Will hoar frost in the western United States be a relic of the past?

William Rudisill (1), Dan Feldman (1), Arielle Koshkin (2), Adrienne Marshall (2), Stefan Rahimi (3)

(1) Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, (2) Colorado School of Mines, (3) University of California Los Angeles

1417578
C11E-1093

EARTH & ENVIRONMENTAL SCIENCES

BERKELEY LAB

Introduction

Example of surface hoar from the Sierra Nevada from the winter of 2023. Photo courtesy of the Sierra Avalanche Center.

- Snow surface hoar is common in western United States snowpacks but is poorly studied
- Relevant for avalanche risk
- Our goals are to:
- *Establish the fundamental thermodynamic and kinetic controls on surface hoar formation*
- *Test process understanding of surface hoar formation using SAIL field campaign data*
- *Examine climate sensitivity of surface hoar formation using CMIP6 dynamically-downscaled projections*

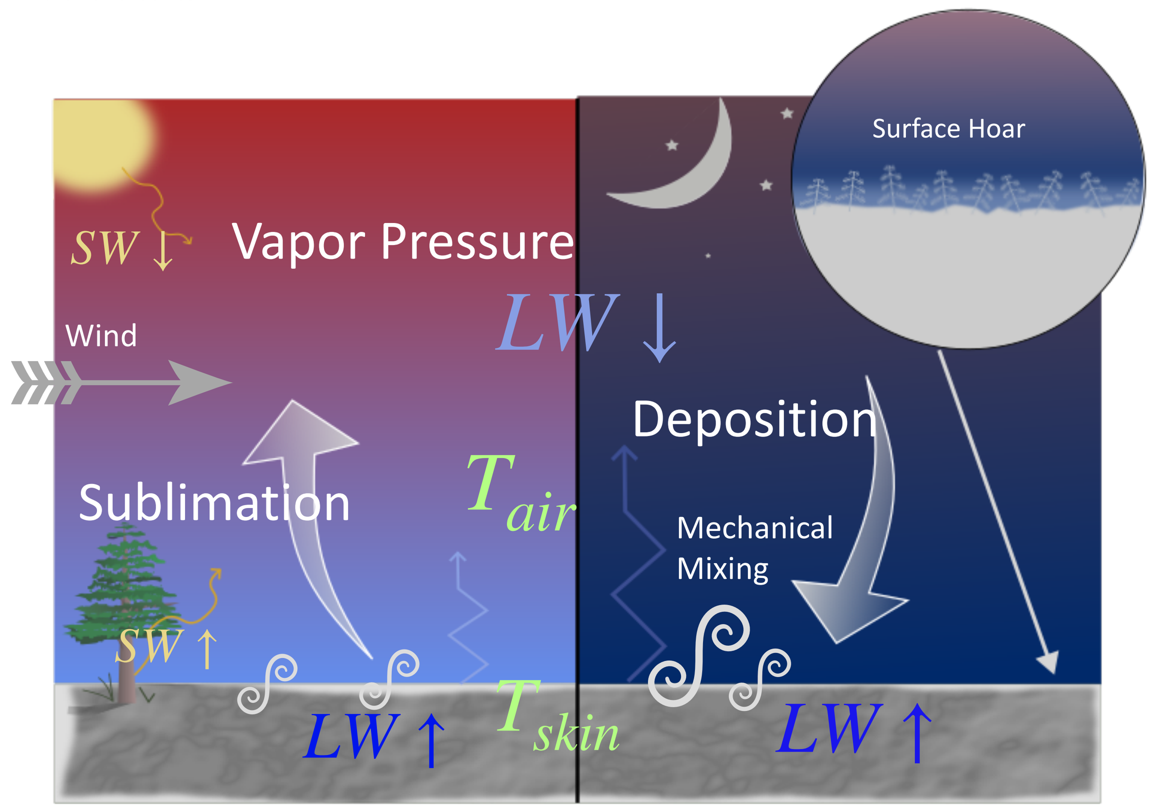

Figure 1: Idealized depiction of energy and moisture fluxes components over a snowpack. Deposition follows moisture gradients between the snow and atmosphere

- Deposition (vapor —> ice) is driven by vapor pressure gradients (or specific humidity) between the atmosphere and the snow surface
- The bulk turbulent flux H_l is proportional to the gradient in specific humidity scaled by the bulk transfer coefficient given by (Armstrong, 2008)
- At night time when there is no solar radiation, H_l is balanced by the sensible heat flux, conduction, and net longwave radiation budget
- Winds may increase bulk transfer coefficient, but possibly enhance mixing of warm air and decrease humidity gradient

