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Surface Atmosphere Integrated Field Laboratory (SAIL) Field Campaign Report

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April 2024

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Executive Summary

Mountains are the natural water towers of the world, effectively turning water vapor into readily available fresh water through precipitation, snowpack, and runoff. They contribute disproportionately to precipitation over land, but are under-observed, leading to large gaps in the scientific understanding of convection, extreme precipitation and weather, and interactions between atmospheric circulation, radiation, and land-surface conditions. The mountain hydrometeorology community has repeatedly called for integrated atmospheric and land observations of water and energy budgets in complex terrain that span these scales to establish benchmarks against which scale-dependent models can be further developed.

The Surface Atmosphere Integrated Field Laboratory (SAIL) campaign responded to these calls by deploying the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility's second Mobile Facility (AMF2), additional ARM instrumentation, and an X-band scanning precipitation radar from Colorado State University to the East River Watershed (ERW), a mid-latitude, continental interior mountain valley near Crested Butte, Colorado. Integrated, collaborative observations were key to the success of the SAIL campaign. SAIL collocated atmospheric observations with long-standing collaborative resources including ongoing surface and subsurface hydrologic observations from DOE's Watershed Function Science Focus Area (SFA). SAIL also worked closely with the Rocky Mountain Biological Laboratory (RMBL), the National Oceanic and Atmospheric Administration (NOAA)'s Study of Precipitation and Lower-Atmospheric impacts on Streamflow and Hydrology (SPLASH), and the National Science Foundation (NSF)'s Sublimation of Snow (SOS) campaigns. SAIL also deployed ARM's tethered balloon system (TBS) over six times and 13 additional guest instrumentation that collected information on atmospheric processes.

This incredibly dense set of observations addressed the four key atmospheric science and land-atmosphere interaction questions that motivated the deployment of the SAIL campaign:

- SQ-1. How do multi-scale dynamic and microphysical processes control the spatial and temporal distribution, phase, amount, and intensity of precipitation?
- SQ-2. How strongly do aerosols affect the surface energy and water balance by altering clouds, precipitation, and surface albedo, and how do these impacts vary seasonally?
- SQ-3. What are the contributions of snow sublimation, radiation, and turbulent fluxes of latent and sensible heat to the water and energy balance of the snowpack?
- SQ-4. How do atmospheric and surface processes set the net radiative absorption that is known to drive the regional flow of water into the continental interior during the summer monsoon?

The campaign started on September 1, 2021 and ended on June 15, 2023, enabling observations of precipitation, aerosol, cloud, radiative, and surface processes as they impact mountainous hydrology across multiple seasonal cycles. The dozens of independent, high-quality datastreams from SAIL have already enabled a wide range of ongoing scientific investigations that continues to expand. New research efforts using SAIL data are now being facilitated through the formation of an ongoing partnership, called S^3, that connects researchers using SAIL, SPLASH, and SOS data to advance the scientific understanding of atmospheric and surface processes in the East River Watershed. S^3 research is addressing SAIL's science sub-questions and building robust mechanisms to transfer the process insights

derived at the East River Watershed across the Upper Colorado River Basin. The transferability of process research and methods in complex terrain will address many persistent problems in next-generation process and Earth system models, as some examples in this report demonstrate.

Acronyms and Abbreviations

5G	fifth-generation
AMF	ARM Mobile Facility
ANL	Argonne National Laboratory
AOS	Aerosol Observing System
ARM	Atmospheric Radiation Measurement
ASO	Airborne Snow Observatories
ASR	Atmospheric System Research
AYP	Avery Picnic
BCK	Brush Creek
BER	Biological and Environmental Research
CASTNET	Clean Air Status and Trends Network
CCN	cloud condensation nuclei
CPA	Cloud Processing of Aerosol during SAIL
CSU	Colorado State University
DOE	U.S. Department of Energy
EMSL	Environmental Molecular Sciences Laboratory
EPA	U.S. Environmental Protection Agency
ERW	East River Watershed
ESS	Environmental System Science
FICUS	Facilities Integrating Collaborations for User Science
FIDP	Field Instruments Deployment Office
GOES	Geostationary Operational Environmental Satellite
HS	Handix Scientific
INP	ice nucleating particles
KPS	Kettle Ponds
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LCL	lifting condensation level
LFC	level of free convection
MASL	meters above sea level
MRMS	Multi-Radar Multi Sensor
NADP	National Atmospheric Deposition Program
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NPF	new particle formation

NSF	National Science Foundation
ORNL	Oak Ridge National Laboratory
PBAS	Profiling of Bioaerosol at SAIL
PBL	planetary boundary layer
PI	principal investigator
POPS	printed optical particle spectrometer
PPI	plan position indicator
RHI	range height indicator
RMBL	Rocky Mountain Biological Laboratory
SAIL	Surface Atmosphere Integrated Field Laboratory
SAILAEROSSAMPL	Aerosol Sampling during SAIL Campaign
SAIL-AVP	SAIL Aerial Vehicle Program
SAILCAIVIMT	CCN and INP Variability in Mountainous Terrain
SAILCORSIPP	Characterization of Orography-Influenced Riming
SAIL-ISO	Water Vapor Isotopic Measurements during SAIL
SAIL-Net	Network of SAIL Aerosol Instruments
SAILTOBS	Targeted Observations of Blowing Snow during SAIL
SAILVAPS	Vertical Aerosol Profiling during SAIL
SEB	surface energy balance
SFA	Science Focus Area
SIP	secondary ice production
SNOTEL	Snow Telemetry Network
SOS	Sublimation of Snow
SPLASH	Study of Precipitation and Lower-Atmosphere Impacts on Streamflow and Hydrology
SQUIRE	Surface Quantitative Precipitation Estimation
SSB	SAIL Super-Micron Bioaerosol
STAC	Size- and Time-Resolved Aerosol Collector
SWE	snow-water equivalent
TBS	tethered balloon system
TWSTSAIL	Field Validation of Cloud Properties – SAIL
UC	University of Colorado
UCRB	Upper Colorado River Basin
WFSDB	Watershed Field Science Data Backhaul
WF-SFA	Watershed Function Scientific Focus Area
WY	Water Year
XBPWR	X-band dual-polarimetric weather radar

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1.0 Background

Most worldwide water resources (60-90%) emerge from mountains (Huss et al. 2017). In North America, mountains comprise a quarter of the continent's land area, but store 60% of the snowpack (Wrzesien et al. 2018). However, these water towers of the world are threatened by many factors contributing to elevation-dependent climate warming (Barnett et al. 2005, Mote et al. 2018, MRI 2015, López-Moreno et al. 2017, Musselman et al. 2017), with deleterious implications for snow cover, water resources, and even atmospheric dynamics (Chen et al. 2017, MRI 2015, Mote et al. 2018). This warming is expected to induce modifications to snow accumulation, melt, and subsequent water budget partitioning and is expected to decrease streamflow (Clow 2010, Barnhart et al. 2016, Li et al. 2017, McCabe et al. 2017). Recent work summarized the multi-faceted changes that the atmosphere and surface in high-altitude complex terrain will face in a low-to-no-snow future (Siirila-Woodburn et al. 2021).

At the same time, the central role of atmospheric processes and land-atmosphere interactions in governing water resource availability must be recognized: the source of water and one of its major sinks is the atmosphere, and yet the atmosphere exhibits first-order variability in precipitation (Houze 2012), radiation (Lee et al. 2015, Feldman et al. 2022), thermodynamic state (MRI 2015), clouds, aerosols, and surface energy budget terms.

Unfortunately, approaches that focus on comprehensive and/or exhaustive observations that circumscribe the variability in the atmospheric and surface states in complex terrain are non-convergent. The challenges of collecting in situ observational data in complex terrain are great, since safety, access, and land-use restrictions issues can separately or together preclude data set collection (Varadharajan et al. 2019, Thornton et al. 2022). Indeed, the vast majority of the 24% of the Earth's land surface covered by mountains (Marston 2008) will likely remain under-observed into the near future. Therefore, the processes that impact mountainous hydrology in mid-latitude continental interior watersheds will be under-constrained for the foreseeable future. Consequently, the atmospheric and surface processes that impact mountainous hydrology will continue to be inferred from atmospheric models and/or coarse satellite-based retrievals (Seidel et al. 2010) for some time.

An alternative approach to exhaustive observations for advancing the scientific understanding of precipitation, aerosol, clouds, and radiation processes, and their connections to land-atmosphere interactions in high-altitude complex terrain, is to achieve sufficient observational density in a smaller area to enable strong observational constraints on these processes that can lead to widely applicable scientific insights. That is the central thesis of the SAIL campaign (Feldman et al. 2023). An info-graphic summary of the most important lower-atmosphere and surface processes in complex terrain is shown in Figure 1.

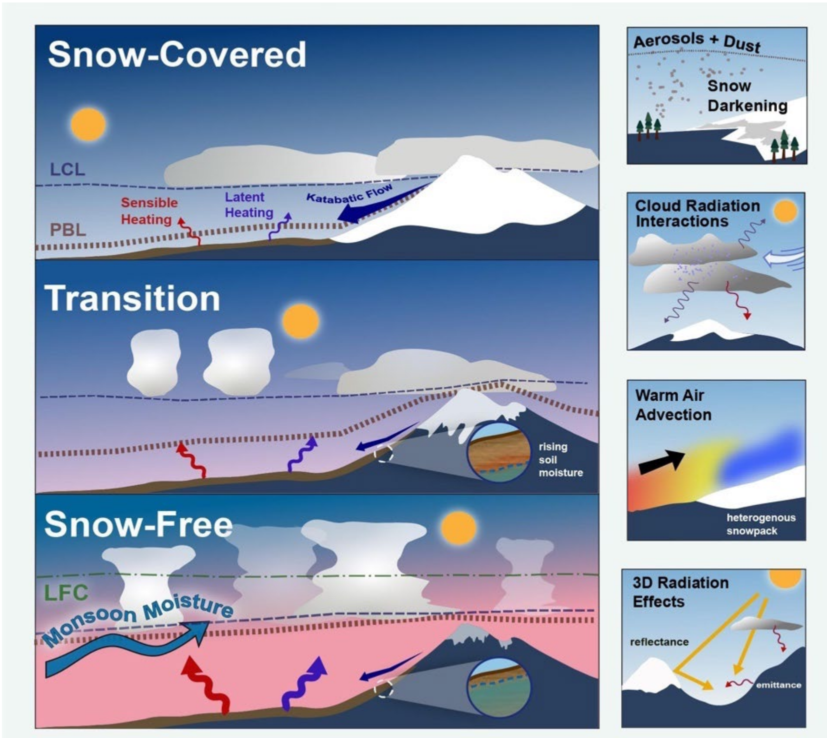


Figure 1. Surface-atmosphere exchange processes in the planetary boundary layer (PBL) in high-altitude complex terrain (right column), with demonstration of the PBL and lifting condensation level (LCL) and level of free convection (LFC) variations across seasons (left column). Winds and turbulent fluxes of sensible and latent heat are also depicted. These processes couple the atmosphere to the surface but their interactions, controlling factors, and importance for model development continue to be uncertain.

The SAIL campaign is a response from DOE and a team of scientists (the SAIL science team) to the repeated calls of the scientific community for ambitious, comprehensive observations of precipitation, aerosols, clouds, radiation, and atmospheric thermodynamics in a location that has significant surface and subsurface observational infrastructure (Bales et al. 2006, Viviroli et al. 2011, Lundquist et al. 2015, Clark et al. 2015a, 2015b, U.S. DOE 2019).

The focus on observational density with SAIL is designed to provide a level of benchmarking for mountainous hydrological modeling that has yet to be achieved. This benchmarking, in turn, supports a robust observational foundation for model development ranging in complexity and domain from process models to Earth system models. An effort to develop this ambitious demonstration motivates four distinct science questions that drive the campaign's science objectives. The science questions focus on a set of intertwined processes that ultimately set the surface energy and mass balances, which have been repeatedly identified as most critical for mountainous hydrology, while also supporting the programmatic interests that DOE expressed in studying turbulence, aerosols, and land-atmosphere interactions in complex terrain (U.S. DOE 2019).

- SQ-1. How do multi-scale dynamic and microphysical processes control the spatial and temporal distribution, phase, amount, and intensity of precipitation?

- SQ-2. How strongly do aerosols affect the surface energy and water balance by altering clouds, precipitation, and surface albedo, and how do these impacts vary seasonally?
- SQ-3. What are the contributions of snow sublimation, radiation, and turbulent fluxes of latent and sensible heat to the water and energy balance of the snowpack?
- SQ-4. How do atmospheric and surface processes set the net radiative absorption that is known to drive the regional flow of water into the continental interior during the summer monsoon?

To address these science questions, SAIL involved the deployment of the Second Mobile Facility of the ARM user facility (AMF2; Mather and Voyles 2013, Miller et al. 2016) **from September 1, 2021 to June 15, 2023** to a mountainous location near Crested Butte, Colorado (specifically, Gothic). In addition to the AMF2, ARM also supported the deployment of an X-band weather radar guest instrument, and, on seven occasions, the TBS.

This deployment then used the AMF2 to address its central science objectives, which were to:

1. Characterize the spatial distribution of orographic and convective precipitation processes on diurnal-to-seasonal time scales and how those processes interact with large-scale circulation.
2. Quantify cold-season land-atmosphere interactions that alter snowpack mass balance through wind redistribution and sublimation and the spatial scaling of those processes.
3. Establish aerosol regimes, the processes controlling the life cycle of aerosols in those regimes, and quantify the impacts of aerosols in those regimes on the atmospheric and surface radiative budget.
4. Quantify the sensitivity of cloud phase and precipitation to cloud condensation nuclei (CCN) and ice nucleating particle (INP) concentrations.
5. Quantify the seasonally varying surface energy balance (SEB), the land surface and atmospheric factors controlling it, and the spatial variability in those factors.

Figure 2 shows the general area where SAIL was deployed in the Colorado River Basin. In North America, the Colorado River is the most hydrologically significant watershed, draining an area of 640,000 km^2 with approximately 74 km^3 of annual discharge (60 million acre-feet). These water resources enable ~53 gigawatts of electric power generation capacity, support ~$1.3 trillion of economic activity annually, and provide ~15 million jobs (James et al. 2014), but water resources from this river have been dwindling – over the past 100 years, they have decreased by 9.3 %/°C of warming (Milly et al. 2020).

Figure 2. The location of the SAIL deployment within the Colorado River Watershed.

From a hydrological perspective, the functional processes of the Colorado River Watershed are not evenly divided. The Upper Colorado River Basin receives ~90% of the precipitation of the basin and is more heavily vegetated than the Lower Colorado River Basin, which is arid and has more aerosol entrainment and evaporative demand. Given its science questions, SAIL focused on the Upper Colorado River Basin and looked within that basin at the Gunnison River Watershed, which represents 10,270 km^2, but drains nearly 25% of the entire Colorado River. Among areas of significant research and modeling focus within the Gunnison watershed, one stands out because it has been extensively studied with long-duration biological experiments and, more recently, has been the focus of sustained and intensive research activity. From a logistical and science perspective, this was the most favorable area for SAIL: the East River Watershed (ERW). The ERW is ~300 km^2 and its outline is shown in Figure 3. It is the most heavily instrumented watershed for both atmospheric and surface observations in North America by a large margin.

Since 1928, observations of the surface conditions, including plant and animal life, snowfall, snowpack, and precipitation, have been collected in Gothic, Colorado at the Rocky Mountain Biological Laboratory (RMBL). The timeline of measurements is depicted in Figure 3, indicating a substantial observational record to build from and complement with SAIL. The pace of measurement collection in the ERW has been increasing rapidly in the last 15 years.

