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Article

Supporting Advancement in Weather and Water Prediction in the Upper Colorado River Basin

The SPLASH Campaign

Gijs de Boer, Allen White, Rob Cifelli, Janet Intrieri, Mimi Hughes, Kelly Mahoney, Tilden Meyers, Kathy Lantz, Jonathan Hamilton, William Currier, Joseph Sedlar, Christopher Cox, Erik Hulm, Laura D. Riihimaki, Bianca Adler, Laura Bianco, Annareli Morales, James Wilczak, Jack Elston, Maciej Stachura, Darren Jackson, Sara Morris, V. Chandrasekar, Sounak Biswas, Benjamin Schmatz, Francesc Junyent, Jennifer Reithel, Elizabeth Smith, Katya Schloesser, John Kochendorfer, Mike Meyers, Michael Gallagher, Jake Longenecker, Carrie Olheiser, Janice Bytheway, Benjamin Moore, Radiance Calmer, Matthew D. Shupe, Brian Butterworth, Stella Heflin, Rachel Palladino, Daniel Feldman, Kenneth Williams, James Pinto, Jackson Osborn, Dave Costa, Emiel Hall, Christian Herrera, Gary Hodges, Logan Soldo, Scott Stierle, and Robert S. Webb

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ABSTRACT: Water is a critical resource that causes significant challenges to inhabitants of the western United States. These challenges are likely to intensify as the result of expanding population and climate-related changes that act to reduce runoff in areas of complex terrain. To better understand the physical processes that drive the transition of mountain precipitation to streamflow, the National Oceanic and Atmospheric Administration has deployed suites of environmental sensors throughout the East River watershed of Colorado as part of the Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology (SPLASH). This includes surface-based sensors over a network of five different observing sites, airborne platforms, and sophisticated remote sensors to provide detailed information on spatiotemporal variability of key parameters. With a 2-yr deployment, these sensors offer detailed insight into precipitation, the lower atmosphere, and the surface, and support the development of datasets targeting improved prediction of weather and water. Initial datasets have been published and are laying a foundation for improved characterization of physical processes and their interactions driving mountain hydrology, evaluation and improvement of numerical prediction tools, and educational activities. SPLASH observations contain a depth and breadth of information that enables a variety of atmospheric and hydrological science analyses over the coming years that leverage collaborations between national laboratories, academia, and stakeholders, including industry.

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Corresponding author: Gijs de Boer, gijs.deboer@colorado.edu

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SIGNIFICANCE STATEMENT: Water is a limited and critical resource in the western United States. To protect water access for millions of people and ecosystems, and to preserve our ability to irrigate millions of acres of cropland, policymakers and water managers require advanced weather and water prediction systems. To improve these forecast systems in high-altitude complex terrain, the National Oceanic and Atmospheric Administration (NOAA) has deployed instrumentation in the East River watershed of the Upper Colorado River basin as part of the Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology (SPLASH). SPLASH observations are being used to advance fundamental understanding of mountain weather and water and to advance predictive capabilities across weather and climate time scales.

AFFILIATIONS: de Boer—NOAA/Physical Sciences Laboratory, and Cooperative Institute for Research in Environmental Sciences, and Integrated Remote and In Situ Sensing, University of Colorado Boulder, Boulder, Colorado; **White, Cifelli, Intrieri, Hughes, Mahoney, Currier, Cox, Wilczak, Morris, Longenecker, Moore, Osborn, Costa, and Webb**—NOAA/Physical Sciences Laboratory, Boulder, Colorado; **T. Meyers and Kochendorfer**—NOAA/Air Resources Laboratory, Oak Ridge, Tennessee; **Lantz and Hall**—NOAA/Global Monitoring Laboratory, Boulder, Colorado; **Hamilton, Adler, Bianco, Morales, Jackson, Gallagher, Bytheway, Shupe, and Butterworth**—NOAA/Physical Sciences Laboratory, and Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado; **Sedlar, Riihimaki, Herrera, Hodges, Soldo, and Stierle**—Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/Global Monitoring Laboratory, Boulder, Colorado; **Hulm, Schmatz, and Reithel**—Rocky Mountain Biological Laboratory, Crested Butte, Colorado; **Elston and Stachura**—Black Swift Technologies, Boulder, Colorado; **Chandrasekar and Junyent**—Colorado State University, Fort Collins, Colorado; **Biswas**—NOAA/Physical Sciences Laboratory, Boulder, and Colorado State University, Fort Collins, Colorado; **Smith**—NOAA/National Severe Storms Laboratory, Norman, Oklahoma; **Schloesser and Calmer**—Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado; **M. Meyers**—Grand Junction Weather Forecast Office, NOAA/National Weather Service, Grand Junction, Colorado; **Olheiser**—NOAA/Office of Water Prediction, Chanhassen, Minnesota, and RTI International, Fort Collins, Colorado; **Heflin**—The University of Arizona, Tucson, Arizona; **Palladino**—Northern Vermont University, Lyndon, Vermont; **Feldman and Williams**—Lawrence Berkeley National Laboratory, Berkeley, California; **Pinto**—National Center for Atmospheric Research, Boulder, Colorado

Regions of complex terrain offer distinct challenges when it comes to prediction of weather and water. These challenges must be addressed because climate-driven modifications of precipitation and surface-exchange processes in mountainous watersheds are likely to impact the water supply of many of Earth's inhabitants (e.g., Huss et al. 2017; Beniston 2003). This has become particularly concerning in the Colorado River basin (CRB; please see complete list of acronyms in appendix), a primary source of water for over 40 million people in 7 U.S. states, 30 federally recognized tribes, and Mexico. The CRB also provides irrigation water for over 5.5 million acres of cropland, making it critical to the nation's food supply. This approximately

1,400-mile (2,250-km) river is particularly vulnerable to projected changes in temperature and precipitation, which could reduce runoff by 10%–50% by midcentury (Vano et al. 2012). Recent years have seen persistently dry conditions over the CRB, driving the depletion of water reservoirs. In combination with warming conditions, such changes result in great uncertainty regarding the long-term reliability of the CRB as a critical water source for a growing regional population (Siirila-Woodburn et al. 2021). These challenges enhance the need for careful water resource management, and elevates the importance of reliable river flow prediction (Lukas and Payton 2020) to support policy governing river basins across the western United States.

In addition to driving considerations for water availability, weather in mountainous regions like the CRB can have significant societal and economic impacts. For example, mountainous regions offer potential for harvesting renewable energy due to elevated and diurnally regular wind regimes resulting from orographic forcing and unique solar conditions (e.g., Mann et al. 2017; Bilal et al. 2016). Additionally, atmospheric boundary layer processes occurring over complex terrain help to drive and develop convection and precipitation. Such convective events are not only important to water supply issues, but also to understanding lightning and wind regimes relevant to prediction of fire weather (e.g., Rorig and Ferguson 2002; Sun et al. 2009). Extending beyond the local environment, mountains excite atmospheric gravity waves that can grow in amplitude with altitude and break, resulting in the alteration of large-scale atmospheric flow that helps to "steer" weather patterns and redistribute heat and energy throughout the planet (McFarlane 1987). Gravity waves can also cause turbulence that affects aviation safety and route planning (e.g., Sharman et al. 2012).

The weather governing these societally relevant issues in mountainous regions like the CRB is influenced by a variety of factors, including local gradients in surface and air temperatures, precipitation amounts, soil moisture and its seasonal evolution, snowpack properties, evapotranspiration and sublimation, and the general exchange of energy between the surface and overlying atmosphere, as characterized by the surface energy budget (SEB). Robust, real-time observations of these key properties and the processes governing them represent important inputs to weather and streamflow forecasting systems, though single-point measurements only provide limited information and do not capture the spatial variability present in the physical system (Lukas et al. 2020). While satellite-based products offer enhanced spatial coverage, their spatial resolution is limited, and they can only provide information on a limited set of variables. Additionally, many spaceborne data products often require cloud-free conditions, which can be difficult to obtain during important times of year, and they are limited by issues related to observing over complex terrain and snow-covered surfaces (e.g., Tian and Peters-Lidard 2010; Kummerow et al. 2015; Derin and Kirstetter 2022). Similarly, airborne snowpack and soil moisture surveys are limited in spatial and temporal coverage, in part due to asset availability and relatively high costs associated with deployment of this infrastructure. As a result of these observing challenges, there are knowledge gaps that hinder our understanding and predictive abilities.

