Seasonality and Albedo Dependence of Cloud Radiative Forcing in the Upper Colorado River Basin

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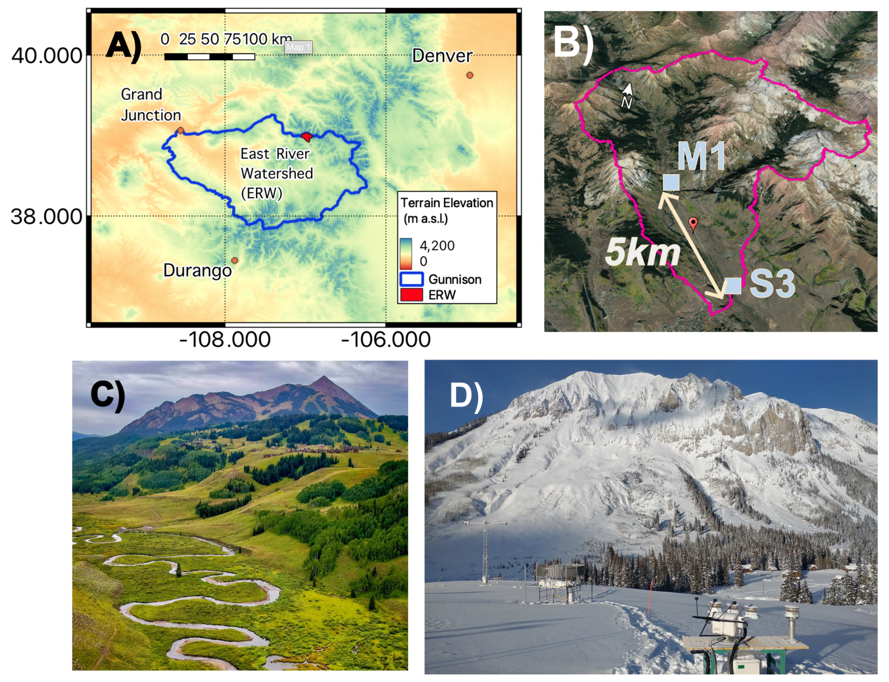
Motivation — Clouds and the Surface Energy Budget



- The **Upper Colorado river is drying**, and the exact reasons are uncertain—more work is needed to quantify the **surface energy budget constrains** and dominant processes required for successful modeling of key processes.
- Globally, clouds have a ~20 w/m2 cooling effect. But regional variations are poorly quantified.
- The radiative effects of clouds is poorly studied in the Rockies.
- The SAIL (Feldman et al., 2023) and partner campaigns offer unprecedented records of radiative forcing and cloud properties in mountain UCRB.

A) The topography of the ERW, surrounding mountains, and the greater Gunnison river watershed, B) A zoom-in view of the ERW, with the primary SAIL site (M1) and supplemental site (S3) highlighted, C) A summer view of the ERW valley, approximately looking south from the S3 site, D) mid-winter view of the M1 site looking approximately west towards Mt. Gothic. The radiometer system used in this study is visible in the bottom right.

Goal: Quantify CRF Using SAIL Data

Cloud Radiative Forcing Equation

$$CRF_{LW} = (LW\downarrow - LW\uparrow)_{all-sky} - (LW\downarrow - LW\uparrow)_{clear}$$

$$CRF_{SW} = (1-\alpha)(SW\downarrow_{all-sky} - SW\downarrow_{clear})$$

$$CRF_{NET} = CRF_{SW} + CRF_{LW}$$

Positive —- *clouds warm the surface relative to clear skies*

Negative — *clouds cool relative to clear skies*

Instrument or Data Product	Variables
Microwave Radiometer	precipitable water vapor; liquid water path
Radiosondes	2x daily temperature, humidity, pressure
Pyranometer/ Pyrgeometer	broadband down and upwelling short/longwave radiation
Multifilter Shadowband Radiometer	Down/upwelling irradiance at discrete wavelengths 409, 497, 610, 673, 866, 936 nm
ARSCL Cloud product	cloud base height, cloud fraction
NOAA Ozone Sonde	O_3 concentration

