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Project Title: Constraining Physical Understanding of Aerosol Loading, Biogeochemistry, and Snowmelt Hydrology from Hillslope to Watershed Scale in the East River Scientific Focus Area

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Final Report? Yes

Project Summary

The mountain snowpack is a critical component of regional hydrology, ecology, biogeochemistry, and climate in the Western US. This project leveraged the East River Scientific Focus Area (SFA), as an outdoor laboratory to address a significant gap in our understanding of the mountain snowpack; namely, how atmospheric constituent deposition on snowpack influences snow energy balance and nutrient/chemical cycling, and how snowmelt timing and intensity exerts controls on emergent biogeochemical and ecohydrologic behavior. This aligned with East River SFA goals to integrate landscape scale measurements and physical based modeling tools to improve understanding of controls on runoff production, ecohydrology, biogeochemical cycling, and land surface energy partitioning in high mountain watersheds. The project included observations of snowpack at multiple scales, measurements of snow and deposited aerosols properties, *in situ* time series of surface energy balance, and spatially distributed, process-based snowmelt modeling.

Project Accomplishments

1. What are the major goals of the project?

The primary goal of this project was to (1) quantify the timing, intensity, and magnitude of snowpack meltwater contributions to the multi-scale water budget of the East River SFA, while taking into account the physical mechanisms that control snowpack ablation processes and surface hydrologic partitioning. A growing body of literature has established that dust on snow deposition can be a primary control on snowmelt timing and magnitude in this region, and that modern deposition levels are a relatively new process relating to surface disturbance and land use change. Therefore, a related objective was to (2) constrain the spatial and time-varying impacts of aerosols, with a primary focus on dust, on snow albedo in the East River SFA. Dust deposition can continue to impact watershed processes after snowmelt, for example by elevating the availability of key macronutrients, such as phosphorus and nitrogen. Therefore, an additional objective was to (3) characterize the biogeochemical and ecohydrologic effects of dust deposition within the East River catchment.

2. What was accomplished under these goals?

We have completed modeling and observation activities that have allowed us to make progress toward meeting our project goal and objectives. Below, we discuss these in reference to each listed above.

For our primary goal, we have set up the spatially distributed Automated Water Supply Model (https://data.nal.usda.gov/dataset/automated-water-supply-model-awsm) over the East River watershed at 50 m resolution. For model inputs, we use downscaled data from the High Resolution Rapid Refresh (HRRR; https://rapidrefresh.noaa.gov/hrrr/) model. We are also updating the net solar radiation in the model using remotely sensed snow albedo from MODIS (Fig. 1). The installation and modeling environment is open access: https://github.com/UofU-

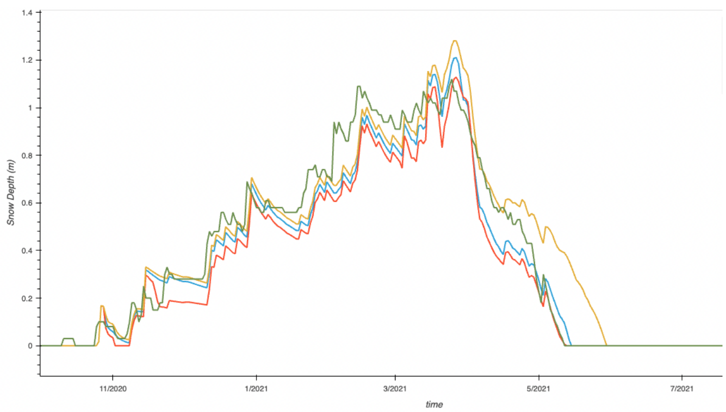

Figure 1 Simulated and observed snow depth during Water Year 2021 at Butte Snotel Site. Observed is the green line, simulated with no snow darkening by dust is the yellow line, updated solar radiation from HRRR is the blue line, and MODIS adjusted HRRR solar radiation, which includes dust darkening impacts is the red line (and best match to observations).

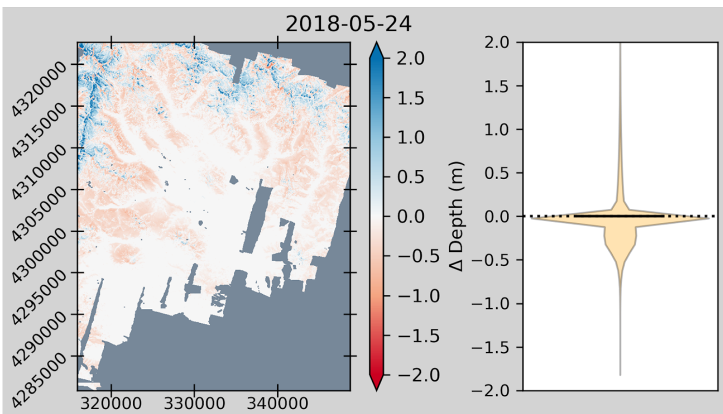

Figure 2 Differences in snow depth between ASO lidar (observed) and AWSM (simulated) on May 24th, 2018. The mean difference is 0 m; spatial variations balance out at the watershed scale.

