The Color of Snow

Understanding controls on snow albedo from ground and airborne measurements

S. McKenzie Skiles, Caltech Postdoctoral Scholar

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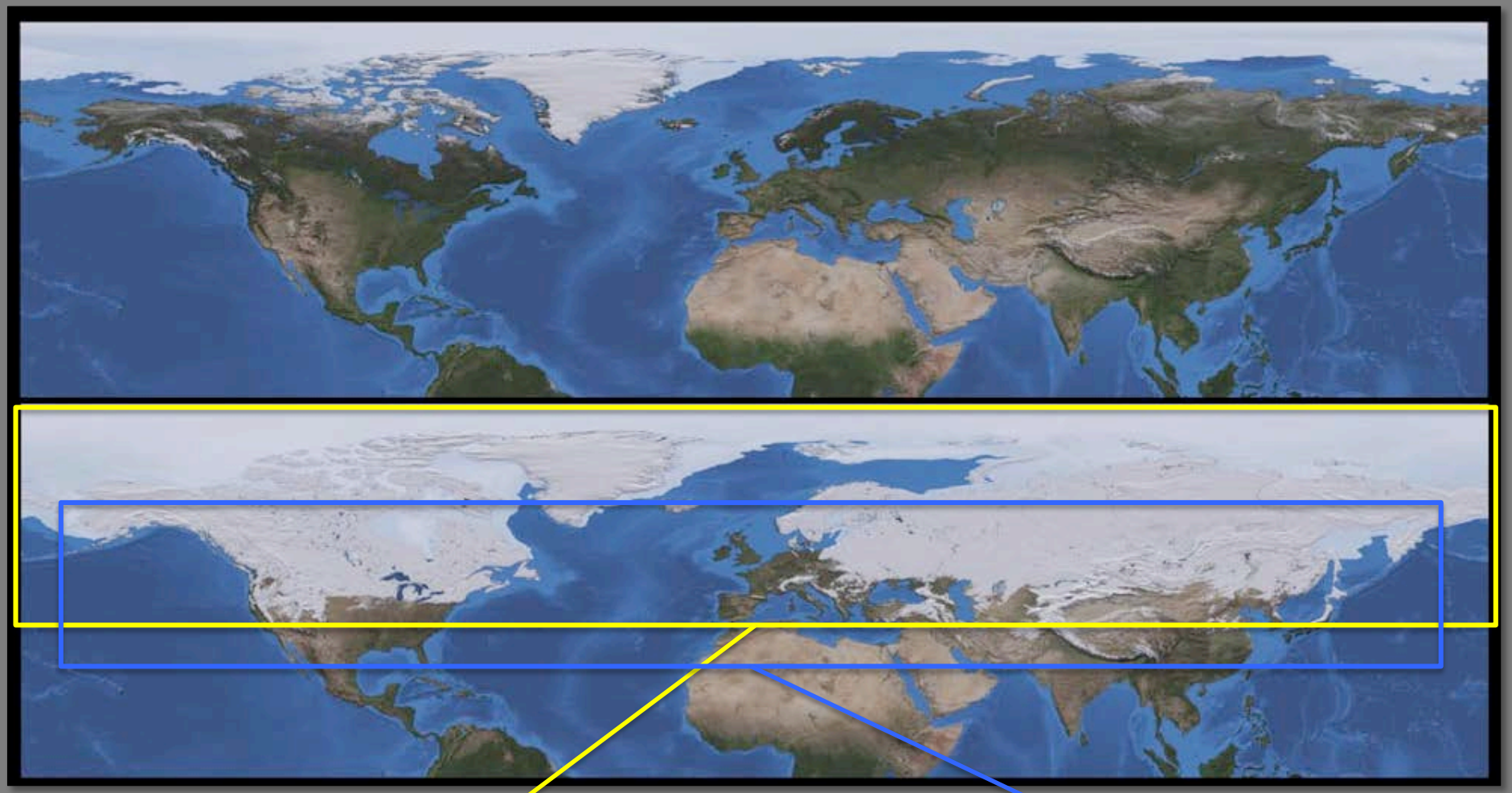
Surface Hydrology Group, Earth Science

Introduction: The Cryosphere



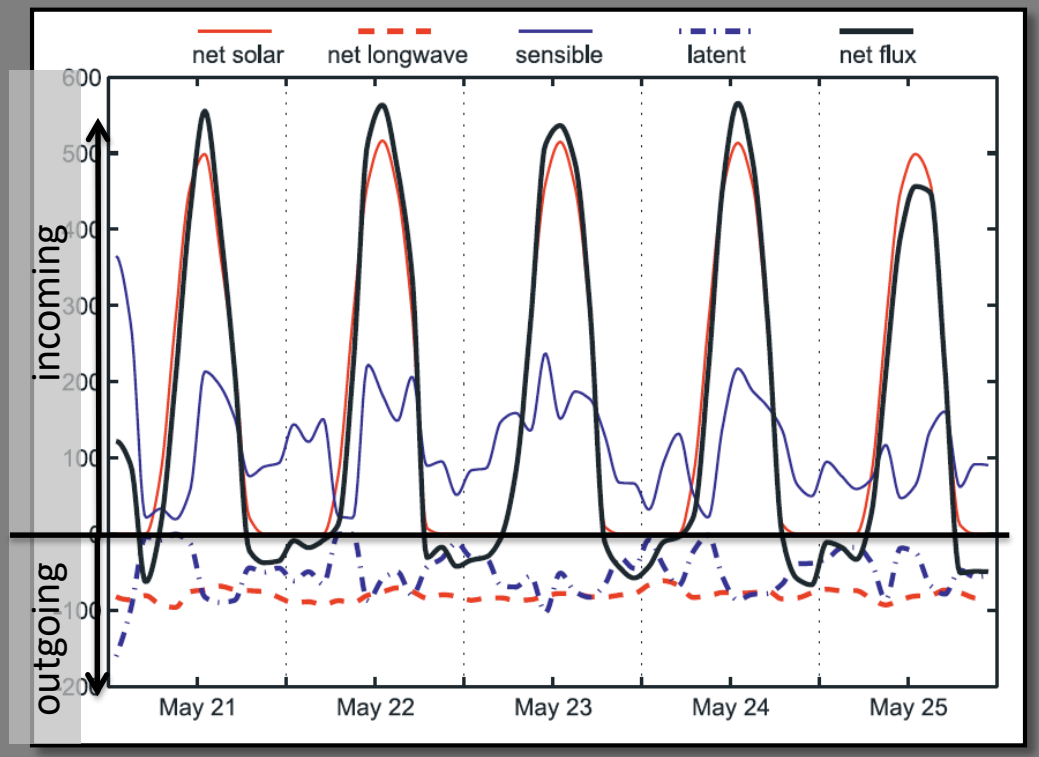
Snow is the most reflective natural surface on earth (climate)

Snow is a natural water reservoir (hydrology)

