Linking streamflow, clouds and radiation in the mountain boundary layer

William Rudisill*, Dan Feldman*

*Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory

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Motivation — Clouds impact the surface energy budget

Figure 1a). Field photos of the upper **East River Watershed** (ERW) and SAIL campaign, near Gothic, CO with different cloud conditions.

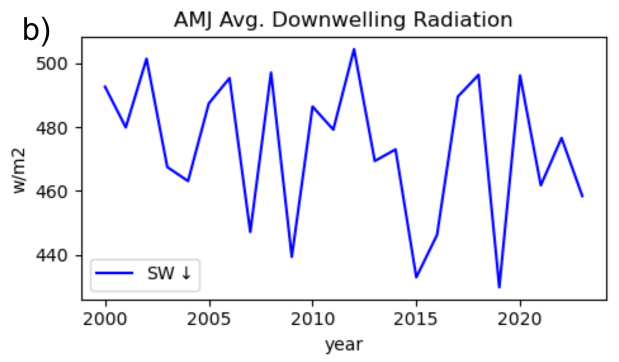


Figure: 1b). 24 years of ***April-May-June*** *downwelling shortwave ($SW \downarrow$) radiation from the 1x1˚ CERES SYN1deg_Ed4A remote sensing based product for the 38.5˚N, 106.5˚ grid cell encompassing the ERW. Average is computed for daytime hours only. Decadal trends of SYN1deg_Ed4A may not be representative of climate trends.*

- 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
- The radiative effects of clouds is poorly studied in the Rockies (this study only looks at shortwave effects)
- Preliminary work shows significant regional variability of downwelling shortwave radiation during the spring snow-ablation season (Figure 1b) caused by cloud cover
- The SAIL (Feldman et al., 2023) and partner campaigns offer unprecedented records of radiative forcing and cloud properties in mountain UCRB

Goal: Quantify cloud radiative effect (CRE) using SAIL data

Goals:

1) Determine the magnitude of cloud radiative effects, seasonality, relationship to cloud properties, and significance for hydrologic variability
2) Examine abilities of community data products (e.g., Daymet) to capture those effects

Methods:

1) Quantify Cloud Radiative Effect (CRE) using

$$CRE = SW_{allsky} \downarrow - SW_{clear} \downarrow$$

(E.g. Shupe et al., 2004)

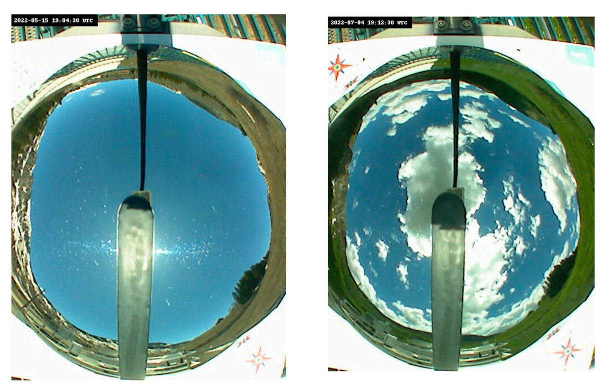


Figure 2). Example hemispheric images from the SAIL Total Sky Imager (TSI) at noon from May 15 and July 2, 2022.

Instrument or Data Product	ARM Abbrev.	Location	Variables
Microwave Radiometer	MWR	M1	precipitable water vapor; liquid water path
Radiosondes	INTERPSONDE	S4	2x daily temperature, humidity, pressure
Pyranometer	SEBS	M1, S3	Broadband down and upwelling shortwave radiation
	QCRAD	M1	Broadband down and upwelling shortwave radiation
AWS	MAWS	M1, S3	Temperature, humidity, pressure
Sun Photometer	SUNPHOT	M1	Aerosol optical depth at 500 nm
Total Sky Imager	TSI	M1	Daytime cloud fraction
ARSCL Cloud product	ARSCL KAZR1KOL	M1	Cloud base height
NOAA Ozone Sonde	N/A	Boulder	O_3 concentration

Table 1: Measurements and data streams used in this study

Estimating $SW_{clear} \downarrow$

- 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)
- Month avg. AOD from the sun-photometer is used with the ECMWF aerosol option (opt=6)
- Time periods where shadows are not considered in the CRE calculation
- Other 3D terrain effects such as diffuse reflection of shortwave are not accounted for