Cryosphere/isnoda. The initial description of the model, as set up in the East River Watershed, is currently under discussion in *Geoscientific Model Development*, please see citation below.

Simulated snow depths from the model, run between Water Years 2018 and 2022, was validated using Snow Telemetry sites (SNOTEL; Schofield, Butte, Taylor), Irwin Study Plot, and spatially distributed snow depth from lidar, provided by the Airborne Snow Observatory (Fig. 2). Snow albedo and net solar radiation from the model was validated at Irwin Study Plot, where new solar radiation sensors were installed for this project (discussed below). Initial runs indicated that when snow albedo was not accurately represented simulated snow melt dates occur up to a month earlier than observed. This demonstrated that representing dust impacts on snow albedo is critical for accurately simulating snow melt timing and magnitude, with important implications for projecting snow water availability to the broader watershed. This same data was used to assess and parameterize simulated snow albedo, and improve snow energy balance, in the Noah-MP Land Surface Model. This study is currently in review in the *Journal of Advances in Modeling Earth Systems,* please see citation below.

For the first related objective, we have done a range of observation and analysis activities. On March 20th, 2019 we installed a set of pyranometers to measure incoming and outgoing broadband, near infrared, and visible shortwave radiation, from which we can retrieve a continuous, hourly, records of snow albedo (Fig. 3), snow grain size, and dust-on-snow radiative forcing. These were installed at Irwin Study Plot, adjacent to the East River SFA. In 2019, and again in 2021, we carried out snow observations for snow depth, density, and water equivalent, collected full profile snow samples for dust and black carbon concentrations, and measured spectral snow albedo. We missed 2020 due to the COVID-19 pandemic and travel restriction. This dataset will be published for open access distribution via Zenodo at the end of the 2022 Water Year (September 30th).

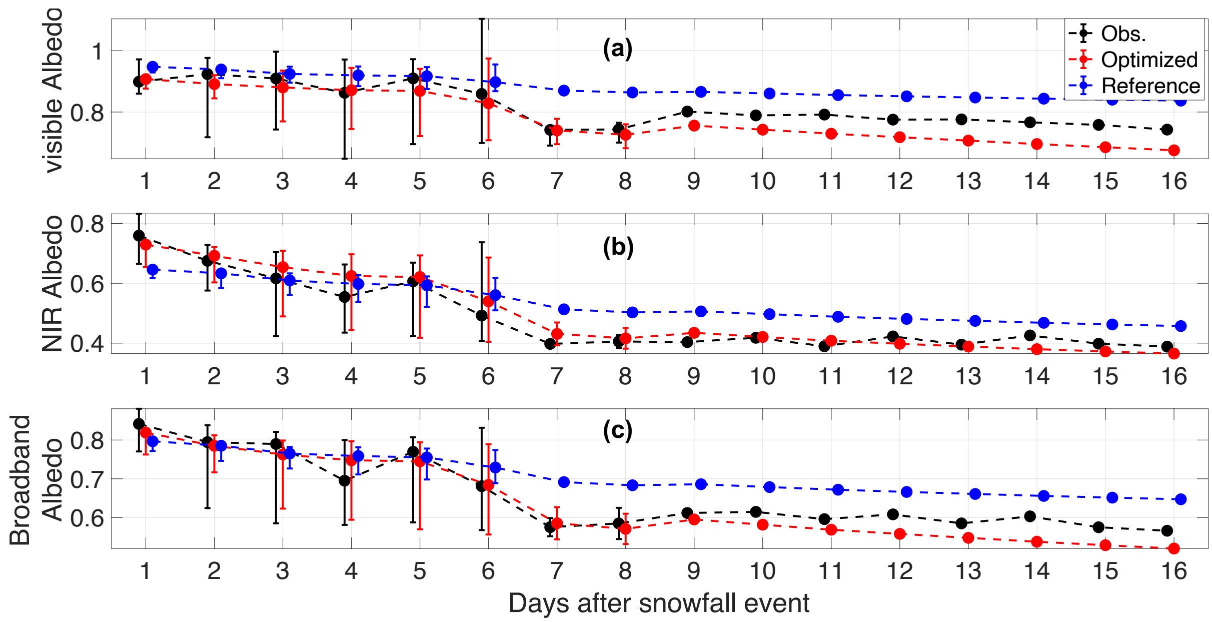

Figure 3 Observed and Noah-MP simulated snow albedo at the Irwin Study Plot with reference and optimized being before and after using observations to update the albedo parameterization. Following the updates, the simulated albedo is lower and close to observations. From Abolafia-Rosenzweig et al., 2022 (in review).