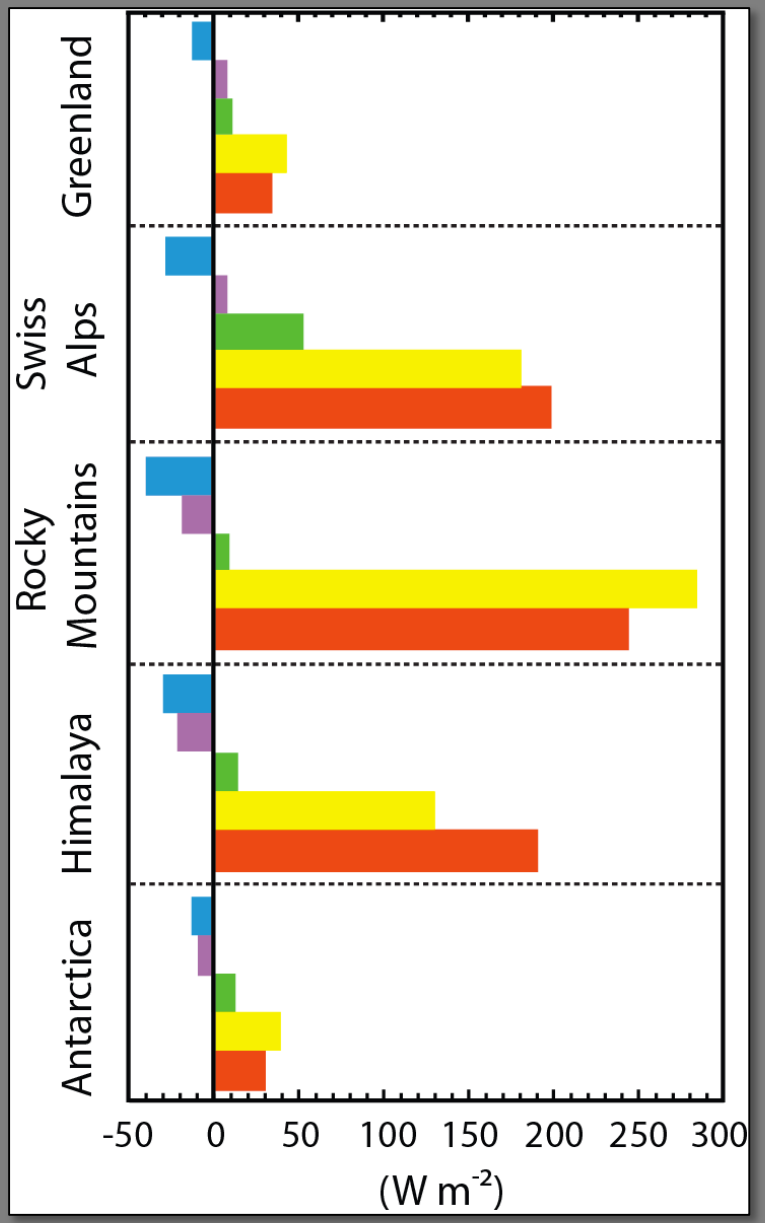
Introduction: What drives snow and ice melt?

Energy available for melt — *Net Solar* — *Net Longwave* — *Sensible Heat* — *Latent Heat*

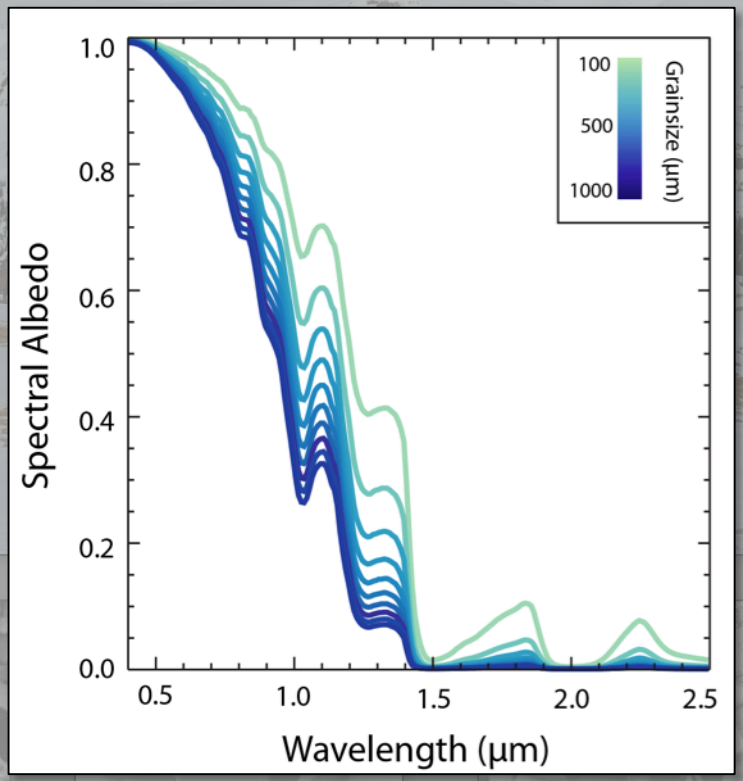
$$\frac{dU}{dt} + Q_m = (1-\alpha)S + L^* + Q_s + Q_v + Q_g$$



San Juan Mountains, 2005



Introduction: The Color of Snow



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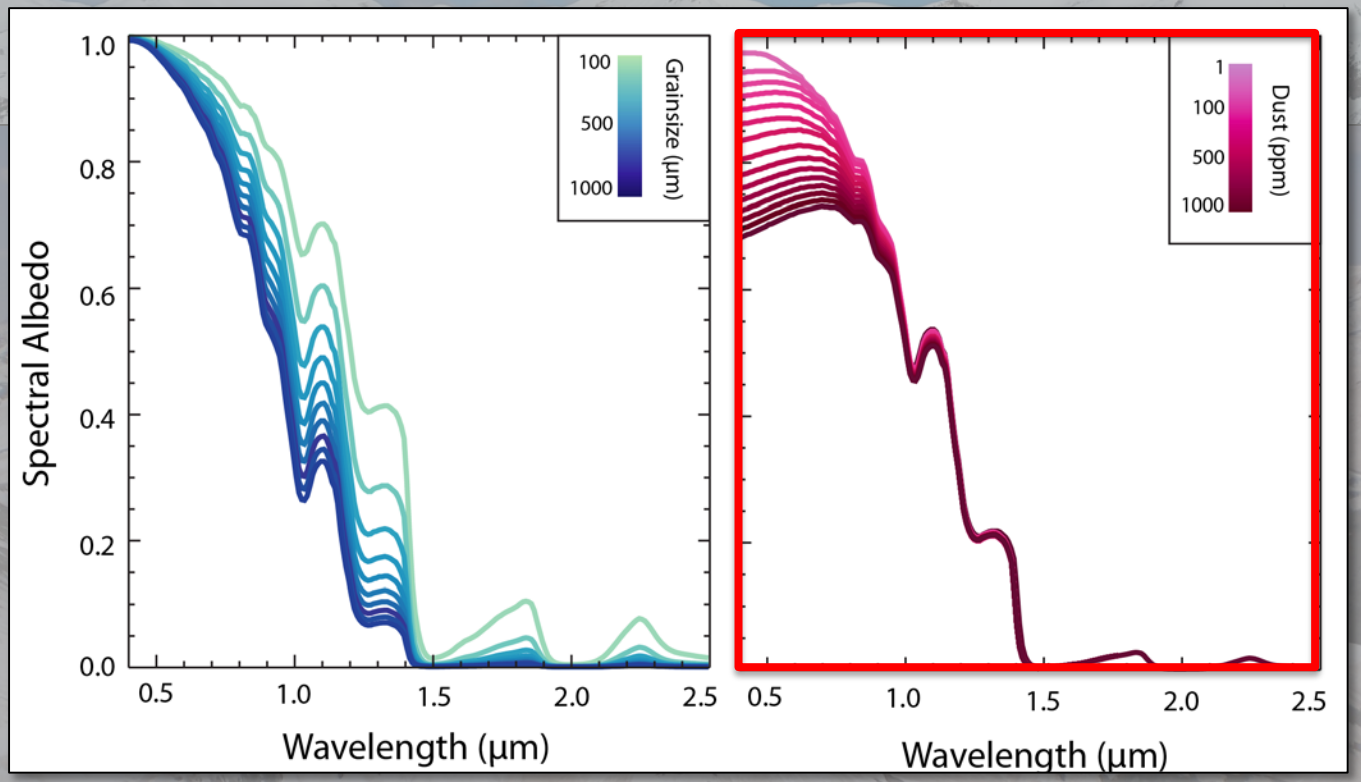