Results

1) Cloud Frequency

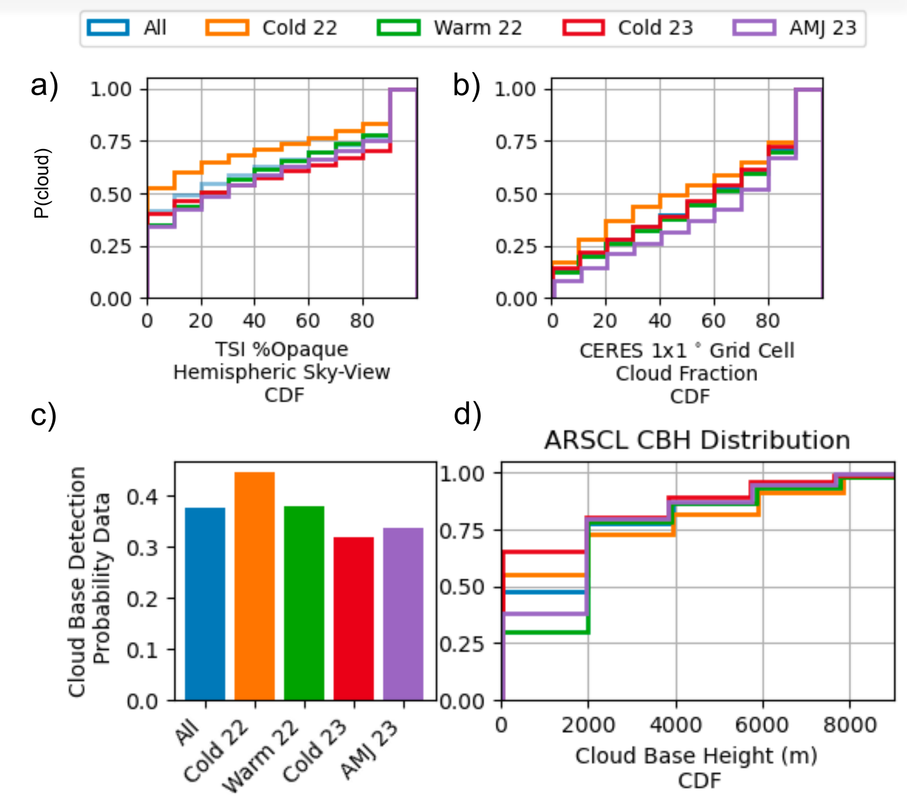


Figure 3). ***DAYTIME*** *Cloud detection in the ERW from three different platforms for the SAIL period. a) CDF of the Total Sky Imager hemispheric cloud fraction , b) CDF of the 1x1˚ CERES SYN1deg_Ed4A cloud fraction for the 38.5˚N, 106.5˚ grid cell, C) Probability of the ARSCL detecting a cloud base, and c) CDF of the ARSCL cloud base height.*

Box 1: Accounting For Terrain Shadowing

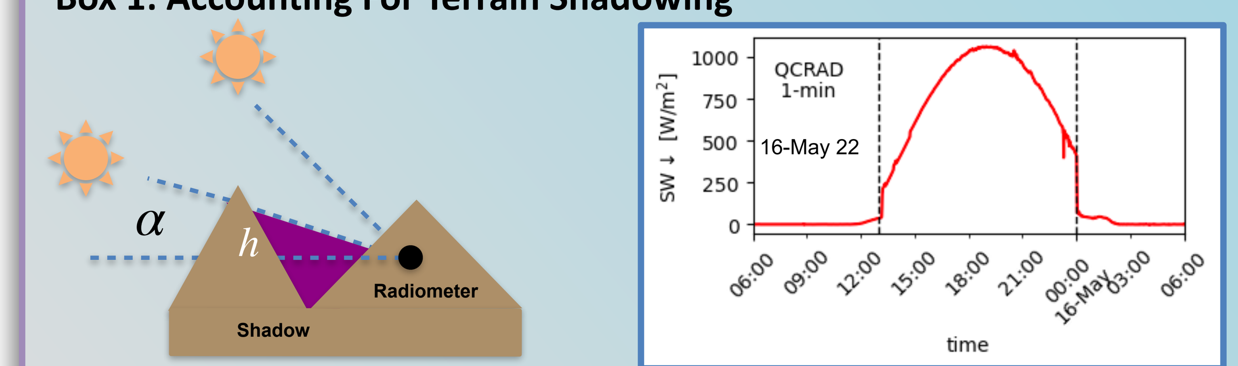


Figure b1). Cartoon illustration of terrain shadowing effects. A shadow is cast when the solar elevation angle (α) is less than the horizon angle (h) in the direction of the solar azimuth. The NEON airborne lidar 5 meter digital elevation model, in conjunction with the "topocalc" method of computing horizon angle was used to determine when the radiometer is shadowed for a given solar azimuth angle. Gray lines in B show the shadow incidence for one day in May.

