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DOE/SC-ARM-24-021

Sublimation of Snow Field Campaign Report

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September 2024

ARM

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Acronyms and Abbreviations

ARM	Atmospheric Radiation Measurement
EOL	Earth Observing Laboratory
ISFS	Integrated Surface Flux System
NCAR	National Center for Atmospheric Research
SAIL	Surface Atmosphere Integrated Field Laboratory
SLR	snow level radar
SWE	snow water equivalent
UW	University of Washington

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1.0 Summary

Snow is a vital part of water resources, but sublimation may remove 10% to 90% of snowfall from the system. The processes controlling sublimation span multiple scales of measurement and multiple disciplinary fields. Due to a critical lack of reliable direct measurements of snow sublimation, we do not fully understand the physics that govern current rates of sublimation, let alone how those amounts might change with the climate.

With financial support from the National Science Foundation, we deployed the National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL)'s Integrated Surface Flux System (ISFS) from October 2022 to June 2023 in conjunction with the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility's Surface Atmosphere Integrated Field Laboratory (SAIL) campaign in the East River Watershed, Colorado (Feldman et al. 2023, Lundquist et al. 2024). SAIL measured vertical and horizontally distributed wind fields from radiosondes, a radar wind profiler, a doppler lidar, and distributed meteorological stations. The ISFS system provided surface flux observations at multiple levels to better understand how basin-scale wind fields interact with surface turbulence and fluxes. These measurements, combined with energy and mass balance observations and terrestrial lidar scans of the evolving snowfield, provided benchmarks of the most reliable approaches to measuring snow sublimation in different conditions and improved understanding of sensible and latent heat fluxes in complex terrain. The work is unique because it embeds a detailed study of snow evolution and complex boundary-layer turbulence (requiring flux measured at multiple heights) within a comprehensive field study of larger-scale flows and mixing (SAIL). Together, these measurements provide insight into how blowing snow influences latent heat fluxes at heights 0-20 m above the snow surface and how wind fields above a stable boundary layer interact with complex terrain to create intermittent turbulent mixing at the surface. The data set provides new insight into the evolution of the near-surface boundary layer over snow in complex terrain and which processes are most important to understand total seasonal sublimation.

The winter of 2022-23 had several notable events, which are detailed in a paper recently published in the *Bulletin of the American Meteorological Society* (Lundquist et al. 2024). Overall, snow depths reached about 1.5 to 2 m in late March, with about 0.4 m of snow water equivalent, and a total of about 0.04 m of total vertical water vapor loss, or sublimation. December 22, 2022 had the strongest blowing snow event of the year, which resulted in the greatest rates of sublimation and dramatic snow relocation across the study site (Figure 1). This resulted in snow accumulating in distinct drifts. On April 7, 2023, a large amount of dust was deposited on the snowpack, which resulted in a dramatic change in snow albedo and net radiation, leading to accelerated snowmelt (Figure 2). Snowmelt began on April 9, 2023.