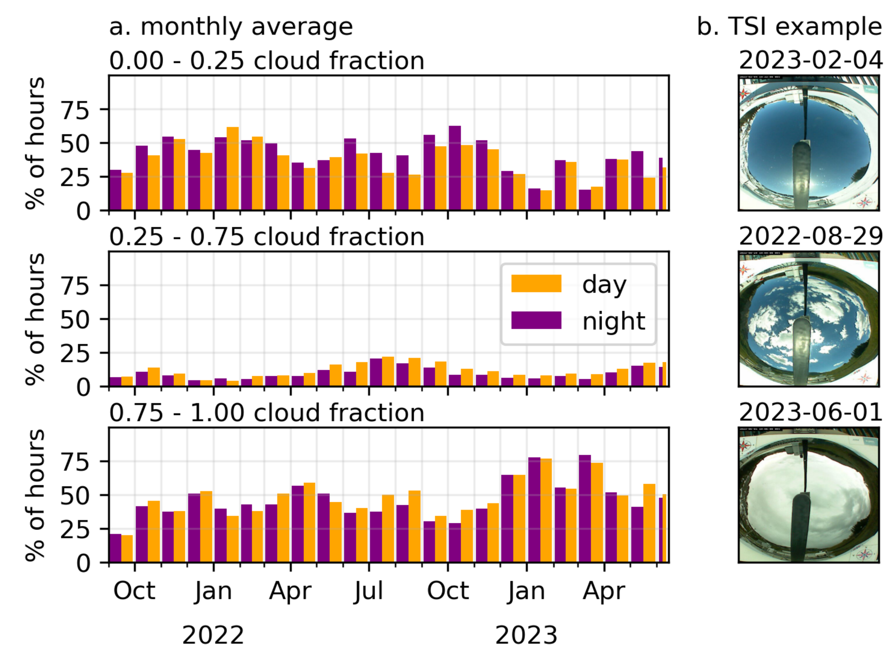
Table 1: Measurements and data streams used in this study.

Estimating Clear Sky ↓ Terms

- The **RRTMG v4 radiative transfer model** (Iacono et al., 2008) is used to produce clear sky estimates.
- Inputs include sonde pressure, temperature, moisture (scaled by MWR) and ozone from NOAA ozone sonde in Boulder (Table 1).
- Time periods where shadows are not considered in the CRF calculation
- CRF depends on the albedo of the land surface due to the shortwave term.

