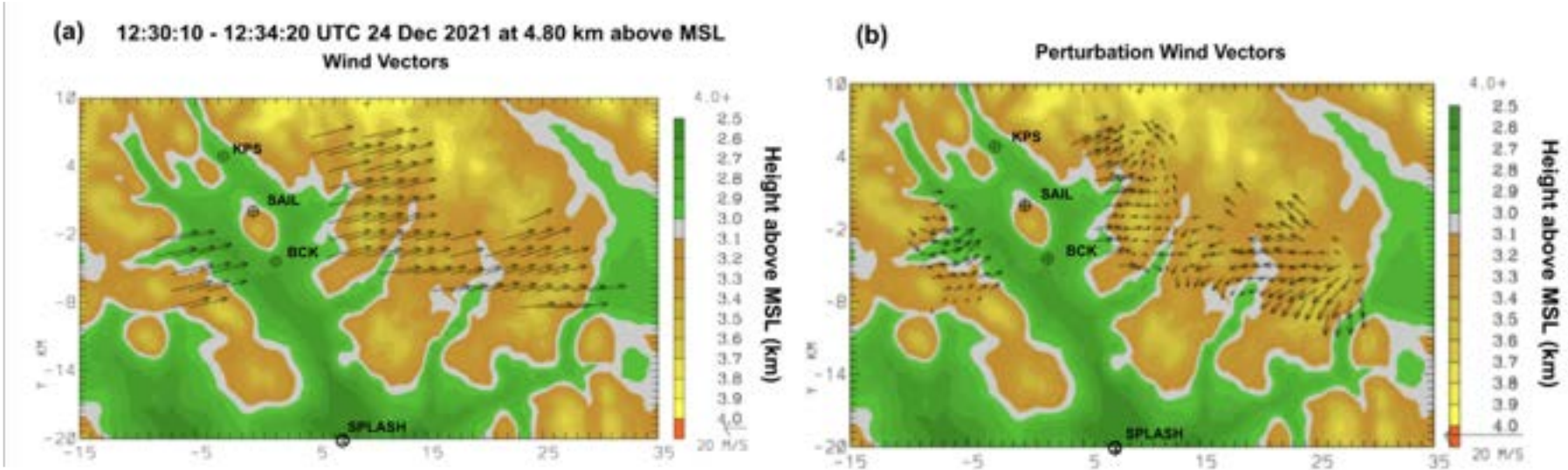


Rudisill et al. (2024) *BAMS*

Case Study on the Santa Slammer Precipitation

- Why are there very different patterns of snowfall for major storms, even at the same elevation?