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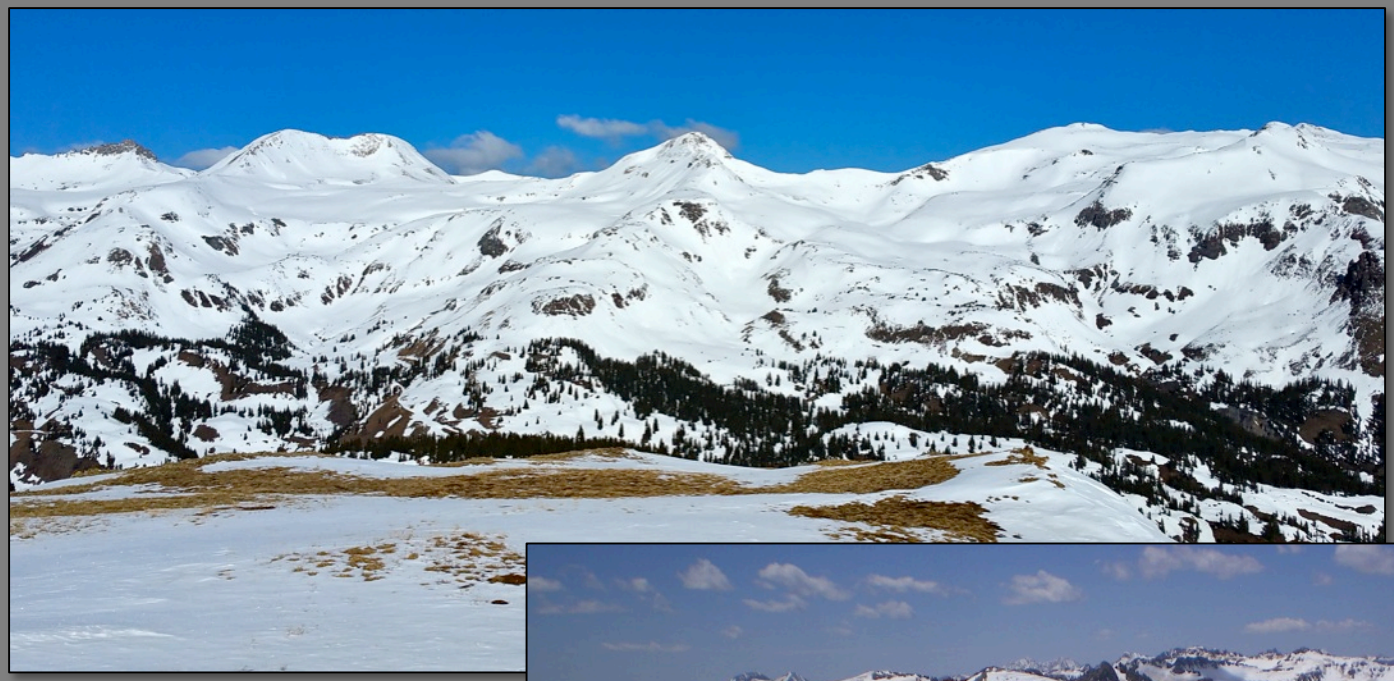


June, 2015

May, 2013

Introduction: Light Absorbing Impurities

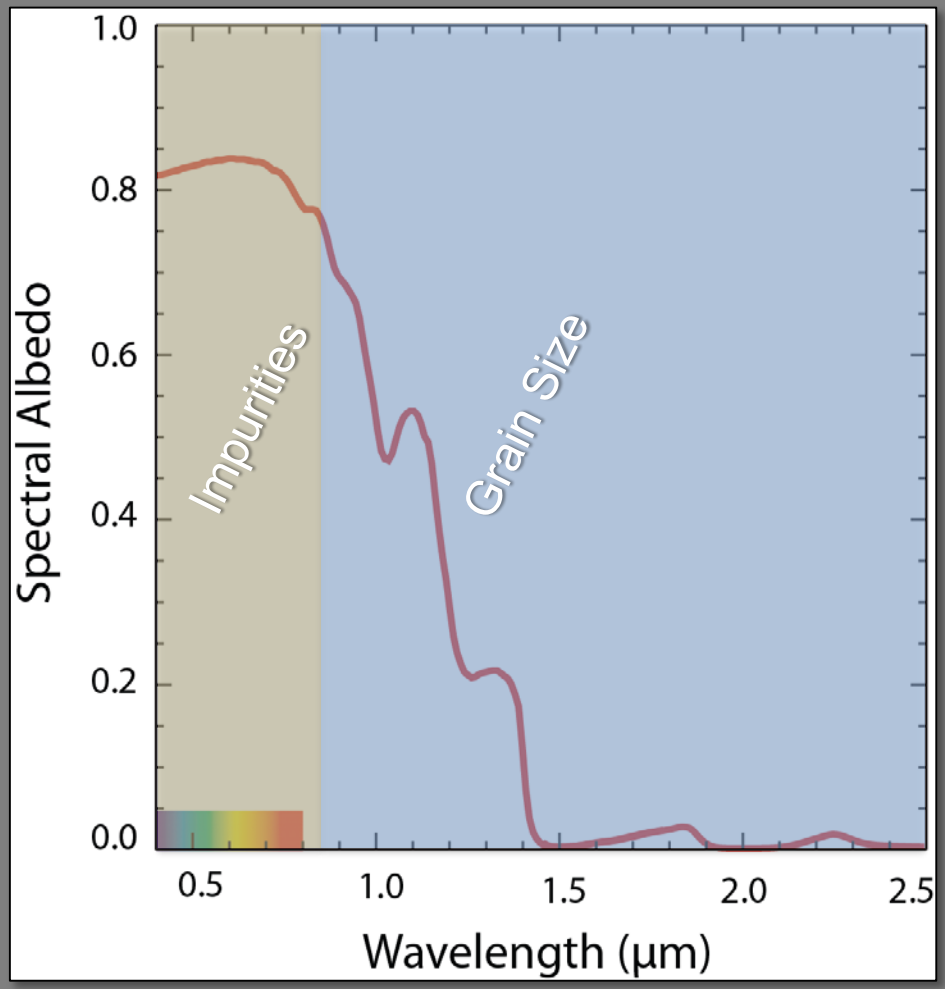
Black Carbon or ‘Soot’

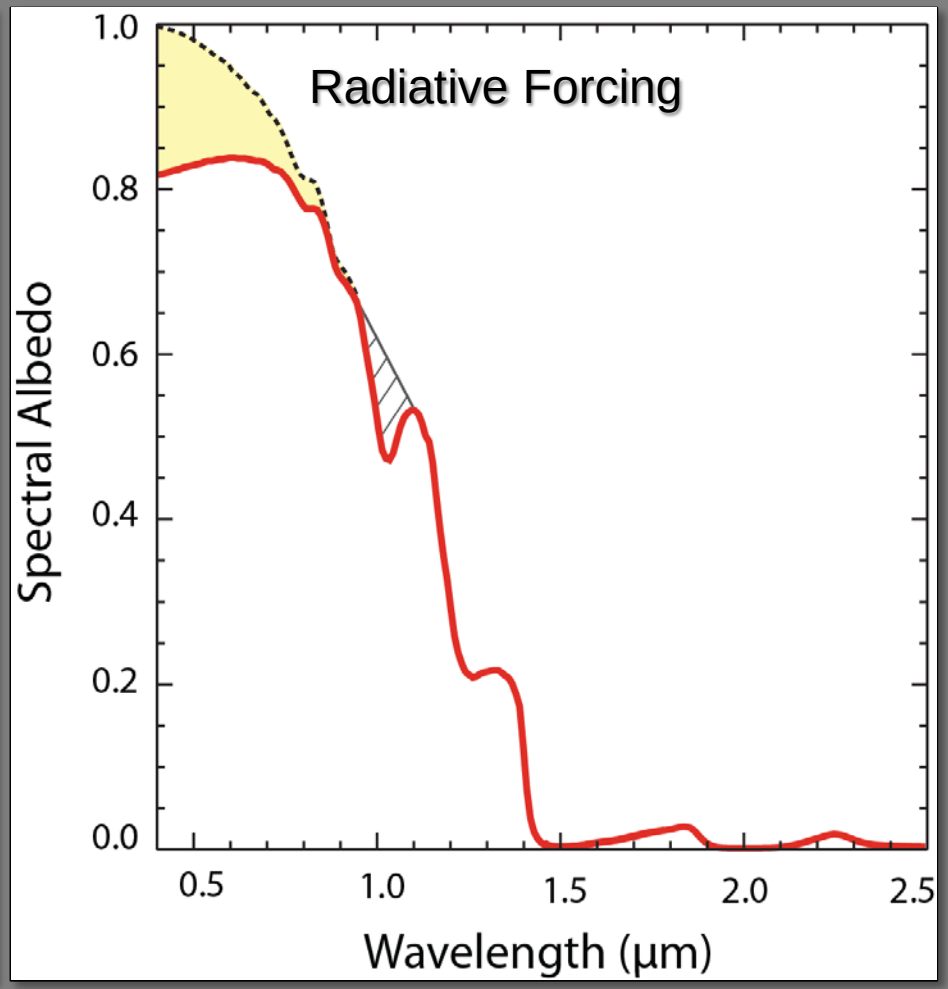
Mineral Dust

Biological Material

Introduction: How do we measure snow albedo?

