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Investigating Spatial Variability of Aerosol, Cloud Condensation Nuclei, and Ice Nucleating Particles in Mountainous Terrain Field Campaign Report

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Acronyms and Abbreviations

AMF2	second ARM Mobile Facility
AOS	Aerosol Observing System
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
CCN	cloud condensation nuclei
CV	aerosol volume concentration
ERW	East River Watershed
INP	ice nucleating particles
PM	particulate matter
POPS	portable optical particle spectrometer
SAIL	Surface Atmosphere Integrated Field Laboratory
SPLASH	Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology
TRAPS	time-resolved aerosol filter sampler

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1.0 Summary

The U.S. Department of Energy Atmospheric System Research (ASR)-supported Surface Atmosphere Integrated Field Laboratory (SAIL) campaign in the East River Watershed (ERW) of the Upper Colorado River Basin in southwestern Colorado ran from fall 2021 to spring 2023. Two monitoring sites were deployed in the ERW as part of SAIL. The two sites were the Aerosol Observation System (AOS) located on Crested Butte Ski Mountain, and the second ARM Mobile Facility (AMF2), located at the Rocky Mountain Biological Laboratory in Gothic, Colorado. To gain a more comprehensive understanding of aerosols in complex, mountainous terrain, Handix Scientific deployed SAIL-Net, a distributed network of six measurement nodes spanning the domain of the SAIL research area from October 2021 to July 2023.

Each node measured aerosol particles between 140 nm and 3.4 µm in diameter using a small portable optical particle spectrometer (POPS; Gao et al. 2016), cloud condensation nuclei (CNN) using a miniature CCN counter (CloudPuck), and ice nucleating particles (INP) using the time-resolved aerosol filter sampler (TRAPS; Creamean et al. 2018). Our approach was similar to other studies that aimed to better characterize and understand aerosols and gas-phase pollutants using networks of lower-cost sensors (Caubel et al. 2019, Kelly et al. 2021, Asher et al. 2022). Such studies have identified neighborhood-level variations in pollutant concentrations (Schneider et al. 2017, Popoola et al. 2018, Caubel et al. 2019). Small-scale variations such as this are poorly represented in models and poorly measured by a single monitoring system (Caubel et al. 2019). Previous work has shown the representation error (the ability of measurements to represent a larger area) increases with complex orography, leading to decreases in model accuracy (Schutgens et al. 2017). The overall goal of SAIL-Net was to improve our understanding of the variability of aerosol in the ERW, thus increasing our knowledge of aerosol-cloud interactions in this region and informing the usefulness of distributed networks of measurements for future studies. We met this goal by answering the following science questions:

1. What is the aerosol temporal variability, and how does aerosol inhomogeneity vary seasonally? Is there significant seasonal variability in sources, or are short-term meteorological conditions the most important determining factor in sources for cloud nuclei?
2. What is the aerosol spatial variability? What are the aerosol characteristics at cloud base, presumably the particles most representative of those acting as cloud nuclei?
3. How should measurement networks be designed to capture aerosol-cloud interactions, and what do they need to measure? Can a single measurement site accurately represent aerosol properties in regions of complex terrain?

SAIL-Net consisted of six measurement nodes spread across the ERW near Crested Butte, Colorado. The primary objective in site placement was to select locations that captured the vertical variation in aerosol properties while also spanning the domain of the SAIL campaign. The elevation of the sites ranged from roughly 2750 m along the valley floor of the ERW to approximately 3500 m near the top of Crested Butte Mountain, which is one of the taller peaks in the ERW. The farthest distance between sites was 14 km, while the closest two sites were approximately 1 km apart. Two of the sites were collocated with the ARM SAIL sites; our instruments sat on top of one of the trailers at AOS and another one of our sites was located in a meadow just above AMF2.

Figure 1. Map of the six sites in SAIL-Net.