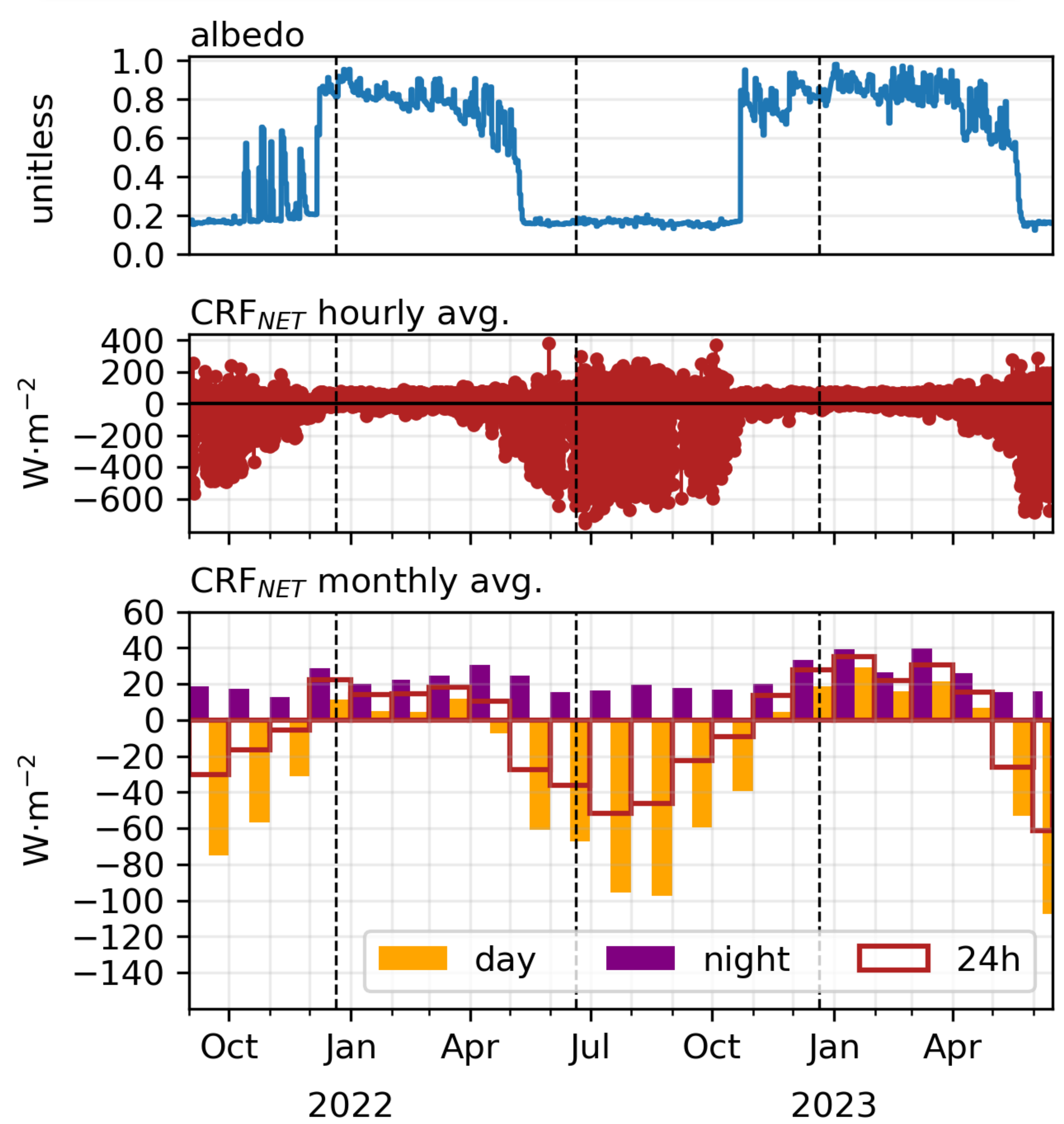
Results

1) Cloud Frequency



The monthly percentage of hourly scenes with 0-0.25, 0.25-0.75, and 0.75-1.0 Cfrac cloud fraction during the SAIL period. Cloud fraction is defined using the ARSCL cloud product. Example daytime scenes for each category from the total sky imager are depicted on the right hand side of each row.

