

We thank the two reviewers, Dr. Pérez and Dr. Dhandapani for their effort and time reviewing our manuscript “A multi-decadal climatology of dust-on-snow from wet deposition in the Upper Colorado River Basin”. Each reviewer left valid and useful comments that will improve the manuscript and we are very appreciative of their time to provide thorough and thoughtful feedback. Each reviewer’s comments were responded to point-by-point, with reviewer comments in **red font** and responses in black font. All points were addressed below along with proposed changes to the manuscript that we will make if acceptable to the editor

Best,  
Felix Yu, on behalf of co-authors

#### **Reviewer #1 - Dr. Pérez**

This paper studies the dust-on-snow deposition in the Upper Colorado River Basin. Varied periods and datasets were used, since the MERRA-2 dataset was considered from 1980 to 2023. However, field measurements extended from 2022 to 2023 together with MODIS and SPIReS dust concentration data. Since the paper handles a noticeable amount of information and it is focused on a quite specialised issue, only some minor changes should be considered.

The study considers a limited number of events in the years 2022 and 2023 from available measurements. Since the authors highlight the interannual variability of dust deposition, they should comment the study representativeness.

Thank you for the comment. We believe that this study’s long-term climatology of dust deposition on snow, developed from the years of 1980 - 2023, is representative of long-term trends in dust deposition in the UCRB. For the detailed look on deposition for 2022 and 2023, along with the field data, we believe that 2022 is representative of a slightly higher dust deposition year and 2023 is representative of a slightly lower dust deposition year compared to the long-term dust deposition average. Neither year is significantly anomalous nor too different from an average dust deposition year, as seen by the z-score values in Table 3. More language on the study’s representativeness will be added to section 4.2. We will also reference Gibson et al, 2026, <https://doi.org/10.1038/s41612-026-01446-0>, wherein those authors, in Supplementary Material Table S4, analyze 2005-2025 for documented dust deposition from the Colorado Dust on Snow (CODOS) project and find that 2022 and 2023 are typical in terms of number of dust deposition events during the snow accumulation season.

Most of the analysis refers to spring. However, Figure 5 considers the period November-May and the period February-June is used in Figure 6. A comment about the selection of these varied periods would be acknowledged. Moreover, the authors should justify if comparisons are possible with these varied periods.

Thank you for the comment. Previous analysis has shown a majority of the dust deposition on snow events in the UCRB occur during the February - May period (Painter et al. 2012, <http://dx.doi.org/10.1029/2012WR011985>). This is also seen in our field data (Table 1). Therefore, for our long-term climatology analysis from 1980-2023, we focused on February - May, as that period represents the vast majority of deposition in the UCRB and had the largest

impacts on dust radiative forcing and early snowmelt. Furthermore, it was more computationally efficient to focus on this period too. Still, we wanted to investigate the years 2022-2023 in detail due to the field data available to us from 2022-2023. Therefore, we included the marginal amounts of dust deposition in November - February for the years 2022-2023. We will add language regarding this point to the manuscript.

For the associated dust concentration analysis (the “effects” of deposition) for 2022 - 2023, we added the month of June to consider a period of February - June (Figure 6) to maximize the completeness of our analysis. Dust concentration values tend to maximize during the end of the snowmelt period as dust layers in the snow aggregate together. Without adding June, we would lose valuable dust concentration information in higher elevation areas with snow that last until early-mid June. This is in contrast to deposition, where June events are often associated with rain instead of snow and the effects of dust wet deposition in rain on snowpack is outside of the scope of this manuscript. Additionally, the SPIReS product we used for dust concentration analysis filters out areas without snowpack, and therefore we can be certain that any June dust concentration values have an associated snowpack. This in contrast to the MERRA-2 deposition product, which doesn’t mask out areas without snowpack in June. We will add language regarding this point to the manuscript in the SPIReS analysis portion.