Key Takeaways

1) The ERW is very cloudy — there is a 50% chance the TSI is at least 30% covered by clouds (Figure 3A)
2) Shadowing can be well accounted for using the 5m NEON DEM (box 1)
3) The *current configuration* of RRTMG is high-biased by ~9% compared to the QCRAD Best Estimate Downwelling Hemispheric radiation data
4) Discrepancy between QCRAD and SEBS needs to be accounted for (not shown) — SEBS is low compared to QCRAD best estimate
5) Largest CRE observed during the summertime (high solar zenith angle) with high LWP and high TSI cloud fraction
6) CRE is sometimes positive! with moderate cloud fractions and low LWP
7) The CERES SYN1DEG product does a reasonable job (better than DAYMET) of capturing daily solar insolation, even though it is at a drastically different scale
8) Prelim. results show that streamflow can respond very quickly to the attenuation of radiation by clouds

2) RRTMG $SW_{clear} \downarrow$ Validation

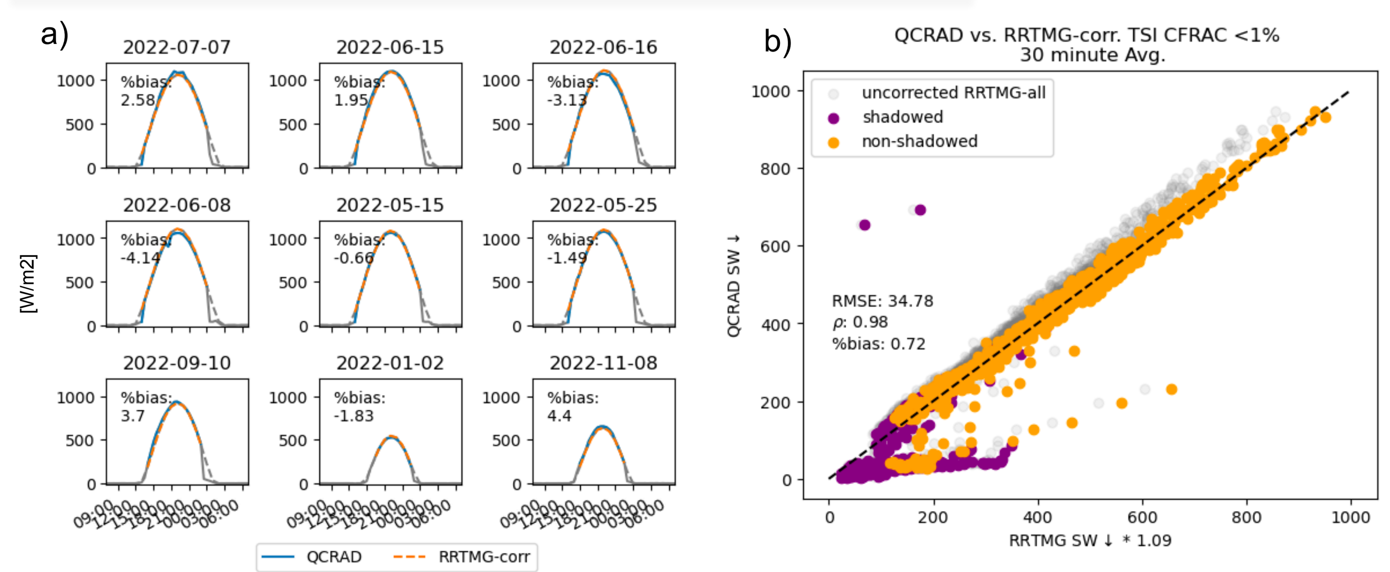
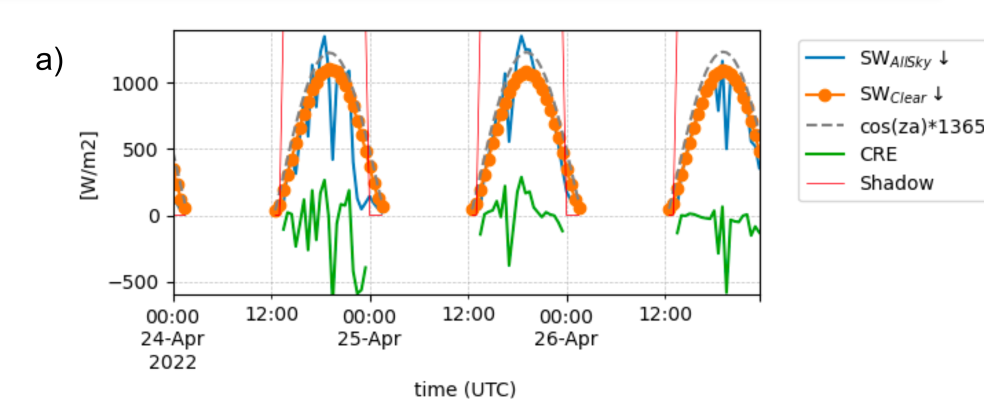


