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A multi-decadal climatology of dust-on-snow from wet deposition in the Upper Colorado River Basin

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Abstract. Dust-on-snow deposition is the dominant factor in earlier snowmelt timing in the Upper Colorado River Basin (UCRB), which gets ~70% of its annual streamflow from snowmelt. Previous studies have demonstrated the radiative effects of dust-on-snow deposition, but have not quantified what deposition types, whether from atmospheric turbulence (dry deposition) or hydrometeor scavenging (wet deposition), drive these radiative effects. Here, we produce a climatology of the total amount and type of dust-on-snow deposition in the UCRB using the Modern-Era Retrospective analysis for Research and Applications (MERRA-2) reanalysis dataset from 1980-2023 and evaluate its accuracy using Surface Atmosphere Integrated Laboratory (SAIL) field measurements taken in 2022 and 2023 and Moderate Resolution Imaging Spectrometer (MODIS) Snow Property Inversion from Remote Sensing (SPIReS) dust concentration data. The results show that wet deposition is the dominant form of dust-on-snow deposition in the UCRB, comprising 73.8% of total dust deposition. Additionally, the eastern areas in the UCRB, particularly the Gunnison Watershed, experience 16% higher wet deposition monthly totals (69.33 mg m^{-2}) than the entire UCRB average (59.80 mg m^{-2}). These results highlight the importance of persistent spatial patterns but also interannual variability in accounting for dust deposition. This climatology also contextualizes the long-term records of dust deposition by showing how the relationships between dust at several sites with decadal records project onto the entire Basin, while also supporting water resource planning, especially for areas with elevated wet deposition levels.

1 Introduction

The Colorado River is one of the most important rivers in the US, providing water resources for 40 million people and helping to power 4.2 gigawatts of hydroelectric capacity (U.S. Bureau of Reclamation, 2012). The Upper Colorado River Basin (UCRB), which stretches across 5 Western states, provides nearly 90% of the Colorado River's total flow (McCabe and Wolock, 2007). However, the UCRB has faced drought conditions for over 20 years, which has stressed its water resources (McCabe et al., 2024). Within mountainous areas like the UCRB, snowmelt accounts for 70% of the total runoff and is vital to sustaining the Western water supply (Li et al., 2017). The dominant control on snowmelt timing in the UCRB is the deposition of mineral dust on snow, with dust comprising 90% of the concentration of light absorbing particles in the

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area (Skiles and Painter, 2017). Mineral dust is composed of soil particles with diameters ranging from 0.1 - 50 µm, although dust particles larger than 6 µm have limited transport (Ginoux et al., 2001) and most deposited dust is transported from hundreds to tens of thousands of kilometers away (Painter et al., 2010; Neff et al., 2008; Heald et al., 2006; Chin et al., 2007; Wells et al., 2007). Dust particles in the snow decrease the snow's albedo, leading to increased radiative forcing (RF) that accelerates snowmelt by 3-7 weeks compared to a clean snowpack (Naple et al., 2025). Rapid snowmelt due to dust deposition decreases total runoff due to increased evapotranspiration and produces errors in snowmelt forecasting, straining water resources in an already drought-stressed area (Painter et al., 2010). Therefore, a robust understanding of the UCRB's water resources necessitates a characterization of the spatiotemporal dynamics of dust-on-snow deposition.

Dust deposition on snow can occur through two main ways: wet deposition, where precipitation scavenges dust particles, and dry deposition, when dust settles through turbulent mixing and gravity without precipitation. Both types of deposition occur in the UCRB, with the majority of events appearing in the spring (Colorado Dust on Snow Program). Dust deposition events, especially wet deposition events, are difficult to quantify from a remote sensing perspective due to storm cloud cover obscuring sensor views and precipitation particle sizes dwarfing mineral dust particle sizes by a magnitude of 1000x (Adibiyi et al., 2023).

In-situ monitoring of UCRB dust deposition is the primary source of information on dust-on-snow events in the Basin but is limited to in-person observations of the number of deposition events and qualitative observations of the severity of each storm (Colorado Dust on Snow Program). Due to the remote sensing challenges and lack of quantitative in-situ data, we draw insights from a modeled dust deposition product from NASA's Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2).

Although some studies exist looking at dust-on-snow radiative forcing impacts and its effects on melt-out dates, runoff, and streamflow timing across the UCRB (Skiles and Painter et al., 2012, Deems et al., 2013, Bryant et al., 2013, Fassnacht et al., 2022, Naple et al., 2025), they do not quantify the amount of dust deposition at a basin-wide scale or investigate the differences between wet deposition and dry deposition. Studies outside of the UCRB have used the GEOS-Chem model to quantify total black carbon deposition and light absorbing particle impacts in the Tibetan Plateau (He et al., 2014, Hao et al., 2023). Others have used MERRA-2 in combination with WRF-Chem to quantify wet and dry deposition in the Sierra Nevada (Huang et al., 2022). MERRA-2 has also been used to study dust sources and transport in the Colorado Plateau (Huang et al., 2026). Thus, the goals for this study were to develop a dust-on-snow climatology that is differentiated by deposition type and explore how well the spatiotemporal patterns of dust deposition are known with the following questions:

1. How accurate is MERRA-2 at detecting dust-on-snow events, particularly with wet deposition?
2. What are the most significant climatological features of dust-on-snow in the UCRB?

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3. How did the dust-on-snow deposition patterns recorded at the Surface Atmosphere Integrated Laboratory (SAIL) field campaign compare to the rest of the UCRB?

To examine the amount of dust-on-snow deposition across space and time in the UCRB, we use a MERRA-2 product over a long period of record (1980-2023) to develop a climatological analysis. We then compare the MERRA-2 product to the SAIL campaign measurements in Gothic, CO from 2022 - 2023 to validate the accuracy of the modeled product and contextualize in-situ observations temporally and spatially across the UCRB. Within the UCRB, we focus our analysis in the Gunnison Watershed, which provides 16% of natural streamflow to the UCRB (Miller et al., 2013) and contains the SAIL field site. We finally validate the MERRA-2 product using Moderate Resolution Imaging Spectrometer (MODIS) Snow Property Inversion from Remote Sensing (SPIReS) to analyze the measured dust concentration in the snow from a remote sensing perspective (Bair et al., 2021).

2 Data and Methods

Dust deposition totals were taken from the MERRA-2 Aerosol Diagnostics product (M2T1NXADG), which is an hourly two-dimensional reanalysis product that separates the deposition of different types of aerosols, from black carbon to mineral dust (GMAO & Pawson 2015). All dust deposition analysis used DUWT and DUDP quantities, which were M2T1NXADG variables representing rates of mineral dust wet deposition and mineral dust dry deposition, respectively. Dust deposition is split into 5 mass bins based on particle sizes, ranging from a radius size of 0.73 - 8 μm (GMAO 2023). For our purposes, we summed up all dust deposition bins together to get a single deposition number, as our analysis concerns all sizes of dust deposition. The resolution of the MERRA-2 product is 0.625 x 0.5 degrees (longitude x latitude) which translates to a ~54km x ~55km resolution in meters across the UCRB.