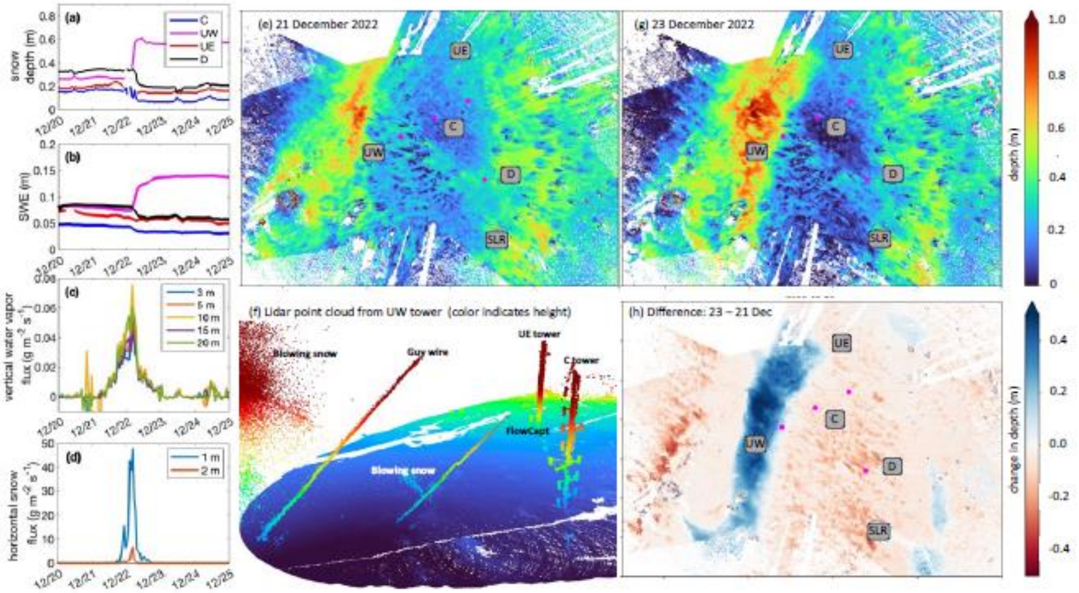


Figure 1. (from Lundquist et al. 2024) .(a) Snow depth, averaged over the footprint of each snow pillow (~1m^2), from the lidars, (b) snow water equivalent (SWE), (c) vertical water vapor flux from the eddy covariance sensors on the central tower, (d) horizontal snow particle flux from the FlowCapt on the upper-east tower. Lidar-derived snow depths on (e) 21 December and (g) 23 December, with (h) the change between them. Rectangles indicate the four tower locations and the snow level radar (SLR), and pink dots indicate snow pillow locations. Small-scale variations highlight drifts near bushes. (f) Illustration of lidar point cloud, including blowing snow, towers, and surface elevations.