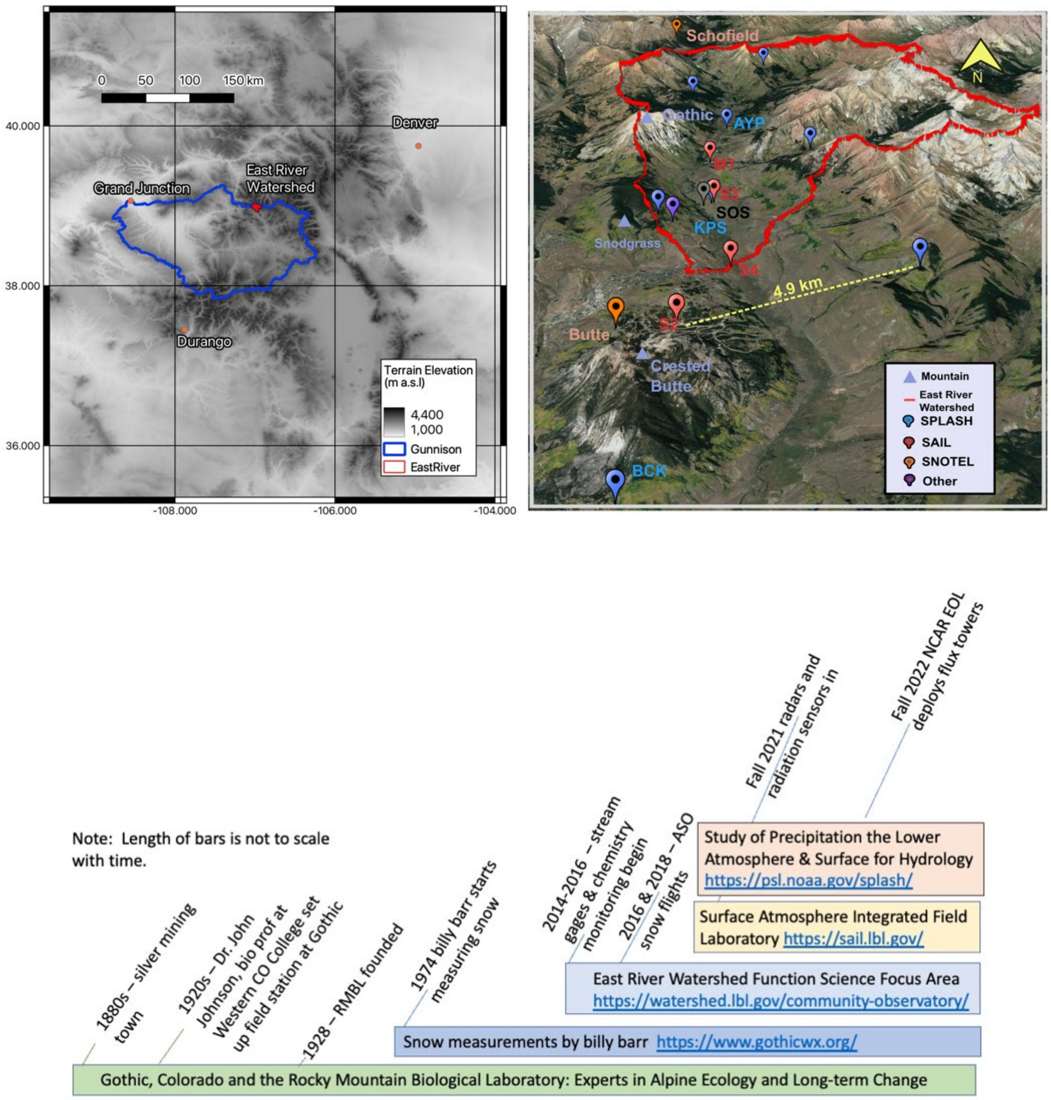


Figure 3. (Upper left panel) The high-altitude complex terrain of the Colorado Rockies with the 10,270 km^2 Gunnison River Watershed (outlined in blue) and 300 km^2 East River Watershed (ERW) in red. (Upper right panel) Perspective view of the locations of SAIL, SPLASH, SOS, Snow Telemetry Network (SNOTEL), and some of the Watershed Function SFA measurements in the ERW (red outline). Primary measurement sites include Gothic (M-1), Avery Picnic (AYP), Kettle Ponds (S-3 and KPS), Brush Creek (BCK), Crested Butte Mountain (S-2), Snodgrass Mountain, and Pumphouse (S-4). Secondary sites and their campaign affiliations are also shown. (Lower panel) a cartoon of the timeline of observations collected at Gothic.

Specifically, since 2016, the ERW has been the central field study area of surface and subsurface hydro-biogeochemistry research sponsored by DOE's Environmental System Science (ESS) program and managed by LBNL through the Watershed Function Scientific Focus Area (WF-SFA) (Hubbard et al. 2028, 2020). It was chosen in part because of the large gradients in snowpack, temperature, and precipitation, as well as the presence of RMBL to provide immediate information that contextualizes measurements in terms of seasonal, interannual, decadal, and multi-decadal variability. As a result, many of the atmospheric and surface processes in the ERW are known, at least qualitatively.

However, the quantification of those processes, the importance of those processes hydrologically, and their fundamental controls remains highly uncertain. The upper left panel of Figure 3 show the location of SAIL within the larger Gunnison River Watershed, and the density of observations deployed in the ERW (upper right panel of Figure 3). SAIL included measurements at a main site (M-1) in ~1-km-deep, ~3-5-km-wide mountain valley, a supplemental site ~7.5 km horizontally from M-1 and ~250 m above it on Crested Butte Mountain (S-2), and two additional supplemental sites in the valley between M-1 and S-2 (denoted S-3 (Kettle Ponds) and S-4 (Pumphouse)).

For SAIL, the containerized instruments were deployed adjacent to Gunnison County Road 317 (38°57'22.35"N, 106°59'16.66"W), while the field instruments were deployed on an adjacent hill (38°57'22.99"N, 106°59'8.79"W). These locations constituted M-1. The containerized instruments were located within the East River Valley at an elevation of ~2885 meters above sea level (MASL) with the instruments on the adjacent hill at ~2917 MASL. In addition to the AMF2, SAIL also deployed a scanning, X-band dual-polarimetric weather radar (XBPWR) to provide observations of precipitation amount and type across the East River Watershed. Colorado State University (CSU) provided the XBPWR. The XBPWR and ARM's Aerosol Observing System (AOS) were placed together at an elevated location on Crested Butte Mountain near the Old Teocali Lift (38°53'52.66"N, 106°56'35.21"W) at an elevation of ~3137 MASL. The XBPWR and AOS measurements were separated by ~7.5 km from the AMF2. This supplemental site location constituted S-2. A single eddy covariance system was deployed to Kettle Ponds (38°56'39.39"N, 106°58'49.39"W) at S-3. The Pumphouse location (38°55'18.88"N, 106°57'5.68"W) was where the TBS was deployed for five of its seven deployments.

The importance of advancing the scientific understanding of atmospheric processes and land-atmosphere interactions in complex terrain was made extremely apparent at the start of the SAIL campaign. In Water Year 2021, the long-term decline in Colorado River water resources took a punctuated turn: the reservoir levels of the Basin dropped to elevations without any historical precedent and led to the first-ever Level 1 Shortage Condition declaration at Lake Mead (Santos and A Pivarnik 2021) in August, 2021. But, as Figure 4 (left panel) shows, this emergency shortage occurred amid a slightly below-average year for precipitation in the UCRB. The forecast for water resources in the summer and fall of 2021 only shows that an emergency was imminent in June, 2021, which was only two months before the Shortage Condition declaration (right panel of Figure 4).

Understanding the cause(s) of the mismatch between precipitation in the UCRB and water resource availability so that they can be incorporated into forecasts is most critical, but forensic analysis of what exactly occurred in 2021 is ongoing. Precipitation and peak snowpack during Water Year 2021 (WY21) were 70% and 50-80% of the 1990-2020 average in the Upper Colorado, respectively, while streamflow and unregulated discharge into Lake Powell were 8-57% and 28% of the 1990-2020 average, respectively (Bailey et al. 2021). While discrepancies between precipitation and discharge have happened in the past (Xiao et al. 2018), explanations for such discrepancies in WY21 include (1) lack of April precipitation, (2) snow sublimation, (3) evapotranspiration, (4) dry antecedent soil moisture from drought in previous years, and (5) an overestimation of winter snowpack from sparse observations (Abatzoglou et al. 2021), with (Börk et al. 2022) suggesting dry soils as a primary culprit. Regardless, this mystery highlights how a range of processes interact to control the hydrological output of the Upper Colorado River and water availability in the southwestern United States.

These events highlighted the urgent need to understand the sensitivities of coupled atmosphere-through-bedrock processes that together determine water resources supply and the possibility of sustainable water governance (Gerlak et al. 2021).

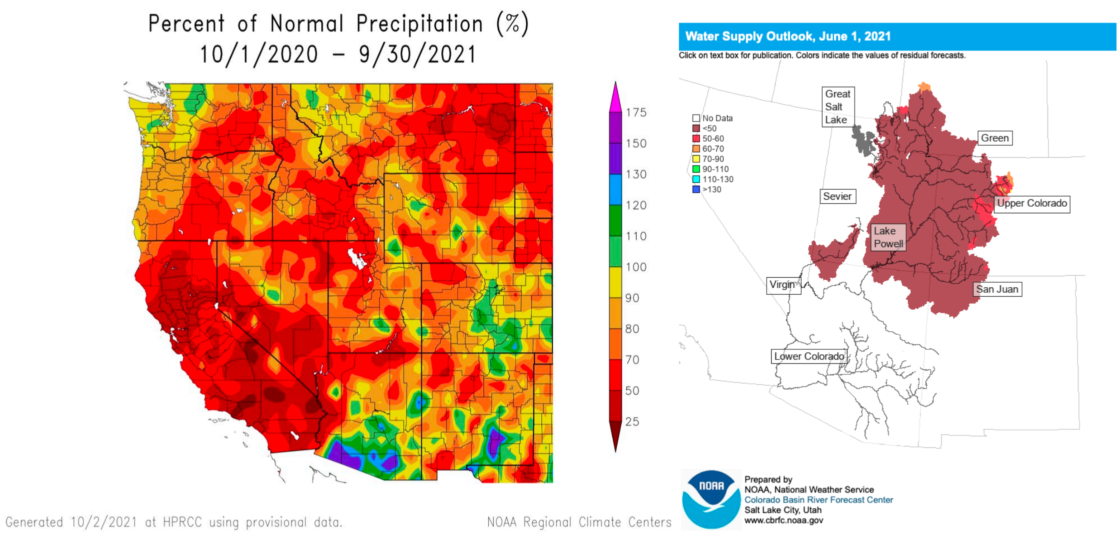


Figure 4. WY21 percent of normal precipitation, showing that the UCRB received average precipitation while the Lower Basin did not. The NOAA water supply outlook in June as it shifted to less than 50% of its historical average.

With a well-posed set of science questions and strong societal interest in the campaign, the SAIL science team, in close collaboration with ARM's Field Instruments Deployment Office (FIDO) and with logistical support from the Watershed Function SFA and RMBL, embarked on an ambitious set of research activities. Figure 5 shows the setup of SAIL, which became an iconic campaign photo, and highlighted the range of atmospheric and surface processes at play. Surface-cloud interactions, convection, three-dimensional radiation, and major influences of topography all appear in this photo.

Figure 5. Containerized instruments of the AMF2 at the SAIL M-1 site at the base of Gothic Mountain during the installation phase of SAIL. Photo taken by Ken Williams in June, 2021.

Given the significant interest in the changes occurring in Colorado River water resources, the SAIL campaign was able to catalyze and/or partner with additional research activities that contributed to, and significantly augmented, SAIL's science objectives. These included:

- The Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology (SPLASH) campaign supported by NOAA (de Boer et al. 2023).
- The Sublimation of Snow (SOS) campaign supported by the NSF (Lundquist et al. 2024).
- The Clean Air Status and Trends Network (CASTNET) supported by the U.S. Environmental Protection Agency (EPA) as part of the National Atmospheric Deposition Program (NADP).
- Thirteen guest instrument deployments including:
  - **CCN and INP Variability in Mountainous Terrain (SAILCAIVIMT)**: A network of low-cost aerosol sensors to measure aerosol particle size distributions, cloud condensation nuclei, and ice nucleating particles by Handix Scientific to characterize aerosol spatial variability and its causes and implications in ERW.
  - **Cloud Processing of Aerosol during SAIL (CPA)**: A Size- and Time-resolved Aerosol Collector (STAC) by the Pacific Northwest National Laboratory to determine aerosol size-resolved chemical composition.
  - **Aerosol Sampling during SAIL Campaign (SAILAEROSSAMPL)**: An aerosol particle collector with chemical imaging and molecular characterization by Purdue University to establish a relationship between the composition of aerosol particles and their atmospheric impacts.
  - **Field Validation of Cloud Properties Sensor – SAIL (TWSTSAIL)**: A cloud optical depth, droplet effective radius, and thermodynamic phase instrument by Aerodyne, Inc. to validate Aerodyne's cloud property sensors in high-altitude complex terrain.
  - **Watershed Field Science Backhaul (WFSDB)**: A citizens band radio service by LBNL to develop a high-bandwidth 5G wireless network to connect field instruments.
  - **Sail Super-micron Bioaerosol (SSB)**: Super-micron aerosol and bioaerosols instruments by LANL to determine if super-micron bioaerosols influence aerosol processes, aerosol-cloud interactions, and the hydrological cycle.
  - **Vertical Aerosol Profiling during SAIL (SAILVAPS)**: Instruments that measure time-resolved vertical profiles of CCN and INPs by CSU to assess vertical gradients in condensation nuclei on TBS.
  - **Profiling of Bioaerosol at SAIL (PBAS)**: Instruments that measure the vertical profiles of bioaerosols by Brookhaven National Laboratory to assess vertical gradients in bioaerosols on TBS.
  - **SAIL Aerial Vehicle Program (SAIL-AVP)**: Instruments that measure the vertical profiles of CCN and INPs by LANL to assess vertical gradients in aerosols on TBS.
  - **Water Vapor Isotopic Measurements during SAIL (SAIL-ISO)**: Instruments that measure the stable isotopic composition of water vapor by the University of New Mexico to collect information on sources and sinks of atmospheric water vapor.

- **Targeted Observations of Blowing Snow during SAIL (SAILTOBS)**: Snowflake cameras and acoustic mass-flux sensors by the University of North Dakota to observe mixed-phase and frozen hydrometeor morphologies in winter.
- **Characterization of Orography-Influenced Riming (SAILCORSIPP)**: A W-band scanning radar and snowflake camera by the University of Leipzig to characterize orographically induced riming.
- **Sublimation of Snow (SOS)**: A wide range of instruments that measure snow properties and water fluxes by the Earth Observing Laboratory of the National Center for Atmospheric Research (NCAR) to study the sublimation of snow.

The national user facility capabilities of ARM greatly enabled all these collaborations.

Because of SAIL's ambitious, wide-ranging scope of science questions and science objectives, the science team organized into several sub-groups:

Precipitation process sub-group led by Venkatachalam Chandrasekar of CSU with major contributions from Scott Collis, Max Grover, Joseph O'Brien, Bobby Jackson, Zach Sherman, Adam Theisen, and Nicki Hickmon of ANL. This group focused on SAIL Science Objective 1.

Snow process sub-group led by Daniel Feldman of LBNL with major contributions from Will Rudisill of LBNL, Ethan Gutmann of NCAR, Danny Hogan and Eli Schwat of the University of Washington, Joseph O'Brien and Bobby Jackson of ANL, and Jingfeng Wang of Georgia Tech University. This group focused on SAIL Science Objective 2.

Aerosol process sub-group led by Allison Aiken of LANL with major contributions from Jim Smith of the University of California, Irvine, Jiwen Fan of ANL, Anna Hodshire, Ezra Levin, and Leah Gibson of Handix Scientific, Jessie Creamean of CSU, and McKenzie Skiles of the University of Utah. This group focused on SAIL science objectives 3 and 4.

Radiation process sub-group led by Daniel Feldman of LBNL with major contributions from Chris Cox, Joe Sedlar, and Laura Riihimaki of NOAA, and Will Rudisill of LBNL. These support SAIL Science Objective 5.

2.0 Notable Events and Highlights

The installation of the M-1 site (Figure 6 and Figure 7)went very smoothly, with all the instruments at M-1 collecting data beginning on September 1, 2021 as planned. Many more logistical challenges occurred while installing the S-2 site. This location was on Crested Butte Mountain Resort and the X-band radar required additional construction permits due to its size. Some of those permits were not finalized until after the start of the campaign. Fortunately, the permits were secured in October, 2021 and the site was fully installed that month by FIDO at LANL. From October, 2021 onwards, SAIL data collection continued with minimal interruptions until the campaign completed in June, 2023.