Fundamental thermodynamic controls on surface hoar formation

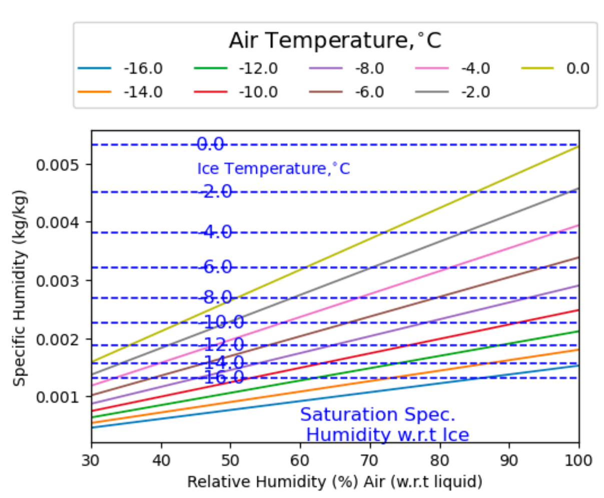

Figure 2: Relationship between specific humidity, temperature, and relative humidity with respect to ice and water. The ice surface always saturated (blue dashed lines). Deposition is favored for atmospheric RH and T conditions that have a higher specific humidity than a given ice surface temperature (blue line).

- The non-linear relationship between temperature and saturated specific humidity (Clausius-Clapeyron relation) means that, for a given RH, a warmer atmosphere is further away from the frost-point temperature
- Figures 2 illustrates the atmospheric RH, T, and ice surface temperatures in which a gradient for deposition is favored for various snow (ice) temperatures