The MERRA-2 model simulates dust entrainment, transport, evolution, and deposition using the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model coupled with the Goddard Earth Observing System (GEOS) (Ginoux et al., 2001). This dust is transported by advection along with turbulent and convective mixing and then is removed through simulated dry deposition (Wesely 1989) and wet deposition (Liu et al., 2001, Wang et al., 2011). Wet deposition removal is based on MERRA-2 precipitation fluxes and typical scavenging efficiencies of liquid and solid precipitation (Colarco et al., 2014, Randles et al., 2016). Because MERRA-2 is a reanalysis dataset, data lags real-time measurements by a few weeks to account for assimilation using historical precipitation and aerosol measurements.

In-situ data on dust deposition dates and types were obtained from the SAIL Campaign conducted in Gothic, CO from 2021-2023 (Feldman et al., 2023). Dust deposition events were identified by detecting increased aerosol concentrations through an Optical Particle Counter (OPC) and decreases in 415 nm surface albedo from a SKYRAD broadband instrument (Gibson et

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al., 2025). Wet deposition events were characterized by increases in precipitation data from a Pluvio2-L weighing bucket (Zhu et al., 2021) and lagged surface albedo changes. Dry deposition events had no precipitation bucket events and immediate surface albedo effects (Gibson et al., 2025).

To compare dust deposition to the presence of dust in the snow on the ground, we took dust concentration data in parts per million weight (ppmw) from a remotely sensed MODIS SPIReS 500m product (Bair et al., 2021). This product estimates the dust concentration in a snow-covered pixel by computing the scattering properties of light-absorbing particles (LAPs) using the Mie theory. Then, it uses a spectral mixing linear mixture model to solve for multiple variables, including dust concentration, snow-covered area, photometric shade, and grain radius, by minimizing the modeled surface reflectance and observed surface reflectance from MOD09GA. Therefore, additional dust deposition on the snowpack would theoretically lead to higher dust concentration values for the snowpack. Although SPIReS cannot differentiate between the concentrations of different LAPs (such as black carbon versus dust), this is of limited concern in the UCRB context, as the dominant LAP during spring melt is mineral dust (Naple et al., 2025), and black carbon's effect on snow albedo is spectrally indistinguishable from that of dust from a MODIS standpoint (Bair et al., 2021). This algorithm performs similarly in accuracy for estimating snow albedo compared to MODIS Snow Covered Area and Grain-size (MODSCAG) and MODIS Dust Radiative Forcing in Snow (MODDRFS), but has the advantage of directly obtaining dust concentrations instead of additional radiative forcing due to dust (Painter et al., 2009, Painter et al., 2012, Palomaki et al., 2025).

All outputs were clipped to the UCRB shapefile taken from the United States Geological Survey's (USGS) Watershed Boundary Dataset 2-digit hydrologic unit, and the Gunnison Watershed in this study refers to the USGS 4-digit hydrologic unit within the UCRB.

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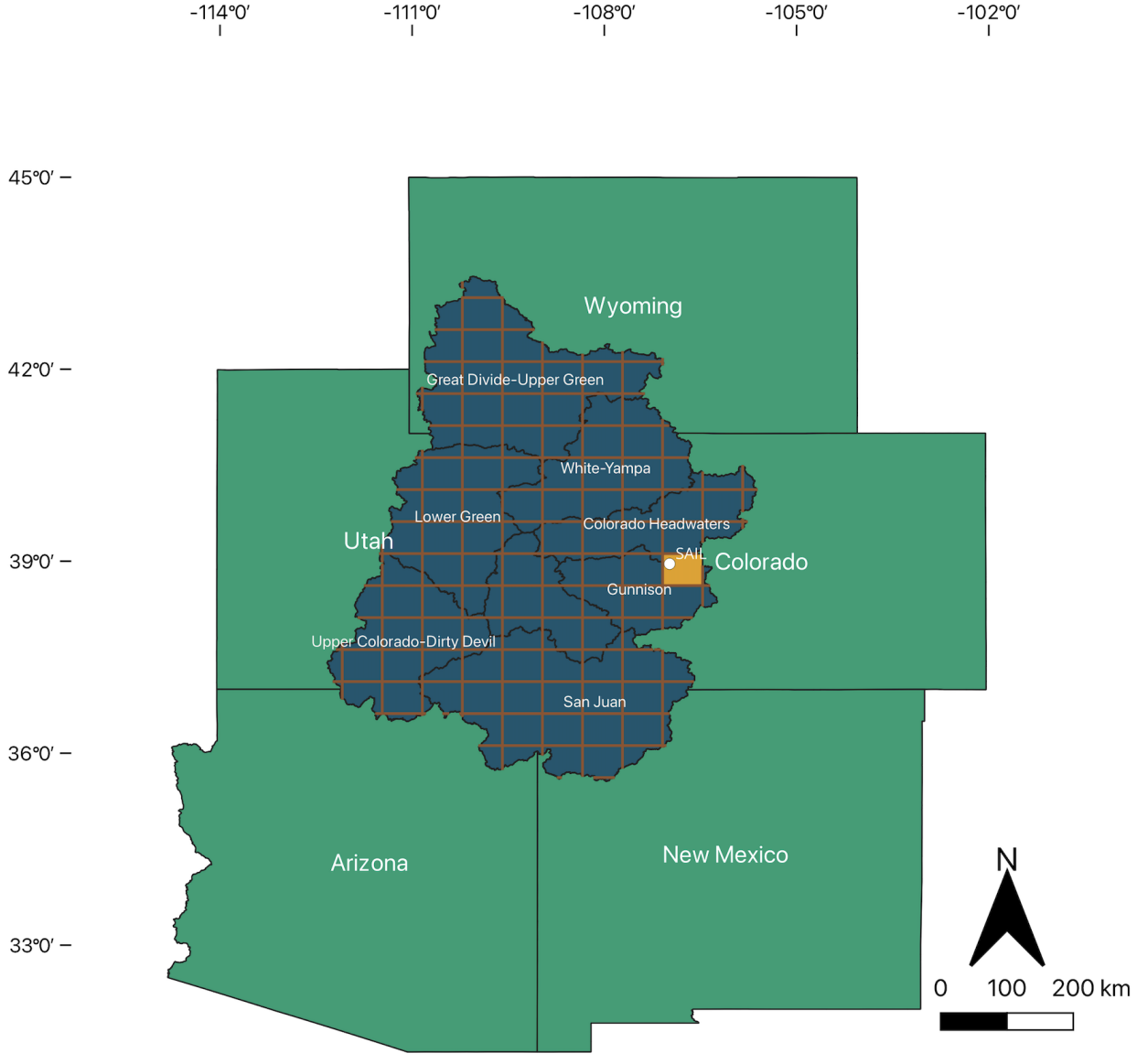