Figure 4 indicated that the spatial analysis for dry deposition led to similar values and it could be ignored since the wet deposition determines the spatial distribution. The authors should underline the convenience of this analysis based on wet and dry deposition.

Thank you for the comment. We will add these sentences to section 3.1 of the manuscript, which describes the climatology results: “Thus, the dominant driver of variability in dust deposition across the UCRB was due to wet deposition and not dry deposition. Therefore, further spatial analysis, such as the comparison of this climatology with other areas in the UCRB, focused on wet deposition.”

Some references are a bit old. The authors should clarify if the lack of recent references could be due to the lack of research interest about this issue. Moreover, potential readers would acknowledge the increase of recent references in the discussion section to compare the results of this paper with previous studies.

Thank you for emphasizing the need for more recent references on this topic not only to provide information to the readers on the most recent scientific findings, but also to indicate to the reader that this area of research continues to be active. We will therefore add the follow references to the revised manuscript:

- Tillman, F. D., Day, N. K., Miller, M. P., Miller, O. L., Rumsey, C. A., Wise, D. R., Longley, P. C., and McDonnell, M. C.: A Review of Current Capabilities and Science Gaps in Water Supply Data, Modeling, and Trends for Water Availability Assessments in the Upper Colorado River Basin, *Water*, 14, 3813, <https://doi.org/10.3390/w14233813>, 2022.

- Wheeler, K. G., Udall, B., Wang, J., Kuhn, E., Salehabadi, H., and Schmidt, J. C.: What will it take to stabilize the Colorado River?, *Science*, 377, 373–375, <https://doi.org/10.1126/science.abo4452>, 2022.
- Brahney, J., Heindel, R. C., Gill, T. E., Carling, G., González-Olalla, J. M., Hand, J., Mallia, D. V., Munroe, J. S., Perry, K., Putman, A. L., Skiles, S. M., Adams, B. R., Aanderud, Z., Aarons, S., Aguirre, D., Ardon-Dryer, K., Blakowski, M. B., Creamean, J. M., Fernandez, D., Foroutan, H., Gaston, C., Hahnenberger, M., Hoch, S., Jones, D. K., Kelly, K. E., Lang, O. I., LeMonte, J., Reynolds, R., Singh, R. P., Sweeney, M., and Merrill, T.: Dust in the Critical Zone: North American case studies, *Earth-Science Reviews*, 258, 104942, <https://doi.org/10.1016/j.earscirev.2024.104942>, 2024.
- Kok, J. F., Storelvmo, T., Karydis, V. A., Adebisi, A. A., Mahowald, N. M., Evan, A. T., He, C., and Leung, D. M.: Mineral dust aerosol impacts on global climate and climate change, *Nat Rev Earth Environ*, 4, 71–86, <https://doi.org/10.1038/s43017-022-00379-5>, 2023.
- Lang, O. I., Naple, P., Mallia, D., Hosler, T., Adams, B., and McKenzie Skiles, S.: Two Decades of Dust Radiative Forcing on Snow Cover Across the Great Salt Lake Basin, *Journal of Geophysical Research: Earth Surface*, 130, e2024JF007957, <https://doi.org/10.1029/2024JF007957>, 2025.
- Proestakis, E., Amiridis, V., García-Pando, C. P., Tsyro, S., Griesfeller, J., Gkikas, A., Georgiou, T., Ageitos, M. G., Escribano, J., Myriokefalitakis, S., Masso, E. B., Di Tomaso, E., Basart, S., Stuut, J.-B. W., and Benedetti, A.: Quantifying dust deposition over the Atlantic Ocean, *Earth System Science Data*, 17, 4351–4395, <https://doi.org/10.5194/essd-17-4351-2025>, 2025.
- Li, L., Mahowald, N. M., Liu, X., Gonçalves Ageitos, M., Ke, Z., Leung, D. M., Pérez García-Pando, C., Miller, R. L., Obiso, V., Ginoux, P., Kok, J. F., Formenti, P., Di Biagio, C., Brodrick, P. G., Thompson, D. R., Clark, R. N., Okin, G. S., Green, R. O., Zhou, B., Albani, S., and Adebisi, A. A.: Modeling Large Dust Aerosols in the Community Earth System Model Version 2 (CESM2), *Journal of Advances in Modeling Earth Systems*, 18, e2025MS005420, <https://doi.org/10.1029/2025MS005420>, 2026.
- Shi, T., Wang, J., Zhang, D., Cui, J., Wang, Z., Zhou, Y., Pu, W., Bai, Y., Han, Z., Liu, M., Liu, Y., Xie, H., Yang, M., Li, Y., Gao, M., and Wang, X.: Insights into microphysical and optical properties of typical mineral dust within urban snowpack via wet and dry deposition in Changchun, northeastern China, *The Cryosphere*, 19, 2821–2835, <https://doi.org/10.5194/tc-19-2821-2025>, 2025.