Observations from the SAIL field campaign

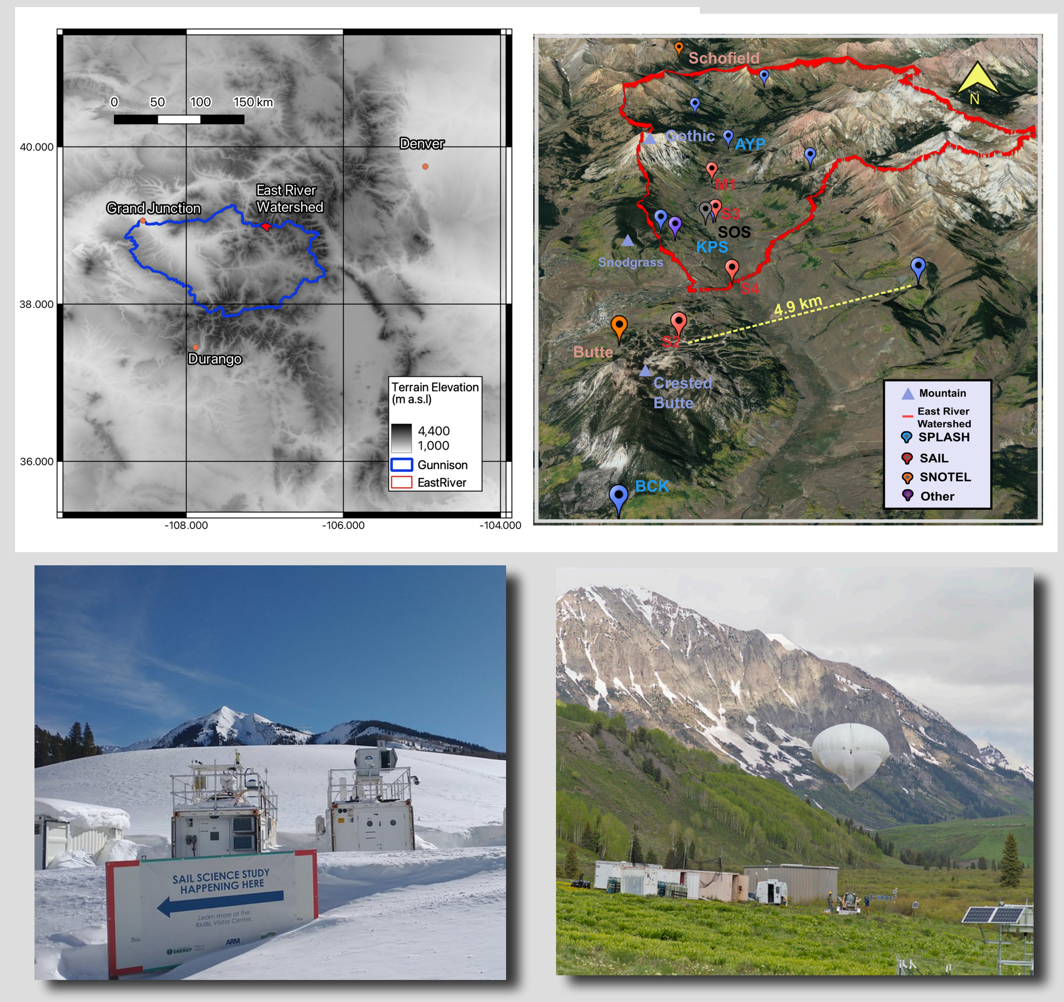

Figure 3: The DOE ARM "SAIL" field campaign near Gothic, CO deployed from September 2021—June 2023 in the upper East River Watershed. The SAIL campaign is described in Feldman et al. 2023. SAIL collected numerous measurements of the atmospheric and surface energy balance (Table 1, and more)

Instrument	ARM Name	Target quantity
Eddy Covariance	ECOR	Sensible Heat, Latent Heat Flux
4-Component Radiometer	QCRAD	Up/Down Long/Shortwave radiation
Met Station	MET	Wind speed + direction, vapor pressure, temperature
IR Thermometer	GNDIRT	Surface snow temperature
Ka-Band Radar	KAZR	Zenith pointing reflectivity at 35 GHz
multiple	ARSCL	Cloud Base Height

Table 1: List of the instrument data used in this study from the SAIL campaign.