2) Cloud Radiative Forcing

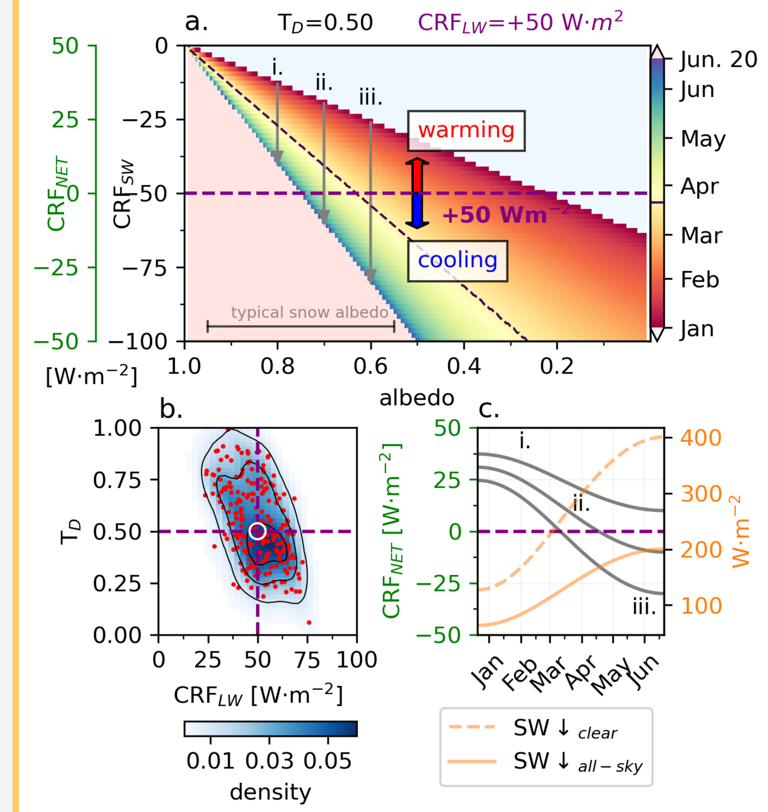


3) Idealized Model of Cloud Radiative Forcing

Right: a) An idealized model of daily average CRFSW as a function of time of year and albedo, a shortwave transmissivity of 0.5, and 38.9 ◦ N latitude. The dashed diagonal line indicates the equinox date. CRF_NET is depicted (green axis) for a constant +50 W·m−2 CRFLW , which is depicted as purple dashed line. (b) The relationship between TD and CRFLW based on SAIL observations. The value of TD and CRFLW are highlighted with the open circle. (c) Shows examples CRFN ET for three different albedo values (0.8, 0.7, and 0.6) depicted in (a). The seasonal variation in clear and all-sky SW ↓ is also depicted on the right y-axis with orange lines.

$$CRF_{SW} = (1-\alpha_k)S_0T_0\overline{\cos[\theta]}_k(T_d - 1)$$

Where $\cos[\theta]$ *is the cosine of the solar zenith angle,* ***T*** *is the transmissivity of the cloud or clear-sky atmosphere, and* ***S*** *is the solar constant (1365 w/m2) and* α *is the land surface albedo.*