Introduction: Retrieval of snow properties





Ground Measurements

San Juan Mountains and Grand Mesa, Upper Colorado River Basin, CO

Snow Dome/Blue Glacier, Mt. Olympus, WA

South Cascade Glacier, Cascade Mountains, WA

Mera Peak, Himalaya, Nepal

Saddle, accumulation zone, Greenland

Dust, Snow, and the Colorado River Basin

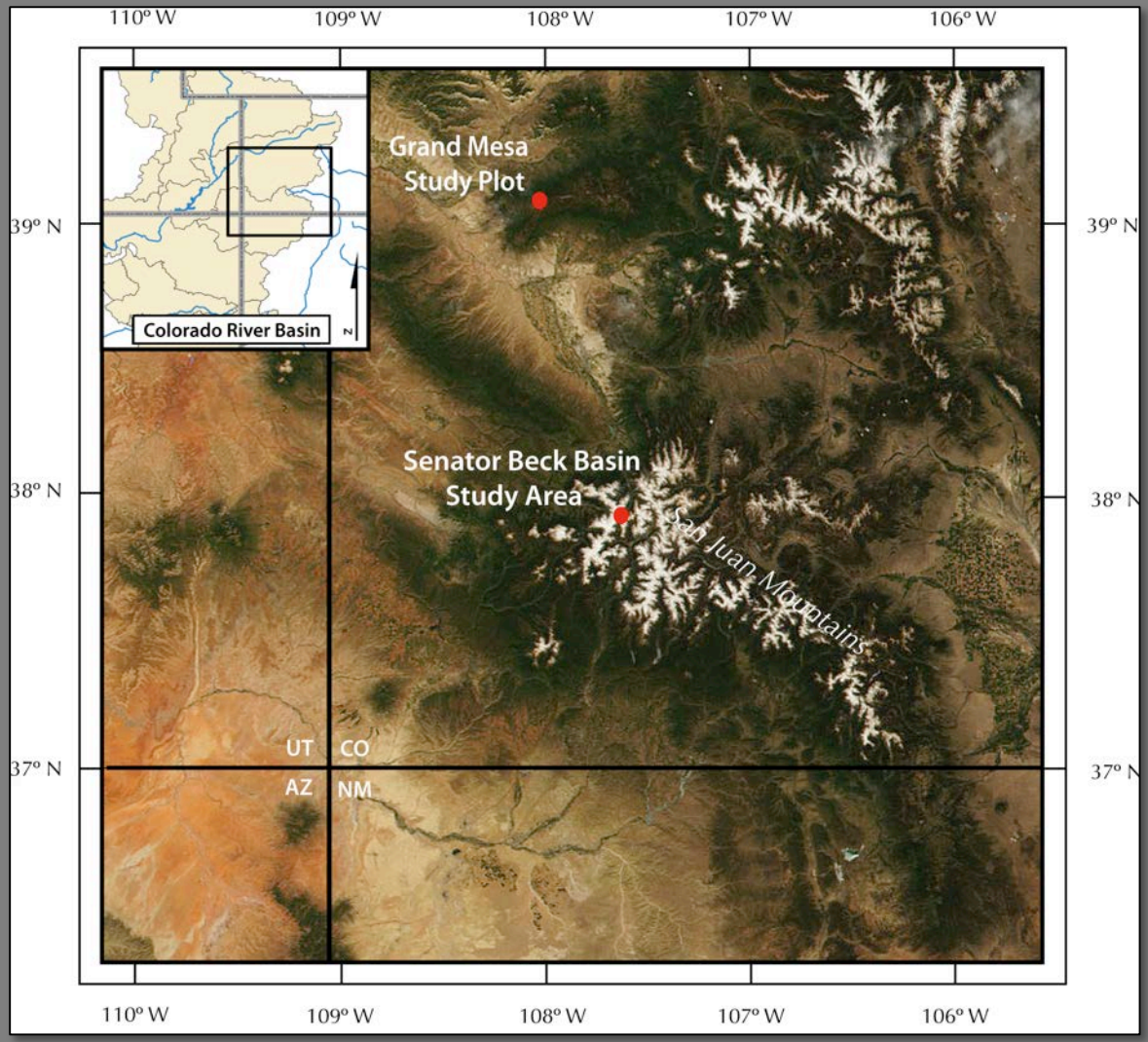
The Rockies are the headwaters of the Colorado River, which is >70% snow melt fed, a critical water system that provides water to 7 western US states and Mexico

In remote sensing imagery dust plumes are visible from the four corners region/little Colorado River corridor

San Juan Mountains/Southern Rocky Mountains are the first high-altitude area of contact for predominantly southwesterly winds

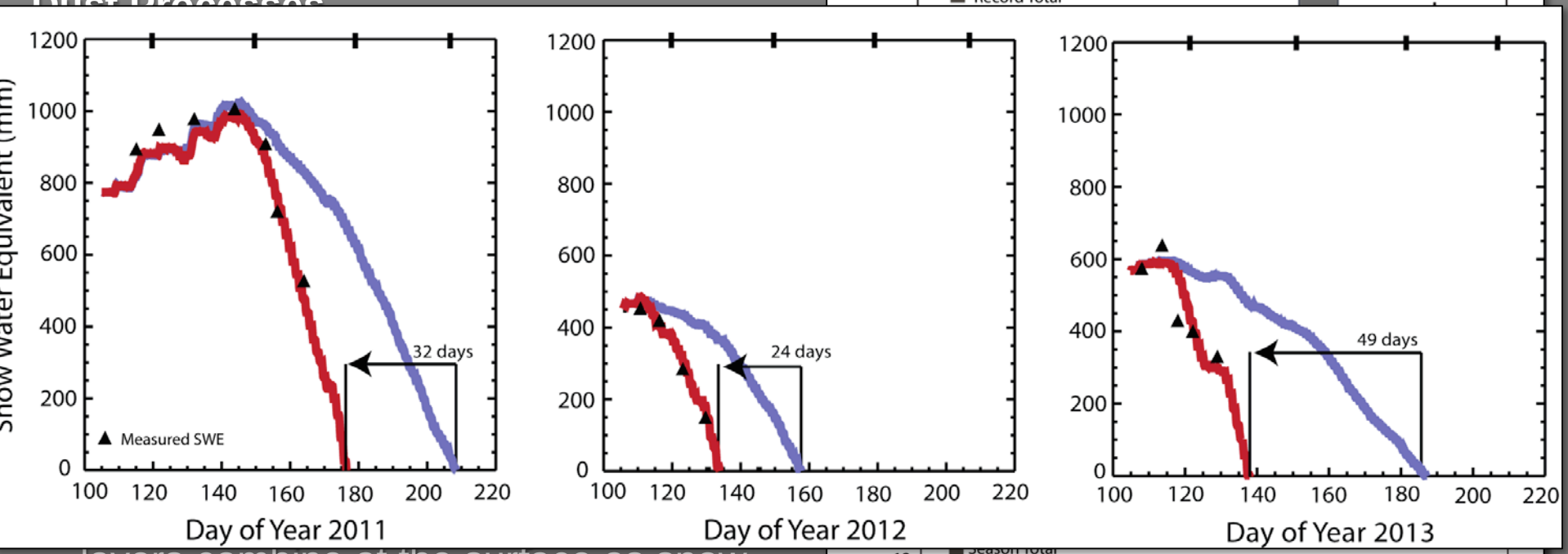
Skiles et al., 2015

Dust, Snow, and the Colorado River Basin



- 2003: Senator Beck Basin Study Area was established to study the hydrologic impacts of dust on snow (DOS)
- 2005: Instrumentation is installed and consistent snow observations begin
- 2010: Grand Mesa Study Plot established