To better observe critical processes driving weather and water in such areas, the National Oceanic and Atmospheric Administration (NOAA) initiated the Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology (SPLASH) in September 2021. SPLASH has contributed an extended observatory in the East River watershed (ERW) of Colorado, providing perspectives on clouds and precipitation, lower-atmospheric and near-surface meteorology, energy exchanged between the lower atmosphere and underlying surface, and surface properties in this Upper Colorado River watershed. SPLASH is being conducted in conjunction with other observing efforts, including the U.S. Department of Energy (DOE) sponsored Surface Atmosphere Integrated Field Laboratory (SAIL) and long-term Watershed Function Science Focus Area (SFA), and the U.S. National Science Foundation (NSF)-supported Sublimation of Snow (SOS) experiment, collectively supporting a critical mass of observations that provide detailed insight on processes driving water availability, extreme weather, wildfire, and regional biogeochemistry over a 2-yr period. This article provides an overview of the SPLASH project, the science it is supporting, efforts being undertaken to translate that science into operational products, and the community and stakeholder engagement that fosters extended relationships with data users and the public.

Campaign overview

Constraining key physical processes related to prediction of weather and water in areas of complex terrain requires a broad spatial network of observations that document surface and atmospheric conditions across the domain of interest. At the same time, logistical challenges often dictate the siting of instrumentation due to requirements associated with power, communications, access, maintenance, potential environmental impacts, and more. For SPLASH, the intersection of scientific needs and logistics were considered resulting in the deployment of numerous sensors across five surface observing sites, the surrounding mountainsides, and on airborne measurement platforms. These facilities complement other observing networks in the area, including from the SAIL and SOS campaigns, and the long-running Watershed Function SFA.

Fixed site locations were selected to cover a range of mountain valley locations that span precipitation, radiation, and snowpack gradients. A map of these locations is provided as Fig. 1, and a complete overview of the sensors deployed to each of these sites is provided in Table 1. The SPLASH campaign is anchored by two core instrument sites. The Brush Creek (BCK) and Kettle Ponds (KPS) sites both include extensive arrays of instrumentation to observe precipitation, the lower atmosphere, and the surface. The BCK

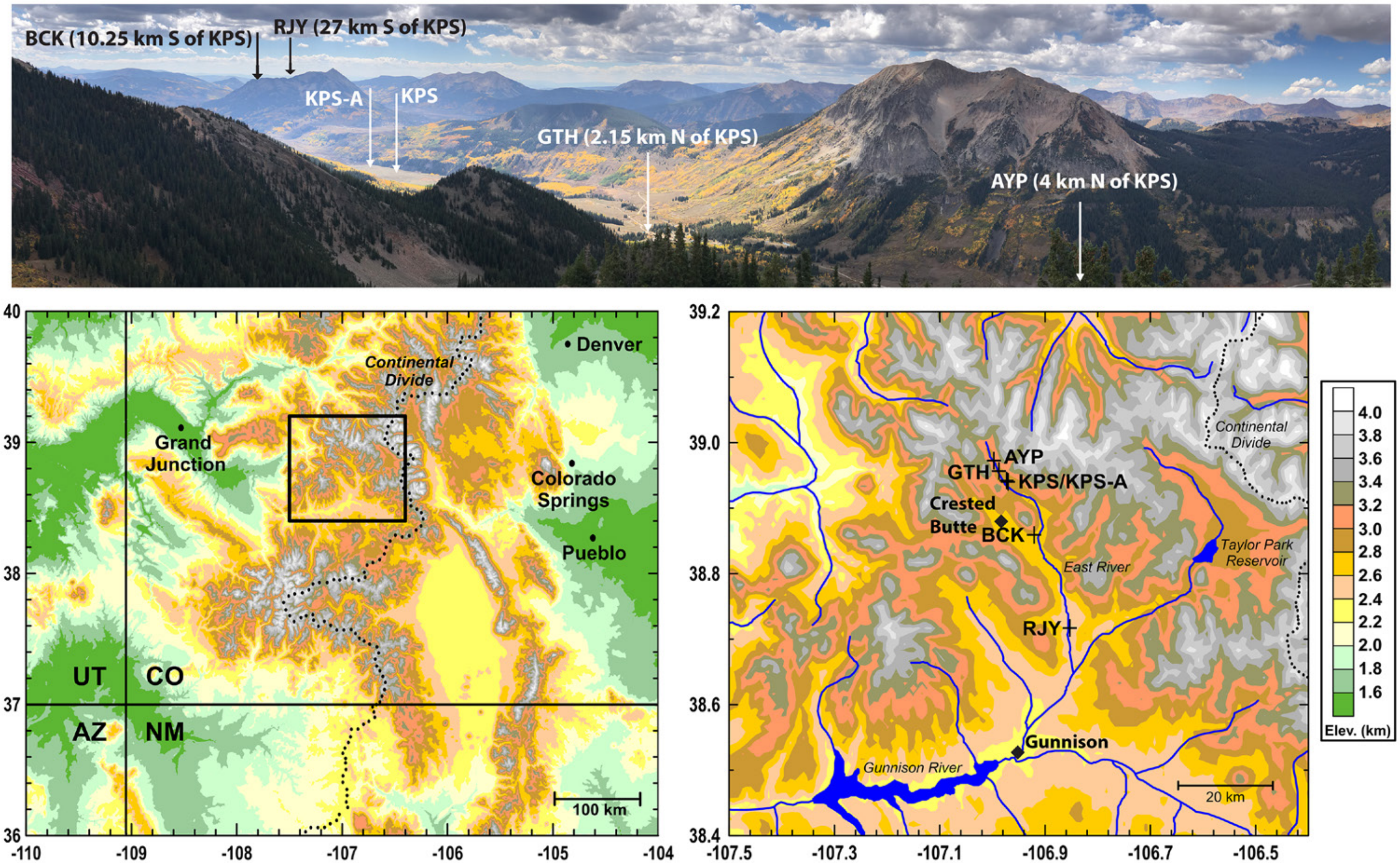

Fig. 1. (bottom) Maps illustrating the distribution of the SPLASH field sites within the ERW, and (top) a photograph providing perspective on the terrain surrounding the SPLASH sites, as seen in fall, looking from the northeastern side of the watershed toward the south.

Table 1. An overview of instrumentation deployed for SPLASH, including at Roaring Judy (RJY), Brush Creek (BCK), Kettle Ponds (KPS), Kettle Ponds Annex (KPS-A), Avery Picnic (AYP), Remote (RMT) sites, and from crewed (AIR) and uncrewed (UAS) aircraft. The asterisks (*) indicate which instruments were only deployed September 2021–January 2022.

	System	Location(s)	Primary measurements
Precipitation	Snow-Level Radar (SLR)	BCK, KPS	Radar reflectivity, Doppler velocity, snow level
	Scanning X-band radar	RJY	Radar reflectivity, differential reflectivity, differential propagation phase, copolar correlation coefficient, Doppler velocity, spectral width
	Precipitation gauge	BCK, KPS	Accumulated liquid equivalent precipitation
	Snow depth stakes	KPS, BCK, RMT	Snow depth, air temperature, relative humidity
	Disdrometer	BCK, KPS	Drop size distribution, precipitation type
Lower atmosphere	ASSIST/AERI*	RJY, BCK	Infrared spectral radiance, atmospheric temperature, atmospheric humidity, liquid water path, precipitable water
	Ceilometer*	RJY	Cloud-base height, cloud fraction
	Microwave radiometer*	RJY, BCK	Microwave brightness temperature, atmospheric temperature, atmospheric humidity, liquid water path, precipitable water
	Doppler lidar*	BCK	Horizontal wind speed, vertical wind speed, turbulent kinetic energy, dissipation
	Surface meteorology	RJY, BCK, KPS, KPS-A, AYP	Air temperature, relative humidity, air pressure, wind speed, wind direction
Surface energy budget	Mobile SURFRAD	BCK	Up-/downwelling SW and LW broadband irradiance, downwelling direct and diffuse SW irradiance, spectral shortwave irradiance, aerosol optical properties, broadband and spectral surface albedo, cloud-base height, cloud fraction, cloud optical depth, hemispheric sky imager (TSI), air temperature, relative humidity, air pressure, wind speed, wind direction
	Flux System and associated precip gauge	BCK, KPS	Up-/downwelling SW and LW broadband irradiance, broadband surface albedo, turbulent heat, moisture and momentum fluxes, snow depth, soil moisture, air temperature, relative humidity, air pressure, wind speed, wind direction, precipitation amount
	Atmospheric Surface Flux Station (ASFS)	KPS-A, AYP	Up-/downwelling SW and LW broadband irradiance, turbulent heat, moisture and momentum fluxes, snow depth, soil moisture and temperature, soil and snow conductive flux, air temperature, relative humidity, air pressure, wind speed, wind direction
	RadSys	KPS	Up-/downwelling SW and LW broadband irradiance, downwelling diffuse SW irradiance, spectral shortwave irradiance, aerosol optical properties, broadband and spectral surface albedo, cloud-base height and cloud fraction, air temperature, relative humidity, air pressure, wind speed, wind direction
	Thermistor string	AYP	Snow and soil temperature
Surface	S2 UAS	UAS	Soil moisture, multispectral imagery, topography, NDVI, surface cover, surface temperature
	E2 UAS	UAS	Soil moisture, multispectral imagery, topography, NDVI, surface cover, surface temperature
	HELiX UAS	UAS	Surface albedo, up-/downwelling irradiance, multispectral imagery, surface cover, topography, NDVI
	NOAA NWS Gamma Snow Survey King Air	AIR	Soil moisture, SWE, visible imagery