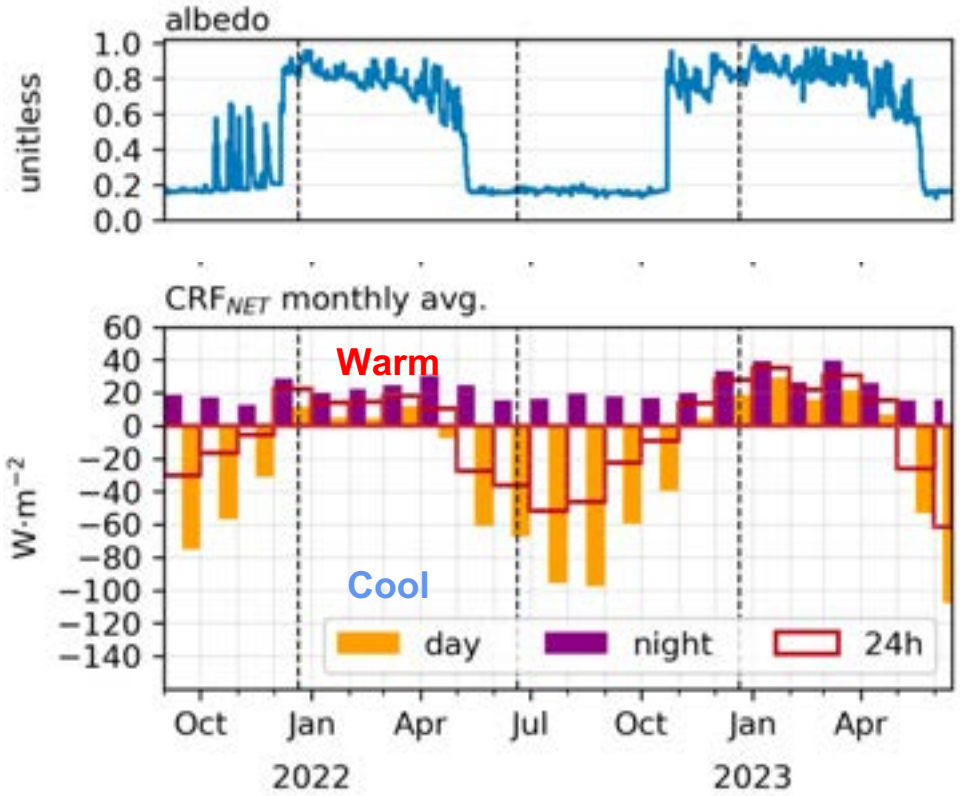
- Coordinated radar scans, radiosonde data, and surface observations from the SAIL and SPLASH show how snow crystal formation and mountain-driven wind patterns produce snowfall near the surface.



Heflin et al. (2024) *J. Hydromet.*

Seasonal Cloud Radiative Forcing in Complex Terrain

- When do clouds warm or cool the surface in high-altitude complex terrain?
- SAIL data show that clouds warm snow-covered surfaces and cool snow-free surfaces.
- The flip in spring is influenced by snow impurities.



Rudisill, (2025) *JGR*

SAIL Activities at 2024 ARM Summer School

- What are the best ways to foster a rising class of scientists to use ever-advancing ARM data?
- Open science approaches foster workforce development and rapid science.
- Cohort found SAIL snow albedo dropped from impurities, but WRF simulations don't.

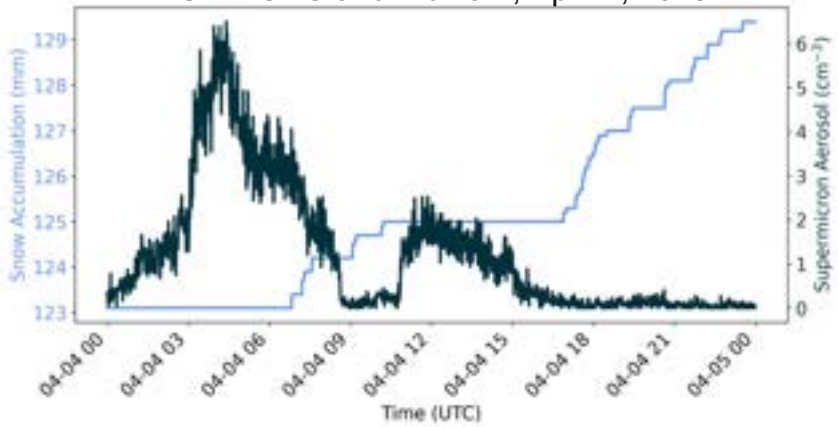
The 2024 ARM Summer School Cohort

Grover et al. (2024) *BAMS*

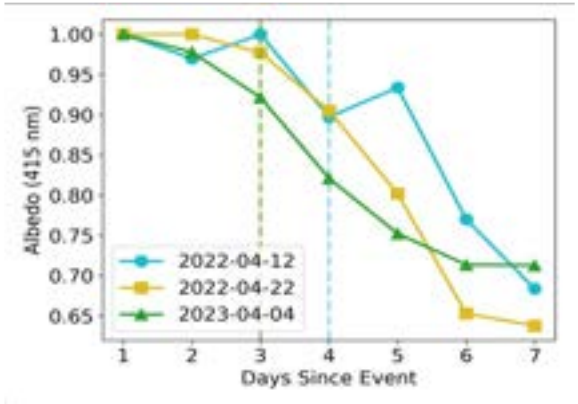
Trojan-Horse Snowfall

- Many SAIL observations allow us to infer that most dust deposition is actually from snow scavenging.
- Quantified snowpack albedo change from dust hidden in snowfall.
- Some snow appears to be a gift for the snowpack, but it has dust inside. An earlier snowpack melt-out date results.