These references will be added to the appropriate sections of the manuscript to supplement the existing, older references that were part of the original manuscript.

Minor remarks.

Equation (1) should be revised.

Thank you for the catch. We will correct the equation such that  $N_i$  will be in the denominator of Eq. 1 in the revised manuscript.

Figure 5. Dot in blue should be in red in the figure (or in blue in the legend). The same colour should go in all the figures.

Thank you for the suggestion. We will change the color scheme for the legend for Figure 5 to match Figure 4 and make it more readable by increasing the size and matching the colors.

Reference Randles et al. should be revised.

Thank you for the correction. We will change the reference in the manuscript to the correct article and year.

Reviewer #2 - Dr. Dhandapani

The manuscript discusses MERRA-2 reanalysis of wet and dry dust deposition over the Upper Colorado River Basin and compares them to SAIL field measurements and MODIS SPIReS observations of dust concentration data. The authors conclude that wet deposition is the dominant form of dust deposition. They also highlight the spatial and temporal variability of dust deposition and dust concentration, stressing the need for advancing aerosol-precipitation scavenging to improve predictions of water resource. The manuscript is well-written with great logical flow and clear explanations. There is potential for more detailed analysis using the precipitation data available in MERRA-2, which is a missed opportunity, and could bolster the scientific rigor of the manuscript. The manuscript is suitable for publication after minor revisions.

#### Specific Comments

1. Section 3 – Line 195: The authors provide wet/dry deposition percentages over 1980-2023. They should also provide these percentages calculated over 2022-2023.

Thank you for the suggestion. We have calculated percentages and will add the following sentences to that section in the revised manuscript: “For the SAIL campaign years of 2022-2023, wet deposition accounted for 73.7% of total dust deposition in 2022 and 77.7% of total dust deposition in 2023. Dry deposition accounted for 26.3% of total dust deposition in 2022 and 22.3% of total dust deposition in 2023.”

2. Figure 2: Why is there a discrepancy between the wet dust deposition on the last hour of April 11 and the first hour of April 12? The authors should extend the hourly averages for the full 24 hours of both days.

The discrepancy is because the MERRA-2 M2T1NXADG product that we use gives the hourly deposition averages instead of instantaneous values, and therefore hour 24 on April 11th, 2026 is the average deposition of hour 23-24, and hour 0 on April 12th, 2026 is the average deposition of hour 0-1. We will add “hourly averages” to the caption in the revised manuscript to make this clearer, as the product is already an averaged amount.

3. Figure 2: Is the wet dust deposition exactly zero for most of April 11? If not, the authors should consider a logarithmic y-axis for the plot.

Thank you for this suggestion. We will change the y-axis to have a logarithmic scale and update the scale of the graph in the revised manuscript.

4. Figure 3: The authors should include precipitation values at Gothic. If the plots end up being too busy, the precipitation values (rain and snow) could be presented in separate subplots.

Thank you for the suggestion. We will add two subplots showing rainfall and snowfall for 2022 and 2023 in Figure 3 as subplots 3c and 3d.