Deposition Case Study: Jan 14, 2023

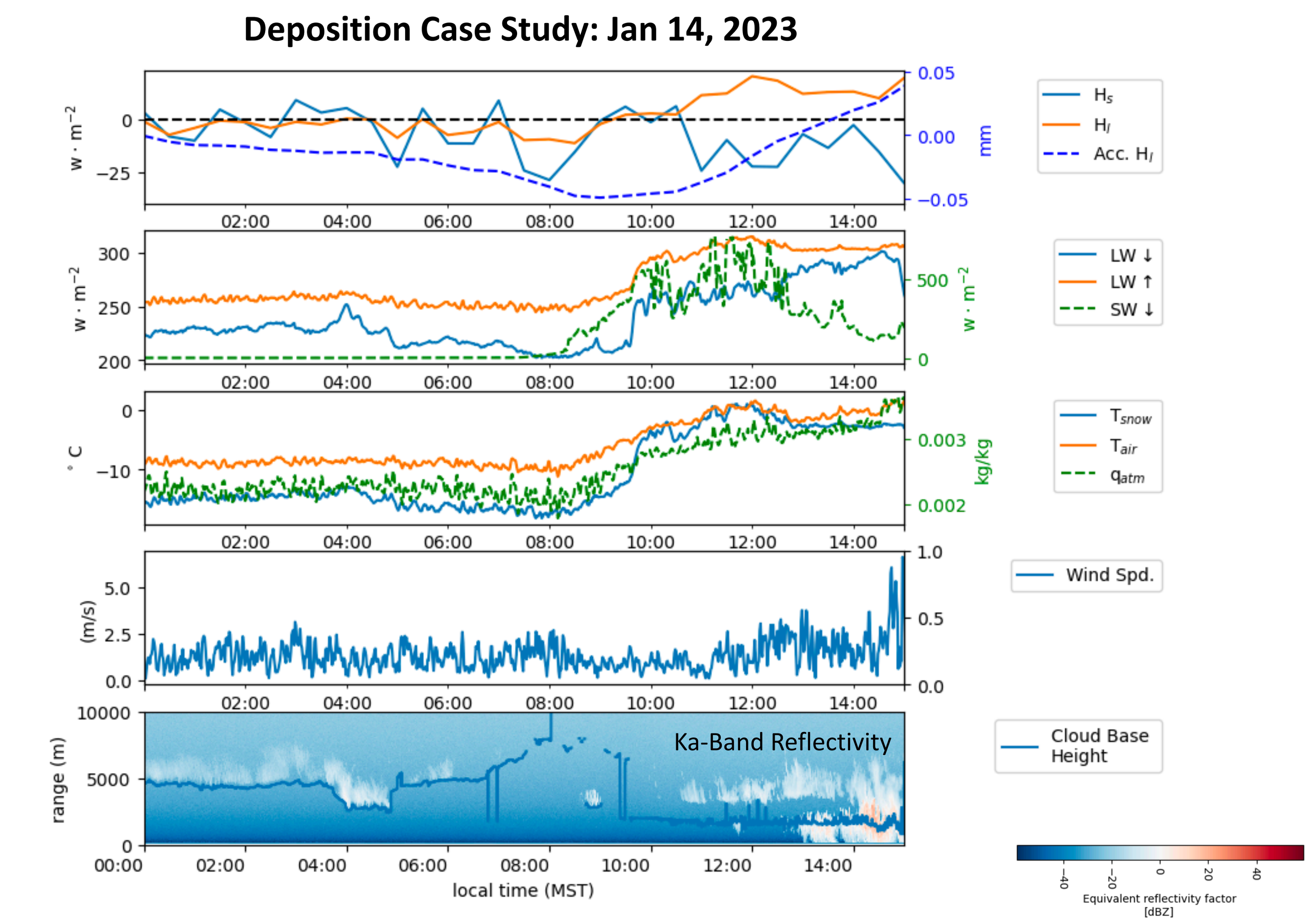

Figure 4: Time series surface hoar development on January 14, 2023 at the SAIL site. The presence of morning surface hoar was confirmed by E. Schawat and D. Hogan from the University of Washington. From top down: sensible heat flux (H_s), latent heat flux (H_l), and accumulated latent heat flux converted to units of mm; up/downwelling longwave and downwelling shortwave radiation; snow skin temperature, air temperature, and specific humidity of the air; cloud base height and vertical pointing Ka-Band radar reflectivity.

Relationship between LW Net, windspeed, humidity, temperature and cloud base height 2021-2023 (Snow covered nights only)