The field data was used to constrain spatial variability, along with the Airborne Snow Observatory flights, which occurred over the Upper Gunnison, including the East River SFA, twice during winter 2019 (April and June). Unfortunately data quality of the imaging spectrometer on board ASO limited our ability to retrieve snow albedo and dust radiative forcing, but this data was still very valuable for assessing the snow energy balance model. To ‘fill in’ observations of dust radiation forcing, we adapted the MODIS dust radiative forcing in snow (MODDRFS) algorithm for Landsat 8 OLI scenes covering the East River SFA. We made the processing algorithms for quantifying dust on snow impacts from Landsat open access: https://github.com/UofU-Cryosphere/DRFS.

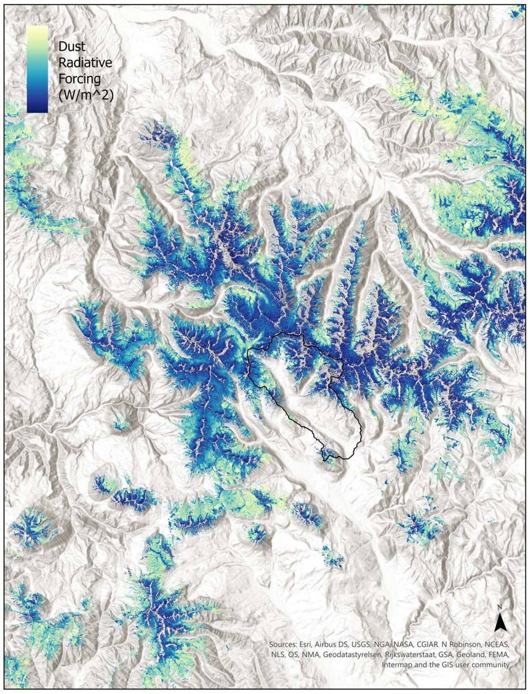

Figure 4 Dust radiative forcing from Landsat 8 OLI on May 24th, 2020. Outline is the boundary of East River Watershed.

For the second related objective, we measured dust deposition through a modification to the National Atmospheric Deposition Program (NADP) Aerochem Metrics Wet and Dry Collector. High dust deposition rates generally occurred in Spring and Fall. Sediment cores from high elevation fens were also collected to be analyzed for isotopes, that will allow us to track dust deposition rates over time. The collection and analysis of this dataset was delayed by COVID-19, but the analysis will still be carried out despite this project ending. Additionally, biogeochemical changes in streamflow were tracked through the melt season, based on data collected in the East River SFA in 2019 and 2020.

3. What opportunities for training and professional development has the project provided?

This project has created opportunities for training and profession development of undergraduate and graduate students and postdoctoral researchers. PI Skiles has one undergraduate and two graduate students who worked on the project at the University of Utah. Baylee Olds, an undergraduate in the Geography Department at the University of Utah, worked with Dr. Skiles to learn lab analysis techniques; she processed the snow samples collected in the East River. She has gone on to enroll in a graduate program in hydrology. Hannah Peterson completed a masters project in snow hydrology, working with Dr. Skiles on remote sensing of snow in the East River SFA. Joachim Meyer, a PhD student in snow hydrology under Dr. Skiles supervision, processes remote sensing retrievals to inform snow energy balance model (AWSM) runs in East River Watershed. Additional graduate students have gained field experience while assisting PI Skiles in snow observation and sampling for the project.

Co-I Brahney had one graduate student, Jiahao Wen, who began August 2019 and under her guidance is working on tracking the biogeochemical changes in streamflow through the melt season. Co-I Gochis worked with postdoctoral researchers in his group, including Ronnie Abolafia-Rosenzweig, to use snow energy balance measurements in the East River watershed to inform snow albedo parameterization in the Noah-MP land surface model.

4. How have results been disseminated to the communities of interest?

The results have been disseminated through conferences, including the 2018 MtnClim Meeting, the 2019 IUGG meeting in Montreal, the 2019 Western Snow Conference, the DOE SBR PI meetings, and the American Geophysical Union Annual Fall Meetings. Presentations have also been made at workshops, including Airborne Snow Observatory annual workshop and the Colorado River Hydrologic Symposium.

The results are also being disseminated through peer reviewed publications. There are three publications currently under review that related to this project, and additional one in preparation. As they are accepted and published, we will upload them to attribute them to this project. The citations are given below:

Abolafia-Rosenzweig, R., C. He, S.M. Skiles, F. Chen, D. Gochis. Evaluation and optimization of snow albedo scheme in Noah-MP land surface model using in-situ spectral observations in the Colorado Rockies. *Journal of Advances in Modeling Earth Systems.*

Meyer, J., S.M. Skiles, J. Horel, P. Kormos, A. Hedrick, E. Trujillo. Operational water forecast ability of the iSnobal-HRRR coupling; an evaluation to adapt into production environments. *Geoscientific Model Development Discussions*, doi: 10.5194/gmd-2022-129 (preprint)

Meyer, J., J.S. Deems, K.J. Bormann, D. Shean, S.M. Skiles. Mapping snow depth and volume at the alpine watershed scale from aerial imagery using Structure from Motion. *Frontiers in Earth Science - Environmental Informatics and Remote Sensing*.

5. What do you plan to do during the next reporting period to accomplish the goals?

Nothing to report, this is the final project report.