SAIL OPC and Pluvio-2, April 4, 2023



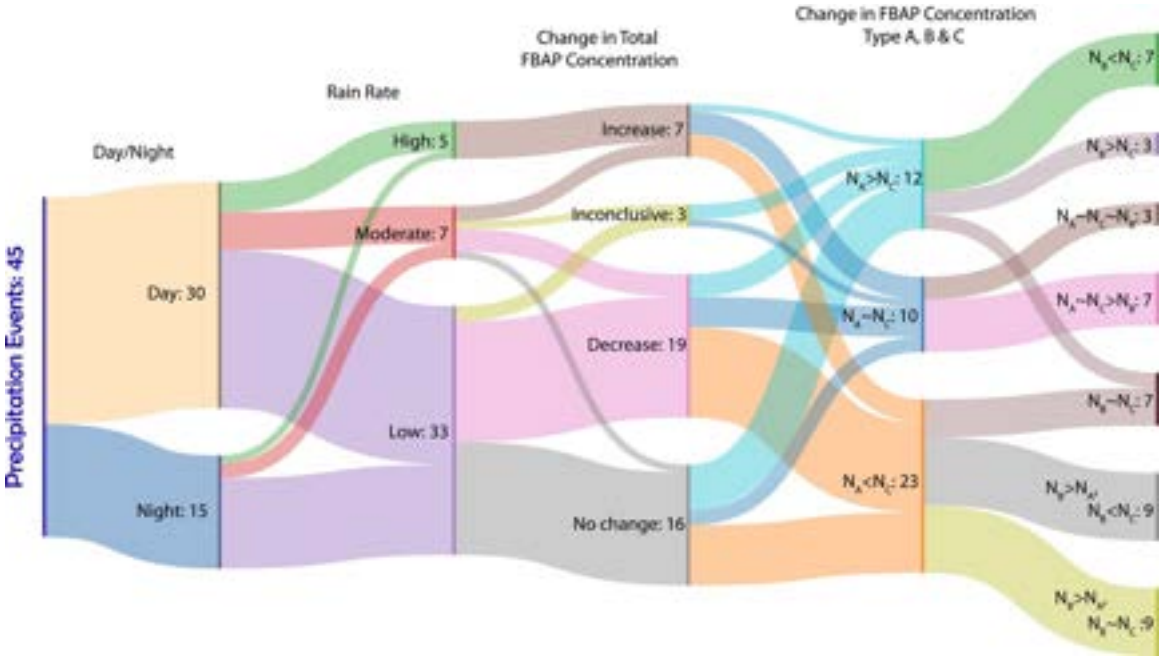
SAIL MFR/MFRSR



Gibson et al. (2025) *(Final prep)*

A Diurnal Cycle in Fluorescent Bioaerosol

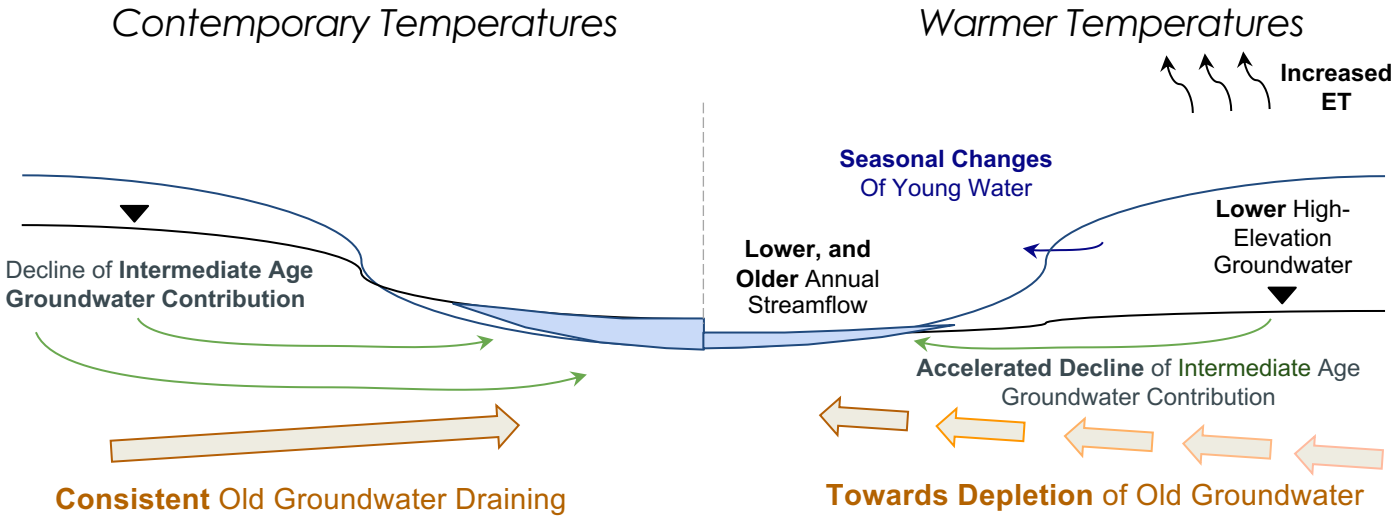
- SAIL observed many fluorescent bioaerosol particles.
- Distinct diurnal cycle in FBAP.
- Precipitation causes both emissions and removal of FBAP.



Shawon et al. (2025) *JGR*

Warmer temperatures decrease streamflow

- Integrated hydrologic modeling, forced with SAIL data, show how warming temperatures lead to streamflow tipping points.



Siirila-Woodburn et al. (2025) *Nat. Geosci. (Under Review)*

Joint ARM User Facility and ASR PI Meeting Posters

Check out the 12 SAIL-related posters!

- **Robert Jackson:** Quantitative precipitation estimation from SAIL (Session 2, Poster 51)

- **Will Rudisill:** Albedo dependence of cloud radiative forcing (Session 5, Poster 1)
- **Matthew Rybecky:** Snowpack & atmospheric processes from vapor isotopes (Session 5, Poster 3)
- **Katherine Benedict:** Supermicron aerosol science (Session 5, Poster 5)
- **Ethan Gutmann:** Diurnal energy cycle and net water vapor flux (Session 5, Poster 21)
- **Bianca Adler:** Boundary layer, clouds, and aerosols (Session 5, Poster 22)
- **Jingfeng Wang:** Observations and modeling of snow energy budget (Session 5, Poster 23)
- **Sierra Liotta:** Precipitation processes in the Rockies (Session 5, Poster 45)

- **Daniel Feldman:** Super-unit albedo (Session 6, Poster 11)
- **Russell Perkins:** Ice-nucleating particle science (Session 6, Poster 13)
- **Marianne Cowherd:** Snow bedforms with terrestrial scanning lidar (Session 6, Poster 16)
- **Swarup China:** Machine-learning for primary biological aerosol particles (Session 6, Poster 20)

Summary

- Atmospheric and surface processes are central to the Mountain West, its water resources, and associated hydropower capacity.
- SAIL and partners headed up to the mountains, gathered data, and solved some missing water mysteries …
- … but uncovered a few more. Many, many science opportunities remain.
- Join the community! We have bi-weekly S^3 seminars, and monthly work sessions and aerosol science meetings.

Email me drfeldman@lbl.gov and/or Sara Hefty (shefty@lbl.gov) to join!