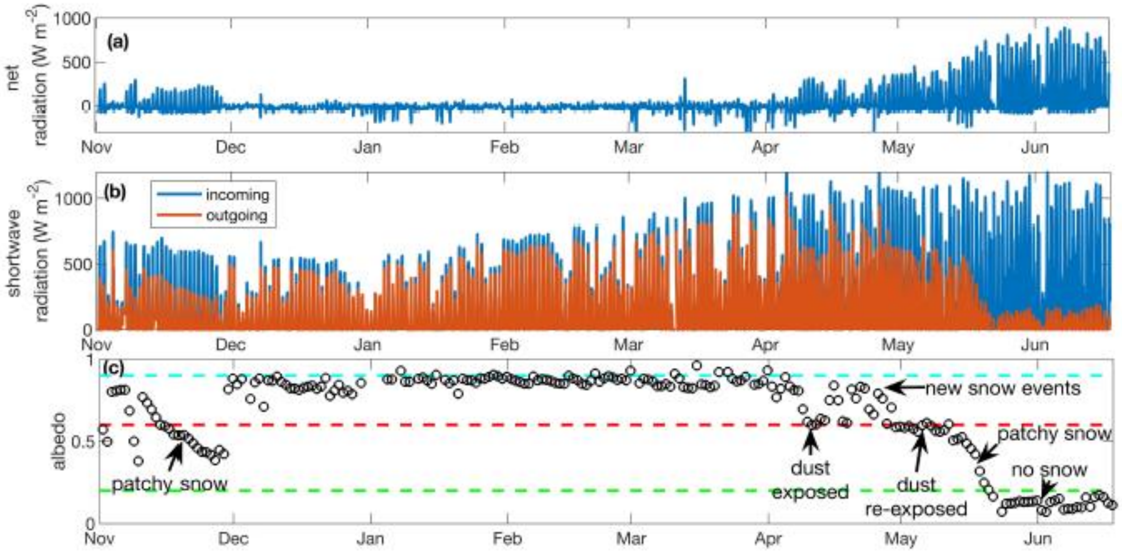


Figure 2. (from Lundquist et al. 2024). (a) Hourly net radiation, incoming minus outgoing longwave and shortwave, primarily measured at the D tower, which had a higher-quality sensor, but patched with data from the UW tower radiometer from 11 to 23 May; (b) incoming and outgoing shortwave radiation from a, (b) albedo, calculated at the time of peak incoming solar radiation each day. Horizontal dashed lines indicate typical albedo values for new snow (0.9), dirty snow (0.6), and bare ground (0.2).

2.0 Results

In addition to the summary results shown in section 1, we are investigating how valley winds relate to turbulent fluxes. These investigations rely on integrating the sublimation measurements, shown above, with the SAIL Doppler lidar, which scanned along the main valley (left) to investigate valley winds and across the main valley to investigate cross-valley structure. Below, we present some preliminary plots of interest from the lidar scans. Repeat doppler lidar scans aligned with the along-valley axis (Figure 3) reveal complex, layered wind directions, during the transition from nighttime to daytime, when nighttime down-valley winds die out. Repeat doppler lidar scans aligned cross-valley reveal the development of shearing motions, eddies, and return flows behind Gothic Mountain. These take a number of different forms at different times of day (Figure 4). Gothic Mountain is the tallest ridge in the vicinity, aligned approximately north-south, perpendicular to the dominant westerly direction of synoptic winds. Understanding how these relate to mixing and energy balances within the valley is a further research opportunity, which we are currently pursuing.

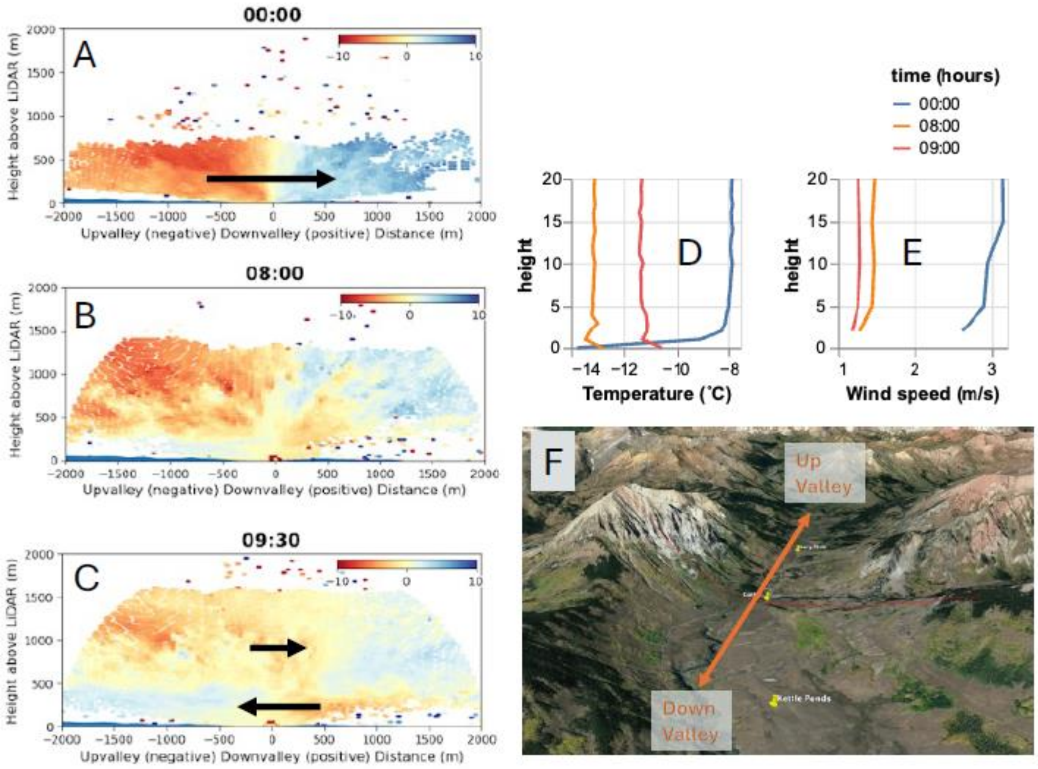
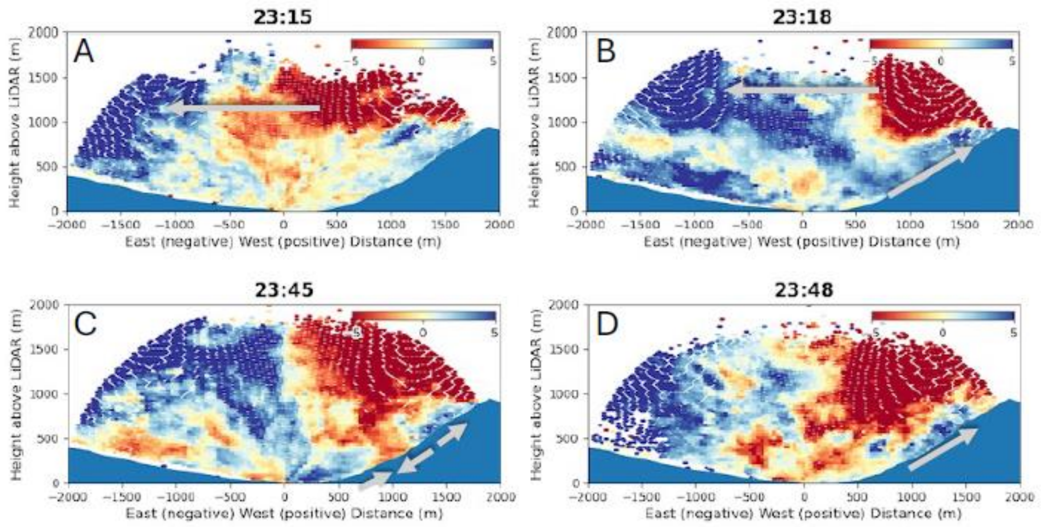