Figure 1: Map of the Upper Colorado River Basin in MERRA-2 grid resolution

2.1 Validation of MERRA-2 Data with SAIL Data

SAIL field data shows 17 total dust-on-snow deposition events from February 2022 - April 2023 with 13 wet deposition events and 4 dry deposition events (Table 1). We pulled MERRA-2 DUWT (Dust Wet Deposition) and DUDP (Dust Dry Deposition) data from the same time period (February 2022 - April 2023) at a pixel over the SAIL site near Gothic, CO at 38.96° N, 106.99° W. Although the resolution of this data (~55km) is larger than area represented by field measurements, previous analysis shows there is minimal variability in aerosol concentrations on at daily timescales across the East River

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Watershed, and therefore these two data products can be compared (Gibson et al., 2025). Hourly MERRA-2 data was then summed to a single daily total. We created a histogram of each year's monthly dust deposition data split into 6 different dust deposition bins categorized by the amount of dust deposition in μg m^{-2}, with each day's dust deposition as an input. Wet deposition was histogrammed separately from dry deposition. The bins were thresholded such that a majority of days with no dust deposition fell into the first bin, while the second bin onwards captured days of dust deposition. These dust deposition days were then compared to the SAIL field data. The number of bins for each month was adjusted to capture the number of SAIL dust deposition days as closely as possible.

2.2 Comparison with MERRA-2 Climatology

To contextualize the 2022-2023 UCRB MERRA-2 dust deposition results to the historical dust deposition mean, we develop a climatology of the MERRA-2 dataset from 1980 - 2023 for both dry deposition and wet deposition for the months of February, March, April, and May (the heaviest recorded months for dust-on-snow deposition). We summed the total cumulative dry and wet deposition separately for each month and year and then took the average across all years in the period to develop a 43-year climatological mean for each month for both wet and dry deposition. This corresponds to the length of the MERRA-2 record, which itself is driven by the introduction of modern satellite technology, especially with the Television and InfraRed Observation Satellite - N (TIROS-N) systems. We also calculate the standard deviation for each month across the 43-year period to measure interannual variability. The percentage of wet versus dry deposition was calculated by adding together wet and dry deposition to get total dust deposition, then dividing each component by the total dust deposition amount.

We also summed the total dry and wet deposition from MERRA-2 for the pre-melt snow water year (November - May) for 2022 and 2023. This total accumulates all the winter and spring precipitation and dust deposition that affects snowmelt. All summed pixels in a region were spatially averaged together to get one dust deposition value for each region.

To see if additional precipitation was the only factor for increased wet deposition, we calculated a Spearman's rank correlation coefficient (ρ) between total MERRA-2 precipitation and total wet deposition for 2022 and 2023 in the UCRB. Spearman's correlation coefficient is a non-parametric measure of correlation between two variables without assumptions of the underlying distribution of each variable (Spearman 1904). Like an r^2 value, ρ ranges from -1 to 1, indicating the strength of correlation.

Finally, to assess the anomalousness of wet deposition during the SAIL campaign years (2022 and 2023), we computed z-scores using the climatological mean and standard deviation as the population parameters. The z-score method has been used in previous studies to compare MERRA-2 dust aerosols and dust deposition across multiple time periods (Zamora et al., 2022, Bolaño-Ortiz et al., 2023) and is widely used in drought analysis to detect precipitation anomalies (Wu et al., 2002,

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Ford 2014). Each campaign year's wet deposition total was treated as a sample observation, allowing us to express its departure from the long-term climatological average in the context of an outlier analysis. Z-scores were calculated for each area of the analysis within the UCRB separately, ensuring that the same area was compared across different years. We converted the monthly climatology means to a single aggregated climatology mean, and the 2022 and 2023 monthly sample means to two yearly aggregated sample means using Eq. (1), where N_i is the number of days in each month and μ_i is each month's wet deposition mean.

$$\mu = \frac{\Sigma_i^n N_i \mu_i}{\Sigma_i^n} \quad (1)$$

By using the law of total variance, we translated the monthly standard deviations into a combined single standard deviation using Eq. (2), where *Var(X)* is the total variance across time or space, *Var(X|i)* is the variance for each pixel or month's wet deposition, μ_i is taken from Eq, (1), and σ_i is each pixel or each month's wet deposition standard deviation.

$$Var(X) = E[Var(X|i)] + Var(E[X[i])$$
$$Var(X) = E[\sigma_i^2] + Var(\mu_i) \quad (2)$$
$$\sigma = \sqrt{Var(X)}$$

Finally, we used the means and standard deviations to calculate a z-score for the 2022 and 2023 wet deposition totals using Eq. (3), where μ_s is the 2022 or 2023 wet deposition mean calculated from Eq. (1), μ_c is the 43-year climatology mean calculated from Eq. (1), and σ_c is the 43-year climatology standard deviation calculated from Eq. (2).

$$z = \frac{\mu_s - \mu_c}{\sigma_c} \quad (3)$$

2.3 SPIReS Dust Concentration Analysis

Historical SPIReS scenes from February - June of 2022 and 2023 were downloaded from the National Snow and Ice Data Center. Because MODIS scenes have a different projection based on a tiling system, we downloaded three different tiles that together cover the UCRB: h09v04, h09v05, and h10v04. The three tiles were mosaiced together using rioxarray's "merge_arrays" method, then reprojected using nearest neighbor to EPSG:4326 using rioxarray's "reproject" method. Because dust deposition on snow builds up over successive events and accumulates over time before fully emerging as the snowpack melts, we took the maximum dust concentration value across the melt season (February-June) for each pixel to account for this accumulation phenomenon. Previous work has linked SPIReS dust concentration as a proxy of clean snowpack and used the date of maximum MODDRFS, a similar product, as a representation of maximum dust accumulation on the snowpack (Bair et al., 2021, Naple et al., 2025). All 500m maximum pixels in a region were spatially averaged together to get one SPIReS dust concentration value for each region, including the Gunnison Watershed and the wider UCRB.