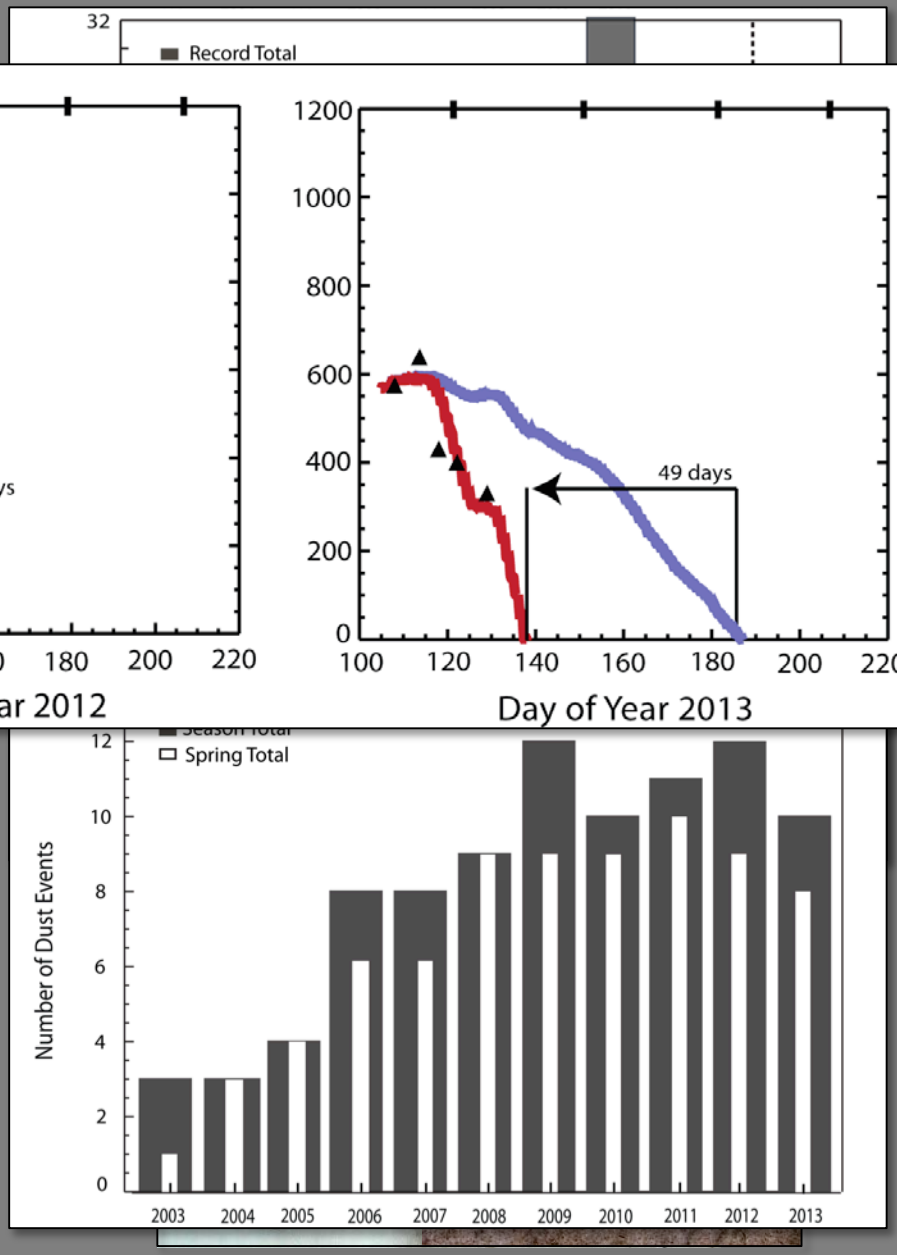
A decade of studying dust on snow in the Colorado River Basin



layers combine at the surface as snow depletes

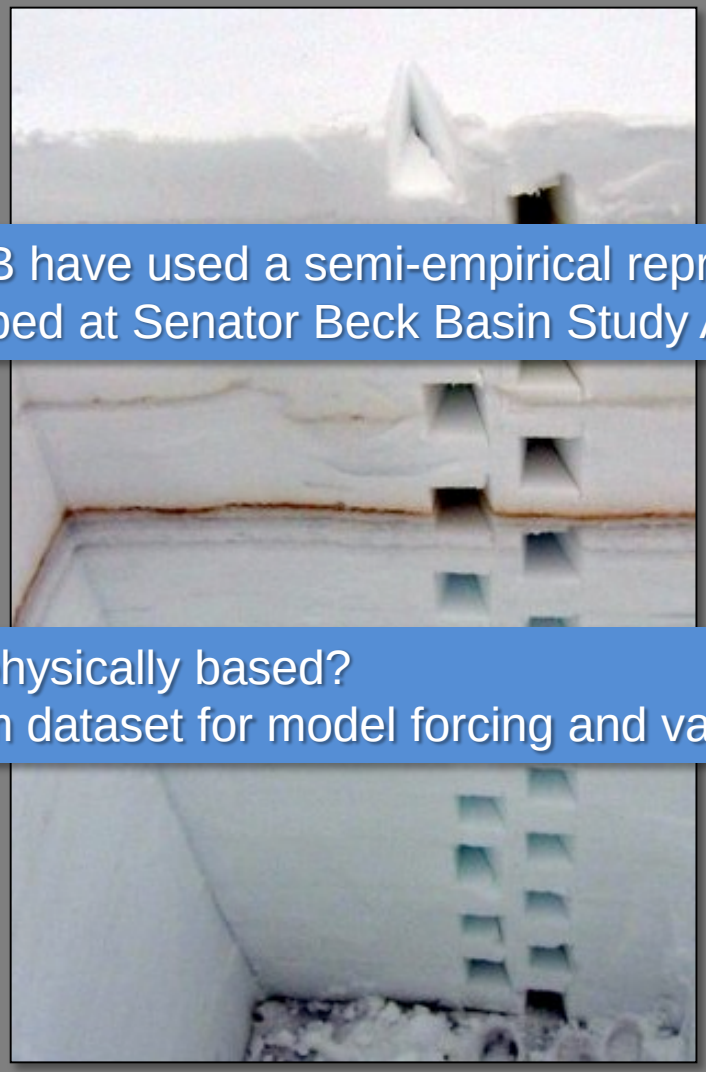
Dust Impacts

- Advances snow melt timing by 1-2 months
- Shifts runoff timing and intensity
- Lowers total water yield
- Correlates with runoff forecasting errors



(Neff et al., 2008; Painter et al., 2012; Skiles et al., 2012)

A decade of studying dust on snow in the Colorado River Basin



All studies of dust on snow in the CRB have used a semi-empirical representation of dust radiative forcing developed at Senator Beck Basin Study Area

Why not physically based?
Missing a high resolution long term dataset for model forcing and validation

Physically based modeling: Filling the observation data gap

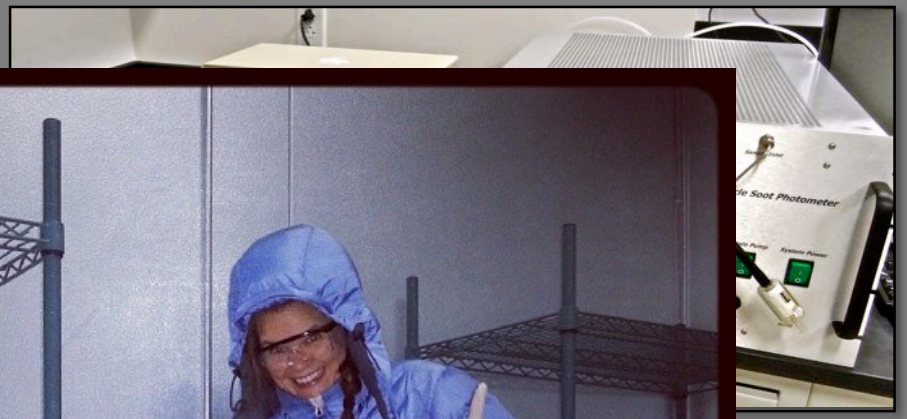
Sparseness of snow impurity measurements and uncertainty in snow effective (optical) radius variability suggest that ***more ground measurements need to be made*** *-Flanner et al*, 2007

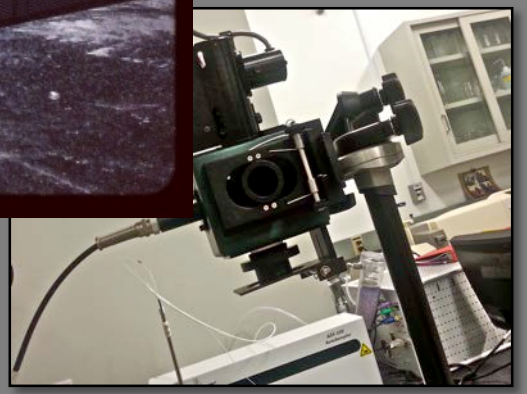
Spring 2013 Dataset

- Daily snow sampling and observations of snow optical and physical properties across 70 days spanning peak snow depth to snow depletion
- 10 snow samples every day from across the top 30 cm of snowpack

(Skiles, 2014)