site (38.859°N, 106.921°W, 2,722 m MSL) is situated on the south side of Crested Butte Mountain. With significant solar exposure on the south-facing mountain slope, the BCK site typically has greater variability in seasonal snow depth than the sites farther north. Additionally, its proximity to the mountain slope is thought to influence wind patterns in the region, and the mountain itself is visible in the field of view of the site's surface-based instrumentation. The Snow-Level Radar (SLR; Johnston et al. 2017) and disdrometer located at BCK are directly beneath the atmospheric area sampled by a scanning X-band radar (see RJY site description below), allowing for comparisons between the observations from those three samples. Also, looking at the sky are a total-sky imager, ceilometer, a solar and near-infrared spectral radiance sensor, and a multifilter rotating shadowband radiometer (MFRSR). Additionally, the BCK site hosts a suite of SEB and surface-meteorological instrumentation, including a flux and weather tripod, and instrumentation to measure up- and downwelling shortwave and longwave broadband irradiance. There is also a ground-facing multifilter radiometer (MFR) to measure reflected spectral irradiance which, using the collocated MFRSR, provides spectral albedo. From September 2021 to January 2022, the BCK facility also saw the deployment of a Collaborative Lower Atmospheric Mobile Profiling System (CLAMPS; Wagner et al. 2019), housing multiple remote sensors including a Doppler lidar, Atmospheric Emitted Radiance Interferometer (AERI), and microwave radiometer, along with near-surface air temperature, humidity, and wind sensors.

The KPS site (38.942°N, 106.973°W, 2,861 m MSL) is located on a generally south-sloping meadow, approximately 75 m above the East River and valley floor, and approximately 2.4 km southeast of Gothic, Colorado. This site hosts a variety of instruments to measure precipitation, lower-atmospheric state, and surface energy exchange. Specifically, this includes a second SLR, disdrometer and precipitation gauge combination, and a 10-m flux tower that is instrumented to observe lower-atmospheric turbulence, near-surface temperature, pressure, humidity, winds, turbulent and radiative energy fluxes at the surface, soil moisture and temperature profiles from the surface to 50 cm below ground, and snow depth. As with the BCK site, KPS also includes a ceilometer, MFRSR/MFR pair, and a surface-based radiation measurement station. Approximately 250 m from the primary KPS site is the Kettle Ponds Annex site (KPS-A; 38.940°N, 106.970°W, 2,851 m), where SPLASH has deployed an Atmospheric Surface Flux Station (ASFS). This system includes sensors that measure turbulent and radiative energy exchange at the surface, snow depth, soil moisture and temperature down to 50 cm, soil conductive flux (−5 cm), and near-surface temperature, pressure, humidity, and winds. This system is designed to run continuously "off the grid" with power supplied by an integrated direct methanol fuel cell. The KPS-A ASFS deployment was added to provide perspectives on spatial variability in the SEB around the KPS tower.

Approximately 4 km NNW of KPS is the Avery Picnic (AYP) site (38.973°N, 106.997°W, 2,923 m MSL), the northernmost and highest SPLASH fixed site. The AYP site sits on a small grass knoll approximately 5 m above the valley floor, inside one of many bends of the East River. The site is locally level and surrounded by steep mountain slopes, providing perspectives at the riverbed, with some tree coverage on the surrounding slopes, including both evergreen and deciduous trees. As is the case at KPS-A, the remote setting limits the instrumentation that can be deployed, and consequently an ASFS was also installed at this site. Starting in fall 2022, the APY ASFS was additionally instrumented to include a thermistor string capable of providing information on temperatures throughout the uppermost soil levels, the snowpack, and the atmosphere directly above the snowpack.

Finally, the southernmost SPLASH site is located at the Roaring Judy fish hatchery (RJY), situated approximately halfway between Gunnison and Crested Butte, Colorado, along State Highway 135 (38.717°N, 106.853°W, 2,497 m MSL). This site was instrumented with a scanning dual-polarization X-band radar system, surface meteorological sensors, and from

October 2021 to January 2022, with an array of additional profilers, including a microwave radiometer (MWR), an Atmospheric Sounder Spectrometer by Infrared Spectral Technology (ASSIST), and a ceilometer. Because of its location, the facility offers good access to power required for these advanced remote sensor systems, excellent accessibility due to a nearby road, and radar coverage of the southern portions of the ERW, including the atmosphere over other watersheds impacting streamflow in the East River, like the Taylor River. Additionally, this site is subject to valley drainage winds due to its down-valley location from the rest of the SPLASH domain, and experiences less snow cover than sites situated farther up-valley. Instrumentation is sited in a grass field that is surrounded by low tree cover, at an elevation comparable to that of the East River at this location.

In addition to fixed sites, SPLASH has deployed various remote and airborne assets. This includes five additional "snow stake" sites, where three 3-m stakes were deployed along with two time-lapse cameras and air temperature/relative humidity sensors to observe the snow depth evolution and low-level meteorological conditions on the slopes above the valley floor. Remote snow stake sites were situated up to 615 m higher than KPS, within forest gaps in Washington Gulch, Rustler Gulch, Virginia basin, Snodgrass Mountain, and near the Deer Creek Trail. Time-lapse camera images and temperature/relative humidity observations were taken at hourly intervals. To provide spatial context for the measurements from the fixed surface sites, SPLASH deployed the NOAA Office of Water Prediction (OWP) Airborne Gamma Radiation Snow Survey Program, which provides information on snow water equivalent (SWE) and soil moisture based on data collected across flight lines of approximately 10 km from the NOAA King Air aircraft. This system was deployed three times annually for SPLASH, including a fall (October) series of flights to collect information on antecedent soil moisture, and two spring (March and May) flight surveys to observe peak and late-season SWE across the ERW and surrounding watersheds.

SPLASH also benefited from deployment of new observing technologies on board small uncrewed aircraft systems (sUAS). In spring 2022, this included deployment of the HELiX UAS (de Boer et al. 2022), which operated at both the KPS and AYP sites and was instrumented with stabilized pyranometers and a downward-looking multispectral camera to provide detailed information on the spatial distribution of surface albedo and surface characteristics during spring melt. During summer 2022 and 2023, the Black Swift Technologies (BST) S2 and E2 sUAS were flown. Equipped with an L-band radiometer and multispectral camera these sUAS collected information on the spatial distribution of soil moisture and other surface properties including normalized difference vegetation index (NDVI), elevation, and surface temperature.

SPLASH-deployed assets are complemented by observational systems fielded by other agencies and teams in the ERW. This includes a wide-ranging suite of sensors deployed as part of the U.S. DOE Atmospheric Radiation Measurement (ARM) Mobile Facility (AMF) and ARM guest investigators at Gothic (GTH; between the KPS and AYP facilities) and on the north side of Crested Butte Mountain Resort (between KPS and BCK) as part of SAIL. SAIL instrumentation is also focused on collecting data on the SEB, clouds, precipitation, and aerosol properties [see Feldman et al. (2023) for a full description of SAIL]. This includes a second scanning dual-polarization X-band radar system that is identical to the SPLASH RJY X-band radar. This ARM-deployed X-band radar provides coverage over the northern portions of the ERW, a region that is blocked from view of the SPLASH radar by the presence of Crested Butte Mountain. The similarities between the DOE ARM-deployed SAIL instrumentation and the NOAA-deployed SPLASH instruments extend the SPLASH network across an even greater spatial domain. In addition to providing a sixth site from which to develop statistical relationships governing mountain meteorology, hydrometeorology, and climate, the collocation of the SAIL and SPLASH campaigns enables coordinated data collection that reveals aspects of the atmospheric precipitation dynamics (e.g., synchronization of the SAIL and SPLASH radar scans for dual-Doppler scanning), thermodynamics (e.g., a transect of surface temperature and humidity from SAIL/SPLASH and profiles of temperature and humidity from SAIL radiosondes), kinematics (e.g., a transect of surface wind measurements and a SAIL scanning Doppler lidar), and radiation (e.g., a transect with SW and LW measurements with different sky views) that are not possible with the observations from either campaign alone.