5. Figure 4: I understand that the authors want to use blue colorbars for the wet deposition and red colorbars for the dry deposition, but they should consider using the same color palette for both colorbars, since they're inviting a direct comparison of the magnitudes. The colorbar palette used in Figure 5 would still get the point across, with wet deposition showing up in blues and dry deposition in warmer colors.

Thank you for the suggestion. We will update the revised manuscript's graph to use the colorbar palette in Figure 5 for graphs a, b, c, and d. We will use a different color palette for e and f due to the difference in scale. We have experimented with using the same color palette for all panels but that obscures much of the information we would like to convey across these 5 panels.

6. Figure 4: Please change the symbol, size and color for Gothic and Senator Beck Basin for improved visibility and contrast. For Gothic, include that it is the SAIL site in the legend. What is the relevance of the Senator Beck Basin, since it isn't referred to anywhere else in the manuscript?

Thank you for the comment. In the revised manuscript, we will change the symbol to a triangle, increase the size of the symbol by 2x, and change the color of the "Gothic" symbol to be orange. We will change the legend to be "Gothic - SAIL site" and "Senator Beck Basin - CODOS Site". We will add a sentence describing the importance of Senator Beck Basin in the introduction: "These in-person, long-duration observations [dust-on-snow observations] are run by the Colorado Dust on Snow Program (CODOS), with its main site at Senator Beck Basin in the southwestern area of the UCRB." We call out both sites to indicate their importance to contextualize the developed climatology.

7. Table 2: Please include precipitation values (rain and snow) and also averages of deposition over the full range (1970-2023), in addition to 2022 and 2023.

Thank you for the suggestion. We will add snowfall and rainfall for 1980-2023, 2022, and 2023 in Table 3 and the wet deposition for the long term climatology averages from 1980-2023, 2022, and 2023 in Table 2. We will also add snowfall and rainfall over the Nov-May period for 2022 and 2023 in an additional Table 5.

8. Lines 278-279, 283: “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”, “disagree slightly” - The temporal disagreement is pretty significant for Gunnison watershed and the SAIL site. Both places show huge decreases (-32% and -42%) in MERRA-2 dust deposition in 2023, but show small increase (+11%) and small decrease (-10%) in SPIReS dust concentration in Gunnison and SAIL site, respectively, in 2023.

We agree that the disagreement is not slight and thank the reviewer for catching this imprecise language in the original manuscript. We will remove that language from the revised manuscript and will also add two additional phrases. One phrase will emphasize that dust deposition doesn't always connect to dust concentration due to additional factors outside of the scope of the study (like timing/dilution), and another sentence will explain how the magnitudes of change between MERRA-2 and SPIReS are difficult to compare because as two different products, MERRA-2 is a simulated flux of deposition and SPIReS is a remotely sensed measurement of concentration.

9. Line 299: The authors mention the total snowfall for 2022 and 2023, please provide z-scores for the snowfall (and possibly rainfall). These values could be included in Table 3, as well.

We will add total snowfall z-scores for 2022 and 2023 in Table 3 (now Table 6). We chose to exclude rainfall because we are most interested in snowfall related dust deposition within the scope of the study, and that snowfall is better correlated with wet dust deposition (see Spearman analysis below).

10. Line 300: The authors report a Spearman's coefficient of 0.42 between precipitation and wet deposition. The reviewer recommends calculating the Spearman's coefficient between snow and wet deposition, and between rain and wet deposition. This would be of interest to include in the manuscript especially if the coefficients are not close.

Thank you for the suggestion. We calculated the Spearman's coefficient between snowfall and wet deposition (0.76) and rainfall and wet deposition (0.50) and will add it to the revised manuscript. As expected, snowfall is better correlated with wet deposition in the later winter and spring months because a majority of the precipitation falls as snow, and snow is a more efficient scavenger of dust particles due to the much larger surface area to volume ratio of snow crystals as compared to raindrops.