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After resampling the 500m maximum SPIReS aggregation to 55km using the average resampling method, we masked out any pixels with less than 25% valid SPIReS pixels for both the SPIReS dataset and corresponding MERRA-2 pixel. Invalid SPIReS pixels exist where the SPIReS fractional snow cover never reaches above or equal to 0.10 (Bair et al., 2021). We calculated a Spearman's correlation coefficient to measure the correlation between dust deposition and the snowpack's dust concentration. We then compared the SPIReS changes for 2022 and 2023 for each area in the basin against the changes in total MERRA-2 dust deposition to assess whether MERRA-2 dust deposition amounts aligned directionally with observed dust concentration levels.

3. Results

Wet deposition was the dominant type of dust deposition in the UCRB. Wet deposition accounted for 73.8% of MERRA-2's total dust deposition, and dry deposition contributed 26.2% to total dust deposition from 1980 - 2023. This is consistent with the SAIL field data, where 13/17 (76%) were wet deposition events and 4/17 (24%) were dry deposition events (Table 1). Wet deposition events were easier to identify than dry deposition events using MERRA-2, as the magnitude of the total dust deposition was significantly elevated (>8x the normal average) during wet deposition events (Figures 1&2) compared to dry deposition events (<1.5x the normal average). Due to the elevated effect of wet deposition events in the UCRB, the increased ability of MERRA-2 to detect these events, and the difficulty of wet deposition detection by traditional remote sensing methods, we decided to focus our MERRA-2 validation analysis with SAIL data on wet deposition.

(a) WY2022 Deposition Date	Deposition Type	Detected by MERRA-2
February 22, 2022	Wet	Yes
March 5, 2022	Wet	Yes
March 31, 2022	Wet	No
April 12, 2022	Wet	Yes
April 20, 2022	Dry	N/A*
April 22, 2022	Wet	No

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May 2, 2022	Wet	Yes
May 3, 2022	Wet	No
May 8, 2022	Dry	N/A*
May 9, 2022	Dry	N/A*

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(b) WY2023 Deposition Date	Deposition Type	Detected by MERRA-2
February 22, 2023	Wet	Yes
February 23, 2023	Wet	No
March 5, 2023	Dry	N/A*
March 30, 2023	Wet	No
March 31, 2023	Wet	Yes
April 4, 2023	Wet	Yes
April 19, 2023	Wet	Yes

204 **Table 1: Dates and type of dust deposition events identified at SAIL, along with MERRA-2 threshold detection agreement for 2022**
205 **(a) and 2023 (b). *Individual dry deposition events were not analysed with MERRA-2.**

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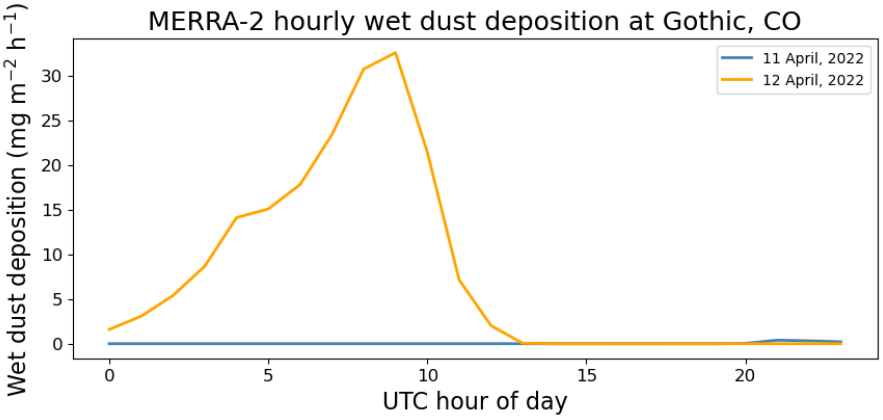
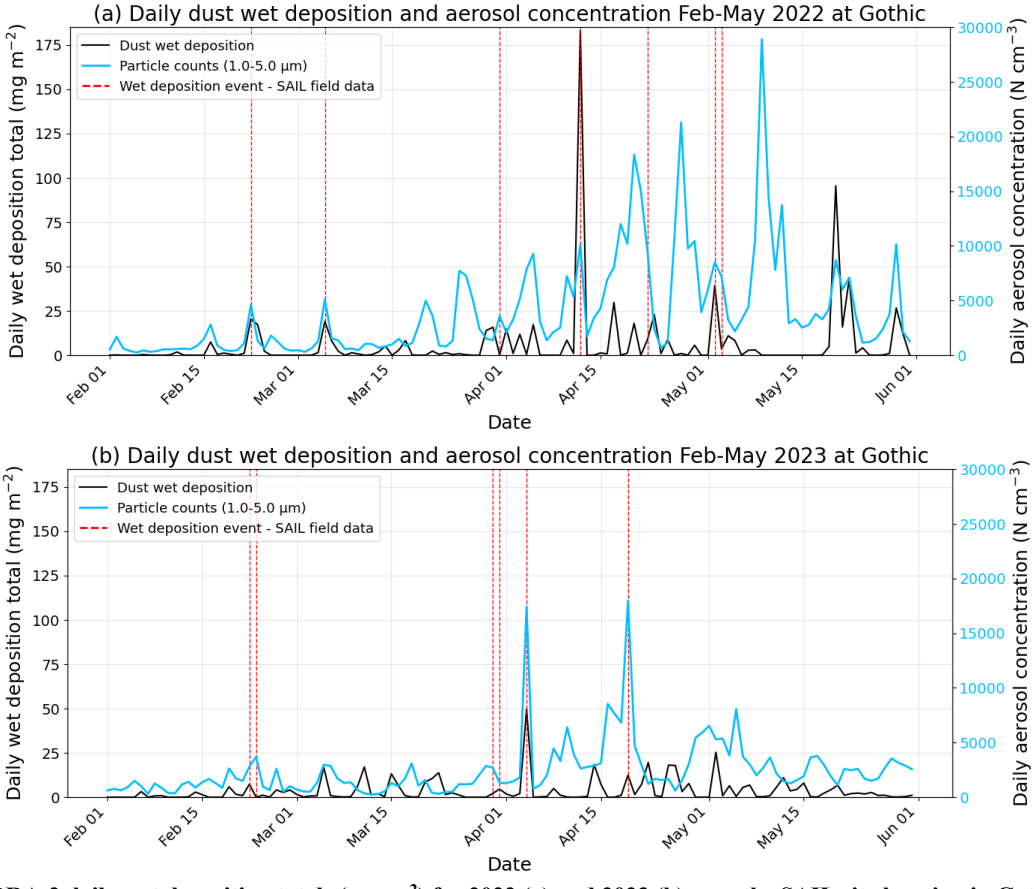


206 **Figure 2: Hourly view of the largest daily deposition event at the SAIL site on 12 April 2022 compared to a normal deposition day**
207 **on 11 April 2022**



208 **Figure 3: MERRA-2 daily wet deposition totals (mg m^{-2}) for 2022 (a) and 2023 (b) over the SAIL site location in Gothic, CO.**

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3.1 MERRA-2 Validation and Climatology Results

MERRA-2 was able to detect most wet deposition events that occurred at SAIL, identifying 8/13 (62%) wet deposition events successfully (Table 1). These wet deposition events (Figure 2) were accompanied by higher supermicron aerosol concentrations observed in the field, which are indicative of dust in the area (Figure 3). Both dry deposition and wet deposition amounts were lowest in February and higher in May, tracking the higher aerosol concentrations observed during the later spring months (Figure 4). Additionally, dry deposition was more uniformly distributed throughout the UCRB compared to wet deposition, which had a heterogeneous spatial pattern (Figure 4).