In addition to SAIL, the 2022/23 winter also included deployment of a cluster of flux towers and associated sensors to document turbulence and the turbulent fluxes of heat and moisture between the atmosphere and the surface to support studies of sublimation under the NSF-supported SOS project. SOS instrumentation, supplied by the National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL) is deployed at the KPS site, providing additional spatial context for statistical evaluation of turbulence and turbulent fluxes of heat and momentum at this location.

Finally, all the efforts described above benefit from context provided by a wide-reaching observational network associated with the DOE-supported Watershed Function SFA. Led by Lawrence Berkeley National Laboratory, the Watershed Function SFA is a long-term project supporting development of new conceptualizations and insights on watershed processes in the ERW. The Watershed Function SFA aims to enhance understanding and predictive capabilities that offer insight into how complex, multiscale interactions can lead to a cascade of effects on downstream water availability, nutrient and metal loading, and carbon cycling. Such understanding requires the detailed measurements provided at fine spatiotemporal scales by SPLASH, SAIL, and SOS while SFA-collected surface and subsurface observations provide larger-scale historical context to relate the SPLASH observations to river streamflow and other relevant processes.

Development of process-level understanding

The instrumentation outlined in the previous section was assembled to address a variety of gaps in our fundamental understanding of mountain meteorological and hydrological processes. Broadly speaking, the topical areas that encompass these gaps are covered under the SPLASH acronym, with research focus placed on precipitation processes, lower-tropospheric meteorology, surface characterization, and the interactions between the surface and overlying atmosphere. These areas are pursued with a broad eye toward understanding the combined influence of atmospheric and surface processes on the hydrologic cycle of this Upper Colorado River watershed.

Streamflow in the East River and Upper Colorado basins is driven primarily by the melting of the winter snowpack. As such, understanding the drivers of spatial distribution in snowfall is a critical component of improving water prediction in this part of the country. SPLASH has deployed a variety of sensors to monitor rain and snowfall and improve our ability to quantify the precipitation reaching the surface across the watershed. The scanning X-band radar deployed as part of SPLASH provides measurements of precipitation over the watershed. An example of data from this X-band radar is shown in the top-right panel in Fig. 2, and demonstrates the challenges imposed through blockage of the radar beam by the terrain surrounding this system and the operational radar operated by the National Weather Service in Grand Junction, Colorado (Fig. 2, top-left panel). While coverage is limited due to the terrain effects, the radar still provides insight into precipitation falling near the surface up to approximately 40 km away from RJY in unblocked directions. Importantly, this includes information across the southern portion of the ERW and over the Taylor River and Reservoir, all of which are hidden from the SAIL-deployed X-band radar due to terrain blockage by Crested Butte Mountain. Coupling X-band data with measurements from surface-based disdrometers, precipitation gauges, and the SLRs at BCK and KPS allows for the development of quantitative precipitation estimates (QPE) around the greater watershed,

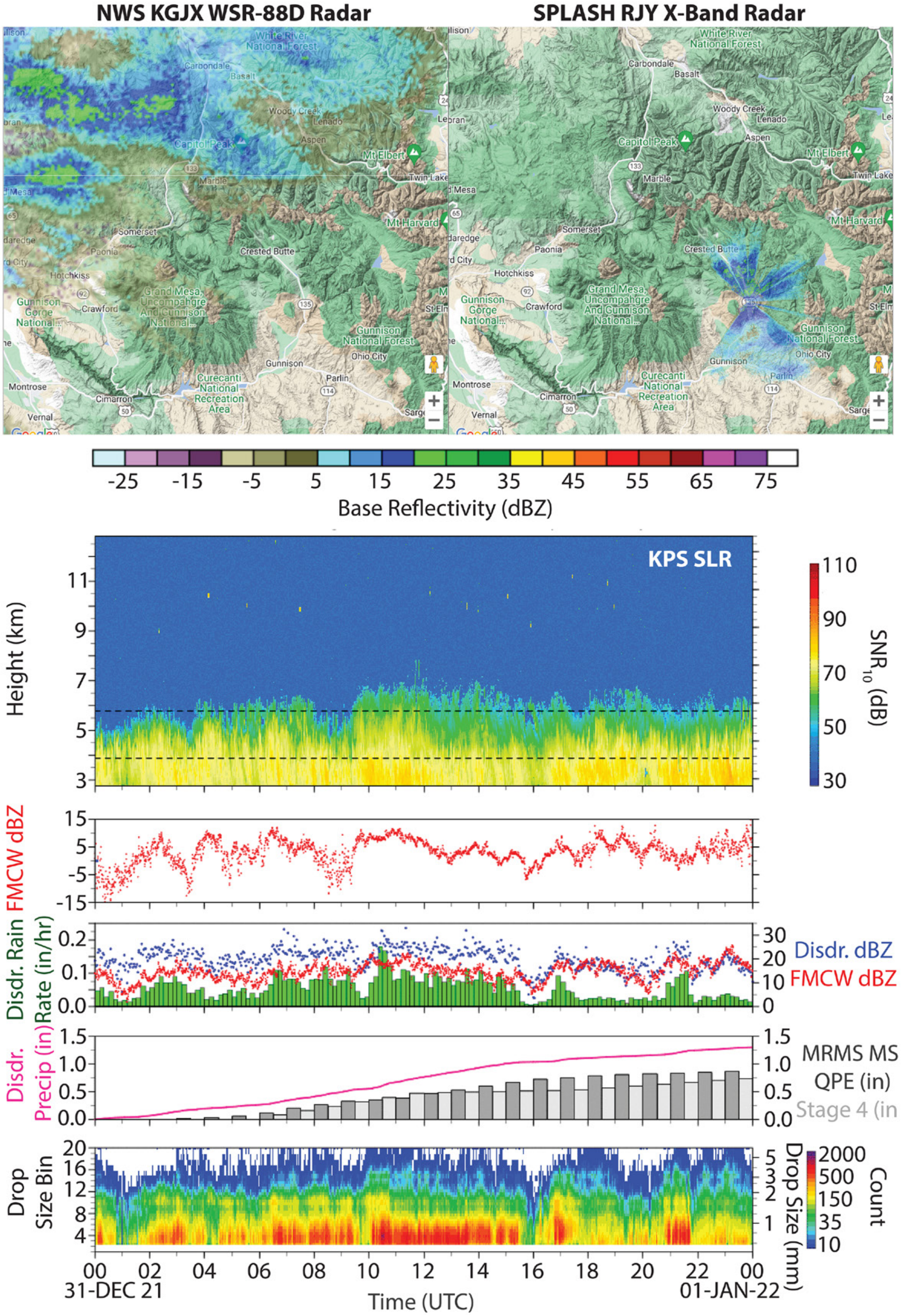

Fig. 2. Examples of radar and surface disdrometer data collected by SPLASH. This includes plan position indicator (PPI) scans from (top left) the NWS WSR-88D radar (KGJX) and (top right) the SPLASH X-band radar (RJY) collected during the "Santa Slammer" heavy snowfall period on 31 Dec 2021. It also includes (bottom) measurements from BCK on 31 Dec 2021, including (top to bottom) a time–height display of radar reflectivity from the SLR, a time series of radar reflectivity from the WSR-88D, SLR, and disdrometer and a disdrometer-estimated rain rate, quantitative precipitation estimates (QPEs) from the disdrometer and two operational products, Multi-radar/Multi-Sensor (MRMS) and Stage IV (fourth panel from top) and the drop size distribution from the disdrometer.

supporting the documentation of spatial gradients in precipitation in the area. The bottom panels in Fig. 2 provide an example of the SLR- and surface-sensor-based precipitation observations from SPLASH, including radar reflectivity and snow level, precipitation rate, accumulated precipitation relative to operational products, and disdrometer-based sizing of near-surface hydrometeors.

In addition to quantifying the amount of precipitation, the different radar systems provide information on cloud and precipitation microphysics. For example, the SLRs offer important insight into the phase of precipitation, helping to detect the height of the atmosphere where snow melts and turns into rain. This element of phase is a very important driver of watershed storage and runoff efficiency; rain-on-snow events are of particular interest due to their ability to rapidly shift watershed dynamics and storage (Li et al. 2019). In addition, information on hydrometeor Doppler velocity and polarization ratio from the X-band radar can be used to document ice crystal properties and processes, potentially including information on how ice is forming (Kumjian et al. 2022). Recent years have seen intense interest in the notion of "secondary ice production" (e.g., Field et al. 2017; Luke et al. 2021), under which additional ice crystals are expected to nucleate in a specific range of atmospheric conditions, altering precipitation efficiency and the removal of water vapor from the atmosphere. Processes like secondary ice production and precipitation efficiency will be better understood by leveraging SPLASH measurements and can be further enhanced by integrating information from SAIL instrumentation.