11. Lines 340-341: “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” - This is not accurate analysis. The 13% and 3% comparison values are between Gunnison and UCRB, not between the SAIL site and Gunnison. The SAIL

site shows significantly more dust-on-snow deposition than Gunnison in 2022 (62%) and 2023 (37%).

Thank you for the correction. We agree that the comparison between the SAIL site and Gunnison was incorrect and will update the percentages to 62% for 2022 and 37% for 2023. We will change our analysis text to say that: "Within the Gunnison Watershed, the SAIL field data may be representative of areas in the Gunnison that receive a similar amount of wet deposition, but are not representative of the entire Gunnison Watershed." Examples of similar wet deposition areas include cells west and southwest of the SAIL site in the Gunnison (Figure 5). Some areas of the Gunnison Watershed receive little snowfall and therefore little wet deposition. These areas cannot be represented by the SAIL site, which receives both more wet deposition and more snowfall. However, the East River Watershed (SAIL site) has been shown to be highly representative of the many snowmelt dominated, high-elevation basins in Colorado that supply much of the water to downstream users in the Gunnison Basin and larger Colorado River Watershed (Markstrom et al, 2012; Hubbard et al, 2018). Text regarding the representativeness of the East River Watershed, and associated references, will be added to the revised manuscript.

12. Figure 6: The authors should plot the dust concentration data over Feb-May or Nov-May to be consistent with the MERRA-2 results in Figures 4 or 5, or justify the choice of Feb-June in detail.

Thank you for recognizing this discrepancy. We will add to the revised manuscript an additional sentence of justification in Section 2.3 as to why June was added to the temporal domain for the SPIReS analysis instead of ending the analysis in May: "June was added to the temporal domain to account for late-season snowpack melt, during which dust concentration tends to peak prior to complete melt-out as the dust layers condense together."

Because SPIReS filters out areas with no snowpack, we ensure that the dust concentration values are dust-on-snow related. This is in contrast to deposition, where MERRA-2 does not discriminate between areas with snow and without snow. Additionally, the complete melt-out date in higher elevation areas in the UCRB ranges from late May - early June (Fassnacht et al. 2022). Therefore, a majority of dust deposition events in June at the UCRB modeled by MERRA-2 likely have no associated snowpack on the ground and are not dust-on-snow events. By excluding June in the SPIReS analysis, we believe that we would lose the maximum accumulation of dust concentration in the snow in areas with late snowpack melt dates. By including June in the MERRA-2 analysis, we believe we would be biasing our dust-on-snow deposition values with non dust-on-snow events. Thus, we believe the temporal period should be Feb-June for SPIReS and Feb-May for MERRA-2. We will add text to the revised manuscript to clarify this point.

13. Throughout the manuscript, the authors use cumulative, total, mean, average, etc, while reporting and plotting the dust deposition, precipitation, and dust concentration values. Sometimes, it is a bit unclear if the totals are temporal and/or spatial sums and the averages are temporal and/or spatial. The authors could clarify the wording

by using consistent terms for temporal/spatial sums/averages throughout the manuscript and by paying extra attention to the units

Thank you for the comment. We will change all units to include the time ( $\text{d}^{-1}/\text{month}^{-1}/\text{y}^{-1}$ ) to indicate if sums/averages were temporal. We will add the words “spatially” or “temporally” to the manuscript’s text, figures, and captions to indicate if aggregation was done spatially or temporally (or both).

### Minor Comments

1. Check that the affiliations of all the authors are correct.

We have confirmed affiliations and will change a font mismatch for the Energy and Resources Group affiliation in the revised manuscript.

2. Colorado Dust on Snow Program is referred to in lines 41 and 48. Please provide citations to specific peer-reviewed literature for reference.

We will add a citation to Painter et al. 2012 to the revised manuscript which show the majority of dust deposition events from 2005-2010 at the UCRB occurred in the months February - May, and a citation to Reynolds et al. 2025 which uses sites in the Colorado Dust on Snow program (and other in-situ samples) to perform their studies.