Figure 6. (From left) Ken Williams, Kate Robinson, and Andrew Wiedlea of LBNL pause in their installation of a wireless backhaul for SAIL and the WF-SFA in August, 2022. Image courtesy of ARM.

Figure 7. (From left) Allison Aiken, John Bilberry, Heath Powers, and Andrew Wolfsberg of LANL at the field instruments at the SAIL M-1 site. Image courtesy of ARM.

With the SAIL instruments installed in late 2021, the collections of observations began in earnest. During the campaign, several historically significant hydrological events occurred that can be summarized with the display of the data on precipitation and snow-water equivalent from Butte SNOTEL station throughout the SAIL campaign relative to the 30-year climatological median (Figure 8).

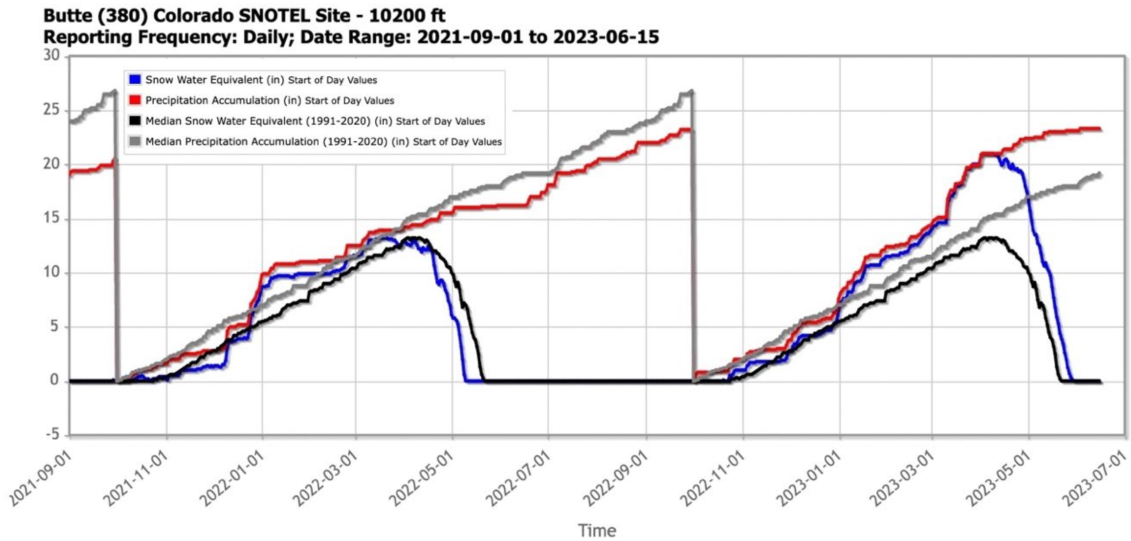


Figure 8. Butte SNOTEL station near the SAIL S-2 site with measured snowpack snow-water equivalent (SWE) in blue, accumulated precipitation in red, the 30-year median SWE covering 1991-2020 in black, and the 30-year median accumulated precipitation covering 1991-2020 in gray. All quantities pertain to the water year in which they were collected.

The campaign began under exceptionally dry conditions, with exceptionally low-snow in the fall of 2021 in the SAIL study area at Gothic (none in September, 31 cm in October, and 30 cm in November). In September, both visible and thermal imagery from the TBS captured these dry conditions (Figure 9).

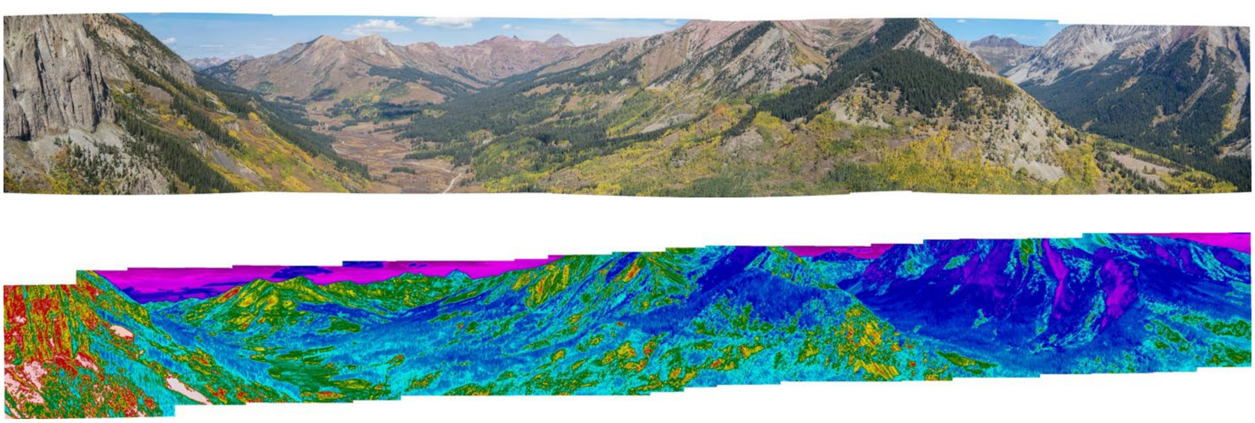


Figure 9. Mosaics of visible and thermal imagery collected by the TBS Mirage 640 from the SAIL M-1 site on September 15, 2021.

The first major meteorological event was a series of snowstorms between December 23, 2021 and January 1, 2022 when nearly 1/3 of the precipitation for Water Year 2022 occurred (Figure 10). This event is being studied thoroughly by SAIL and SPLASH (Heflin et al. 2024).

Figure 10. SAIL's containers at Gothic partially covered in snow amid continued flurries with the late December 2021 snowfall. Photo courtesy of Heath Powers.

After that event, a mid-winter dry spell brought virtually no precipitation in January, 2022 (Figure 11). This enabled a site and science planning meeting with the leadership of SAIL, SPLASH, and SOS in late January, 2022.

Figure 11. (From left) Daniel Feldman of LBNL, Erik Hulm of the RMBL, Jessica Lundquist of the University of Washington, and Gijs de Boer of the University of Colorado at the Snodgrass Trailhead starting to ski to the SAIL M-1 site on January 26, 2022. Photo courtesy of Daniel Feldman.

Next, a series of late-season snowfalls in March, 2022 produced a snowfall total for the winter that was approximately average relative to the 1991-2020 median. However, there was already dust in the snowpack prior to the end of winter, and then several dust storms in April, 2022 dramatically lowered snowpack albedo. As a result, the snowpack melted very quickly, as shown in Figure 12. The data collected by SAIL during this seasonal transition from a snow-dominated mountainous watershed to one that was snow-free with active convection was a first for ARM. The facility had collected data in complex terrain, but not across the seasonal transitions.

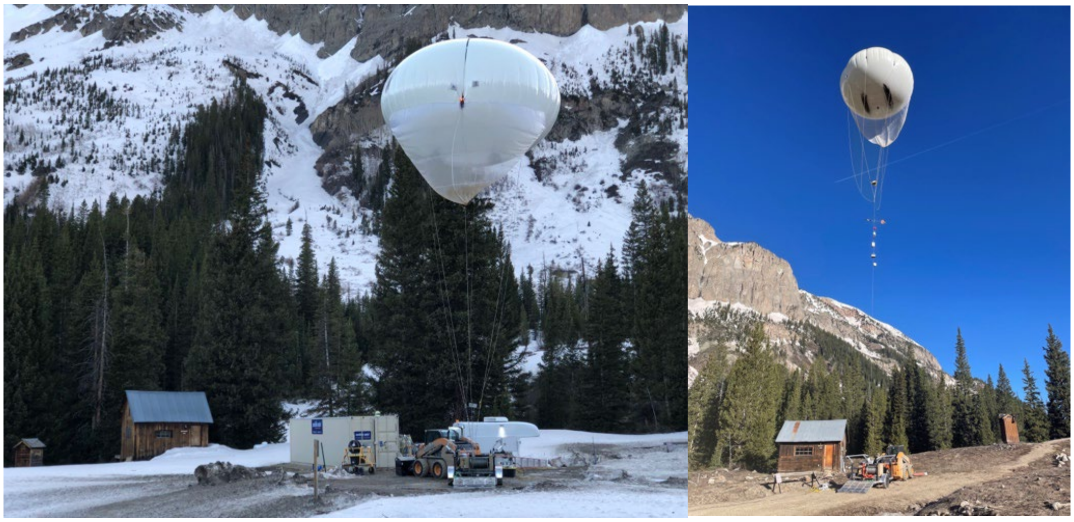


Figure 12. TBS launching from the Gothic townsite for SAIL test flights on May 5, 2022 (left) and May 14, 2022 (right) showing the rapid snowmelt. Images courtesy of Dari Dexheimer.

While some summers in the UCRB experience little to no precipitation, others are more active. The summer of 2022 was extremely active, with a vigorous intrusion of the North American Monsoon (Figure 13). Convective precipitation occurred nearly every day at SAIL during this period.

Figure 13. Afternoon convective clouds forming over the East River valley near SAIL M-1 on July 23, 2022. Photo courtesy of Nathan Bilow.

In the fall of 2022, at the one-year mark for SAIL data collection, a large contingent of SAIL and WF-SFA researchers hosted leadership of DOE's Biological and Environmental Research (BER) Program including program managers for ARM, Atmospheric System Research (ASR), and Environmental System

Science (Figure 14). This tour highlights the many areas of active collaboration between different programs in BER.

Figure 14. SAIL and Watershed Function SFA researchers tour the SAIL S-2 site along with DOE BER program managers on September 20, 2022. Image courtesy of ARM.

With the start of the second year of SAIL data collection, the campaign scope grew in three critical ways. First, ARM supported and scheduled four deployments of the TBS through DOE's Environmental Molecular Sciences Laboratory (EMSL). This supported collaborative research applications through the Facilities Integrating Collaborations for User Science (FICUS) program for the winter and spring of 2023. Second, the SOS campaign, which included guest instrument support from ARM, began, as shown Figure 15. Third, additional guest instruments that including a scanning W-band radar and a snowflake camera, from the University of Leipzig, as shown in Figure 16, were deployed.

These collaborative efforts focused on the cold season in the ERW, with a particular focus on snow processes including sublimation and deposition, a key part of SAIL's science objectives. The winter of 2022/2023 saw exceptionally heavy snow relative to the 1991-2020 median, as shown in Figure 8.

Figure 15. SAIL technicians and SOS team members fill in a snow pit at the SAIL S-3 site in March, 2023. Photo courtesy of Daniel Feldman.

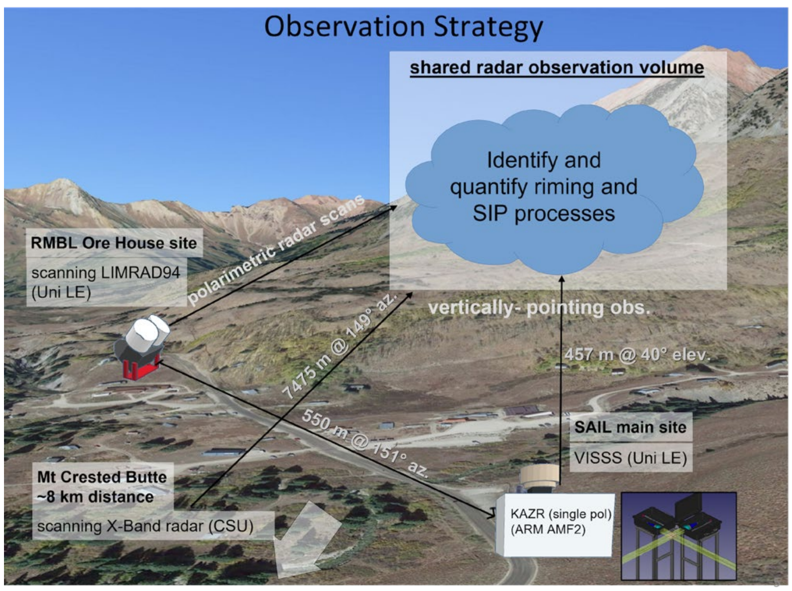


Figure 16. Depiction of the instrument configuration of the W-band scanning radar and visible snowflake cameras deployed by the University of Leipzig to measure riming and develop insights into secondary ice production (SIP) processes. Graphic courtesy of the University of Leipzig.

The collaboration was very important during the winter of 2022/2023 because it was so cold and snowy. Figure 17 shows the challenges of TBS deployments in January 2023, while Figures 18 and 19 show the challenges that SAIL technicians faced day-in, day-out, night-in, and night-out during this winter, with instrument maintenance that included clearing snow from and dealing with riming on instruments, not to mention staying warm. Finally, Figure 20 depicts the process required to access the SAIL M-1 site during the winter. No snow machines were allowed on Gothic Road (the main access road to SAIL M-1), so access was only possible on cross-country skis or snowshoes, except for a monthly re-supply transport.

Figure 17. ARM technician Casey Longbottom, Sandia National Laboratories, assists with the operation of a TBS during ARM's SAIL campaign in Gothic, Colorado. Image courtesy of ARM.

Despite these challenges, the SAIL, SPLASH, and SOS campaigns in the ERW achieved an unprecedented level of data density, as shown by the Kettle Ponds area (the SAIL S-3) site that was bristling with instrumentation (Figure 21). The multiple eddy covariance towers at that site, along with the remote-sensing measurements at SAIL including a Doppler lidar, provided strong constraints on atmospheric processes, especially snow sublimation. The cold, snowy winter provided many opportunities to observe how the atmosphere and surface interact to control the thermodynamics and kinetics of this process. The additional measurements made by the TBS during this time showed an atmosphere very low in aerosols.

Figure 18. An ice nucleation spectrometer (INS) and an X-band precipitation radar (XSAPR) on Crested Butte Mountain, Colorado for the SAIL campaign in January, 2023. Image courtesy of ARM.

Figure 19. The SAIL information poster at the M-1 site is nearly covered in a major snowdrift. Photo by Jeremy Snyder on March 22, 2023.

Figure 20. RMBL technicians Curtis Beutler and Alex Newman with LBNL researchers Marianne Cowherd and Daniel Feldman skiing to the SAIL M-1 site on March 22, 2023. Photo by Jeremy Snyder.

Figure 21. Aerial photo of the Kettle Ponds area facing south with Crested Butte Mountain in the background. The Kettle Ponds super-site included the SAIL S-3 site, the Kettle Ponds SPLASH annex site, and the SOS instrument site. Photo by Jeremy Snyder on March 22, 2023.

With the end of the data collection phase of SAIL in sight, the SAIL science team began to focus on the results in hand. That included hosting a short course at the 2023 American Meteorological Society meeting called Open Science in the Rockies: Working With ARM data from SAIL, as shown in Figure 22. Here, ARM supported researchers from LBNL, ANL, and Oak Ridge National Laboratory (ORNL) to demonstrate the capabilities of ARM's data and analysis packages to students and other interested researchers.

Figure 22. From left, Max Grover of ANL, Daniel Feldman of LBNL, and Monica Ilhi of ORNL at the Open Science in the Rockies Short Course at the 2023 Annual Meeting of the American Meteorological Society.

The transition into spring in 2023 again happened very quickly, as shown in Figure 8. Despite the large amounts of snowfall, the snow melted very quickly and the ERW was nearly snow-free by the end of May, 2023 (Figure 23). Major dust storms occurred in early April, 2023 and there is some preliminary evidence that some of the snowfall events in the winter and spring of 2023 scavenged dust. Therefore, the snow albedo again dropped to less than 0.5 in spring, enabling a large amount of solar energy to melt the snowpack.

Throughout this second spring transition period, SAIL, SPLASH, and SOS collected data and together were able to characterize the atmosphere and surface state evolution to compare to the previous spring and establish a set of events to analyze in detail to advance process understanding.

Figure 23. Launching the TBS at S-4 with Gothic Mountain in the background in June, 2023. Image courtesy of ARM.

Finally, as the middle of June, 2023 (and the SAIL end date) approached, temperatures started to warm and the final data sets were collected, including a late spring set of TBS flights. Unlike the previous summer, there was no early monsoon for the SAIL campaign to measure precipitation.

As a coda to the campaign conclusion in June, 2023, the SAIL, SPLASH, and SOS science team members gathered in person in Boulder and online, as shown in Figure 24. Here, sessions covered instrumentation, precipitation, aerosols, lower-atmospheric processes, and surface processes, as well as connections of the observations to atmospheric process and Earth system modeling.