Fully understanding the different processes playing out over the ERW requires documentation of changes to surface cover and properties over the area. Surface-based sensors at BCK, KPS, KPS-A, and AYP, along with those deployed under the SAIL, SOS, and Watershed SFA efforts, provide continuous information on snow depth, surface albedo, soil moisture, soil temperature, and snowpack temperature at specific locations. All these quantities influence the seasonal evolution of the SEB. Additionally, spectral signatures in surface snow albedo can be used to derive insight into the processes driving reductions in snowpack depth. The SPLASH-deployed MFRSR and downward-pointing MFR measure albedo at seven solar wavelengths throughout the visible and near-infrared solar spectra. Visible wavelengths are impacted by absorbing impurities like dust or black carbon deposition on snow but are not significantly impacted by changes in snow optical properties like grain size. However, longer infrared wavelengths are more sensitive to snow properties that change with aging such as snow particle size and phase, allowing for the separation of surface darkening due to aging versus darkening due to impurities (e.g., Warren 2019; Skiles and Painter 2017).

Ultimately each of these surface-based sensor systems only provide information for a single location in the watershed, leaving open gaps regarding representativeness and spatial variability in an area that features immense surface complexity. To help fill these gaps, sUAS were used as part of SPLASH to periodically map spatial variability in surface conditions, along with their evolution over the annual cycle. For example, sUAS carrying pyranometers were operated near AYP to map the evolution of surface snow cover, vegetation, and albedo during the spring melt in 2022. While some elements of this transition were predictable (e.g., surface albedo decreases as snow melts over the riverbed) these observations also documented the incredibly rapid reductions in snowpack albedo resulting from impurities in the snow during this melt period. Over the course of one week, snowpack albedos were reduced from approximately 0.7 to 0.4, despite over a meter of snow remaining over the study region, because of transported light-absorbing impurities in the snowpack that were exposed during the first weeks of snowmelt onset (see Fig. 3). In addition, the sUAS was operated over different types of vegetation to map the influence of different tree and shrub structures on the surface albedo, over both snow-covered and bare ground surfaces.

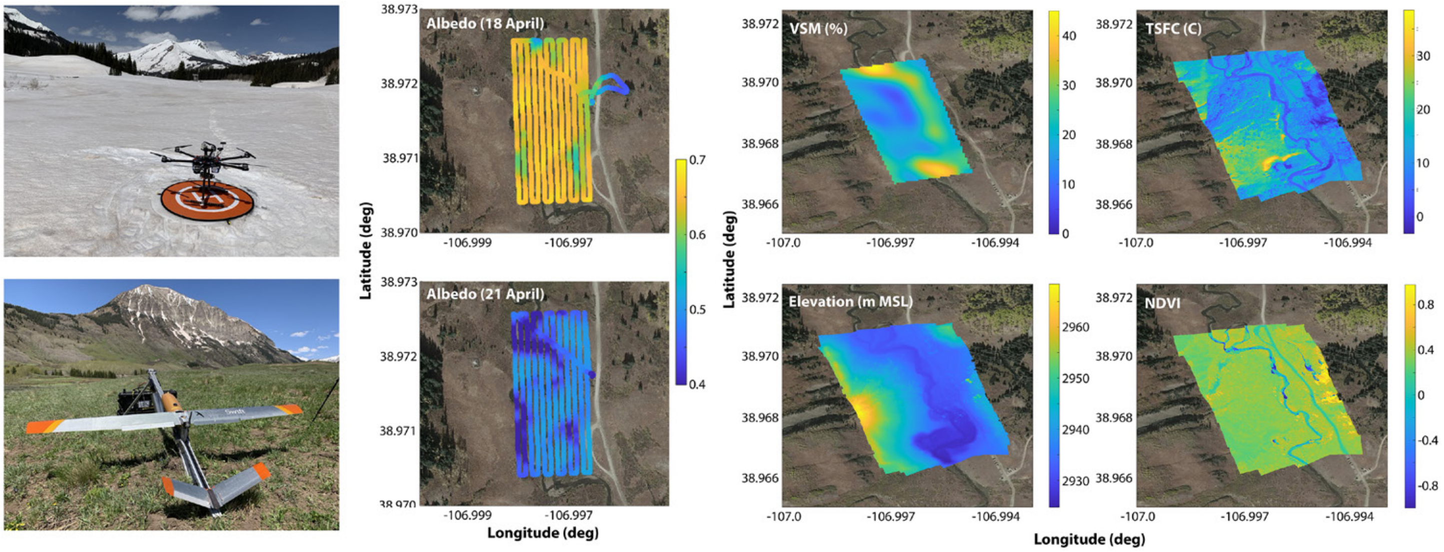

Fig. 3. Examples of UAS-derived data from SPLASH. (top far left) HELiX and (bottom far left) S2 sUAS platforms (photo credits: G. de Boer). The remaining panels show examples of UAS data collected around the AYP site, including maps of (left) surface albedo as measured by the HELiX for two different days in April 2022 and (top center) volumetric soil moisture (VSM; %), (bottom center) surface elevation (m MSL), (top far right) surface temperature (TSFC; C), and (bottom far right) normalized difference vegetation index (NDVI) from a set of BST E2 flights from October 2022.

sUAS were additionally deployed to observe summertime surface properties. Remotely sensed observations obtained with the BST sUAS flights revealed detailed spatial gradients in vegetation cover, surface elevation, and soil moisture and their evolution over the snow-free time periods (see Fig. 3). The L-band radiometer-derived soil moisture estimates represent some of the first estimates derived from sUAS. Surface-based soil moisture sensors and measurements from a handheld soil moisture probe were intercompared with the new sUAS-based soil moisture observations to evaluate differences between these methods of collection and help advance the technical readiness of this new and unique remote sensing capability. The spatial information available from the sUAS surveys will inform the evaluation and development of numerical model parameterizations, which require insight into subgrid-scale variability of soil moisture and vegetation that cannot be derived from a single-point measurement.

In addition to the sUAS deployments, the SPLASH-supported OWP aircraft surveys provide spatial context on SWE and antecedent soil moisture over and around the ERW. Work is being conducted to assess not only the operational products provided by the OWP, but also raw higher-resolution data that can potentially provide insight into small-scale spatial gradients within a particular watershed or portion of a watershed. Such observations can put information from the surface-based sensor network deployed under SPLASH into a broader, regional context. Finally, SPLASH research benefits from deployment of the Airborne Snow Observatory (ASO) to the ERW in spring 2022 (21 April and 18 May) and spring 2023 (1 April), which provided detailed observations of a variety of surface and snow properties, including snow depth, surface albedo, and snow coverage. These observations help to translate details of snowpack melt to a broader region, and also help to understand wind-driven redistribution of snow and the patterns of seasonal melt of snow as a function of elevation, which cannot be derived from the SPLASH surface sensors, as these are primarily deployed on the valley floor.

The surface properties discussed above, together with variable atmospheric forcing and sky cover, contribute to spatiotemporal variability of the SEB over the SPLASH domain. The SPLASH network of SEB sensors was designed to provide detailed information on the variability of the SEB across a variety of scales and conditions. This includes gradients across different parts of the ERW, as well as localized gradients between the instrumentation deployed at the KPS site and those deployed only 300 m away at KPS-A. Furthermore, starting in fall 2022, NCAR deployed a suite of flux towers at the KPS site as part of the SOS project, offering even more insight into spatial variability and surface fluxes. Together, these observations can be used to inform a variety of questions, for example, understanding the influence of advection in the SEB. Over flat terrain, the deployment and processing of energy balance measurement systems is relatively straightforward. However, an unexplained gap between measured available energy and energy fluxes is nearly ubiquitous (Mauder et al. 2020). This problem of energy balance nonclosure is exacerbated over complex, mountainous terrain. Here, measurement sites are more likely to fail the basic eddy covariance (EC) assumptions of horizontal homogeneity and stationarity (Foken and Wichura 1996; Katul et al. 2004), adding uncertainty to calculated fluxes (Hiller et al. 2008). This is because the EC method generally assumes the primacy of vertical turbulent exchange, and that mean advective fluxes are negligible (Hiller et al. 2008). However, the significance of advection is directly correlated to site topography and heterogeneity, with steep slopes and heterogeneous vegetation and soil distributions increasing the relative importance of the advective term (Aubinet et al. 2005; Aubinet 2008). This is tied to the regular occurrence of daytime anabatic (upslope) and nighttime katabatic (downslope) flows that are characteristic of mountain environments (Kossmann and Fiedler 2000). The quantification of the advective term is possible with the deployment of multiple EC towers, as deployed under SPLASH, SAIL, and SOS. Vertical gradients of EC flux measurements, which are recorded at several of the SPLASH sites, allow for the evaluation of vertical flux divergence, and can also be used to help identify and quantify advection.