Snow Sample Analysis

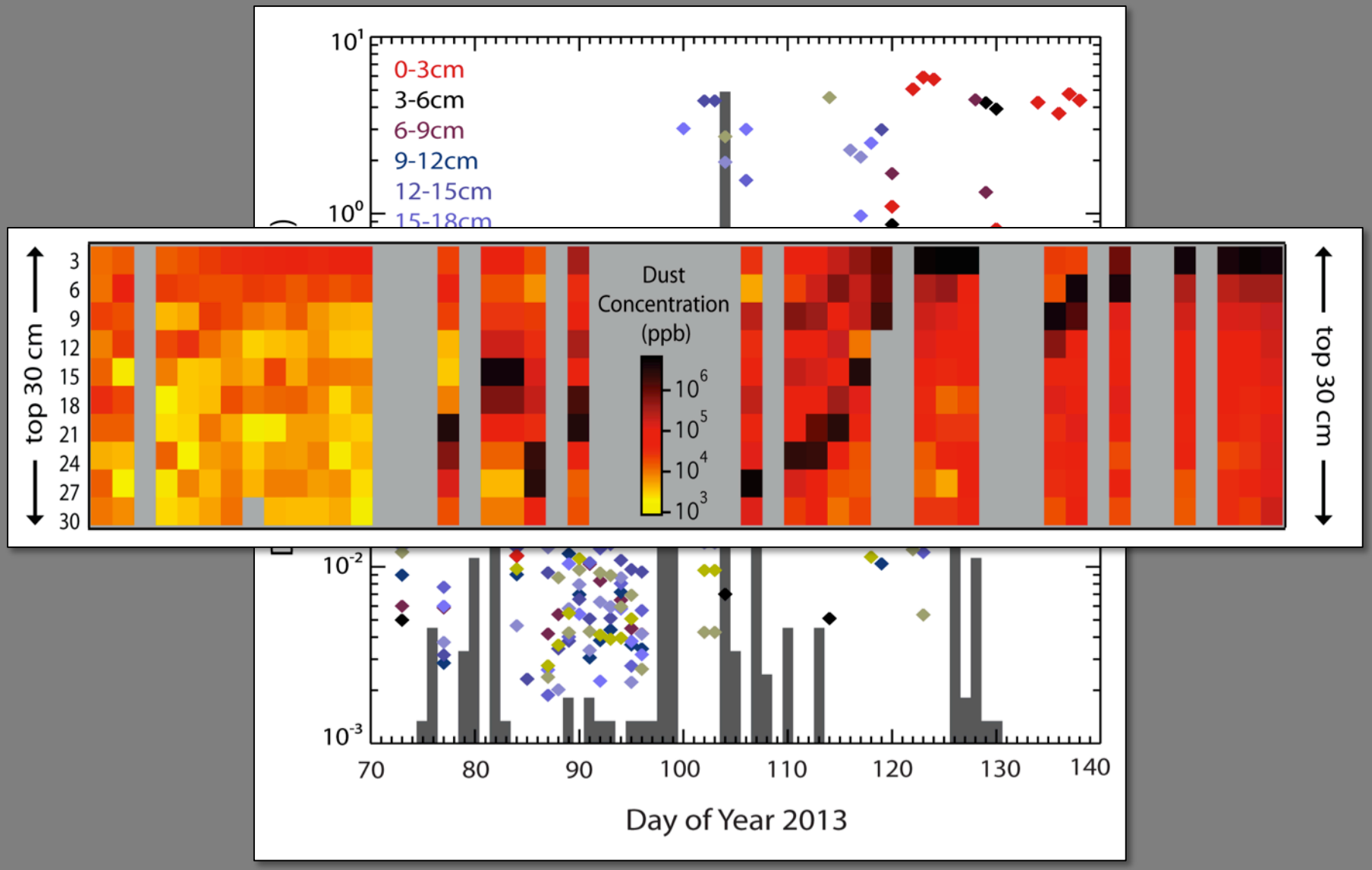




Measurements: Evolution of snow albedo

Measurements: Evolution of grain size

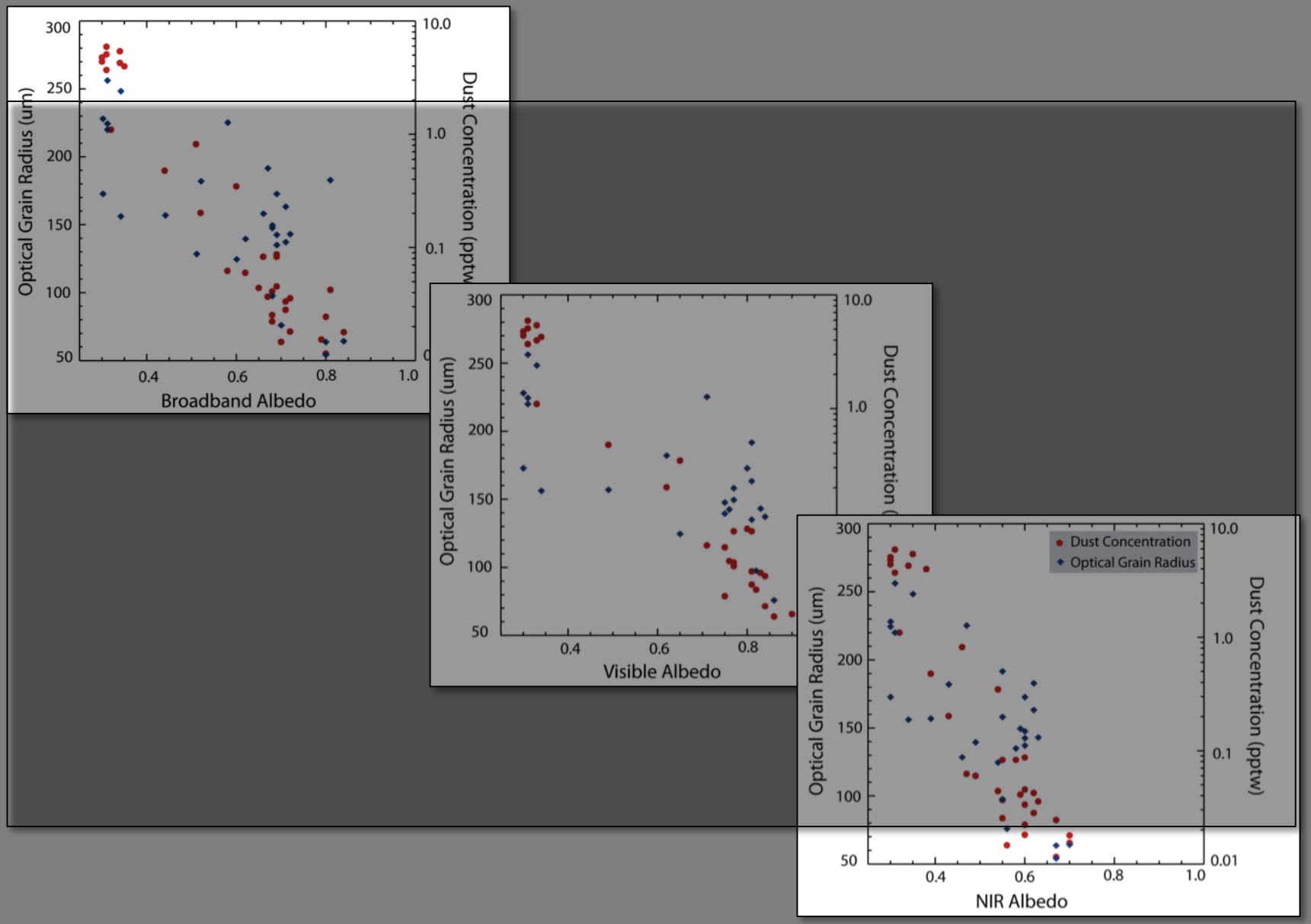
Measurements: Evolution of impurity content