3. Line 82: “which translates to a ~54 km x ~55 km **in meters** across the UCRB”.

Thank you for this correction. We will remove “in meters” from the sentence from the revised manuscript.

4. Line 94: SKYRAD - Please include the full name of the instrument (ARM sky radiometers on stand for downwelling radiation)

Thank you for the suggestion. In the revised manuscript, we will include the full name of the instrument in the sentence: “Atmospheric Radiation Measurement (ARM) sky radiometers on stand for downwelling radiation”.

5. Figure 1: Please include details about the SAIL circle and the corresponding MERRA2 grid point in yellow in the caption. Show the 100 km scale in both the latitude and longitude axes, to clarify that 1:1 aspect ratio is maintained.

We will add details about the SAIL circle and the MERRA-2 grid point to the caption of the revised manuscript.

6. Line 163 - Eqn. (1): Is there an  $N_i$  missing in the denominator?

Yes, we will correct the denominator such that  $N_i$  is now in the denominator of Eq. 1 in the revised manuscript.

7. Section 2.3: Please include the spatial and temporal resolution of SPIReS analysis, when introducing the method.

Thank you for the suggestion. In the revised manuscript, we include a sentence at the beginning of the section: "SPIReS scenes are observed once a day, subject to outages from cloud cover, and have a spatial resolution of 500m"

**8. Line 176: National Snow and Ice Data Center - include (NSIDC)**

We will add "NSIDC" to the line to the revised manuscript.

**9. Table 1 should be moved closer to Sec. 2.1, where it is referenced first.**

Thank you for this suggestion. In the revised manuscript, we will move Table 1 after the paragraph of its first mention in Sec 2.1.

**10. Figure 2 caption: "MERRA-2" and "wet dust" need to be included in the captioning**

In the revised manuscript, we will change Figure 2's caption to be: "Hourly MERRA-2 wet dust deposition at SAIL comparing a wet dust deposition event (12 April 2022) to a normal day (11 April 2022)."

**11. Figure 3 caption: Shouldn't the daily wet deposition totals units be mg m-2 day-1? Also include the explanation of the particle counts and wet deposition events in the caption.**

In the revised manuscript, we remove the units from the caption and change Figure 3's caption to be "MERRA-2 daily wet deposition totals (mg m-2) for 2022 (a) and 2023 (b) over the SAIL site location in Gothic, CO. Particle count data represents supermicron particles counted by an OPC. Wet deposition event dates correspond to Table 1 dates"

**12. Line 210: "was able to detect most deposition events" should be changed to "was able to detect a majority of the deposition events"**

We will revise our language to be "was able to detect a majority of the deposition events" in the updated manuscript.

**13. Table 2 reports UCRB Total Deposition (mg m-2) and UCRB Average Deposition (mg m-2). The reviewer believes the units for one of the quantities needs to be Different.**

We will remove the UCRB total deposition from Table 2, as it does not provide any additional information than the UCRB average deposition. We will also change the average deposition units to be mg m-2 y-1.

**14. Consider combining Tables 2 and 4 for direct comparisons and conciseness.**

Thank you for the suggestion. Because Table 2 and Table 4 are different products (dust deposition and dust concentration), we believe that keeping Table 2 and Table 4 separate is important for the distinction between the two products. Additionally, we believe that combining tables would lead to a table that is too complex. We feel that Section 4.1, which compares the two tables, is sufficient for analysis between the two Tables.

**15. Lines 228-229: Change "total dust deposition" to "(total) mean dust deposition"**

In the revised manuscript, we will change “total dust deposition” to “total mean dust deposition” in all parts of that paragraph.

16. Line 249: “0.63 and 0.44 with p-values below 0.001, respectively” should be changed to “0.63 and 0.44, respectively, with p-values below 0.001”

In the revised manuscript, we will incorporate your suggestion and change the line to “0.63 and 0.44, respectively, with p-values below 0.001”.