The annual cycles of SEB measurements, in connection with lower-atmospheric and cloud observations allow for derivation of relationships between surface cover, lower-atmospheric stability, and the SEB response. As part of SPLASH, these measurements are analyzed to evaluate relationships between downwelling longwave radiation at the surface and lower-atmospheric stability regimes, as have previously been documented in the Arctic (Stramler et al. 2011; Morrison et al. 2012; Shupe et al. 2013; Sedlar and Shupe 2014; Brooks et al. 2017; Sedlar et al. 2020). This work further supports evaluation of how early morning cloud–stability regimes influence the diurnal evolution of the surface, lower troposphere, and sky cover. Such diurnal preconditioning is thought to drive surface–atmosphere feedbacks that impact development of the shallow convective boundary layer (Adler et al. 2023). Estimates of the heat content of the lower atmosphere and time scales and forcing needed to erode the stable layer and the specific contributions of seasonal variations in snowpack to SEB partitioning relative to cloud–stability regime are being derived as part of SPLASH.

The different terms of the SEB, as described above, can significantly influence runoff efficiency through modulation of surface evapotranspiration, sublimation, snowmelt, and soil moisture. Figure 4 shows an example of the SEB as measured at two of the SPLASH sites between October 2021 and 2022. Included are time series of near-surface air temperature, subsurface air temperature and snow depth, surface albedo, net radiative flux at the surface, and the turbulent fluxes of heat and moisture. These show spatial differences between the KPS-A and AYP sites, including in snow depth and coverage, the annual cycle of albedo, and radiative fluxes. In part, the magnitude of these processes is influenced by the near-surface meteorological conditions. The structure and evolution of the atmospheric boundary layer (ABL) strongly depends on local surface energy balance (e.g., Mott et al. 2018; Adler et al. 2023), resulting in internal feedback loops in the system. Thermally and dynamically driven mesoscale flows and low-level clouds all additionally impact the ABL (e.g., Zardi and Whiteman 2013; Serafin et al. 2018). Observing the vertical structure and

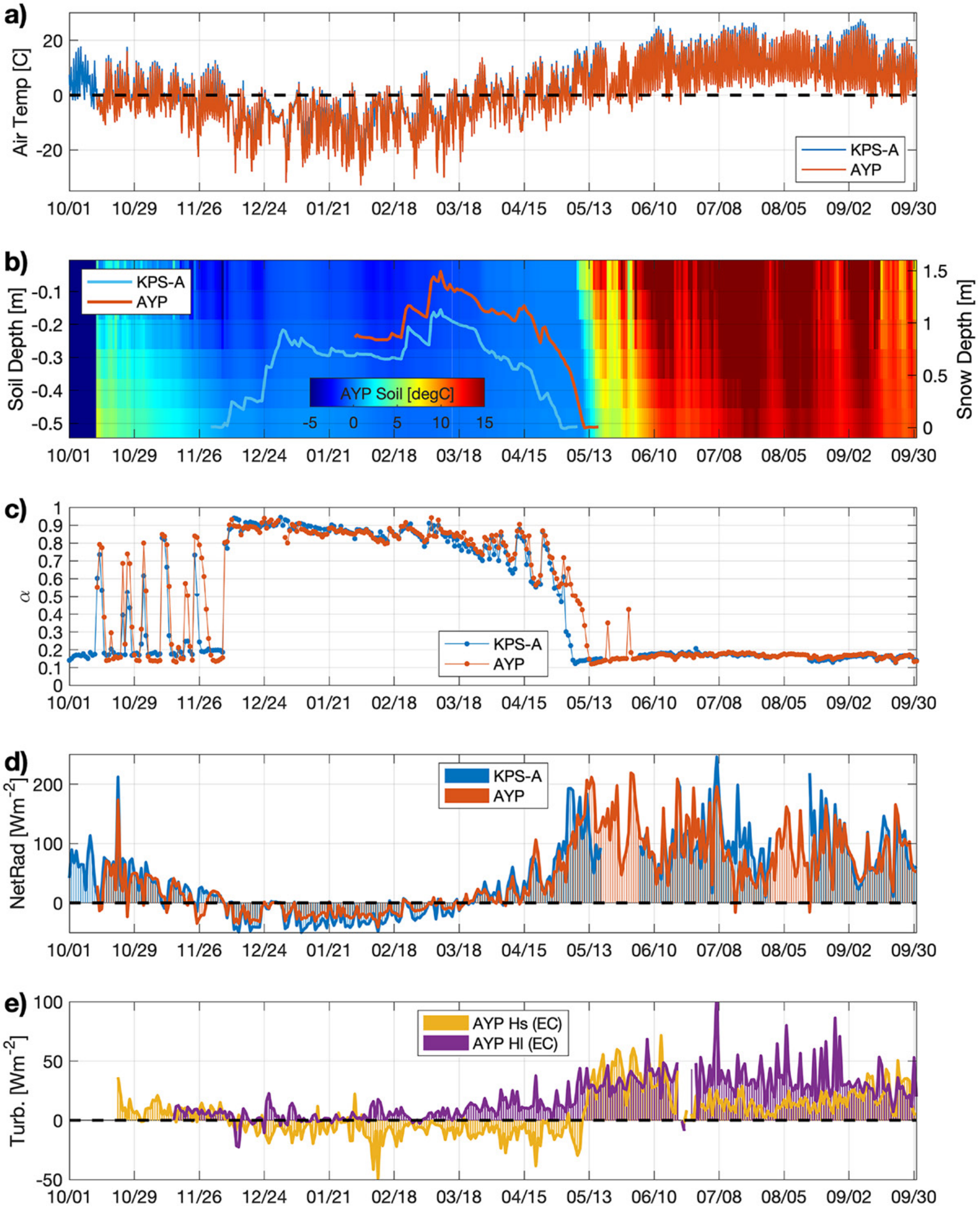

Fig. 4. Different terms of the SEB, as observed by SPLASH instrumentation. This includes (a) the seasonal evolution of air temperature, (b) evolution of subsurface temperatures (AYP) and snow depth (KPS-A and AYP), (c) variability of surface albedo resulting from snow cover and melt (KPS-A and AYP), (d) net radiative energy at the surface (KPS-A and AYP), and (e) the daily mean turbulent sensible and latent heat fluxes as observed at APY.

evolution of the ABL and understanding the processes controlling it are hence crucial for studies of cloud, aerosol, and surface atmosphere interaction processes. SPLASH observations support such evaluations, specifically providing detailed information into the thermodynamic state and wind patterns of the ABL. This includes evaluation of radiatively driven drainage flows, which are the regularly occurring down-valley winds that occur at night and through the early morning and result in regular wind direction and speed regimes that can impact the SEB.

Evaluating and improving operational prediction tools

Numerical prediction systems tend to be less skillful in regions characterized by mountainous terrain (Zhong and Chow 2013). From the representation of the boundary layer to the formation and maintenance of precipitation, most operational weather, climate, and hydrology models do not have sufficient spatial resolution to represent key physical processes that act on very small scales and in regions of large surface heterogeneity. Specifically, an operational model's horizontal grid spacing in these regions cannot represent the detailed orographic structure of mesoscale ridges, valleys, and tributaries, nor the heterogeneity of the underlying land surface and vegetation. The limited resolution of many operational forecast systems can result in underestimation of elevation differences between ridges, valley floors, and the variable and complex elevation bands in between. Finally, observational challenges in complex terrain mean that these regions are data sparse in comparison with more homogeneous regions, which has implications for the constraints on forecast models' initial conditions as well as their evaluation. Ultimately, these challenges are a central motivation for SPLASH.

The SPLASH observations focus on several different processes that are important in NOAA's operational models, and these observations will be used to assess model skill and error characteristics. One of the most critical variables to accurately predict in mountainous regions is the coverage, amount, and type of precipitation. Doing so can be incredibly challenging due in part to observational constraints. In some regions it has been shown that model-produced precipitation estimates outperform observationally rooted gridded estimates (Hughes et al. 2020), highlighting the challenges associated with estimating QPE in areas of complex terrain (e.g., Bytheway et al. 2020) and the general need for higher observational network density in such regions (Lundquist et al. 2019). The SPLASH field campaign has provided an opportunity to augment precipitation observations via both point (gauge) and radar (scanning and vertically pointing) observations to support evaluation of NOAA's high-resolution numerical forecasts of precipitation.