Most of the SAIL-Net sites experienced downtime at some point due to instrument malfunctions or lost power. Since the sites were only visited at most once a month and some malfunctions had to be either manually corrected in the field or the instrument had to be fixed at Handix Scientific, some gaps in data could last multiple months. Figure 2 displays the data completeness for each SAIL-Net site.

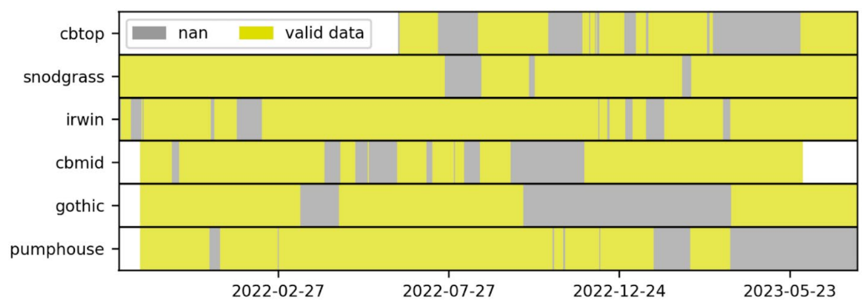

Figure 2. Data completeness for the six SAIL-Net sites.

Other notable events recorded by SAIL-Net include a few smoke and dust events, as listed below:

- June 13-14, 2022: SAIL-Net recorded its highest aerosol concentrations due to wildfire smoke coming from the Flagstaff Wildfires in northeastern Arizona.
- September 9-14, 2022: Elevated PM2.5 concentrations were attributed to widespread smoke from wildfires burning in Idaho and the Pacific Northwest.
- May 20-25, 2023: Elevated PM2.5 concentrations were attributed to smoke from Canadian wildfires.
- April 4, 2023: A substantial dust event hit southwestern Colorado, depositing large amounts of dust on the snow.

2.0 Results

The POPS produced the longest and highest temporal resolution data set, which allowed the study of spatiotemporal variability in aerosol concentrations and distributions. The POPS data are available on ARM Data Discovery: https://doi.org/10.5439/2203692. The CloudPuck data were sparse due to issues with the instrumentation. However, all available CloudPuck data are posted on ARM Data Discovery: https://doi.org/10.5439/2203936. Data from the TRAPS filters are being analyzed by Russel Perkin's group at Colorado State University.

All the sites exhibited similar daily behavior and seasonal trends. The sites experienced higher total aerosol concentrations in the summer and lower in the winter, which was consistent with the seasonal trends of other mountainous regions (Gallagher et al. 2011). Concentrations peaked in the later summer and reached a minimum in January. The maximum recorded concentration occurred on June 13, 2022, at the Gothic site, with an average daily concentration of 672 cm^{-3} due to smoke from the Flagstaff wildfires in Arizona. Since the goal of this campaign was to measure and investigate the spatiotemporal variability of aerosol in complex terrain, we will briefly summarize our primary observations of the spatial and temporal variability of aerosol from the POPS data in SAIL-Net.