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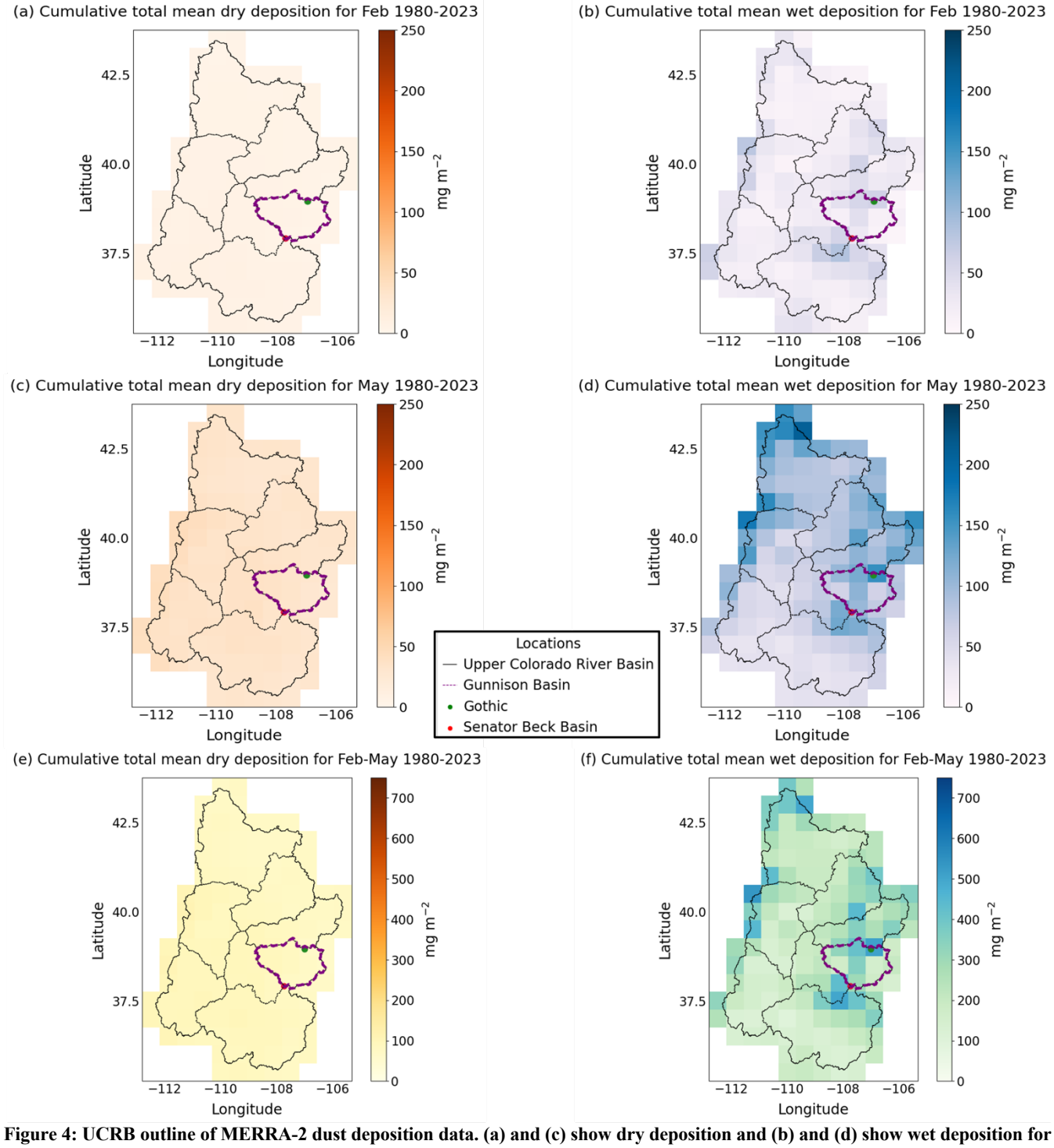

Figure 4: UCRB outline of MERRA-2 dust deposition data. (a) and (c) show dry deposition and (b) and (d) show wet deposition for individual climatology months. (e) and (f) show total average dry and wet deposition for the total 4-month deposition period

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The Gunnison Watershed experienced 16% higher monthly dust wet deposition averages for the MERRA-2 climatology dataset from February - May (69.33 mg m^{-2}) compared to the whole UCRB region (59.80 mg m^{-2}, Figure 4). In particular, the mean monthly wet deposition value over the SAIL site was 114% higher (127.79 mg m^{-2}) than the UCRB average.