Figure 24. Attendees of the First S3 Workshop in Boulder, Colorado. Photo by Gijs de Boer, November 1, 2023.

3.0 Results

With 21 months of data collected, the catalysis of two additional collaborative campaigns from SPLASH and SOS, 13 guest instruments, and the connections to the Watershed Function SFA, it is not straightforward to summarize all the science results that have occurred from SAIL to date. However, some highlights of the science are presented, and they necessarily begin with a presentation of the extent of the data that were collected. Figures 25 and 26 show the data quality and availability of the dozens of primary datastreams collected as part of the campaign. They show very limited outages and/or data quality issues, indicating a very solid foundation for the science being undertaken from SAIL.

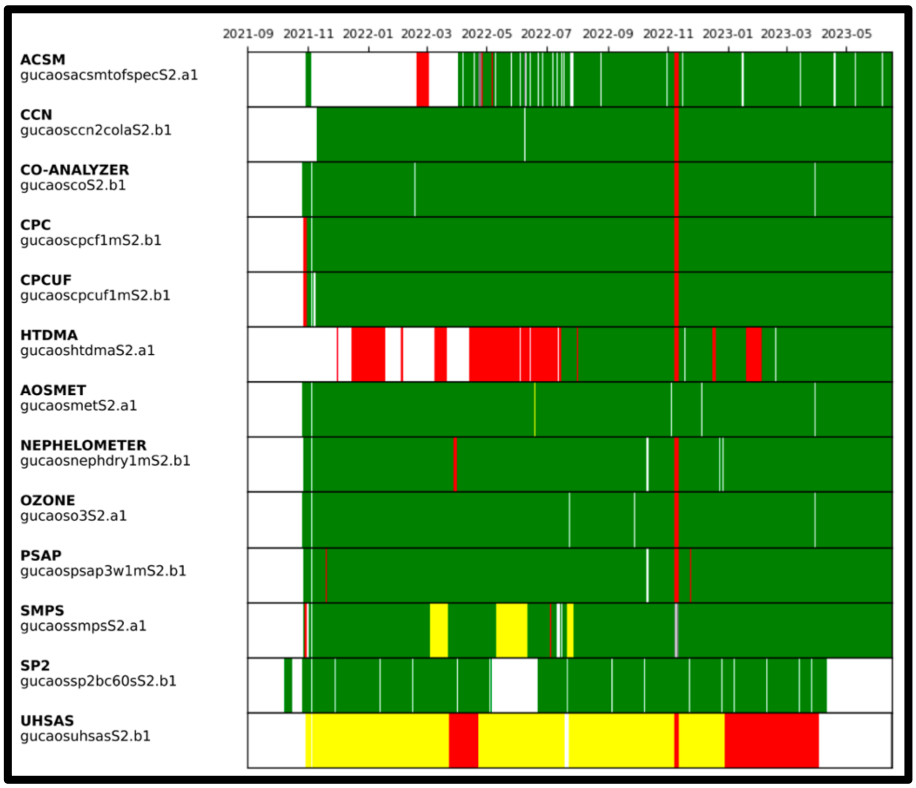


Figure 25. Depiction of the data quality and data availability from the SAIL AOS. Green indicates the data are available to download and have no identified data quality issues. Yellow indicates the data are available to download, but there may be data quality issues. Red indicates the data are available to download but known data quality issues exist. White indicates data are not available to download.

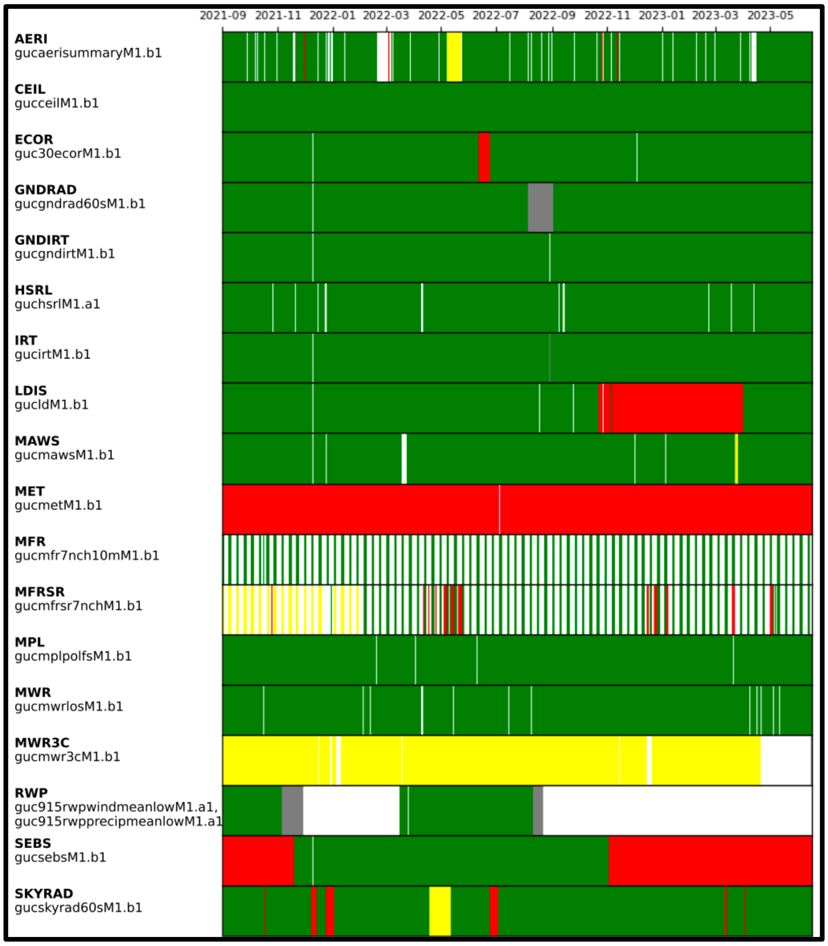


Figure 26. Same as Figure 25, but for the SAIL instruments at M-1.

3.1 Science Objective 1: Precipitation

In support of Science Objective 1, the SAIL instruments collected significant information on precipitation processes. Due to beam blockage from operational radar measurement in complex terrain, especially in the Upper Colorado River Basin, estimates of precipitation are challenging. The situation is so problematic that process model calculations of precipitation across the UCRB often exceed the skill that observational networks exhibit in estimating that precipitation (Lundquist et al. 2019).

Figures 27 and 28 shows SAIL filling this observational gap with regular scans of the X-band precipitation radar during a snowstorm that occurred in late winter of 2022. This figure also shows that the scanning capabilities of that radar enable a detailed analysis of the vertical distribution of precipitation. Furthermore, those measurements can be validated against the in situ snowfall measurements that SAIL collected with a Pluvio weighing-bucket rain gauge. In addition to depicting the temporal and spatial details of snowfall, the X-band radar measurements show the interactions between the complex terrain and precipitation patterns, which Figure 28 depicts. The location in altitude and range of the orographic enhancement of precipitation is clearly visible at 5 km from the radar and up to 0.5 km above the radar.

The details of the interactions between terrain and precipitation, shown in Figure 29, can be further explored, as in a recent paper by Heflin et al. (2024) that showed, for the first time, how dual-Doppler retrievals in complex terrain can reveal the circulation of air in complex terrain that leads to precipitation.

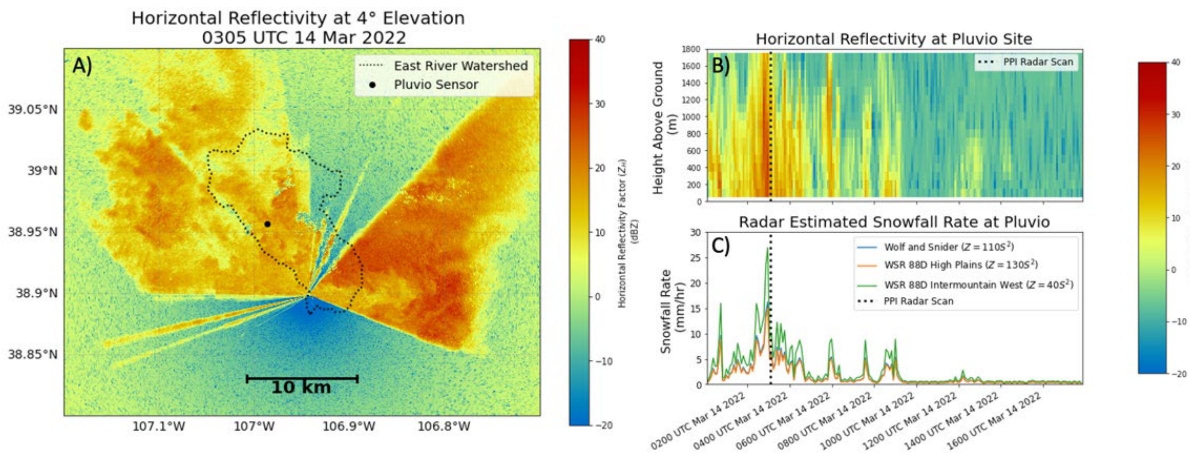


Figure 27. (a) Horizontal reflectivity collected at SAIL across the outline of the East River Watershed from a single plan position indicator (PPI) scan on March 14, 2022. (b) Reflectivity in the gate over the SAIL M-1 site from the range height indicator (RHI) scans that occurred throughout March 14, 2022. (c) Estimates of snowfall rate from published Z-S relationships as part of the Surface Quantitative Precipitation Estimation (SQUIRE) precipitation product.

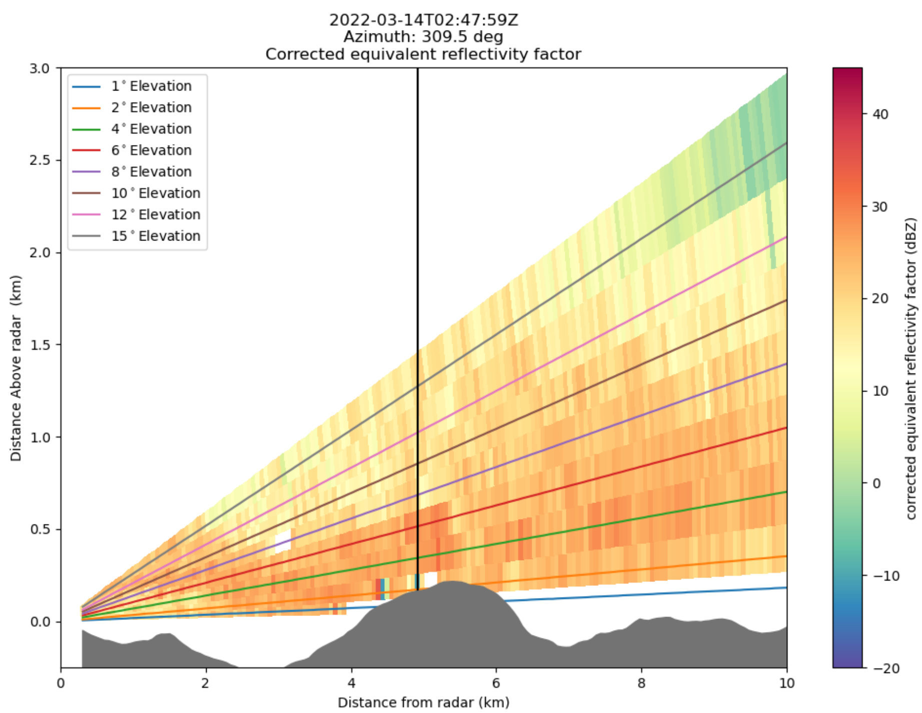


Figure 28. A single range height indicator scan from March 14, 2022 over Snodgrass Mountain showing the corrected equivalent reflectivity factor from the X-band scanning instrument.

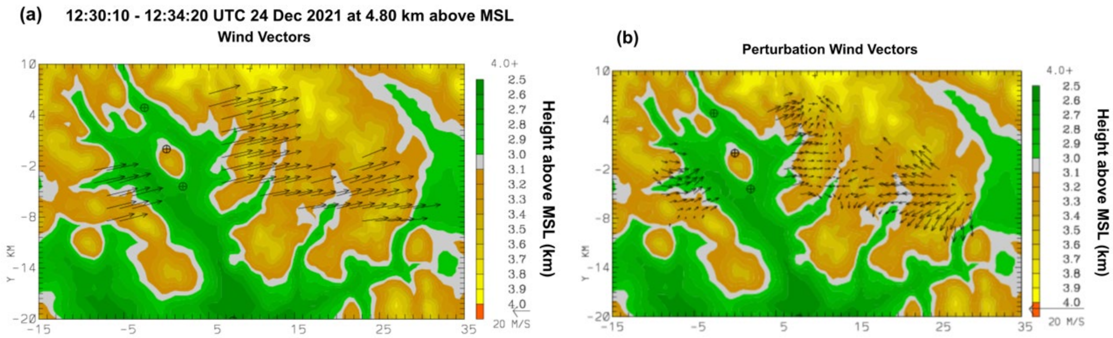
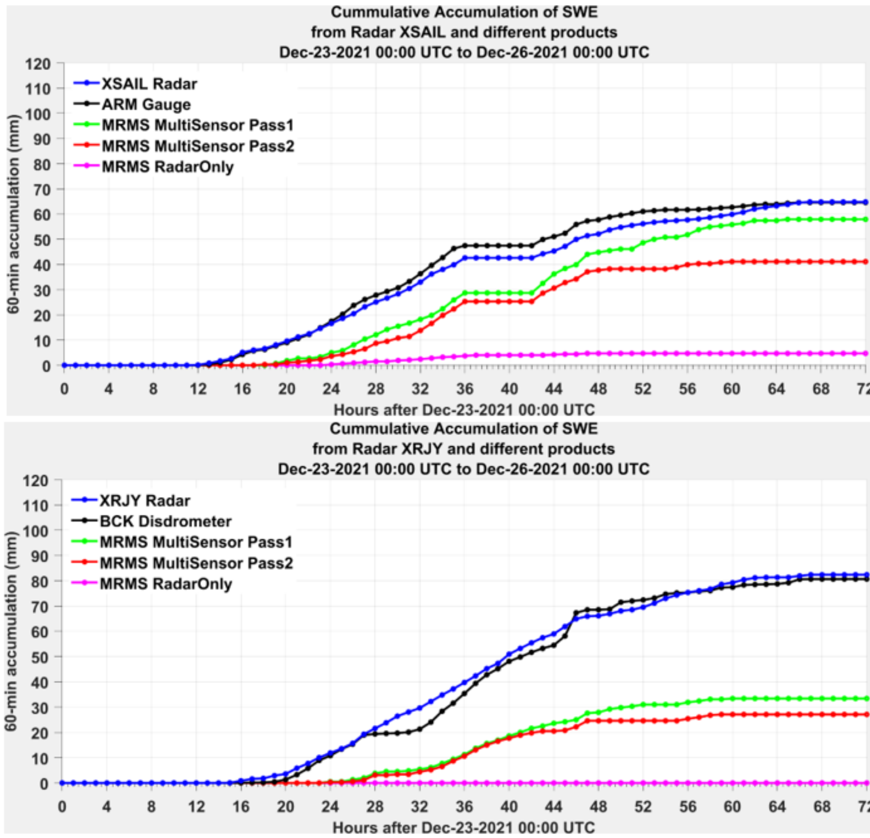


Figure 29. Doppler velocities in the East River Watershed on December 24, 2022 showing (a) the dominant wind flow associated with this storm, and (b) the local circulation that produces orographic precipitation enhancements during this storm. Adapted from Heflin et al. (2024).