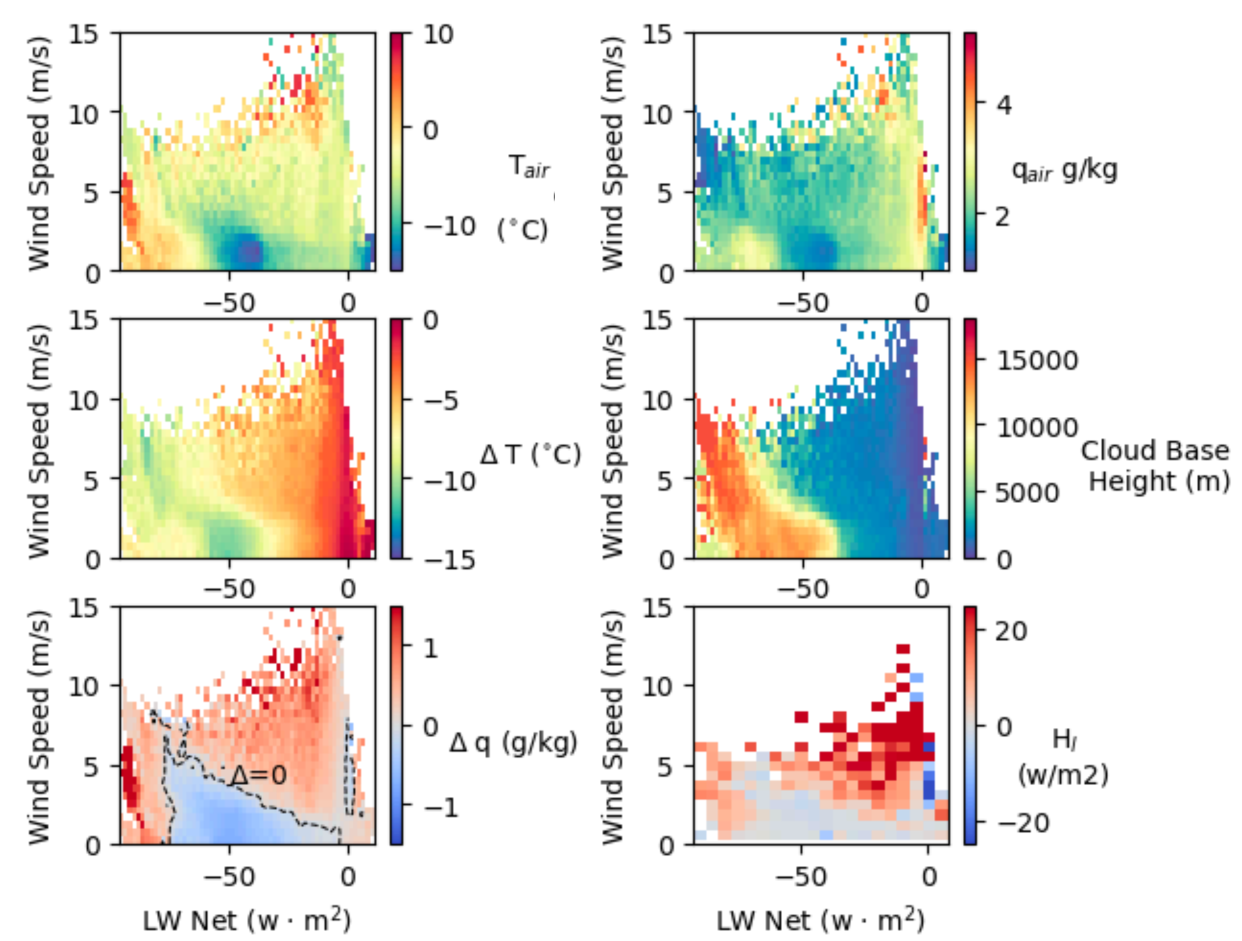

Figure 5: Net longwave (down - up) versus wind speed with averages of A) T_{air}, B) q_{air} C) temperature gradient ($T_{air} - T_{skin}$) D) cloud base height from the ARM ARSCL product (derived from SAIL observations), E) specific humidity gradients ($q_{air} - q_{skin}$), and E) 30-minute averaged latent heat flux (H_l) from eddy covariance measurements.

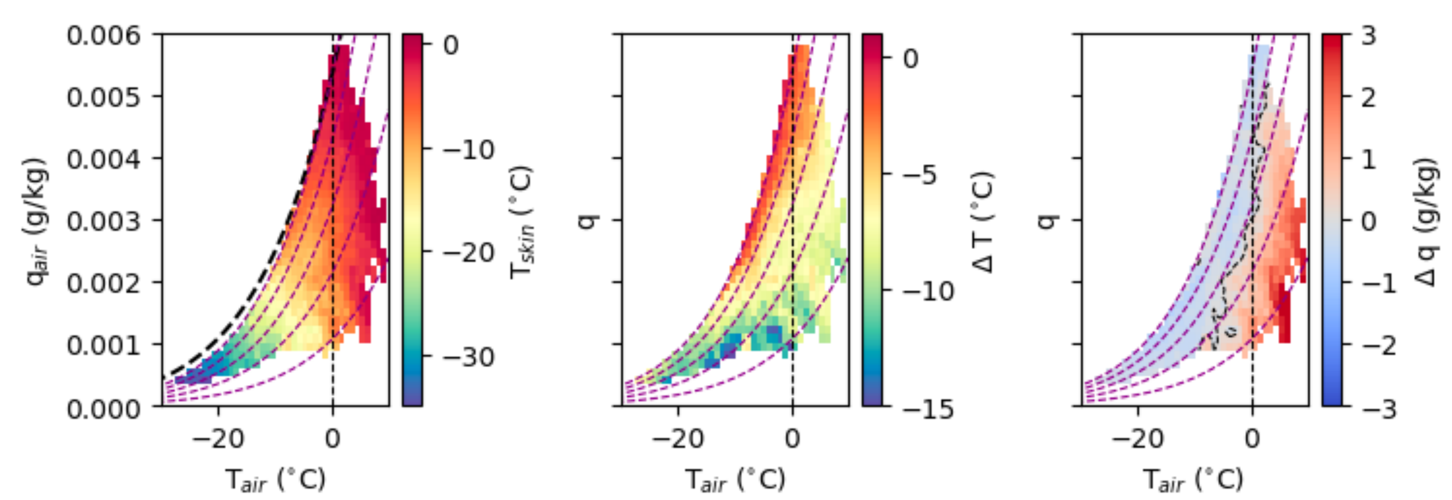

Figure 6: Averaged snow skin temperature (T_{skin}), temperature gradient ($T_{air} - T_{skin}$), and specific humidity gradients ($q_{air} - q_{skin}$) between the surface and atmosphere in temperature-specific humidity space. Contours of relative humidity (with respect to ice) are shown, from 100% to 20%.