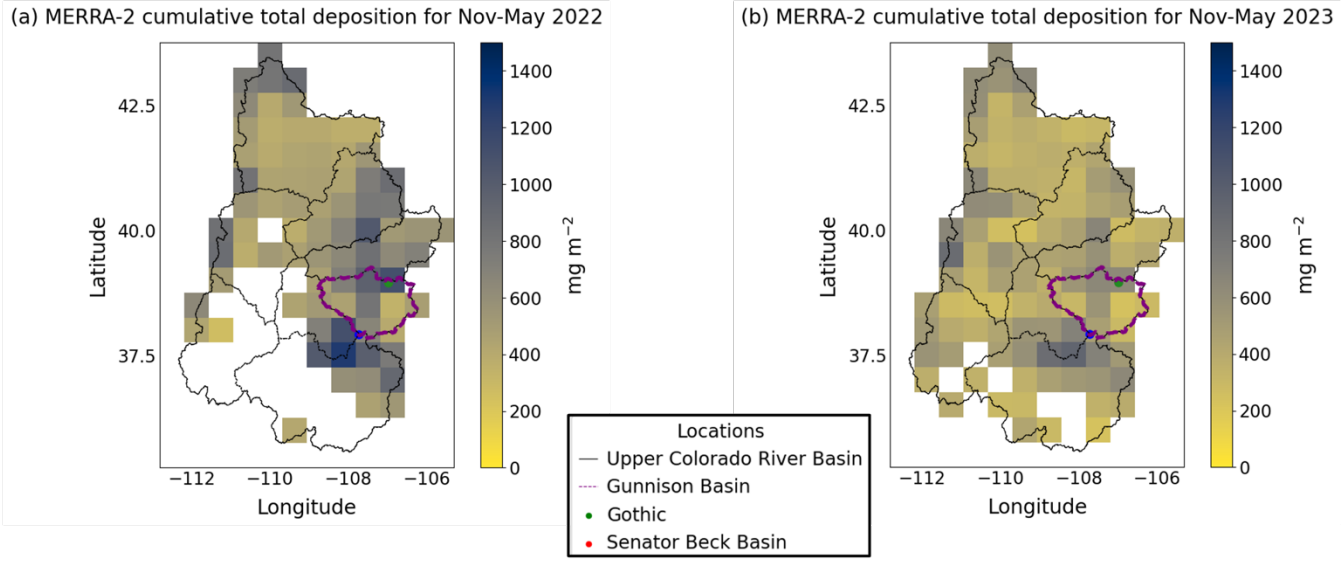

Figure 5: UCRB Outline of total dry and wet deposition from the WY 2022 (a) and WY 2023 (b) spanning November 2021 - May 2022 and November 2022 - May 2023. Pixels with less than 25% of snow cover are masked out

Water Year	UCRB Total Deposition (mg m^{-2})	UCRB Average Deposition (mg m^{-2})	Gunnison Watershed Mean Deposition (mg m^{-2})	SAIL Site Mean Deposition (mg m^{-2})	SAIL Site vs. UCRB Average % Difference	Gunnison Watershed vs UCRB % Difference
2022	48077	608.58	685.63	1110.22	+82%	+13%
2023	46119	452.15	464.96	638.99	+41%	+3%
% Yearly Change	-4%	-4%	-32%	-42%	-41%	-10%

Table 2: Summary of changes in total dust deposition in the UCRB region in WY2022 and WY2023 taken from Figure 5

The SAIL site experiences significantly more total dust deposition (82% in 2022 and 41% in 2023) than the UCRB, while the Gunnison Watershed experienced slightly more total dust deposition than the UCRB in 2022 (+13%) and 2023 (+3%).

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The entire UCRB experienced more dust deposition in 2022 than 2023. The Spearman's coefficient calculation between MERRA-2's wet deposition and corrected precipitation variables yield a value of 0.42 with a p-value below 0.001.

3.2 Z-score Results

Location	2022 Z-score	2023 Z-Score
UCRB	0.24	0.08
Gunnison Watershed	0.50	-0.02
SAIL Site (Gothic, CO)	0.80	-0.22

Table 3: Z-scores comparing the total average monthly wet deposition from February - May in 2022/2023 to the 43-year February - May climatological total average monthly wet deposition in the same area

During the 2022–2023 SAIL campaign years, UCRB z-scores indicate slightly above-average wet deposition compared to the climatology average, with 2022 dustier than 2023 (Table 3). This pattern is reflected in the field data, with one additional wet deposition event recorded in 2022 compared to 2023 (Table 1). In 2023, although wet deposition was elevated across the UCRB, the Gunnison Watershed and SAIL site recorded below-average deposition relative to climatology. None of the years showed an extreme deviance of wet deposition compared to the climatological average, as all z-score magnitudes were less than 1.0.

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3.3 SPIReS Result

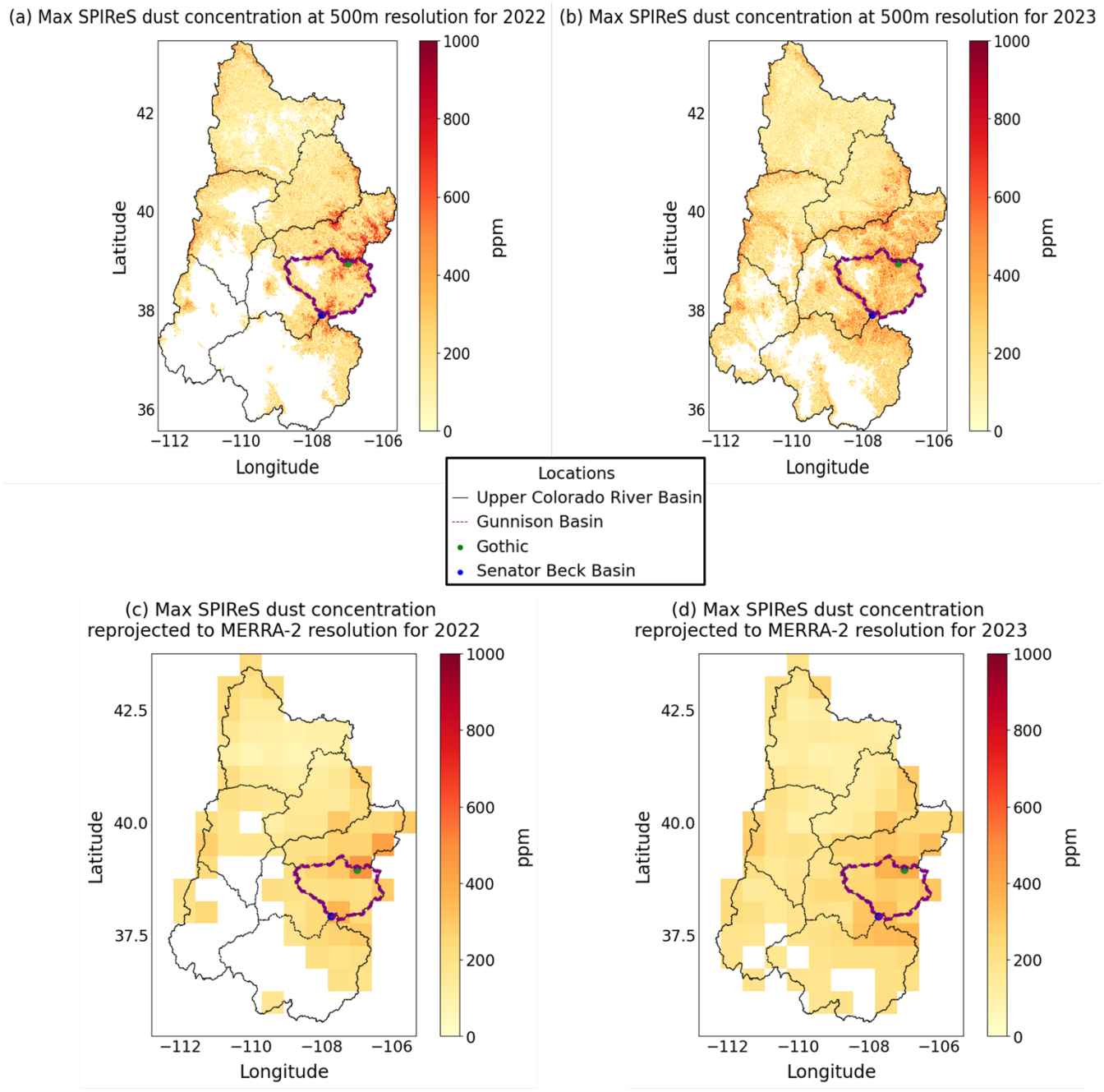

Figure 6: UCRB outline of MODDRFS data. (a) and (b) show SPIReS dust concentration data at the original 500m resolution for February - June (the melt season) 2022 vs 2023. (c) and (d) show SPIReS dust concentration values resampled to MERRA-2 55km resolution in 2022 vs 2023