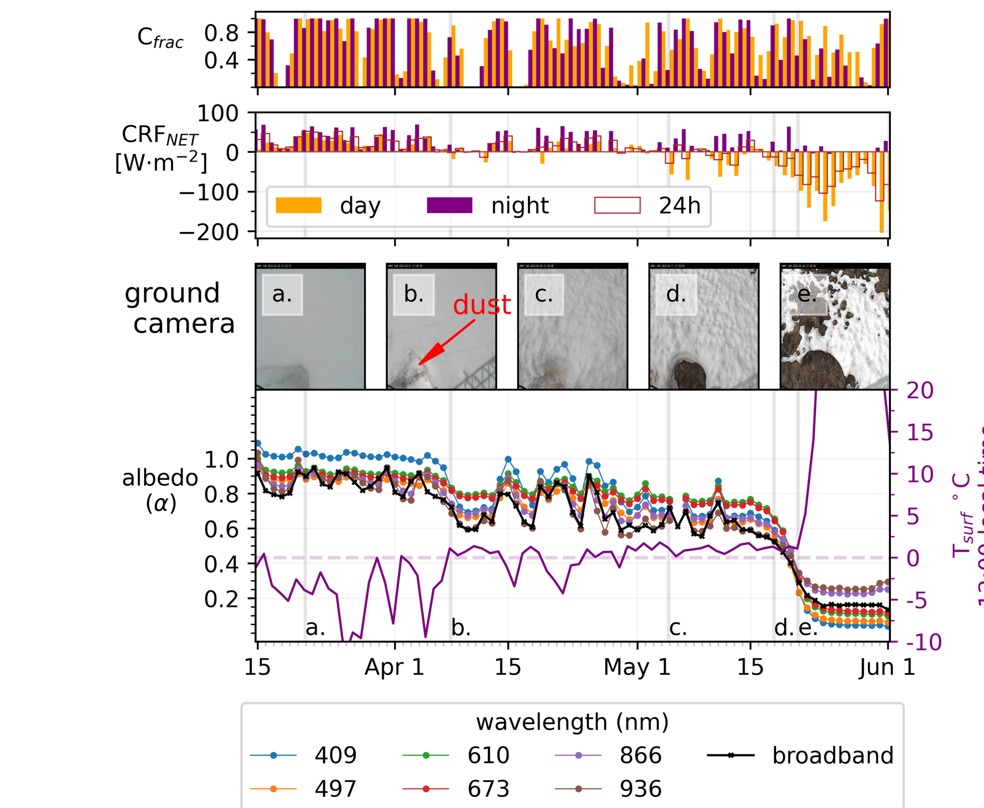


Key Takeaways

- The sign (cooling or warming) of cloud radiative forcing is highly dependent on the albedo of the land, and particularly if it is snow covered or not.
- Monthly average CRF is positive on the order of 20 w/m2 during the cold snow covered months, but -40 to -60 w/m2 during the warm snow free season.
- The transition from warming to cooling occurs in May of both years.
- Dust-on-snow processes that reduce the broadband snow albedo from ~.8 to ~.5 are partially responsible for the sign change of CRF in the Spring of 2023.
- We are able to quantify the short period of time in which clouds have a mitigating effect on snowmelt — all other times clouds have a net warming effect.
- The potential shortwave cooling is masked by snow surface albedo and exceeds the longwave warming effect, implying that, in addition to an earlier ***the magnitude of CRF will increase as snow recedes in the UCRB,*** *with implication for the hydrologic cycle.*

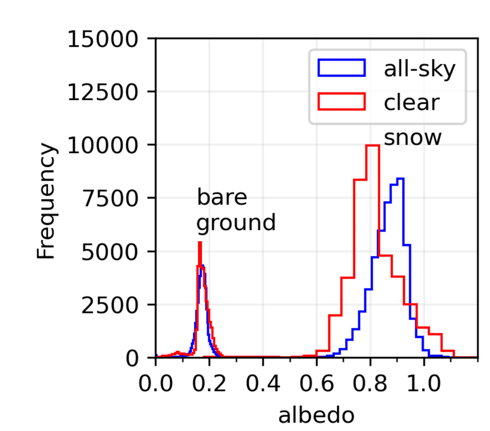
Left: Land surface albedo (top), hourly average CRFN ET (middle), and monthly average CRFN ET for daytime (orange), nighttime (purple), and total (red) time periods. Daytime is defined as all times when the solar altitude angle is greater than zero (middle). The daytime and nighttime bars are unweighted by the length of the day, but the total bars are.

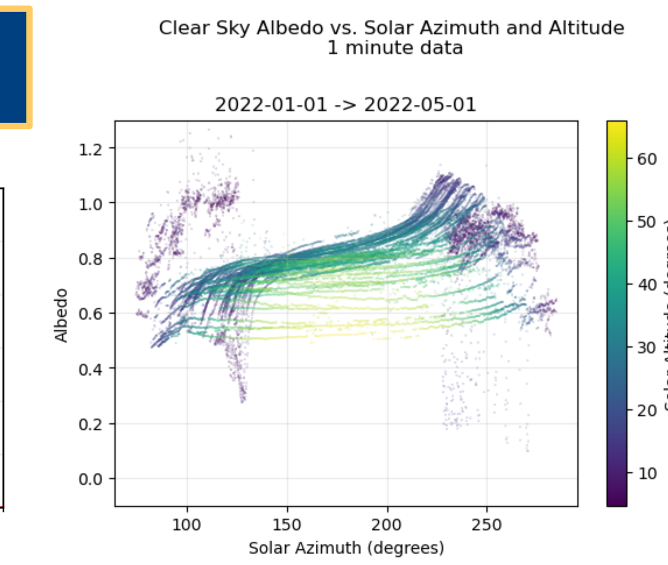
Dust On Snow and CRF



The impact of dust-on-snow albedo and CRFNET . From top to bottom: daytime Cfrac , nighttime Cfrac , CRFNET for the day (yellow) and night (purple), camera images of the ground surface near the radiometer, and the spectral albedo of the surface in five discrete wavelengths and broadband shortwave (black line). The surface temperature (Tsurf at noon is also shown (purple line).

Ongoing Work





- The albedo of the snowpack depends on the incident character of radiation (Male and Granger, 1982). Both the diffuse fraction and spectral character lead to *increased albedo during cloudy conditions.*
- Snow surface slope effects are also clearly present from the albedo observations. Ongoing work seeks to address this and improve albedo characterization of the snow in the ERW.

References and Acknowledgements

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