Figure 4a). Comparison of corrected RRTMG against QCRAD Best Estimate Downwelling Hemispheric data for select clear-sky days. Gray areas shown time periods where shadows are present. b). Scatterplot showing the same, but for all 30-minute time periods where the TSI imager shows <1% cloud cover. Purple areas are when the QCRAD is in a shadow.

3) Seasonal and Temporal Characteristics of CRE



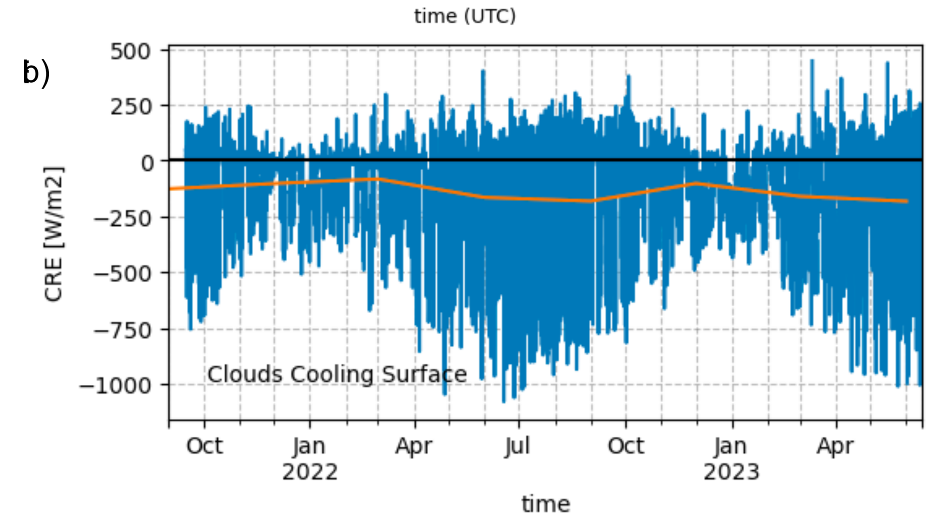


*Figure 6a). example of 30-minute avg. CRE (****QCRAD observed - RRTMG-Clear-Sky****) with observed and modeled clear/all sky shown b) CRE for the duration of the SAIL period. Monthly moving average applied (orange line). RRTMG data produced at the hourly frequency are interpolated to 30minute for comparison with QCRAD.*

4) Cloud Radiative Effect and Cloud Properties

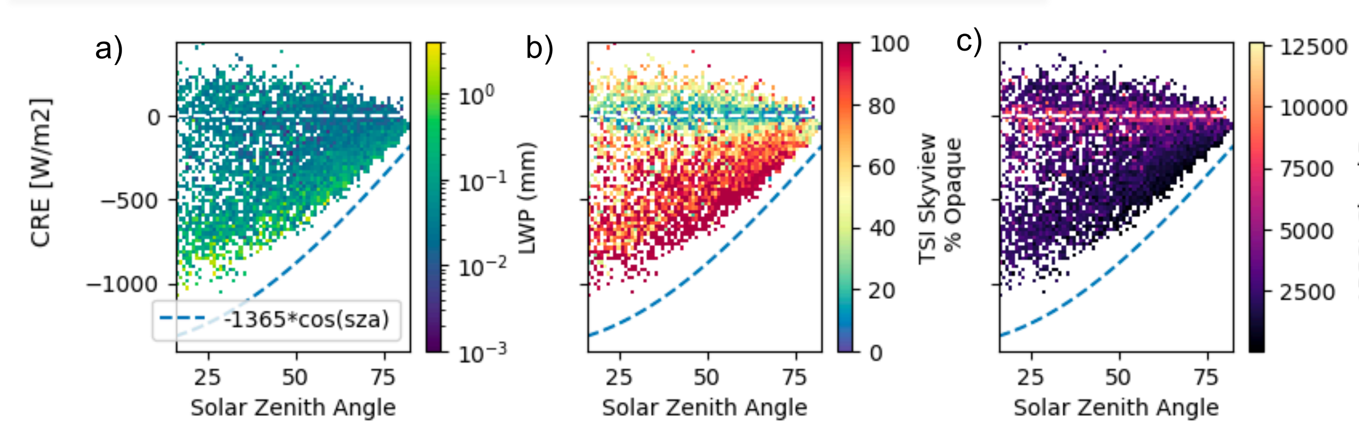


Figure 5). Relationship between solar zenith angle and cloud radiative effect for different a). liquid water path conditions (LWP), b). percent of the hemisphere obscured by opaque clouds measured by the TSI, and c). cloud base height as measured by the ARSCL cloud product.