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Water Year	Average UCRB SPIReS (ppm)	Average Gunnison Watershed SPIReS (ppm)	SAIL Site SPIReS (ppm)	SAIL Site vs. UCRB % Difference	Gunnison Watershed vs. UCRB % Difference
2022	195.18	270.84	503.0	+158%	+39%
2023	199.39	299.44	453.0	+127%	+50%
Yearly % Change	+2%	+11%	-10%	-31%	+11%

Table 4: Max 500m SPIReS values averaged across all pixels in a respective region for February - June of each year.

The spearman correlation coefficient between total MERRA-2 dust deposition from WY 2022 and WY 2023 and maximum SPIReS dust concentration during the 2022 and 2023 melt season was 0.63 and 0.44 with p-values below 0.001, respectively. The SPIReS data over the UCRB showed similar trends spatially to MERRA-2, with a higher dust concentration in both the Gunnison and SAIL site when compared to the broader UCRB (+39% and +158%). The SAIL site showed a decrease in dust concentration from 2022 to 2023, consistent with MERRA-2's modelled decrease in total dust deposition over the same period. However, the SPIReS dataset showed a slight increase in dust concentration for the UCRB and the Gunnison Basin from 2022 to 2023, whereas MERRA-2 showed a slight decrease in dust deposition over the same regions from 2022 to 2023.

4. Discussion

4.1 MERRA-2 and SPIReS Detection Accuracy and Limitations

Although MERRA-2 was able to accurately detect the occurrence of most wet deposition events (62%) when validated with field data in a particular location, the accuracy of the exact projected amounts of dust deposition is still unknown due to the lack of quantitative field data in the area. The excess dust deposition days identified by MERRA-2 relative to the SAIL field record are likely attributable to a combination of MERRA-2's coarse pixel resolution, which integrates deposition signals from a broader area than the field site alone, and its known tendency to overestimate dust deposition flux over the Northern Hemisphere (Koke et al., 2023). Accuracy could be further improved with the development of a finer-resolution dust

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deposition model. Lastly, MERRA-2 does not distinguish between precipitation types of rain or snow in wet deposition, which may overestimate dust-on-snow in areas with low snowpack.

SPIReS has some known limitations when estimating dust concentration. In particular, the dust concentration is fixed at a measured peak value during melt out, and an optically thick layer of snow is assumed during calculation. Thus, the maximum dust concentration may be an underestimate of the total amount of dust in the snow, as dust layers usually aggregate together during spring snowmelt (Naple et al., 2025). Additionally, the main goal for the SPIReS dust concentration estimation is to mimic the LAP's effect on snow albedo instead of maximizing the accuracy of the total amount of dust concentration in the snow (Bair et al., 2021). Therefore, the actual amount of dust concentration in the snow may differ compared to the numbers reported by SPIReS. Lastly, remote sensing retrievals have uncertainties due to cloud cover and must make assumptions about snow grain and dust particle sizes. Even with these limitations, we still believe that SPIReS is a valuable tool to inspect the larger temporal and spatial observational patterns of dust concentrations in the snowpack.

When comparing MERRA-2 with SPIReS, we see that MERRA-2 and SPIReS generally align on dust-in-snow spatially and have a slight disagreement temporally. There is a clear spatial correlation between MERRA-2 dust deposition and observed SPIReS dust concentration, as seen through the spearman's correlation coefficient between MERRA-2 and SPIReS (0.63 in 2022 and 0.44 in 2023). Both MERRA-2 and SPIReS data agree that the SAIL site and the Gunnison Watershed experience higher amounts of dust deposition and dust concentration than the UCRB, with less deposition and concentration at the SAIL site from 2022 to 2023. MERRA-2 and SPIReS disagree slightly regarding dust deposition versus dust concentration at the UCRB and Gunnison Watershed from 2022 to 2023. MERRA-2 shows a slight decrease in dust deposition versus SPIReS' slight increase in dust concentration from 2022 to 2023. Because the magnitude of temporal differences is small, whether the disagreement is due to MERRA-2 errors, SPIReS errors, spatial upscaling of SPIReS to MERRA-2 resolution, or a disconnect between dust deposition and dust concentration remains to be seen. Lastly, we note that comparing dust deposition fluxes to observed snowpack dust concentrations represents a simplification of snow-dust interaction dynamics. While the limited spatial coverage and availability of in-situ dust deposition measurements preclude direct quantitative validation of MERRA-2, the correlated patterns between modeled dust deposition and observed snowpack dust concentrations provide support for the MERRA-2's reliability in simulating dust deposition in this region.

4.2 SAIL Field Campaign Comparisons to the Larger UCRB

In general, the MERRA-2 climatology shows that the Gunnison Watershed receives more dust deposition on average than the rest of the UCRB. Because dry dust deposition is largely spatially uniform, areas like the Gunnison with heavier wet deposition experience higher total dust deposition. Within the Gunnison Watershed, the SAIL region receives more dust deposition than average. Specifically, 2022 was a higher dust deposition year than average for SAIL (0.80 z-score), and 2023

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was closer to an average dust deposition year (-0.22 z-score). Thus, during the field campaign, 2023 is a more representative year for total dust deposition than 2022. This contrasts with total snowfall for each year, where 2022 was close to the median snow-water equivalent for the Gunnison Watershed and 2023 was a higher-than-normal snow-water equivalent year (NRCS 2022 & 2023). Additionally, a Spearman's coefficient of 0.42 between precipitation and wet deposition demonstrates that while increased precipitation is correlated with increased wet deposition, precipitation alone cannot capture the patterns of wet deposition.

4.3 Applications to dust monitoring and other models

Currently, important work is being done by the Colorado Dust on Snow Program (CODOS) to track dust deposition event types and dates, along with qualitative observations of dust on the snowpack, for water resource management. With a more sophisticated dust deposition detection algorithm validated with known CODOS dust deposition dates, the MERRA-2 dataset could be utilized to understand dust deposition types and events in areas where in-person observations are scarce, too difficult to obtain, or obscured due to weather. Additional field measurements of direct dust-on-snow deposition quantities would provide a means to validate the accuracy of the model's simulated deposition rates beyond event detection accuracy, unlocking the full potential of dust deposition analyses. Future work will connect MERRA-2 deposition rates to some existing measured black carbon and mineral dust concentrations (Gleason et al. 2022).