Together, the continuous collection of precipitation measurements allowed for the determination of emergent patterns in precipitation, as well, which supports the connection to water resources. Figure 30 shows the value of X-band precipitation observations as well as the SAIL and SPLASH in situ observations for improving estimates of precipitation. Figure 30a shows the estimates of precipitation for part of the major precipitation event (the Santa Slammer) that occurred from December 23, 2021 to January 1, 2022. The SAIL X-band radar and the ARM precipitation gauge agree very well for cumulative precipitation, while the various estimates from the Multi-Radar Multi Sensor (MRMS) product do not. First, the MRMS product that is derived from operational radar measurements is extremely low-biased due to beam blockage, but efforts to compensate for beam blockage with in situ observations (excluding SAIL, SPLASH, and SOS data) with the MultiSensor Pass1 and Pass2 are still low-biased. Additionally, a comparable plot based on SPLASH radar measurements in Figure 30b shows that the MRMS radar-only estimate of precipitation is also low-biased relative to the SPLASH X-band radar and in situ observations (which again agree quite well) at the SPLASH Brush Creek location, while the observations from the Pass1 and Pass2 versions of MRMS are also low-biased, albeit less so. The differences in biases in MRMS at locations that are only a few km away at similar elevations point to the challenges of estimating precipitation in complex terrain without measurement campaigns such as SAIL/SPLASH/SOS and what is learned from those data.



(a)¶

(b)¶

Figure 30. Accumulated precipitation estimates for December 23-26, 2021 at (a) the SAIL M-1 site and (b) the SPLASH Brush Creek site from X-band precipitation radar Z-S relationships (blue), in situ disdrometer measurements (black), MRMS radar-only (pink), MRMS Pass1 (green), and MRMS Pass2 (red). From V. Chandra and S. Biswas.

Figure 31 shows the accumulated precipitation estimates from the SAIL X-band radar along with the array of in situ observations collected with SAIL/SPLASH/SOS. At the same time, the Watershed Function SFA worked with the Airborne Snow Observatories (ASO), which collected snow depth information with a scanning terrestrial lidar instrument (Painter et al. 2016). This figure shows broad agreement between the measured precipitation and the measured end-of-season snowfall, with notable exceptions in mountain valleys and some mountain ridges. There are clearly persistent areas of orographic precipitation enhancement that the SAIL radar measurements reveal, and those areas are persistent across years. The time-scales at which these patterns emerge is also relatively short.

Many of these results that advance SAIL's Science Objective 1 have been presented at scientific meetings with preliminary results being demonstrated in the published literature (Feldman et al. 2023, de Boer et al. 2023, Heflin et al. 2024).

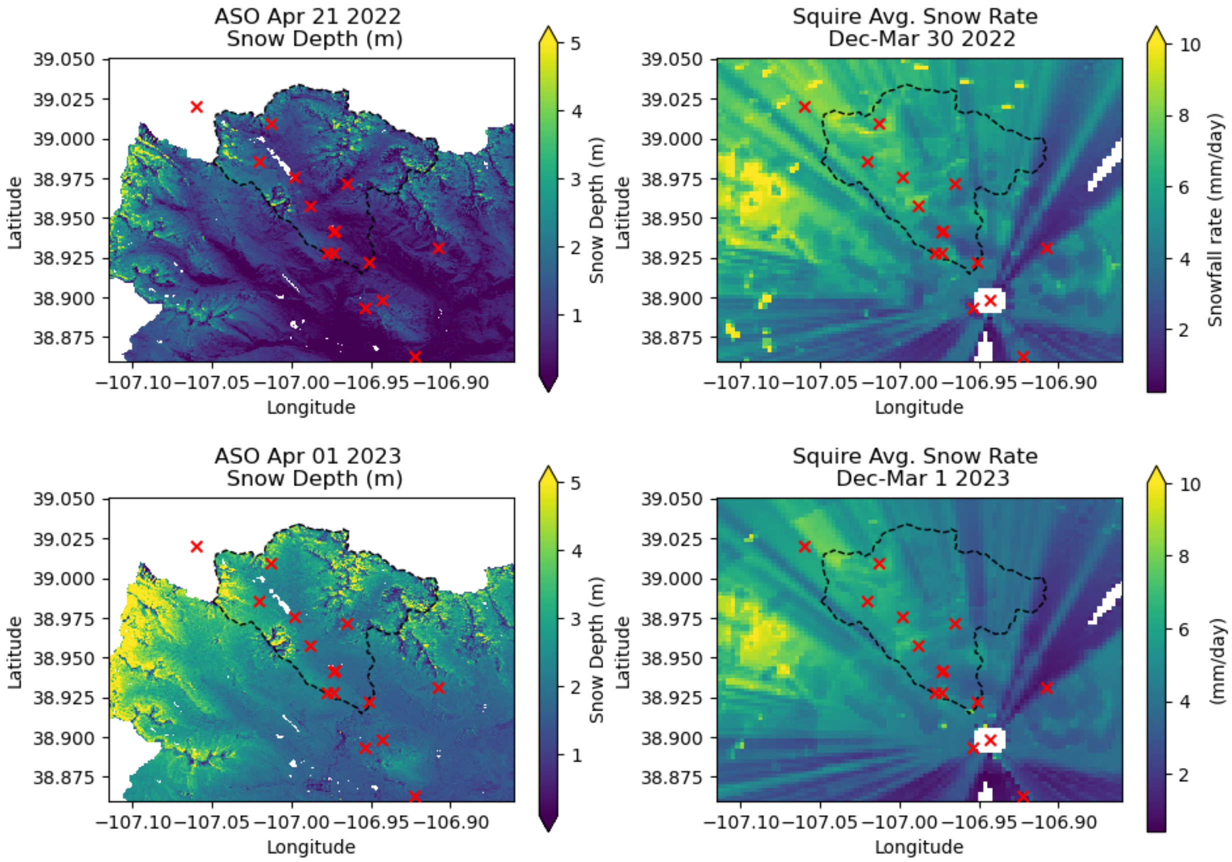


Figure 31. Spatial patterns of end-of-winter snowpack observed from ASO in 2022 and 2023 and daily average surface snowfall rate estimated in SAIL's SQUIRE data set for December 1, 2022 to March 30, 2022 and December 1, 2022 to March 1, 2023. The X-band radar from which the SQUIRE data is derived is located at the SAIL S-2 site denoted by the white circle at the bottom of the right panels. Snow depth measurements are shown as red dots.

3.2 Science Objective 2: Snow Processes

With SAIL, SPLASH, and SOS focusing on snow processes including wind redistribution, sublimation, and deposition, there has already been substantial work that represents a new frontier for ARM.

Figure 32 shows estimates of accumulated snowpack (in snow-water equivalent, or SWE) from SAIL and SPLASH instruments at Avery Picnic, Kettle Ponds, and at two measurements at the SAIL M-1 site (the SAIL Pluvio weighing-bucket rain gauge and the long-term observations collected by RMBL scientist Billy Barr) for the winter of 2021/2022 along with estimates of sublimated mass from eddy covariance systems. Also shown are the SWE estimates from the ASO snow survey on April 21, 2022. This plot indicates that sublimation is occurring during the spring snow melt, which is surprising given that sublimation was previously thought to occur mostly in winter (Vionnet et al. 2014, Mott et al. 2017).

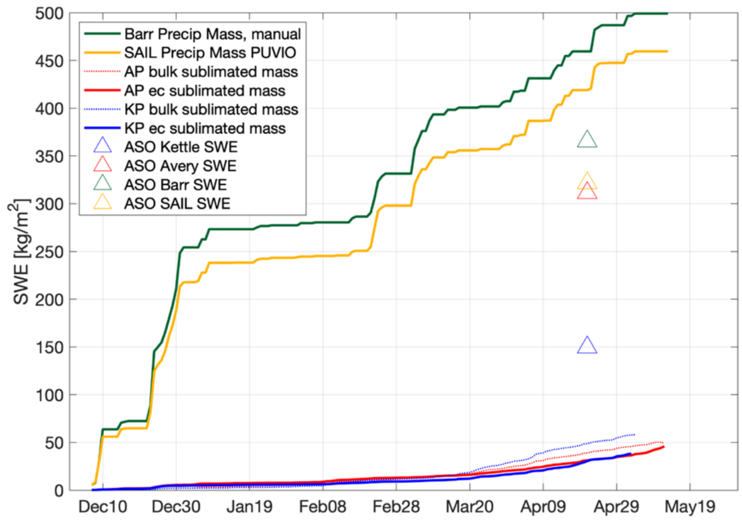


Figure 32. Seasonal estimates of accumulated precipitation at the SAIL M-1 site (green and orange), bulk thermodynamic (bulk) and eddy covariance (ec) estimates of sublimated mass, and ASO estimates of SWE at the Avery Picnic (AP) and Kettle Ponds (KP) SPLASH sites. From C. Cox.

Additionally, the detailed observations of the wind field over SAIL from the Doppler lidar have enabled a detailed characterization of the turbulence in the East River valley – in particular, how it forms and dissipates with westerly flow over Gothic Mountain. A single scan from the Doppler lidar is shown in Figure 33; these were collected every few minutes for the duration of the campaign.

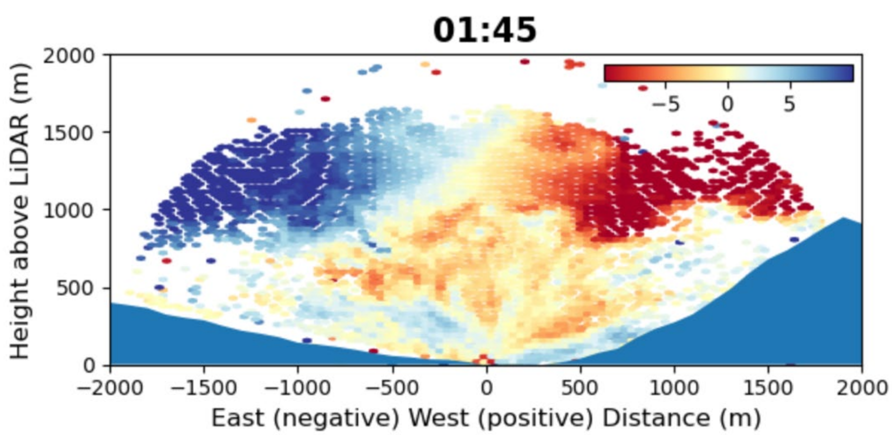


Figure 33. A single SAIL Doppler lidar range height indicator scan from January 12, 2023. Red indicates wind movement from Gothic Mountain (on right) towards the SAIL M-1 site, while blue indicates wind movement away from Gothic Mountain. From E. Schwat.

Finally, another surface-atmosphere snow process that has not been studied by ARM is thermodynamic deposition. A small amount of water from the atmosphere deposits to the surface during cold winter nights, creating frost layers that influence snow stability (Colbeck 1988). The observations at SAIL of surface temperature and humidity, as shown in Figure 34, indicate the occurrence of deposition (blue) and sublimation (red).

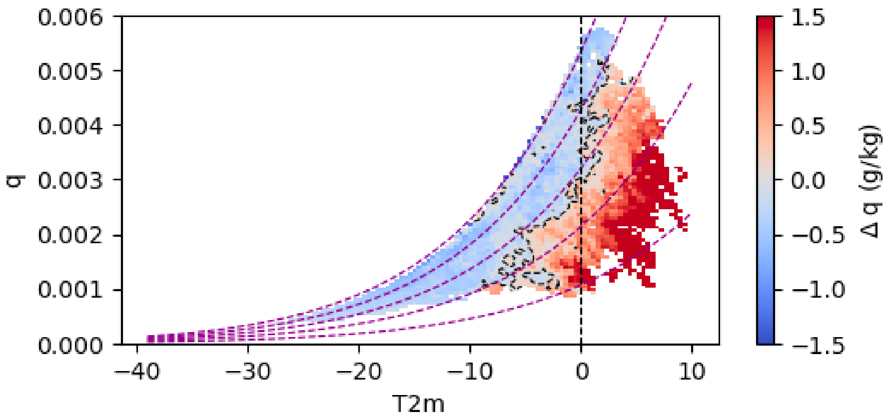


Figure 34. Dashed purple lines show vapor pressure curves with respect to ice, with top-most representing 100% saturation and lower curves representing 10% decrements of relative humidity. Color dots represent the SAIL near-surface (2 meter to surface) specific humidity gradient based on surface 2-meter air temperature and humidity and surface skin temperature.

3.3 Science Objective 3: Aerosols

The wide set of aerosol measurements collected at SAIL have provided insights into the aerosol regimes in the UCRB. The data show that, overall, there is strong seasonality to the aerosol number concentrations, with very pristine conditions in winter and punctuated aerosol intrusion events from dust storms and wildfire smoke, as shown in Figure 35.

The dust storms that regularly deposit dust onto the snowpack in the ERW occurred throughout both the spring of 2022 and spring of 2023. Figure 36 shows that there were two dominant synoptic flow patterns associated with dust deposition: from the southwest and from the northwest associated with a synoptic-scale trough and ridge, respectively. Meanwhile, Figures 37 and 38 show broad concurrence across the SAIL study area with aerosol number concentration, as SAIL-Net shows that horizontal variability in aerosols is minimal (Figure 37) while the TBS shows that vertical variability in aerosols is minimal (Figure 38). This is a remarkable finding, indicating that a single time-series measurement of aerosol number concentration in complex terrain, absent local sources, can characterize the aerosol concentration throughout the boundary layer.

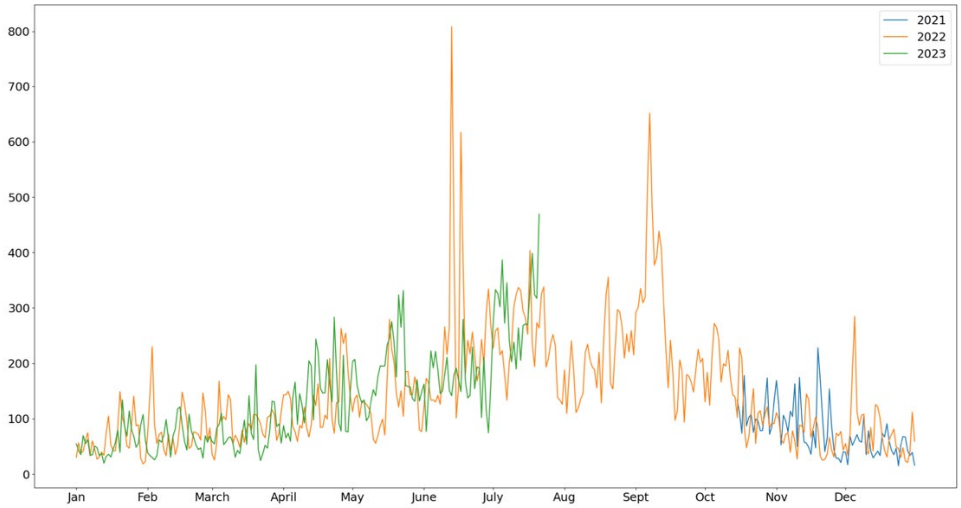


Figure 35. The seasonal cycle, with punctuated aerosol intrusion events, of sub-micron aerosol concentrations (y-axis) as measured by the AOS in 2021, 2022, and 2023.

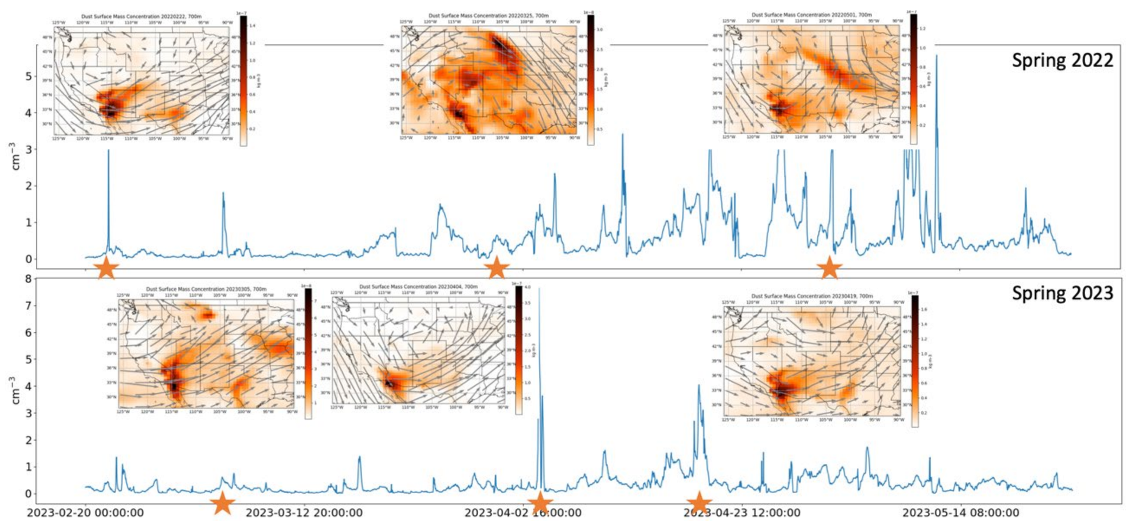


Figure 36. Spring 2022 and spring 2023 time-series of total aerosol super-micron concentration measured by the SAIL AOS with six events highlighted by stars and the MERRA-2 dust surface mass concentration with 500-mbar wind vectors overlain, showing the two synoptic patterns that deposit dust on the East River Watershed.