Figure 3. (Work in progress, by Eli Schwat.) Up/down-valley Doppler lidar scans and wind and temperature profiles at Kettle Ponds from February 27, 2023. Scans at 00:00 demonstrate well-developed down-valley winds (A). By 08:00, the down-valley winds have decreased in speed and near the surface, a light up-valley wind is developing (B). By 09:30, an up-valley wind has developed into a thicker layer (C). Some down-valley motion remains above. Temperature profiles measured at Kettle Ponds (D) demonstrate that valley-scale wind changes are associated with changes in temperature profiles near the snow surface. A strong temperature inversion (6 ˚C/5 meters) accompanied down-valley winds and near-neutral temperature profile accompanied the slow-down of down-valley winds and light up-valley winds (D). Down-valley wind speeds are greater than up-valley wind speeds (E).



Axis across East River valley

Figure 4. (Work in progress, by Eli Schwat.) Four doppler lidar scans between 23:15 and 23:48 on 8 March 2023 reveal complex interactions between above ridgeline, westerly winds, and below-ridgeline winds on the lee side of Gothic Mountain. Strong westerly winds are apparent coming over Gothic Mountain at 23:15 (A). Three minutes later. At 23:18, a strong up-slope flow has developed, going up the lee side of Gothic Mountain (B). 27 minutes later (the time of the next cross-valley scan), the above-ridge westerly has reached down towards the ground and ”broken” up the up-valley flow (C). Three minutes later, the flow upslope on Gothic Mountain has become more continuous again.