Operational snow and water supply forecasting models, such as iSnobal, SNOW17, or M^4 are vital to understand and predict the timing and magnitude of snowmelt runoff (Marks et al., 1999, Anderson 2006; Fleming et al, 2021). However, known model gaps exist, particularly due to the exclusion of dust deposition events that change the albedo of the snow within these models (Meyer et al., 2023). Incorporating MERRA-2 dust deposition data with remote sensing solutions into these models could improve predictions and fill in gaps, particularly during hard to detect wet deposition events.

5. Conclusion

The impact of light-absorbing particles, especially dust, on snowpack dynamics, can hardly be overstated in the mountain west (Painter et al, 2010; Skiles et al, 2018, Fassnacht et al, 2022). Yet the physical processes by which dust deposits onto the snowpack, remain complex and very difficult to observe (Lawrence and Neff, 2009). Direct estimates of dust deposition itself beyond just the exposure of dust radiative impacts of snow are important to pinpoint the timing, type, and total amounts of dust deposition in different areas in the UCRB, especially since dust deposition can impact snowmelt and water resources (Painter et al., 2010). However, wet deposition processes, even though they are central to dust deposition dynamics in the UCRB, are particularly difficult to measure because the clouds and precipitation that are co-occurring with dust wet deposition necessarily interfere with optical remote sensing in the wavelengths typically used for dust remote sensing.

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Therefore, assimilation approaches are a useful way to understand the processes and total amount of dust deposition, which are missing in existing literature over the UCRB area.

This study quantified dust deposition patterns across the Upper Colorado River Basin from 1970-2023 with a focus on the Gunnison Watershed and the SAIL field campaign site in Gothic, CO. Our findings show that MERRA-2 can be used to understand spatial and temporal trends in dust deposition in the UCRB, as MERRA-2 detected a majority (62%) of wet deposition events over the Gothic, CO area when compared to field data from 2022-2023. Within the UCRB, wet deposition is the dominant form of dust deposition, comprising ~74% of total dust deposition in the area and exhibiting more spatial heterogeneity than dry deposition.

Spatial climatological trends show eastern areas of the UCRB receive more wet deposition than average, with the Gunnison Watershed receiving 16% more monthly wet deposition (69.33 mg m^{-2}) than the UCRB average (59.80 mg m^{-2}) from 1970-2023. During the years of the SAIL field campaign, the SAIL site received significantly more total dust-on-snow deposition compared to the UCRB in 2022 (82%) and in 2023 (41%). The SAIL site received slightly more total dust-on-snow deposition than the Gunnison Watershed in 2022 (13%) and in 2023 (3%). This means that the SAIL field data cannot accurately represent dust-on-snow deposition rates in the broader UCRB but are representative of dust-on-snow deposition in the Gunnison Watershed. Based on a z-score analysis, neither 2022 (0.80) nor 2023 (-0.22) total dust-on-snow deposition amounts at the SAIL site were significantly anomalous compared to the climatological record in the same area. Thus, the SAIL field campaign was a representative sample within the wider temporal context of dust-on-snow deposition in its associated area.

It should be noted that MERRA-2 potentially overestimates total dust deposition in the UCRB, as it detects more wet deposition events over the SAIL site than were recorded. Whether this over detection stems from MERRA-2's coarse spatial resolution including other deposition events in the area or its inherent detection accuracy remains an open question that additional field data on dust deposition amounts across the region could help resolve. This overestimation tendency is consistent with previous studies of MERRA-2 dust concentration simulations in other areas (Buchard et al., 2017).

Datasets that are proven to be competent in dust deposition will be increasingly important as they will enable researchers to study not just pieces of dust impacts on snow, but the entire life cycle: from entrainment to transport to deposition to albedo impacts. This life cycle, while populated by processes that may at first appear to be straightforward to characterize, has many sizable gaps, and wet deposition is, arguably, the largest of those gaps. This process is exceedingly difficult to observe directly with remote sensing, as electromagnetic scattering from hydrometeors dominates the scattering from dust, and hydrometeor scattering changes imperceptibly with dust scavenging. Even with in-situ measurements, aerosol collects are swamped by hydrometeors, and even the signal of wet deposition in snow pits is subtle. However, we show here that

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MERRA-2, by assimilating dust, transporting it, and including aerosol-precipitation scavenging, is indeed competent at capturing spatial and temporal patterns of dust deposition in the UCRB.

We can use this to develop a climatology and have done so here. This climatology reveals consistent, persistent patterns of deposition, and points to the dominance of wet deposition as the vehicle for dust deposition in the UCRB, especially in certain areas like the Gunnison Watershed.

These findings can support water resource prediction, especially where sub-seasonal timing and amount are critical. For those applications where the prediction of snow melt-out across the UCRB requires sub-weekly accuracy, we show that advancing aerosol-precipitation interaction science is necessary.

Data availability

The Optical Particle Counter (OPC), Pluvio2-L weighing bucket, and SKYRAD data collected during the SAIL campaign are available on the ARM data discovery portal.
The MERRA-2 M2T1NXADG data is available through the NASA Earthdata Portal.
The historical SPIReS is available through the National Snow and Ice Data Center.
The Watershed Boundary Dataset is available through the United States Geological Survey.
Links to MERRA-2, SPIReS, OPC, and Pluvio2-L weighing bucket data are provided below.

MERRA-2 Climatology Dataset: https://doi.org/10.5281/zenodo.19957854
MERRA-2 M2T1NXADG: https://disc.gsfc.nasa.gov/datasets/M2T1NXADG_5.12.4/summary
Historical SPIReS: https://nsidc.org/data/spires_hist/versions/1
Pluvio2-L Weighing Bucket:
https://adc.arm.gov/discovery/#/results/id::gucwbpluvio2M1.a1_accum_total_nrt_upperair_wb_sfcmet?dataLevel=a1&showDetails=true
Optical Particle Counter (OPC):
https://adc.arm.gov/discovery/#/results/id::gucaosopcS2.b1_dN_dlogDp_microchem_opc_aerosol?dataLevel=b1&showDetails=true
Watershed Boundary Dataset:
https://www.usgs.gov/national-hydrography/watershed-boundary-dataset

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Author contributions

D.R.F and F.Y. conceptualized the research. F.Y. carried out general analysis, visualization, validation, and first draft of the manuscript. D.R.F coordinated, funded, and guided the research. W.J.R. contributed to the SPIReS dust concentration analysis. L.D.G. analyzed dust deposition field data. All authors edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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