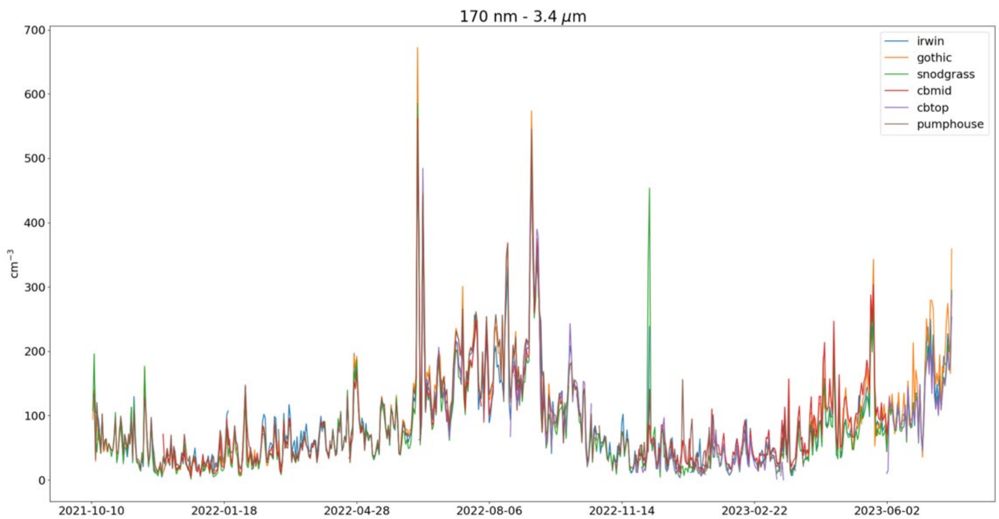


Figure 37. SAIL-Net aerosol number concentration as measured by printed optical particle spectrometer (POPS) for size-cut from 170 nm-3.4 µm showing a seasonal cycle with punctuated large aerosol intrusion or local formation events with broad concurrence in aerosol amount across the East River Watershed.

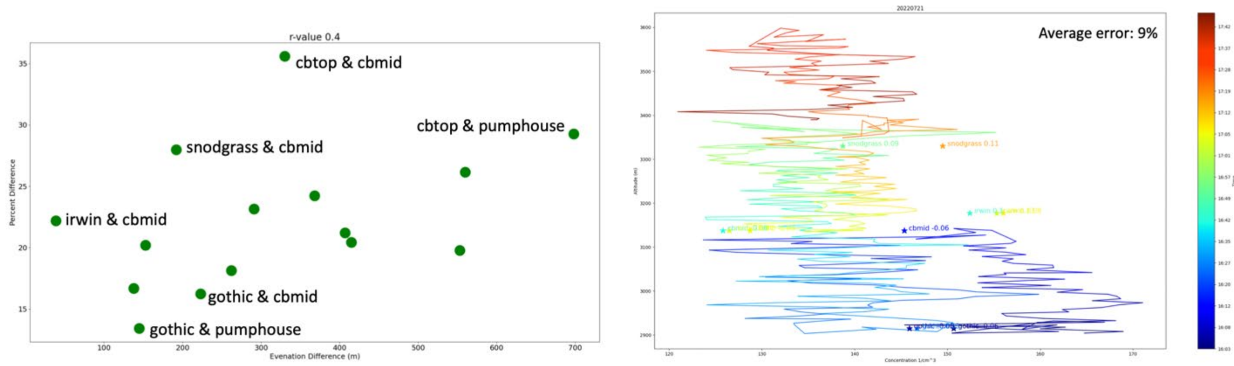


Figure 38. Intercomparison of SAIL-Net aerosol number concentrations relative to measurements at the S-2 site for a size-cut from 170 nm-3.4 µm with the number concentration of that same quantity, but measured by POPS on the TBS.

The impact of these aerosols on atmospheric radiation, including surface albedo, is significant. Figure 39 shows the spectral surface albedo measured at M-1 from the AMF-2 MFRSR instrument. Impurities in the snowpack greatly influence albedo at 415 nm, while changing snow-grain size impacts the albedo at 870 and 940 nm (Warren 1982). The time-series show snow aging (increasing grain size) in winter (little change in 415-nm albedo but variability in 870 -and 940-nm albedo) in between precipitation events and then rapid decreases in snow albedo across all channels associated with snow impurities (dust deposition), and then rapid snowmelt in spring.

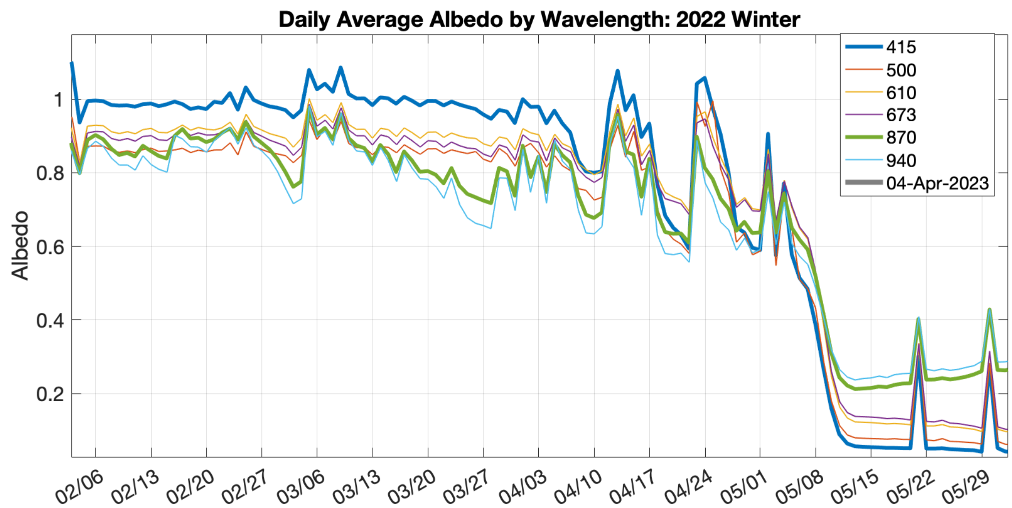


Figure 39. Spectral albedo from the SAIL MFRSR instrument at M-1 from February 6 to June 1, 2022. Courtesy of L. Riihimaki.

Additionally, many aerosols in the transition and warm seasons at SAIL reveal new particle formation (NPF) events that arise when all the snow has melted (Figure 40). These aerosols are biogenic and range from 10-100 nm in diameter, and the 21 months of SAIL data show that NPF events occur regularly each spring when the snow disappears.

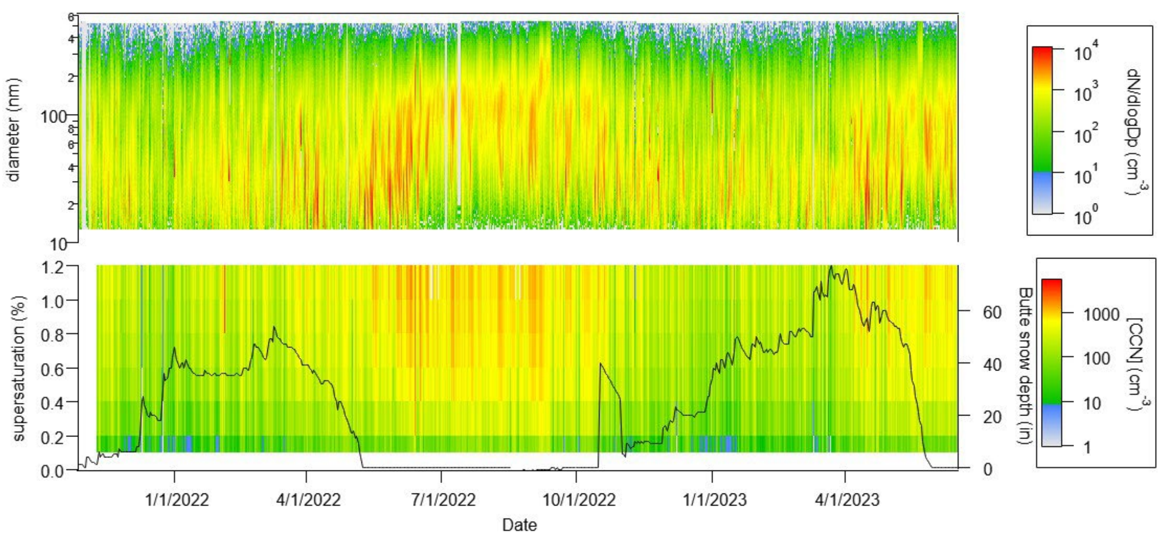


Figure 40. Evidence of new particle formation at the SAIL S-2 site during the campaign. Courtesy of J. Smith.

3.4 Science Objective 4: Ice Nucleating Particles

The horizontal and vertical information on INP collected by SAIL was unprecedented in complex terrain, with INP data collected at the SAIL S-2 site, by SAIL-Net, and with the TBS. The seasonality of INP spectra already reveal that biogenic and aeolian processes are responsible for INP at different times of year.

Researchers principally from CSU are leading efforts to analyze the INP data to determine their seasonal variability as well as the underlying causes (such as dust deposition or biogenic formation) of such variability (Figure 41). The observations of INP provide a critical data set for understanding the importance of INP for precipitation. That is, these data will help show if precipitation is limited by INP in the East River Watershed, and if so, when and why.

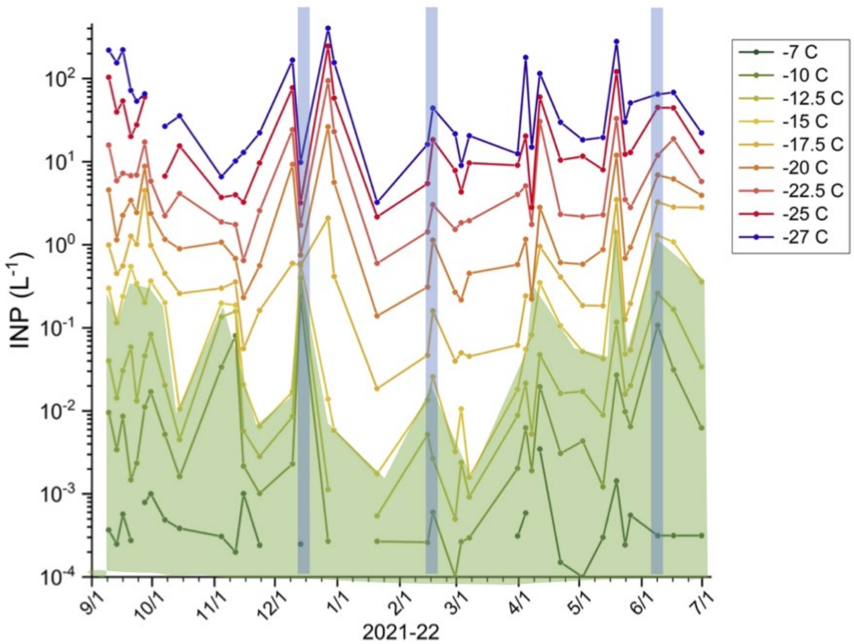


Figure 41. The seasonality of INP spectra as measured at the SAIL S-2 site. Courtesy of J. Creamean and S. Kreidenweis.

3.5 Science Objective 5: Surface Energy Balance

The SAIL, SPLASH, and SOS campaigns collected unprecedented information on the surface energy balance in the East River Watershed. The contributions of net radiation, sensible and latent heat fluxes, and ground and storage flux terms were all measured, allowing for direct efforts to achieve SEB closure.

First, as Figure 42 shows, there is significant seasonal and diel variability in the terms that contribute to the SEB. The net radiation dominates the SEB in summer and winter, while sensible, latent, and ground heat flux terms are smaller. Additionally, the substantial amount of under-closure of the SEB indicates that measurements of these quantities do not capture the entire set of processes that contribute to the SEB. More analysis is required.

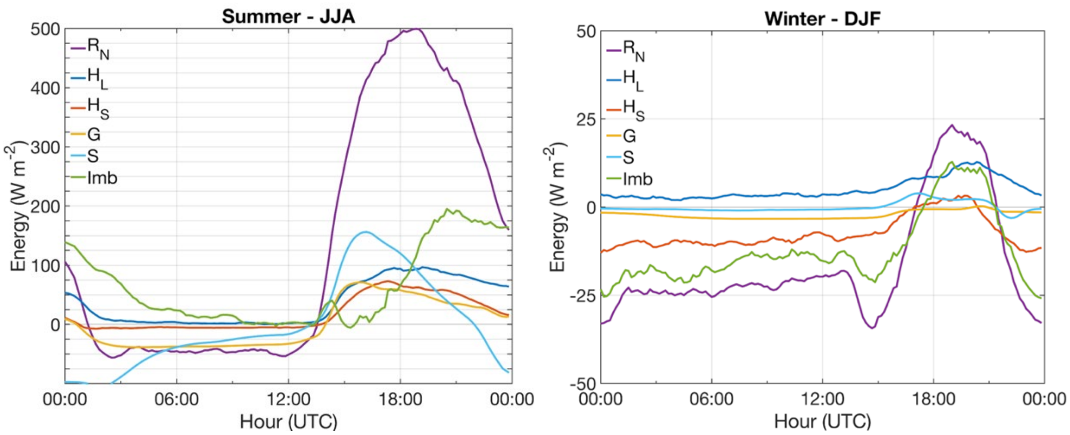


Figure 42. Diel variability in SEB terms measured at SAIL M-1 during (a) summer 2022 and (b) winter 2021/2022. RN = net shortwave and longwave radiation. HL = turbulent flux of latent heat. HS = turbulent flux of sensible heat. G = ground heat flux, S = storage heating, and Imb = imbalance (under-closure).

The imagery and videography collected by SAIL afford a unique opportunity to understand the hyper-local conditions under which SAIL data were collected to understand this imbalance further. Figure 43 shows an example of thermal imagery collected at the S-4 site indicating the very large impacts of three-dimensional radiation on surface temperature.

Project	TBS SAIL IV	Ambient	13.6 °C
Date	June 10, 2023 15.40.08	Humidity	25.2%
Date	2023:06:10	GPS Latitude	38° 55' 18.14" N
Time	16:56:30	GPS Longitude	106° 57' 1.26" W
Comments	100m	GPS Altitude	2896.000000 m
Emissivity	0.9	GPS Heading	23.459999°

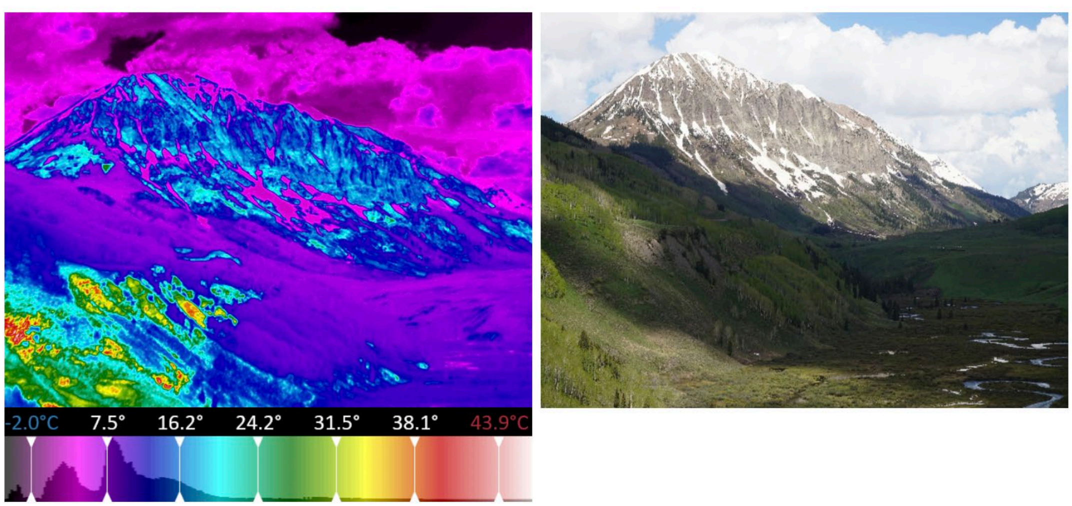


Figure 43. Visible and thermal imagery collected at SAIL S-4 on June 10, 2023.