Box 2: How Well Do Other Products Estimate SW ↓ in the ERW?

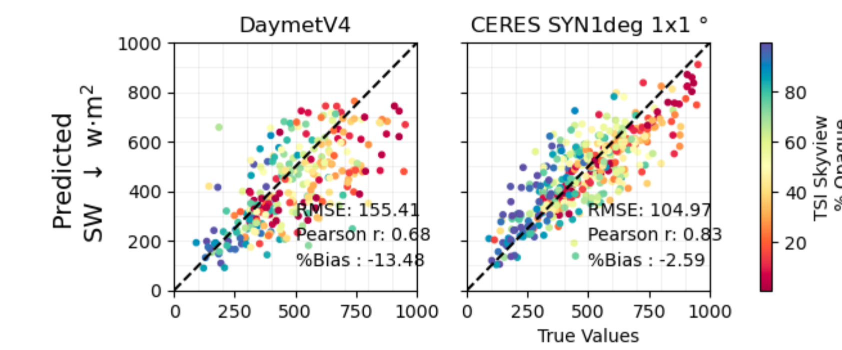


Figure b2). Daily downwelling shortwave from Daymet V4 (downloaded from https://daymet.ornl.gov/single-pixel/), and the 1x1˚ CERES SYN1deg_Ed4A Remote Sensing data product (https://ceres.larc.nasa.gov/data/). Colors correspond with the average daytimeTSI cloud fraction.

Connections to Snowmelt and Streamflow

"Back of the envelope" estimates — how much does CRE matter hydrologically? What if the energy attenuated by clouds instead went into snowmelt?

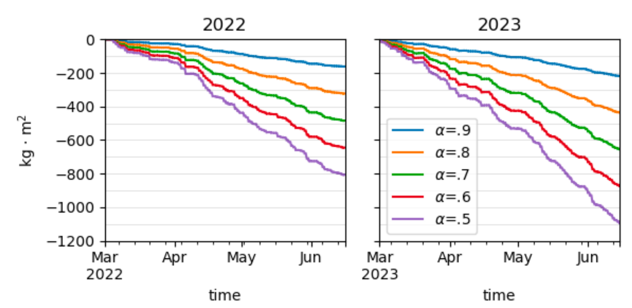
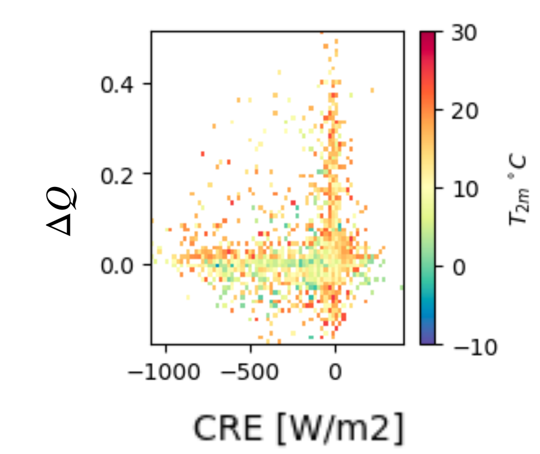


Figure 7). CRE in units of equivalent snowmelt (assuming all energy goes into melting a snowpack with latent heat of melting 3.35E5 J/kg) for various snow surface albedos. Data shown for Spring 2022 and 2023

30 minute change in Spring Streamflow vs. CRE and temperature

Figure 8). Relationship between the 30-minute rise in daytime streamflow (measured at "Pumphouse" by Carroll et al.) versus CRE and air temperature. Peak streamflow in the ERW is ~10 $m^3 \cdot s^{-1}$ for reference. ΔQ is computed by forward difference ($\Delta Q = Q_{i+1} - Q_i$)



Discussion and Next Steps:

1) Address/diagnose RRTMG clear sky bias (2)
2) Examine roles of time step for CRE computation (3)
3) Incorporate additional observations of cloud properties, including ice water path
4) Further examine instances of positive CRE during periods of sparse clouds (also documented in Berg et al., 2010)
5) Establish reasonable estimates of ERW total albedo to scale CRE to surface radiative forcing
6) Develop reasonable constraints on longwave CRE effects for discussion purposes

References and Acknowledgements

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