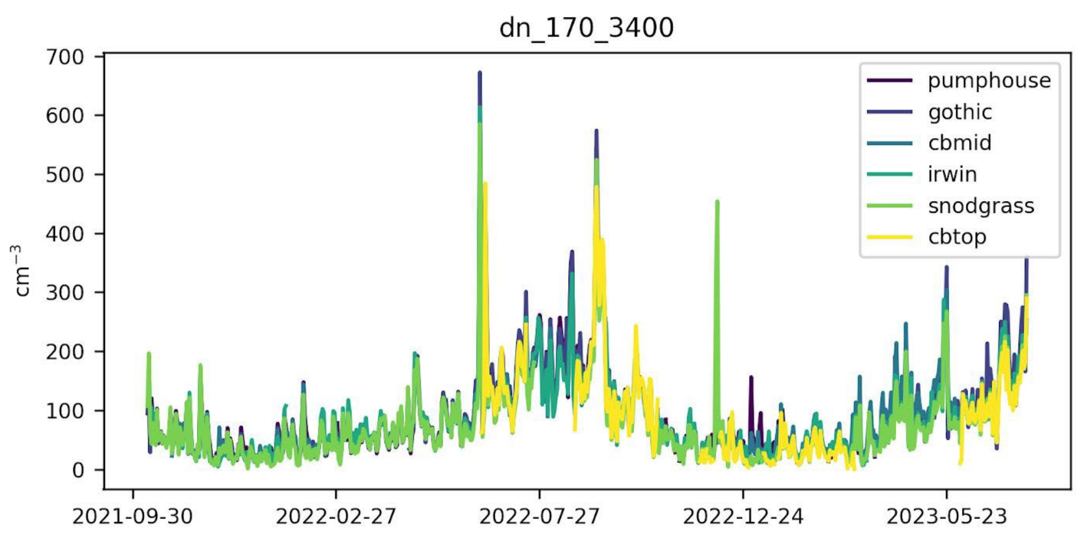

Figure 3. Seasonal variation in aerosol concentrations across the six SAIL-Net sites.

Observation 1: Sites at similar elevations are more similar to one another than sites that are geographically close. We found a positive correlation (Pearson R = 0.48) when looking at the average percent difference between 170-300 nm-sized aerosol concentrations as a function of the vertical (elevation) difference between sites. We compared this to the average percent difference as a function of the geographic distance between the sites, which had a slight negative correlation (Pearson R = -0.37).

This result is particularly surprising because it is commonly assumed that spatially close measurements should be more similar to one another. It is possible that we see the negative correlation for nearby sites because some of the farthest apart sites have a closer elevation and vice versa. For example, the two closest sites, CBMid and CBTop, which are around 1 km apart, are the most different from one another.

Observation 2: There appears to be higher variability amongst the SAIL-Net sites in the winter. The data were grouped by time, so that each time step provided a set of data for which to compute the aerosol volume concentration (CV). Each set was normalized using min-max scaling before computing the CV. This choice was made to account for the seasonality of the data while maintaining the relative distance between values. Based on our results, there was less variability among the sites during the summer of 2022 than in other seasons. The variability also began trending downward as the weather warmed in 2023 but then increased in the last few weeks of deployment. We hypothesize that the increased variability in the cooler seasons could be partially due to the impact of snow-covered ground on the daytime convective boundary layer. Adler et al. (2023) saw a low convective boundary layer over snow-covered terrain in the East River Watershed and observed inversions at night. In some observations, the boundary layer was low enough that some high-elevation sites in SAIL-Net would be above the boundary layer, and thus measure different aerosol concentrations than below the boundary layer. However, another factor that likely affected the higher variability in the winter months was the low aerosol concentrations across the sites. The depths of winter experienced concentrations of less than 100 cm^{-3} on average. In these clean conditions, any local variability would amplify the differences between sites.

Observation 3: While the overall trends and absolute concentrations are pretty similar across the sites, the representation errors of all of the sites were still higher than those observed by Asher et al. (2022) during the POPSNet study over the same averaging period of one day. This could be due to a number of factors such as SAIL-Net being deployed for longer periods, or the lack of colocation of two POPS at each site. However, this may also suggest that there is indeed increased aerosol variability in complex terrain.

Future research opportunities include:

- Further investigating the relationship between wintertime variability and the height of the convective boundary layer. Are there truly times when the high-elevation sites are above the CBL?
- Integration of these data sets into models.
- Further investigation of the relationship between site similarity and elevation.

3.0 Publications and References

3.1 Journal Articles

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3.2 Meetings and Presentations

- Global Monitoring Annual Conference 2023, Boulder, Colorado (poster)
- AAAR Conference 2023, Portland, Oregon (poster)

- SAIL/Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology (SPLASH) biweekly meetings hosted by Lawrence Berkeley National Laboratory, 2023 (presentation)
- SAIL, SPLASH, SOS Meeting, 2023, Boulder, Colorado (presentation)

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