As Figure 43 shows, clouds have a substantial role impacting the SEB. This represents an emerging scientific finding from the SAIL, SPLASH, and SOS data. Figure 44 shows impressive variability in cloud frequency across seasons and times of day. The many processes at play can be investigated using detailed information from multiple SAIL datastreams, as well as characterization based on large-scale circulation, as shown in Figure 45 with satellite imagery. That figure shows that dynamically driven clouds (with turbulence contributing to high cloud amounts during melt) occur in spring, while thermally driven clouds are generated in the summer, clearly evident in the frequency of afternoon (not morning) clouds in the warm season at SAIL

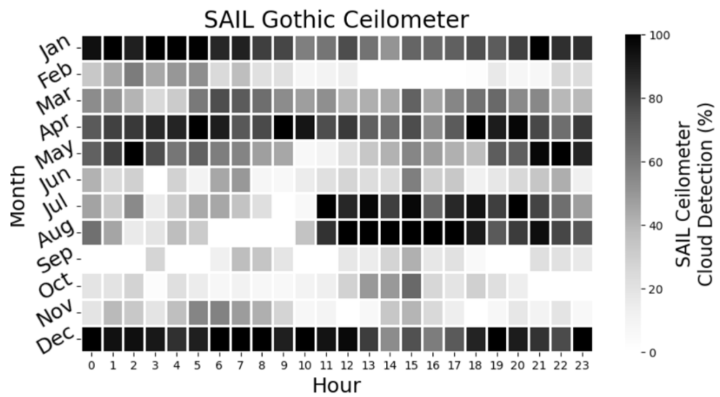


Figure 44. Ceilometer cloud detection frequency at the SAIL M-1 site versus time of day and month. Courtesy of D. Hogan.

Figure 45. Visible imagery from the Geostationary Operational Environmental Satellite (GOES) highlighting the different cloud patterns that occur across spring and summer and hinting at the different processes responsible for cloud generation in the UCRB.

3.6 The S^3 Community

Building off the momentum of the November 1-3, 2023 SAIL/SPLASH/SOS Science Summit, the community of researchers supported by DOE, NOAA, and NSF to focus on mountainous hydrometeorological and hydroclimatological research recognized the need for an organizational structure to facilitate communication, collaboration, and scientific synergy. The result is the S^3 Community, which has not just a logo (Figure 46) but an ambitious set of science activities, as shown in Figure 47.

Figure 46. Joint S³ Community Logo generated as part of the November 1-3, 2023 SAIL/SPLASH/SOS Science Summit. The logo helps connect the SAIL, SPLASH and SOS science efforts.

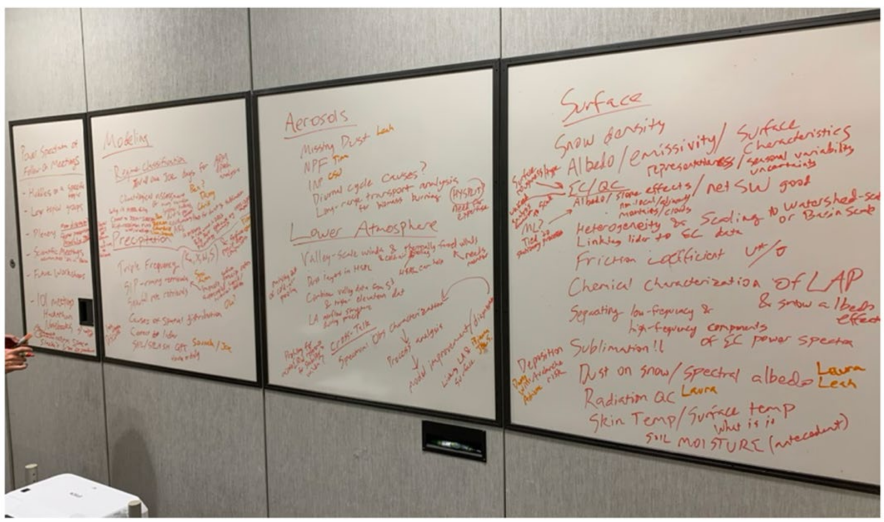


Figure 47. Idea board created at the First S³ workshop (Boulder, Colorado November 1-3, 2023) outlining near-term S³ science activities using SAIL, SPLASH, and SOS data.

4.0 Public Outreach

The SAIL campaign involved a wide range of public outreach activities that contributed to the profile of the campaign, which in turn had follow-on science benefits in terms of attracting guest instruments and the SPLASH and SOS campaigns and their associated collaboration.

From the start of the SAIL campaign, the science team recognized the critical importance of water resources in the UCRB and was able to leverage the widespread societal interest in Colorado River water resources that arose due to the record low water levels that occurred in August, 2021.

The ARM communications team worked actively with the Strategic Communications teams at LBNL and LANL to produce a slew of news articles describing the launch of the campaign. These proliferated in the Washington Post, Science Magazine, EOS, and local news articles across the Western Slope of Colorado and the Rockies. Additional outreach connected with local newspapers and radio and television stations. SAIL was featured on Colorado Public Radio and on documentary television pieces including Wings above the Rockies. SAIL was also regularly featured in the ARM and ASR newsletters with the following nine blog posts:

Blog posts:

- November 17, 2020: Setting a Course for SAIL
- June 16, 2021: SAIL Group Makes Snow Trek to Survey Sites in Colorado
- July 20, 2021: SAIL ARM Mobile Facility Site Takes Shape
- October 21, 2021: TBS Put to the Test for SAIL Science Flights
- January 25, 2022: Snow Finally Comes to SAIL
- July 28, 2022: Dust in the Wind at SAIL
- September 27, 2022: Summertime, and the Living is Soggy at SAIL
- April 20, 2023: Not SAIL-ing into Spring 2023
- July 20, 2023: After a Long Stop, ARM Instruments Await their Next Destination

Additionally, SAIL's close partnership with RMBL enabled significant public outreach by engaging the hundreds of scientists who work at RMBL each year and the thousands of elementary and high school students that tour the facility. The students got first-hand experience with SAIL data collection, as shown in Figure 48 where high school students from Amigos de las Americas learned how to launch a weather balloon.

Figure 48. High school volunteers from Amigos de las Americas stay dry while filling a weather balloon in SAIL's M-1 sonde shelter in preparation for a sonde launch on July 27, 2022.

Figure 49. Aerial footage of the East River Watershed facing north towards the SAIL M-1 site and Gothic Mountain on March 22, 2023. Photo by Jeremy Snyder, LBNL.

5.0 Publications

5.1 Journal Articles/Manuscripts

Adler, B, JM Wilczak, L Bianco, L Bariteau, CJ Cox, G de Boer, IV Djalalova, MR Gallagher, JM Intrieri, TP Meyers, TA Myers, JB Olson, S Pezoa, J Sedlar, E Smith, DD Turner, and AB White. 2023. "Impact of seasonal snow-cover change on the observed and simulated state of the atmospheric boundary layer in a high-altitude mountain valley." *Journal of Geophysical Research – Atmospheres* 128(12): e2023JD038497, https://doi.org/10.1029/2023JD038497

Cowherd, M, U Mital, S Rahimi, M Girotto, A Schwartz, and D Feldman. 2024. "Climate change-resilient snowpack estimation in the Western United States." *Communications Earth and Environment* (in revision).

de Boer, G, A White, R Cifelli, J Intrieri, M Hughes, K Mahoney, T Meyers, K Lantz, J Hamilton, W Currier, J Sedlar, C. Cox, E Hulm, LD Riihimaki, B Adler, L Bianco, A Morales, J Wilzcak, J Elston, M Stachura, D Jackson, S Morris, V Chandrasekar, S Biswas, B Schmatz, F Junyent, J Reithel, E Smith, K Schloesser, J Kochendorfer, M Meyers, M Gallagher, J Longecker, C Olheiser, J Bytheway, B Moore, R Calmer, B Butterworth, S Heflin, R Palladino, D Feldman, K Williams, J Pinto, E Hall, C Herrera, G Hodges, L Soldo, S Stierle, and RS Webb. 2023. "Supporting Advancement in Weather and Water Prediction in the Upper Colorado River Basin: The SPLASH Campaign." *Bulletin of the American Meteorological Society* 104(10): E1853–E1874, https://doi.org/10.1175/BAMS-D-22-0147.1

Feldman, DR, M Worden, N Falco, Z Xu, B Dafflon, PJ Dennedy-Frank, and H Wainwright. 2022. "Three-dimensional Surface Downwelling Longwave Radiation Effects in the Upper Colorado River Basin." *Geophysical Research Letters* 49(4): e2021GL094605, https://doi.org/10.1029/2021GL094605

Feldman, DR, AC Aiken, WR Boos, RWH Carroll, V Chandrasekar, S Collis, JM Creamean, G de Boer, J Deems, PJ DeMott, J Fan, AN Flores, D Gochis, M Grover, TCJ Hill, A Hodshire, E Hulm, CC Hume, R Jackson, F Junyent, A Kennedy, M Kumjian, EJT Levin, JD Lundquist, J O'Brien, MS Raleigh, J Reithel, A Rhoades, K Rittger, W Rudisill, Z Sherman, E Siirila-Woodburn, SM Skiles, JN Smith, RC Sullivan, A Theisen, M Tuftedal, AC Varble, A Wiedlea, S Wielandt, K Williams, and Z Xu. 2023. "The Surface Atmosphere Integrated Field Laboratory (SAIL) Campaign." *Bulletin of the American Meteorological Society* 104(12): E2192–E2222, https://doi.org/10.1175/BAMS-D-22-0049.1

Gibson, L, E Emerson, N Good, A Hodshire, E Levin, G McMeeking, K Patterson, T Ramon, and B Swanson. 2024. "SAIL-Net: An investigation of spatial variability of aerosol in mountainous terrain." *Atmospheric Chemistry and Physics* (in preparation).

Heflin, S, M Hughes, S Biswas, A Morales, R Cifelli, J Sedlar, D Feldman, V Chandrasekar, and P Kennedy. 2024. "X-band Radar and Surface-based Observations of Cold Season Precipitation in Western Colorado's Complex Terrain." *Journal of Hydrometeorology* (in revision).

Lundquist, JD, J Vano, E Gutmann, D Hogan , E Schwat , M Haugeneder, E Mateo, S Oncley, C Roden, E Osenga, and L Carver. 2024. "Sublimation of Snow." *Bulletin of the American Meteorological Society* (in press).

Maahn, M, D Moisseev, I Steinke, N Maherndl, and M Shupe. 2024. "Introducing the Video In Situ Snowfall Sensor (VISSS)." *Atmospheric Measurement Techniques* 17(2), https://doi.org/10.5194/amt-17-899-2024

Moran, M, K Woputz, D Hee, M Girotto, P D'Odorico, R Gupta, D Feldman, P Vahabi, A Todeschini, and CJ Reed. 2022. "Snowpack Estimation in Key Mountainous Water Basins from Openly-Available, Multimodal Data Sources." *Computer Vision and Pattern Recognition 2022 MultiEarth*, https://doi.org/10.48550/arXiv.2208.04246

Nie, Y, X Li, Q Paletta, M Aragon, A Scott, and A Brandt. 2024. "Open-source sky image datasets for solar forecasting with deep learning: A comprehensive survey." *Renewable and Sustainable Energy Reviews* 189(Part B): 113977, https://doi.org/10.1016/j.rser.2023.113977

Rudisill, WJ, AN Flores, HP Marshall, E Siirila-Woodburn, DR Feldman, AM Rhoades, Z Xu, and A Morales. 2024a. "Cold-Season Precipitation Sensitivity to Microphysical Parameterizations: Hydrologic Evaluations Leveraging Snow Lidar Datasets." *Journal of Hydrometeorology* 25(1): 143–160, https://doi.org/10.1175/JHM-D-22-0217.1

Rudisill, W, D Feldman, Z Xu, and A Rhoades. 2024b. "Are atmospheric models too cold in mountains? The state of science and insights from the SAIL field campaign." *Bulletin of the American Meteorological Society* (accepted).

Sedlar, J, T Meyers, CJ Cox, and B Adler. 2024. "Low-level liquid-bearing clouds contribute to seasonal lower atmosphere stability and surface energy forcing over a high-mountain watershed environment." *Journal of Hydrometeorology* (accepted).

U.S. DOE. 2023. *Understanding and Predictability of Integrated Mountain Hydroclimate Workshop Report*. U.S. Department of Energy. DOE/SC-0210. https://doi.org/10.2172/1967878

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Xu, Z, ER Siirila-Woodburn, AM Rhoades, and D Feldman. 2023. "Sensitivities of subgrid-scale physics schemes, meteorological forcing, and topographic radiation in atmosphere-through-bedrock integrated process models: A case study in the Upper Colorado River Basin." *Hydrology and Earth System Sciences* 27(9): 1771–1789, https://doi.org/:10.5194/hess-27-1771-2023

5.2 Meeting Abstracts/Presentations/Posters

Aiken, A, et al. 2023. "Seasonal Aerosol Regimes and Processes Observed in Mountainous Terrain at Surface Atmosphere Integrated Field Laboratory (SAIL)." Presented at the 2023 Joint ARM User Facility and ASR Principal Investigator Meeting.

Biswas, S, et al. 2022. "Wintertime Precipitation Estimation in the East River Watershed of the Colorado Mountains Using X-Band Radar during SPLASH and SAIL Experiments." Presented at the Fall 2022 American Geophysical Union Meeting, H22F-02.

Biswas, S, et al. 2023. "Microphysical Cross-validation of the ARM Ka-band Radar (KAZR) and Dual-polarization X-Band Radar during the SAIL." Presented at the Fall 2023 American Geophysical Union Meeting, H41J-1893.

Collis, S, M Grover, D Feldman, and M Ilhi. 2023. "Open Science in the Rockies: Working with ARM Data from the Surface Atmosphere Integrated Field Laboratory." Short Course presented at the 2023 American Meteorological Society Meeting.

Cowherd, M, et al. 2023. "ML for Climate-change resilient snowpack estimation in the Western United States." Presented at the 2023 HydroML Symposium.

Cowherd, M, et al. 2023. "Future changes in Western U.S. snow distribution predictability: the case for using multi-modal observations within artificial intelligence models." Presented at the Fall 2023 American Geophysical Union Meeting, H41I-1886.

DeMott, P, et al. 2023. "Aerosol Influences on Ice Nucleating Particles (INPs) Interpreted through INP, Online and Single-Particle Aerosol Characterization Measurements in SAIL." Presented at the 2023 Joint ARM User Facility and ASR Principal Investigators Meeting.

Fan, J, et al. 2022. "How do dust and marine aerosols impact snow precipitation over the western U.S. mountainous region?" Presented at the Fall 2022 American Geophysical Union Meeting, H22F-04.

Feldman, D, and S Collis. 2020. "Advancing Atmospheric Process Studies in High-Altitude Complex Terrain with the Surface Atmosphere Integrated field Laboratory (SAIL) Campaign." Breakout Session, 2020 Joint ARM User Facility and ASR Principal Investigators Meeting.

Feldman, DR, and C Kuang. 2020. "ARM Mobile Facility Deployments." Presented at the 2020 ESS Principal Investigators Meeting.

Feldman, DR et al. 2020. "Quantifying Biases from Neglecting Three-Dimensional Longwave Radiative Effects in Simple and Complex Terrain." Presented at the 2020 Joint ARM User Facility and ASR Principal Investigators Meeting.

Feldman, DR, et al. 2020. "The Surface Atmosphere Integrated Field Laboratory (SAIL) Virtual Workshop." September 23-24, 2020.

Feldman, DR, et al. 2020. "The Surface Atmosphere Integrated Field Laboratory (SAIL) ARM Mobile Facility Campaign for Mountainous Hydrology Research." Presented at the Fall 2020 American Geophysical Union Meeting, TH051.