Initial work has demonstrated the importance of local physical processes, including precipitation, radiation, and turbulent exchange on accurate hydrologic modeling (e.g., Xu et al. 2022). Even though SPLASH is still actively collecting data, early work has been conducted to assess the performance of the National Water Model (NWM). Using the first year of SPLASH data, these comparisons (Palladino et al. 2023) reveal a low bias in modeled streamflow in the basin, driven largely by underestimates in simulated snowpack within the hydrologic model (NWM, Office of Water Prediction 2016). The SPLASH observational network deployed in the ERW was used to trace this issue back to biases in the High-Resolution Rapid Refresh (HRRR) precipitation forcings used to drive the hydrologic model. This work revealed that precipitation used to force the extended analysis and assimilation configuration of the NWM between October 2021 and June 2022 over the ERW was substantially underestimated when compared to gauges deployed for SPLASH. As a result, SWE was on average 41% too low when compared to regional snow pillows and data from the ASO, and streamflow volume within the analysis and assimilation configuration of the NWM was 6% of what was recorded at the USGS's East River stream gauge at Almont, Colorado. Meanwhile, retrospective simulations with the NWM for water years 2018 and 2019 that used precipitation estimates from the Analysis of Record for Calibration (AORC) (Office of Water Prediction 2021) led to a much more reasonable simulation of SWE (75% and 77%, respectively) and streamflow volume (93% and 75%, respectively). This has motivated SPLASH research to carefully analyze NOAA precipitation products that are used to initialize operational forecasts [i.e., from the HRRR, and the Multi-Radar/Multi-Sensor (MRMS; Zhang et al., 2016) system] and compare these with gauge and radar-based observations. Previously, the HRRR has been shown to have precipitation and snowfall biases in the Sierra Nevada (Bytheway et al. 2020) and across the western United States (Caron and

Steenburgh 2020), although a process-based evaluation of the reasons for these biases has not been performed. Additional work is underway to conduct a more detailed analysis of the performance of the NWM and other hydrological prediction tools.

To further assess modeled environmental conditions, there are ongoing efforts to use SPLASH data to understand the ability of NOAA's high-resolution models to simulate near-surface meteorological phenomena. For example, recent work has shown large differences between simulated and observed ABL thermal structure that likely result from coarse model resolution (Adler et al. 2023). In addition, surface albedo diagnosed in operational prediction systems has been shown to be too low, when compared to observational estimates over the region, though questions remain about the influence of scale and spatial variability in such comparisons. Figure 5 shows an evaluation of 2-m air temperature biases in the operational HRRR for the 0–23-h forecast period using data collected at four of the SPLASH field sites for the period from October 2021 to January 2022 (Adler et al. 2023). Biases are shown to vary with time of day and surface (snow)-cover and cloud-cover regimes. Similarly, efforts are underway to evaluate the soil moisture data that are used to define surface boundary conditions in operational prediction systems. Any biases in these surface properties have significant implications on the simulated SEB, ultimately helping to drive differences in ABL structure and snowmelt rates. As a result, part of the work being pursued under SPLASH is to evaluate the potential for assimilation of surface property data, including soil moisture and albedo, into high-resolution weather prediction systems. Any biases in the simulation of surface properties have potentially significant implications on the simulated SEB, ultimately helping to drive differences in ABL structure and snowmelt rates. Additional work is required to fully understand the extent to which such biases impact both local weather forecasts and streamflow forecasts over a variety of different time scales.

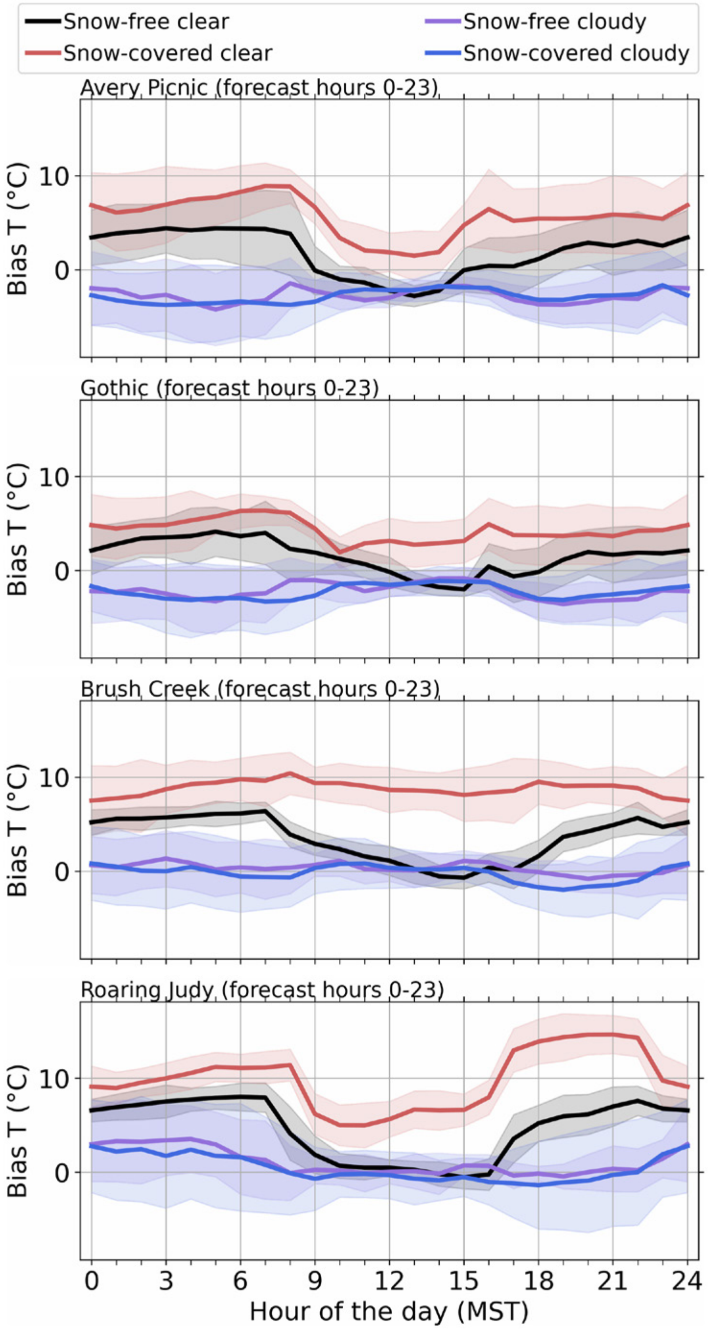

Fig. 5. **An example of initial evaluation of 2-m air temperature biases in the HRRR operational forecast model conducted using data from four of the SPLASH field sites. The different line colors show evaluations for time periods covering a variety of different surface snow-cover and sky-cover combinations.**

Beyond assessing the quality of simulations, it is envisioned that SPLASH data will support the advancement of numerical parameterizations developed to account for scale mismatches between numerical prediction system resolution and the significant gradients that exist in regions of complex terrain. For example, SPLASH data are likely to be relevant for improving upon process-based subgrid-scale parameterizations [e.g., for soil moisture and runoff (Decker 2015) or topographical impacts on solar radiation (Hao et al. 2021)] in numerical weather prediction, climate projection, and water supply forecasting systems. Advancing such parameterizations has significant potential to improve projections of future weather, water, and climate states across a variety of time scales, as most numerical models are heavily dependent on parameterizations such as these for developing such projections.

Community and end user communication and outreach

Coordination of a large field campaign like SPLASH required extensive planning to secure property access, install power and other infrastructure, complete the permitting processes required to work on U.S. Forest Service land, and establish community interest and buy-in. The success of SPLASH relied on effective collaboration across laboratories, institutions, and agencies to accomplish these and other critical tasks. Such coordination was supported by many groups, in particular the Rocky Mountain Biological Laboratory (RMBL) in Gothic. The RMBL team served as a local partner to ensure that SPLASH activities were primed for success and facilitated the integration of activities between the various projects taking place in the ERW (SPLASH, SAIL, Watershed SFA, SOS). This interface between these different projects helps provide complementary perspectives across a wide range of connected processes and research communities that extends across agency and disciplinary boundaries.

RMBL has also directly supported the execution of education and outreach activities for SPLASH. Working together with the CIRES and NOAA education and outreach teams, RMBL has helped the SPLASH team support a variety of activities at the field sites. These include a multiday workshop to disseminate information on watershed science, and mountain meteorology and hydrology, to middle and high school teachers, while simultaneously offering opportunities to develop curricula around these topics. The course, called Atmospheric Science and Climate Modeling in the Gunnison Valley: Field Based Course, was offered through the Western Colorado University’s Teacher Institute, allowing teachers to receive credit hours for enrolling and participating. Teachers were provided a full tour of the different SPLASH sites and instruments and worked to document these through a virtual reality tour using 360° camera technologies. In addition, CIRES and RMBL worked with the Gunnison Watershed School District to support activities in their “Summer Experiences” program. As part of this activity, students were able to spend time outdoors, learning about mountain weather and water, while hiking to different field sites and helping make measurements.