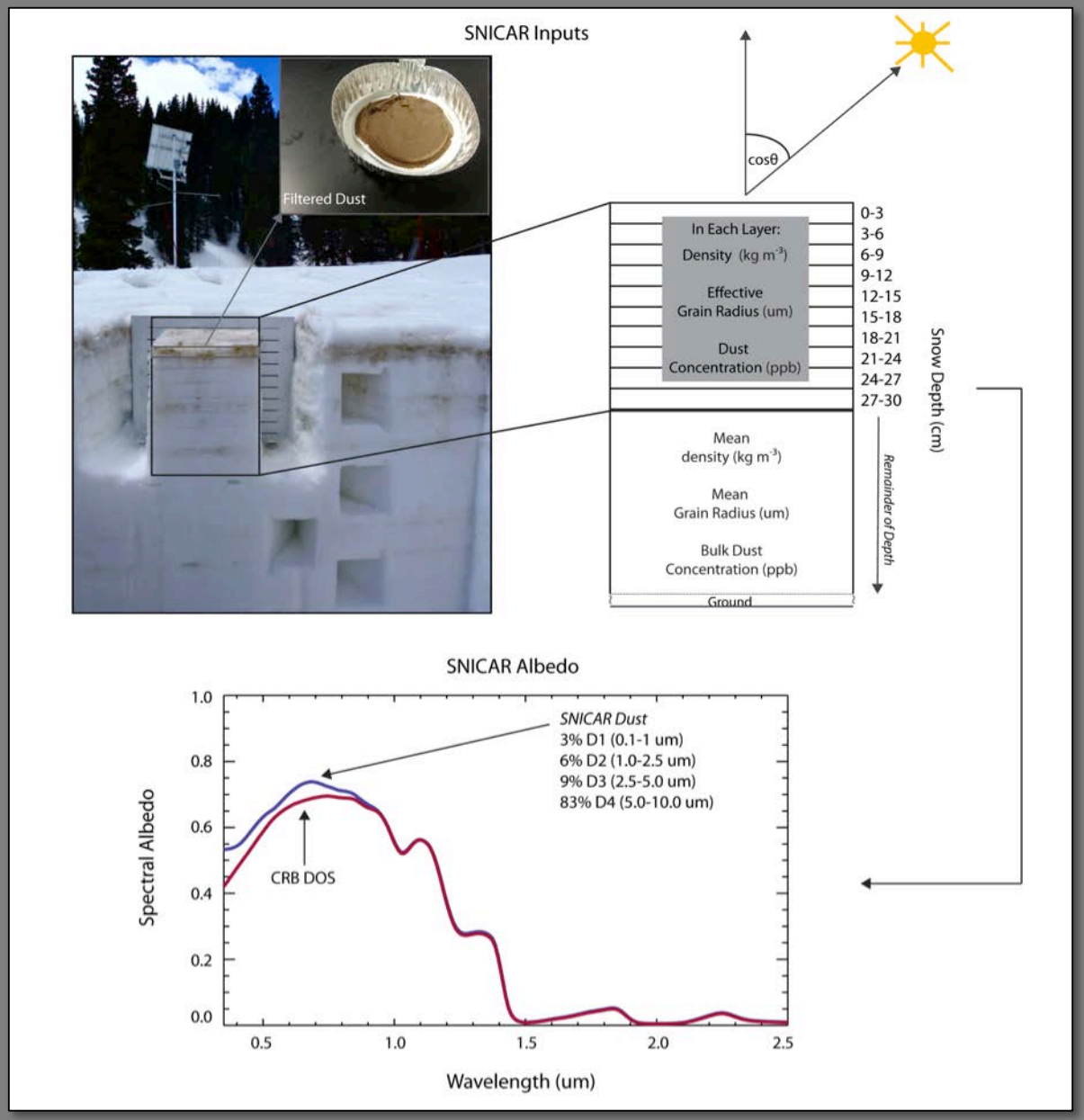
Measurements: Evolution of impurity content

Dust
BC

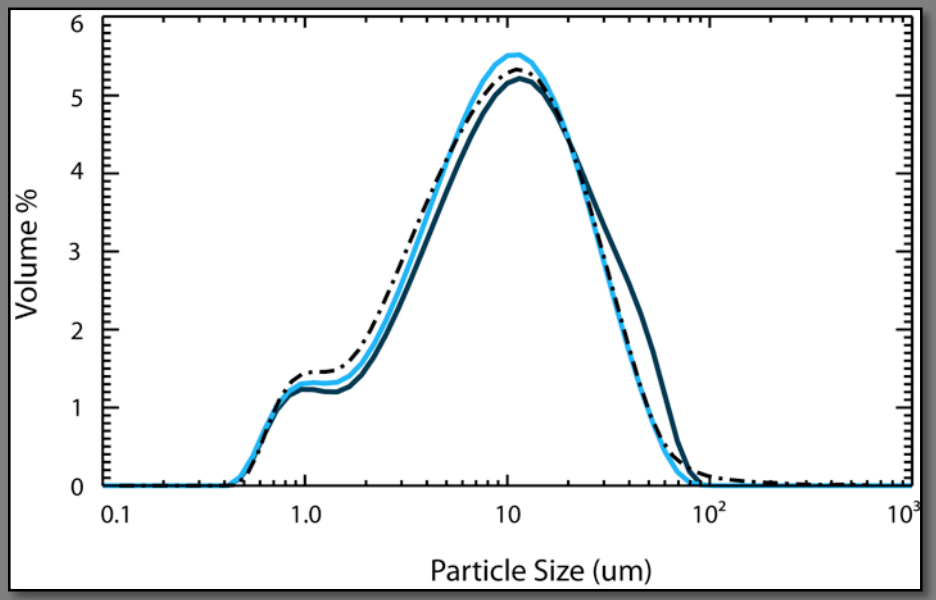
Relationship between grain size, impurities, and albedo