Dynamically downscaled GCM projections of deposition favorability

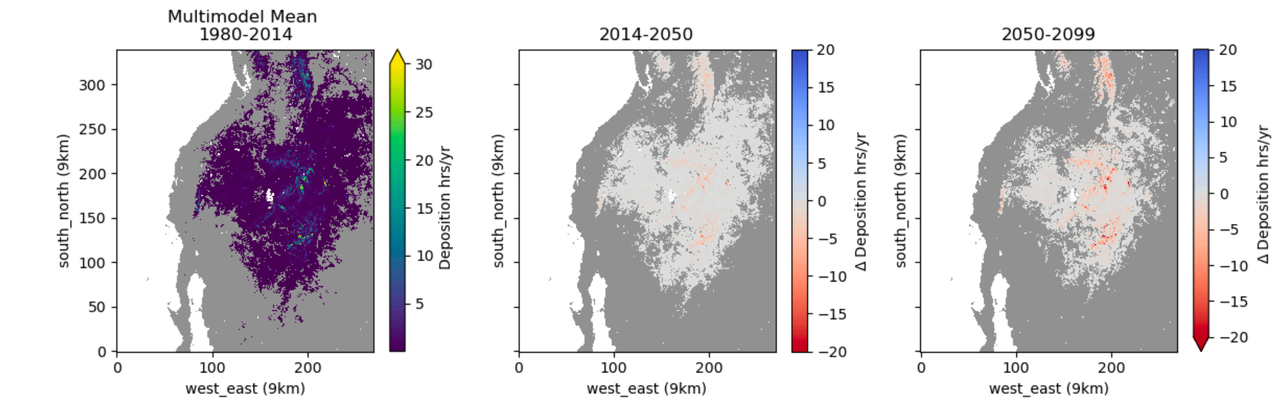

Figure 7: Change in the number of nighttime hours where deposition is favored (specific humidity gradient directed towards the snow surface) from the dynamically downscaled dataset WUS-D3 (Rahimi et. al, 2023)

- The favorability of nighttime snow deposition for historical, near-future, and future climates of the western USA was calculated from 9km dynamically downscaled CMIP SSP-370 scenarios — 9 GCMS total (Rahimi et al., 2023)
- Future scenarios show a decrease in deposition hours, particularly in the intermountain west and Colorado rockies, as well as a reduction in the areal extent of snow cover

Discussion and ongoing work

- The eddy covariance measurements appear to capture deposition flux (also found in Stossl et. al, 2009)
- Small amounts of cloud cover have an impact on net longwave and skin temperatures through the moisture-emissivity relationship (Figure 4, 5)
- Favorable temperature gradients are required for deposition, but is not the only factor— sufficient moisture matters as well (Figure 5)
- For instance, Figure 5 shows nighttime *sublimation*, despite strong longwave cooling and a favorable temperature gradient— warm, very dry cloud free air is advected over a warm snowpack in this case
- Deposition gradients are only favorable during sub-saturated conditions at cold temperatures and can transition to favoring nocturnal sublimation over a short increase in air temperature (Figure 6)
- Next steps will use insights gained from SAIL to further investigate the dynamically downscaled GCM data

References and acknowledgments

- Armstrong, R. L., and E. Brun, 2008: *Snow and Climate: Physical Processes, Surface Energy Exchange and Modeling*. Cambridge University Press, 222 pp.
- Bolton, D. 1980. The computation of equivalent potential temperature. Mon. Wea. Rev., 108. 1046–1053.
- Feldman, D. R., et al. "The Surface Atmosphere Integrated Field Laboratory (SAIL) Campaign." *Bulletin of the American Meteorological Society* (2023).
- Rahimi, S., and Coauthors, 2023: An overview of the western United States dynamically Downscaled Dataset (WUS-D3). Geoscientific Model Development Discussions, https://doi.org/10.5194/gmd-2023-162.
- Stössel, F., Guala, M., Fierz, C., Manes, C., and Lehning, M. (2010), Micrometeorological and morphological observations of surface hoar dynamics on a mountain snow cover, Water Resources Research, 46, W04511, doi:10.1029/2009WR008198.

SAIL Campaign Info

Poster

This work was supported by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research and the Atmospheric System Research Program under U.S. Department of Energy Contract No. DE-AC02-05CH11231

U.S. DEPARTMENT OF ENERGY | Office of Science

AGU Fall Meeting December 11th; 2023