3.0 Publications and References

3.1 Peer-Reviewed Publications

Feldman, DR, AC Aiken, WR Boos, RWH Carroll, V Chandrasekar, S Collis, JM Creamean, G de Boer, J. Deems, PJ DeMott, J Fan, AN Flores, D Gochis, M Grover, TCJ Hill, A Hodshire, Erik Hulm, CC Hume, R Jackson, F Junyent, A Kennedy, M Kumjian, EJT Levin, JD Lundquist, J O’Brien, MS Raleigh, J Reithel, A Rhoades, K Rittger, W Rudisill, ZS Sherman, E Siirila-Woodburn, SM Skiles, JN Smith, RC Sullivan, A Theisen, M Tuftedal, AC Varble, A Wiedlea, S Wielandt, K Williams, and Z Xu. 2023. “The Surface Atmosphere Integrated Field Laboratory (SAIL) Campaign.” *Bulletin of the American Meteorological Society* 104(12): E2192–E2222, https://doi.org/10.1175/BAMS-D-22-0049.1

Lundquist, JD, J Vano, E Gutmann, D Hogan , E Schwat , M Haugeneder, E Mateo, S Oncley, C Roden, E Osenga, and L Carver. 2024. "Sublimation of Snow." *Bulletin of the American Meteorological Society* 105(6): E975–E990, https://doi.org/10.1175/BAMS-D-23-0191.1

3.2 Data Sets

Hogan, D, E Schwat, JD Lundquist, E Gutmann, and J Vano. 2023. SOS: Weather Blog. Version 1.0. UCAR/NCAR – Earth Observing Laboratory. https://doi.org/10.26023/E1WQ-JRNX-8205

Hogan, D, E Schwat, JD Lundquist, E Gutmann, and J Vano. 2023. SOS: Snow Pit Data. Version 0.2 [PRELIMINARY]. UCAR/NCAR – Earth Observing Laboratory. https://data.eol.ucar.edu/dataset/633.003

NSF-NCAR/EOL-ISFS-Team. 2023. SOS: ISFS Surface Meteorology and Flux Products. Version 1.1. https://doi.org/10.26023/CYK2-SR3N-880J

Schwat, E, D Hogan, JD Lundquist, E Gutmann, and J Vano. 2023. SOS: Thermistor Harp Data. Version 1.0. UCAR/NCAR – Earth Observing Laboratory. https://doi.org/10.26023/RY3F-VVF3-CQ04

Schwat, E, D Hogan, JD Lundquist, E Gutmann, and J Vano. 2023. SOS: Stossel Box Weight Data. Version 1.0. UCAR/NCAR – Earth Observing Laboratory. https://doi.org/10.26023/WBFH-X820-FC0C

3.3 Presentations

Lundquist, J. 2022. "Sublimation of Snow." Invited seminar presented at Department of Energy SAIL conference.Recording available here: https://sail.lbl.gov/events/regular-meetings/ . [Multiple recordings are also available from other team members.]

Schwat, E, D Hogan, JD Lundquist, ED Gutmann, and JA Vano. 2023. "Measuring sublimation of snow on the valley floor of a Colorado River headwater basin. Presented at the American Geophysical Union Fall Meeting. Chicago, Illinois.

Mateo, EI, L Carver, JA Vano, EC Osenga, JD Lundquist, D Hogan, E Schwat, ED Gutmann, and M Haugeneder. 2023. "Developing outreach and educational tools and opportunities for the Sublimation of Snow (SOS) project." Presented at the American Geophysical Union Fall Meeting. Chicago, Illinois.

3.4 Other

- Our efforts to make the results known to a broader community were very successful with media coverage from UW, ARM, National Public Radio, and *High Country News*. These articles are all linked to the main project website: bit.ly/sublimation-of-snow
- Example processing code and laboratory assignments are provided at the University of Washington Snow Hydrology class website and associated github repository: https://mountain-hydrologyresearch-group.github.io/snow-hydrology/
- The ISFS instrument data report is provided under Documentation at: https://data.eol.ucar.edu/dataset/633.001

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