Because the field sites for this project are in areas that are heavily trafficked by recreational hikers, skiers, runners, and cyclists, signs were created and installed at all SPLASH facilities (see Fig. 6) so those who encountered these systems could learn about the instruments and their importance. These signs were meant to simultaneously educate the public about water in the mountain west and deter people from interfering with the measurements. To increase engagement with the different SPLASH sensors and systems, we worked with a local artist to turn many of the SPLASH observing systems into “superheroes” that resembled robots and transforming beings. The superheroes have been used extensively in engagement with the public, including with school groups, and have been featured in a NOAA story map[1] on the “Superheroes of SPLASH.”

Integral to the success of SPLASH has been the integration of early career researchers. Participation by undergraduate and graduate students in SPLASH was supported through

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[1] https://storymaps.arcgis.com/stories/093640ac6bdc479394d7fd9c7068fd27

Fig. 6. Signs informing visitors about SPLASH feature SPLASH "superheroes" being deployed at (left) AYP and (right) KPS. Each site hosts a unique sign to inform the public about the importance of water science across the mountain west, provide information on sensors deployed there, and request that instruments are left alone to capture critical information to advance hydrometeorology in the ERW and beyond.

established programs such as NOAA's Ernest F. Hollings undergraduate scholarship program, the José E. Serrano Educational Partnership Program with Minority Serving Institutions (EPP-MSI) that supported both undergraduate students and students in NOAA's Experiential Research and Training Opportunities (NERTO) program, NOAA's William M. Lapenta Student Internship Program, and the CIRES Research Experiences for Community College Students (RECCS) program. These early career SPLASH team members were able to conduct early research using SPLASH observations, spend time in the field collecting measurements and learning about instrumentation, and engage with the broader SPLASH community. Several of these students continue to participate with the SPLASH team during the project's second year.

Ultimately, the advancement of local weather and water prediction requires assistance of the operational entities responsible for such activities. SPLASH has worked to connect to a variety of stakeholder communities to both inform those entities of the activities being undertaken as part of SPLASH, as well as gain understanding of the primary challenges faced in forecasting in this region. These efforts have been aided by direct, regular engagement with the National Weather Service (NWS) Weather Forecast Office (WFO) in Grand Junction (GJT). WFO forecasters join weekly calls to discuss the science and operations in connection with SPLASH, and have provided valuable insight into needs and challenges. Some of the most significant contributions that SPLASH has made to support forecasting efforts by the GJT office include data from the X-band scanning radar, which help fill a critical observing gap where the operational NWS radars are impeded by terrain in this area (i.e., Fig. 2), webcam information for situational awareness, and data availability on the SPLASH website "SPLASHboard." In addition to GJT NWS involvement, the SPLASH team has connected with local River Forecast Centers (RFCs), the National Water Center (NWC), and other stakeholders.

Looking ahead and summary

SPLASH is scheduled to end in September 2023. At this time, most SPLASH instrumentation will likely be removed from the ERW, though discussions are underway to support extended deployment of some assets. Such an extension would primarily support local stakeholders and water and weather awareness and prediction in the area. It would additionally provide enhanced sampling of the atmosphere and surface state in support of long-term activities such as those undertaken by the Watershed SFA. These extended deployments would also be designed to target a better understanding of environmental conditions that affect wildland fire behavior and the hydrological impacts of extreme precipitation events. Currently, SPLASH datasets are being curated and published on open data archives, and several are already available for public use (see data availability statement). The SPLASH community is working to document their observations through peer-reviewed data papers, and the first scientific results using SPLASH data are starting to be published. The SPLASH team continues to develop partnerships with a variety of research institutions to expand community engagement and the use of SPLASH observations. This has been accomplished in part by a series of sessions at major scientific conferences domestically and abroad. Much work remains to support synthesis across the different field campaigns being undertaken, and the SPLASH team is working to support the homogenization of datasets across SPLASH, SAIL, and SOS to offer consistent data products that are easily accessible and interpretable to the scientific community.

Three major targets of SPLASH included 1) documenting variability of precipitation, lower-atmospheric, and surface properties and processes over a variety of different time scales and the influence of large-scale circulation on driving such variability, 2) characterizing the role of these processes in driving streamflow in the Upper Colorado River basin, and 3) fostering community awareness of the efforts to help inform and improve forecasts of weather and water in the western United States.

The execution of a large field campaign in an area of complex terrain remains a challenging endeavor. The planning for SPLASH involved siting trade-offs that required compromises between logistical considerations (e.g., power availability, access, security) and scientific objectives (e.g., covering different surface types, capturing information over the valley slopes). Such trade-offs will always exist and require that we continue to advance our observational capabilities to support increased autonomy, improve power systems, and foster remote operations. SPLASH took some steps in this direction by deploying autonomous flux systems and uncrewed aircraft, though continued progress is important. Another lesson reinforced by the SPLASH effort is that a single annual cycle is rarely sufficient. SPLASH documented precipitation extremes, from the extended dry periods of 2021 to one of the snowiest winters on record in 2022/23. Documentation of such variability helps provide important context and gain insight into the tails of climatological distributions, and helps weather prediction partners (e.g., the National Weather Service) gain detailed insight into drivers of precipitation in their operational domain. Similarly, adequately documenting, in high resolution and detail, the spatial variability that exists continues to be a challenge. Correctly identifying and sampling representative subdomains in a complex mountain region requires low-cost and distributable sensors. It likely also requires preemptive studies and simulations to identify domains of particular importance and interest. Together with SAIL, SOS, and the multitude of observing activities being undertaken by the Watershed Function SFA, SPLASH provides enhanced coverage of such variability, though only time will tell how much more is required. Ultimately, observing weather and water over mountainous regions remains a difficult undertaking of increasing importance, and SPLASH has demonstrated the importance of having strong community partners, dedicated field technicians, and engaged scientists in ensuring that such efforts are carried out successfully.

Along the way, several high-interest events have taken place, including the December 2021 heavy snow event, locally known as the “Santa Slammer,” that buried Crested Butte and surroundings in several feet of snow. In addition, there were significant deposition events that darkened the snowpack during spring melt, a strong and active summer monsoon season, and water transport associated with several atmospheric river events. The ongoing, coordinated efforts of the SPLASH field campaign have produced a very large number of datasets that will be the focus of scientific research for many years. Ongoing and future research efforts are directed at using these observations to support the testing, development, and ultimate improvement of model subgrid-scale processes and observational retrievals to enable the improved prediction of weather and water in high-altitude complex terrain on diurnal to seasonal time scales.

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Data availability statement. SPLASH data are being made available to the public through Zenodo. While the campaign is ongoing, initial datasets are available through a Zenodo SPLASH community (https://zenodo.org/communities/splash), with additional datasets being added regularly as quality control is completed. Additional data are displayed through the data portal and "SPLASHboard" on the SPLASH website (https://psl.noaa.gov/splash/). SPLASH contributors will continue to provide new datasets through the Zenodo community for public download throughout and after the completion of the campaign. ASO data, not formally part of SPLASH, are hosted on the ASO website, https://data.airbornesnowobservatories.com/.

Appendix: List of abbreviations

AERI	Atmospheric Emitted Radiance Interferometer
ARL	NOAA Air Resources Laboratory
ARM	U.S. DOE Atmospheric Radiation Measurement program
ASFS	Atmospheric Surface Flux Station
ASSIST	Atmospheric Sounder Spectrometer by Infrared Spectral Technology
BST	Black Swift Technologies
CIRES	Cooperative Institute for Research in Environmental Sciences
CLAMPS	Collaborative Lower Atmospheric Profiling System
CRB	Colorado River basin
DOE	U.S. Department of Energy
EOL	Earth Observing Laboratory
ERW	East River watershed
GML	NOAA Global Monitoring Laboratory
HRRR	High-Resolution Rapid Refresh Model
MFRSR	Multifilter rotating shadowband radiometer
MFR	Multifilter radiometer
MRMS	Multi-Radar Multi-Sensor
MWR	Microwave radiometer
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NSSL	NOAA National Severe Storms Laboratory
NWM	National Water Model
NWS	National Weather Service

OWP	Office of Water Prediction
PPI	Plan position indicator
PSL	NOAA Physical Sciences Laboratory
QPE	Quantitative precipitation estimate
RFC	River Forecast Center
RHI	Range–height indicator
RRFS	Rapid Refresh Forecast System
SAIL	Surface Atmosphere Integrated Field Laboratory
SFA	Science Focus Area
SOS	Sublimation of Snow Project
SPLASH	Study of Precipitation, the Lower Atmosphere and Surface for Hydrometeorology
SLR	Snow-level radar
SURFRAD	Surface Radiation network
SWE	Snow water equivalent
sUAS	Small uncrewed aircraft system
UFS	Unified Forecast System
WFO	Weather Forecast Office

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