Feldman, DR, E Gutmann, and V Chandrasekar. 2021. "Improvements to the Analysis and Prediction of Drought. Part II; Advancing Atmospheric and Surface Process Understanding through Modeling and Observations in High-Altitude Complex Terrain. Part I." Presented at the 2021 American Meteorological Society Annual Meeting, 35th Conference on Hydrology.

Feldman, D, et al. 2021. "The Surface Atmosphere Integrated Field Laboratory (SAIL) Field Campaign." Presented at the 2021 Land-Atmosphere Interactions Workshop.

Feldman, D, G de Boer, and S Collis. 2021. "SAIL and SPLASH: Coordinated Observations and Atmospheric Process Studies in High-Altitude Complex Terrain." Breakout Session, 2021 Joint ARM User Facility and ASR Principal Investigators Meeting.

Feldman, D, et al. 2021. "The Surface Atmosphere Integrated Field Laboratory (SAIL) Campaign." Presented at the 2021 Joint ARM User Facility and ASR Principal Investigators Meeting.

Feldman, D, et al. 2021. "SAIL Campaign Aerosol Measurements." Aerosol Process Breakout Session, 2020 Joint ARM User Facility and ASR Principal Investigators Meeting.

Feldman, D, et al. 2021. "Campaign Updates from the Surface Atmosphere Integrated Field Laboratory (SAIL)." Warm Boundary Layer Breakout Session, 2021 Joint ARM User Facility and ASR Principal Investigators Meeting.

Feldman, DR, KH Williams, G de Boer, R Cifelli, and AB White. 2021. "SAIL and SPLASH: Integrated Mountainous Hydrology Science and Observations in the Upper Colorado River Basin." Presented at the Fall 2021 American Geophysical Union Meeting, TH25I.

Feldman, DR, et al. 2021. “Using SAIL Campaign Measurements and Integrated Process Modeling to Better Understand the Headwater Hydrology of the Upper Colorado River Basin.” Presented at the Fall 2021 American Geophysical Union Meeting, H21C-02.

Feldman, DR, et al. 2021. “The Shelf-Life of Hydro-Climate Downscaling Bias-Correction over the Western United States.” Presented at the Fall 2021 American Geophysical Union Meeting, A53E-04.

Feldman, DR, et al. 2022. “A Need for Large-Eddy Simulations to Estimate Snow Sublimation in High-Altitude Complex Terrain.” Presented at the 2022 Large Eddy Simulation Workshop.

Feldman, DR, et al. 2022. “Select Highlights of Integrated Observations and Modeling of the Surface Energy Budget at SAIL.” Presented at the 2022 ESS Principal Investigators Meeting.

Feldman, DR, et al. 2022. “First Light from the Surface Atmosphere Integrated Field Laboratory and their Implications for Atmosphere-through-Bedrock Science.” Presented at the 20th Conference on Mountain Meteorology of the American Meteorological Society, Park City, Utah.

Feldman, D. 2022. “The Surface Atmosphere Integrated Field Laboratory (SAIL) Atmosphere through Bedrock Science to Advance Mountainous Hydrology.” Field Trip, 2022 MtnClim Meeting, Gothic, Colorado.

Feldman, D. 2022. “Measuring, Understanding and Predicting Western Water.” Presented at the Council on State Governments-West. Henderson, Nevada.

Feldman, D, and G de Boer. 2022. “Scientific Findings from the First Year of SAIL and SPLASH Observations and Directions for the Coming Year.” Breakout Session, 2022 Joint ARM User Facility and ASR Principal Investigators Meeting.

Feldman, D, et al. 2022. “SAIL Campaign Aerosol Measurements.” Aerosol Process Breakout Session, 2022 Joint ARM User Facility and ASR Principal Investigators Meeting.

Feldman, D, et al. 2022. “A year in the Colorado Rockies – Perspectives on science opportunities from the first half of SAIL.” Presented at the 2022 Joint ARM User Facility and ASR Principal Investigators Meeting.

Feldman, D, et al. 2022. “Surveying the First Year of SAIL Data and Formulating Hypotheses for its Second Year.” Presented at the Fall 2022 American Geophysical Union Meeting, H25M-1258.

Feldman, DR, G de Boer, J Lundquist, and E Siirila-Woodburn. “Field and remote sensing observations and modeling of hydrology and its change in high-altitude complex terrain.” Presented at the 37th Conference on Hydrology of the 2023 American Meteorological Society.

Feldman, D, KH Williams, B Arora, and M Newcomer. 2023. “Community Research Activities to Support Mountainous Hydrology at the East River Watershed.” Presented at the 2023 ESS Principal Investigator Meeting.

Feldman, DR. 2023. "Know Your Data: Opportunities and Challenges of Using Real (and Messy) Data to Build AI/ML Models for Quantitative Precipitation Estimation in High-Altitude Complex Terrain." Presented at the 2023 HydroML Symposium.

Feldman, DR, et al. 2023. "Summary of and Selected Highlights from the Surface Atmosphere Integrated Field Laboratory (SAIL) Field Campaign." Presented at the 2023 Joint ARM User Facility and ASR Principal Investigators Meeting.

Feldman, DR, G de Boer, A Aiken, and S Collis. 2023. "Atmospheric Observations and Science Highlights to Support Hydrometeorological and Hydroclimatological Studies in Complex Terrain with Highlights from SAIL, SPLASH, and SOS." Breakout Session, 2023 Joint ARM User Facility and ASR Principal Investigator Meeting.

Feldman, DR, et al. 2023. "Surveying the First Year of SAIL Data and Formulating Hypotheses for its Second Year." Presented at the Fall 2023 American Geophysical Union Meeting, H25M-1258.

Flores, A, et al. 2022. "From Snowflake to Snowpack: Examining the Consequences of Cloud Microphysical Representations for Hydrologic Uncertainty." Presented at the Fall 2022 American Geophysical Union Meeting, H22F-09.

Flores, A, et al. 2023. "From Snowflake to Snowpack: How do Cloud Microphysical Representations Influence Hydrologic Response?" Presented at the 37th Conference on Hydrology of the 2023 American Meteorological Society Meeting.

Gibson, L, et al. 2023. "The Results of SAIL-Net: Investigating Spatial Variability of Aerosol and Cloud Nuclei in Mountainous Terrain." Presented at the 2023 Joint ARM User Facility and ASR Principal Investigators Meeting.

Heflin, S, et al. 2023. "Intermountain Sites Experience Differences in Precipitation and Microphysics During the Study of Precipitation, the Lower Atmosphere and Surface for Hydrometeorology (SPLASH) Field Campaign." Presented at the 37th Conference on Hydrology of the 2023 American Meteorological Society.

Hill, TCJ, et al. 2023. "Lessons from long-term measurements of ice nucleating particles at ARM sites." Presented at the 2023 Joint ARM User Facility and ASR Principal Investigators Meeting.

Hogan, D, et al. 2022. "SAILing with a SPLASH: Winter 2021-2022 Analysis to Inform 2023 Sublimation of Snow (SOS) Field Campaign." Presented at the 20th Conference on Mountain Meteorology of the American Meteorological Society, Park City, Utah.

Jackson, R. et al. 2023. "Surface Quantitative Precipitation Estimates (SQUIRE) from the X-band precipitation radar during the Surface Integrated Field Laboratory (SAIL) experiment." Presented at the Fall 2023 American Geophysical Union Meeting, H41J-1895.

Jones, S, et al. 2023. "Cloud Properties from Shortwave Spectroradiometer Retrievals." Presented at the 2023 Joint ARM User Facility and ASR Principal Investigators Meeting.

Lata, N, et al. 2023. "Assessing the Vertical Heterogeneity of Aerosol Composition and its Influence on Ice Nucleation over Crested Butte Mountain." Presented at the 2023 Joint ARM User Facility and ASR Principal Investigators Meeting.

Lata, N, et al. 2023. "Unraveling the Complexity of Aerosol Composition and Ice Nucleation Potential at Variable Altitudes: A Study from Crested Butte Mountain." Presented at the Fall 2023 American Geophysical Union Meeting, H41J-1898.

Mahoney, K, et al. 2023. "Analyzing Precipitation Across Scales during the North American Monsoon in the East River Basin, Colorado." Presented at the 37th Conference on Hydrology of the 2023 American Meteorological Society Meeting.

Matthews, A, et al. 2023. "TRACER and SAIL Field Campaign Radar Data Quality and Calibrations." Presented at the 2023 Joint ARM User Facility and ASR Principal Investigators Meeting.

Mital, U, et al. 2023. "Spatial Downscaling of Future Climate Projections Using GPU-Assisted Deep Learning." Presented at the 2023 HydroML Symposium.

Morales, A, et al. 2023. "Splashing through Spatial Scales: Connecting Large-Scale Weather Patterns and Precipitation Characteristics in an Intermountain Valley of Colorado." Presented at the 37th Conference on Hydrology of the 2023 American Meteorological Society Meeting.

O'Brien, J, et al. 2023. "X-Band Precipitation Estimates for the Surface Atmosphere Integrated Field Laboratory (SAIL) Field Experiment." Presented at the 37th Conference on Hydrology of the 2023 American Meteorological Society Meeting.

O'Brien, J, et al. 2023. "Seasonal Variability within Quantitative Precipitation Estimates for the Surface Atmosphere Integrated Field Laboratory (SAIL) Field Experiment." Presented at the 2023 Joint ARM User Facility and ASR Principal Investigators Meeting.

Raleigh, MS, et al. 2022. "Drivers of snowpack spatial variability in the East River, Colorado: Insights from remote sensing and physically-based modeling." Presented at the Fall 2022 American Geophysical Union Meeting, H22F-01.

Rudisill, W, et al. 2022. "Examining the Hydrologic Implications of Ice-Phase Microphysical Parameterization Choice using Convective-Permitting Regional Climate Simulations over Colorado's East River Watershed." Presented at the 20th Conference on Mountain Meteorology of the American Meteorological Society, Park City, Utah.

Rudisill, WJ, D Feldman, A Rhoades, Z Xu, N Thiros, and E Siirila-Woodburn. 2023. "Confronting Systematic Mountain Cold-Biases in Regional Climate Simulations: Observations, Discussion, and Synthesis with SAIL Field Campaign Observations." Presented at the International Conference on Alpine Meteorology (ICAM). St. Gallen, Switzerland.

Rudisill, WJ, AM Marshall, A Koshkin, D Feldman, and S Rahimi. 2023. "Will hoar frost in the western United States be a relic of the past?" Presented at the American Geophysical Union Fall Meeting, San Francisco, California.

Rudisill, WJ, and D Feldman. 2023. "Linking Daily Cycles of Streamflow, Energy, and ET in the Mountain Boundary Layer." Presented at the American Geophysical Union Fall Meeting, San Francisco, California.

Rudisill, WJ, and D Feldman. 2023. "Why are Regional Climate Models too Cold in Mountains? Observations, Discussion, and Synthesis with SAIL Field Campaign Observations." Presented at the Joint ARM User Facility and ASR Principal Investigators Meeting, Bethesda, Maryland.

Sedlar, J, et al. 2022. "Low-level liquid bearing clouds drive lower atmosphere stability and radiative forcing in a seasonally snow-covered high-mountain watershed environment." Presented at the Fall 2022 American Geophysical Union Meeting, H22F-06.

Shawon, AS, et al. 2022. "Exploring the Properties of Supermicron and Bioaerosol Events during the Surface Atmosphere Integrated Field Laboratory (SAIL) Campaign." Presented at the Fall 2022 American Geophysical Union Meeting, H22F-05.

Sherman, Z, et al. 2023. "CMAC Across ARM: Corrective Moments for Radars Deployed by the World's Largest Climate Research Facility." Presented at the 2023 Joint ARM User Facility and ASR Principal Investigators Meeting.

Siirila-Woodburn, E, et al. 2022. "Determining the role of low-to-no snow years on mountainous water budgets with bedrock through atmosphere models and observations." Presented at the Fall 2022 American Geophysical Union Meeting, C32B-07.

Steinke, I, et al. 2022. "Studying Orography-Influenced Riming and Secondary Ice Production and their Effects on Precipitation Rates Using Radar Polarimetry and Radar Doppler Spectra." Presented at the Fall 2022 American Geophysical Union Meeting, H22F-07.

Thiemen, M, et al. 2023. "Updates to SatCORPS Satellite-Derived Cloud and Radiative Properties ARM Datasets." Presented at the 2023 Joint ARM User Facility and ASR Principal Investigators Meeting.

Wood, A, et al. 2023. "Improving the Prediction of Precipitation, Snowpack and Streamflow in Mountainous Basins through Ensemble-Based Variable-Complexity Watershed Modeling." Presented at the 37th Conference on Hydrology of the 2023 American Meteorological Society Meeting.

Woodburn, E, et al. 2021. "Evidence of a low-to-no snow future and its impacts on water resources in the western United States." Presented at the Fall 2021 American Geophysical Union Meeting, H52A-04.

Worden, M, D Feldman, PJ Dennedy-Frank, N Falco, B Dafflon, J Chen, HM Wainwright, and AG Konings. 2020. "Exploring Surface Temperature, Evapotranspiration, and Downwelling Longwave Radiation Heterogeneity in High-Altitude Complex Terrain with ECOSTRESS." Presented at the Fall 2020 American Geophysical Union Meeting, H093-03.

Xiao, M, et al. 2022. "Exploring the Role of Soil Moisture in Seasonal Streamflow Forecast over the Upper Colorado River Basin." Presented at the Fall 2022 American Geophysical Union Meeting, H22F-03.

Xu, Z. 2022. "Quantifying Uncertainties in an Atmosphere-through-Bedrock Hydrological Process Modeling in the Upper Colorado River Basin." Presented at the 16th Conference on Atmospheric Radiation of the American Meteorological Society, Madison, Wisconsin.

Xu, Z, et al. 2022. "Quantifying Uncertainties in an Atmosphere-through-Bedrock Integrated Process Model in the Upper Colorado River Basin." Presented at the Fall 2022 American Geophysical Union Meeting, H22F-08.

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7.0 Lessons Learned

The science and logistics teams for SAIL learned several important lessons during the planning, implementation, execution, and completion of the campaign. These include:

- The importance of worst-case scenario logistical planning is paramount to ensuring a complete data record from an ARM mobile facility deployment. SAIL experienced several major challenges that were successfully managed with help of FIDO, RMBL, and the WF-SFA. The main lesson here is that when a solution is found to a specific logistical challenge, it should be strongly considered and likely adopted quickly. Logistical challenges included:
  - Deploying SAIL in the middle of the COVID-19 global pandemic that limited the ability of personnel even to leave their homes, not to mention the challenges of transporting equipment internationally along with very extreme travel restrictions.
  - Securing construction permits, especially when the instruments can be easily seen by the public.
  - The transport truck accident that occurred during the transportation of the AMF2 package from LANL to Crested Butte, Colorado.
- The importance of local, on-the-ground knowledge of the site for an ARM mobile facility deployment can hardly be overstated. For SAIL, connections to the WF-SFA and RMBL proved key for site identification, safety, permitting, and planning.
- The maintenance and daily quality assurance efforts of the on-the-ground technicians was critical for ensuring that the datastreams were of high quality and represent an under-appreciated but highly distinguishing feature of ARM field deployments. The importance of these efforts to campaign science should be promoted.
- The support for guest instruments with a mobile facility deployment is under appreciated, especially by the university and commercial instrument communities. A briefing packet describing how guest instrument can be supported, which also highlights all the other collocated instruments that can be compared against guest instrument data, would be valuable for recruiting additional guest instruments.
- Regular meetings between the SAIL science team, especially the principal investigator (PI), and the SAIL data translator proved very valuable for monitoring instrument performance and addressing specific instrument issues as they arose. To that end, while there was not a clear mechanism for the PI to meet regularly with the campaign technicians, such a meeting would be very valuable to understand, at the ground level, any instrument issues that arise.
- The larger scientific community experiences a barrier to entry for exploring ARM data because of the large number of acronyms used. Easily accessible instrument and datastream naming conventions should be considered.

- Additional science from mobile facility deployments occurs when those deployments occur in scenic locations where there are significant recreational opportunities. The appeal of collecting data and performing science in a place where people want to go should not be underestimated.

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