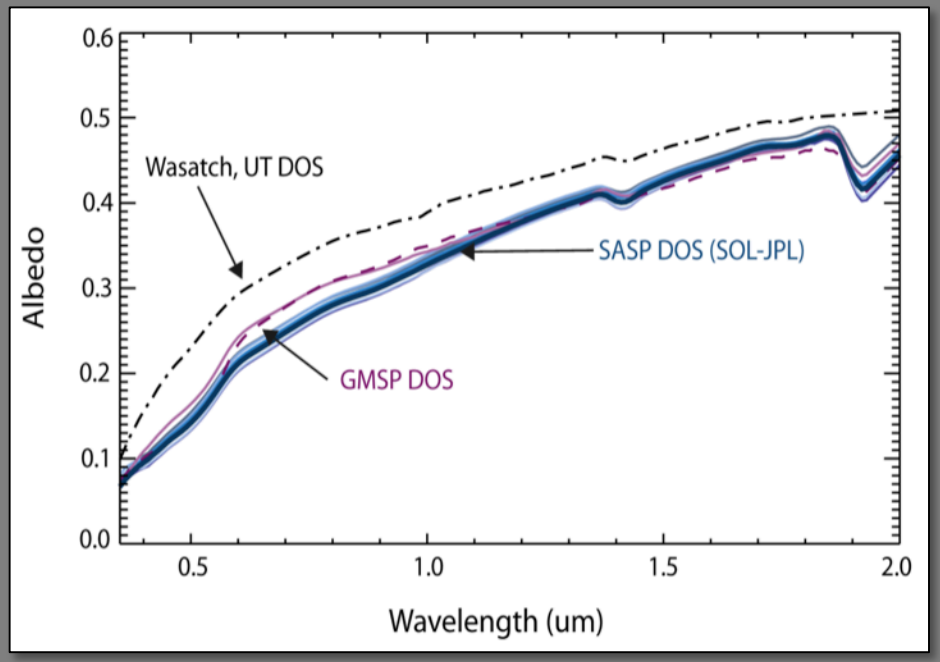


Radiative Transfer Modeling

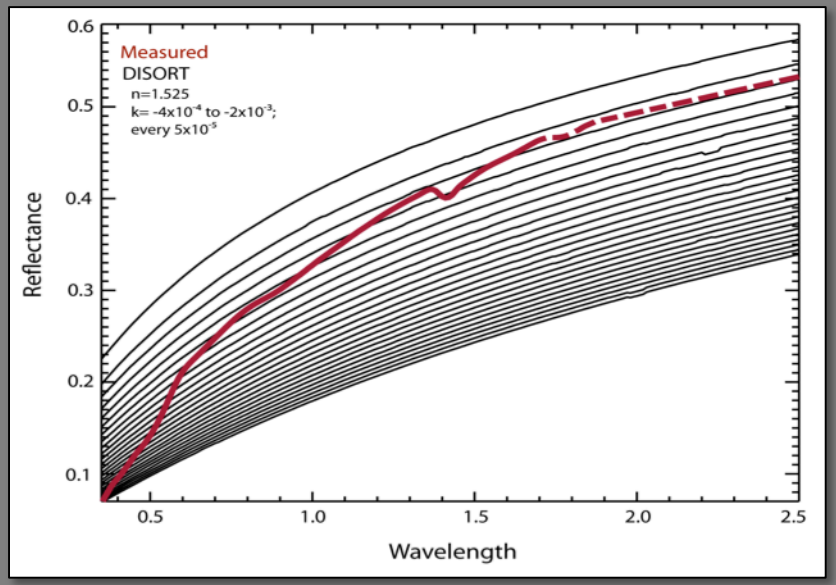


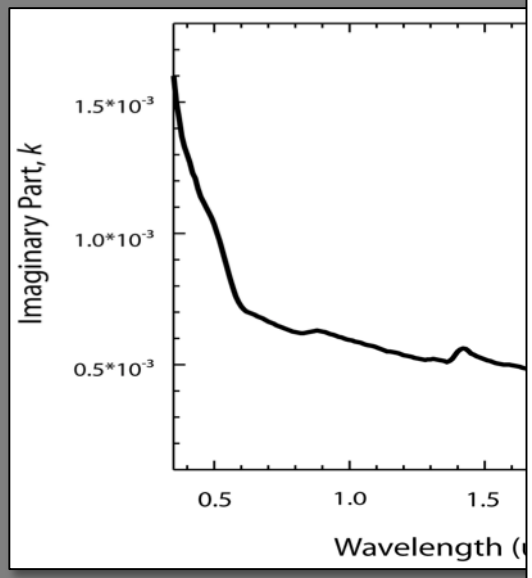
Optical/physical properties of deposited dust



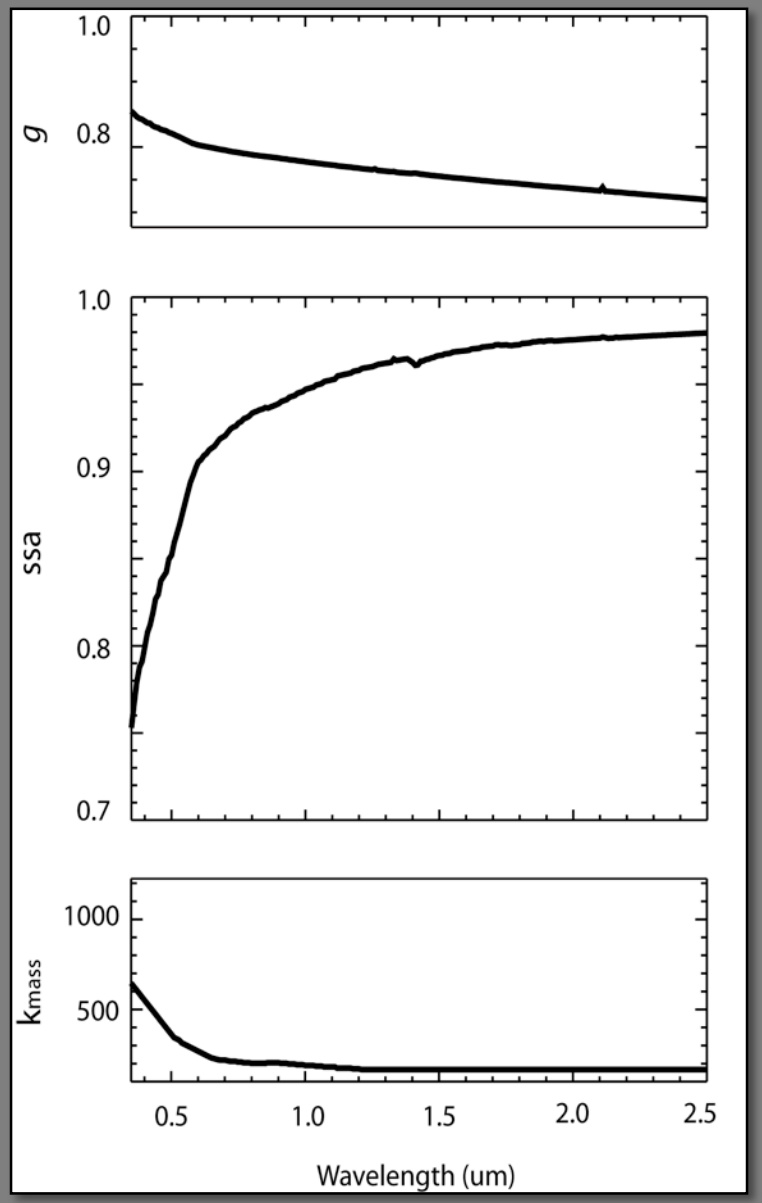


Inverting for the complex refractive index of deposited dust

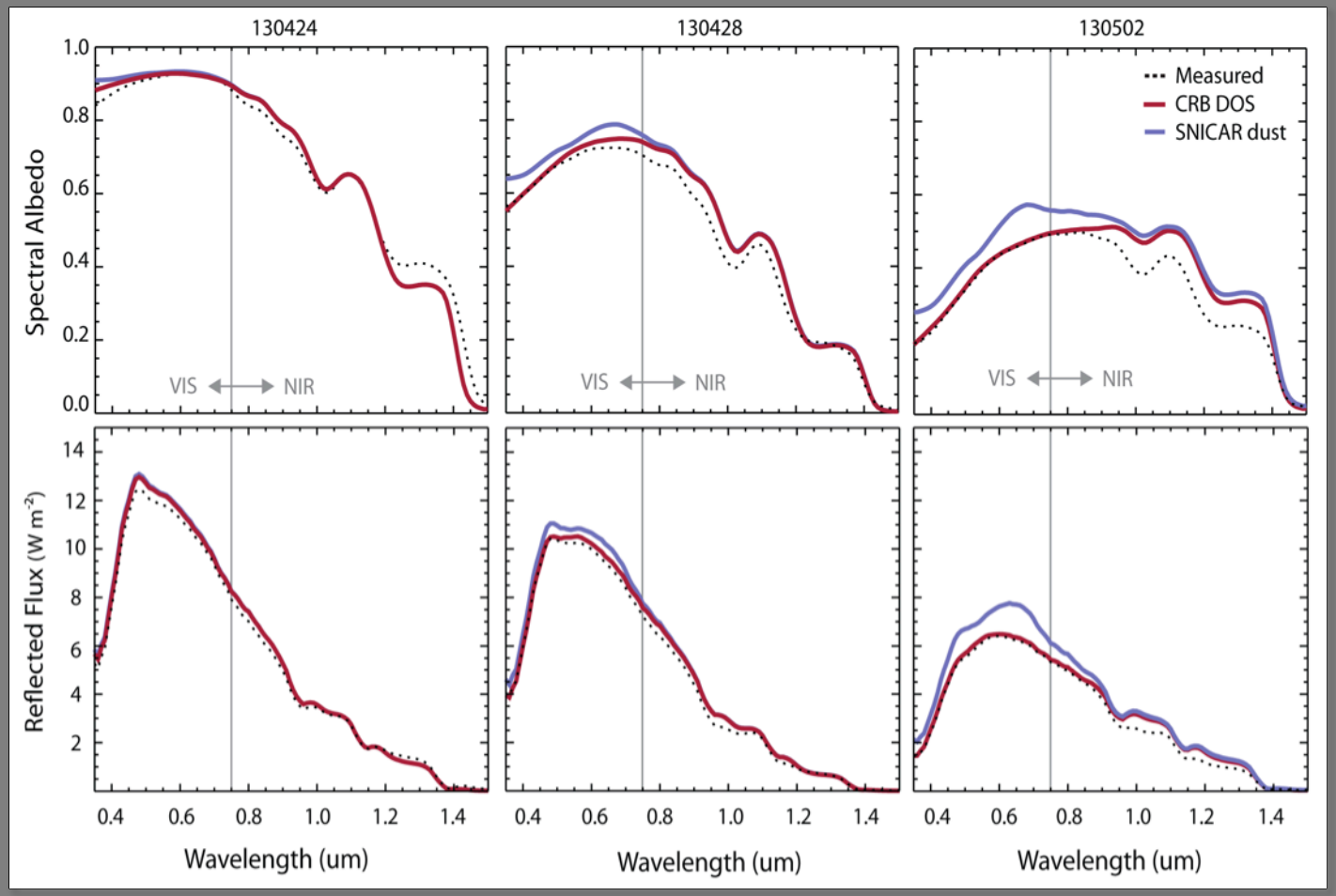




Wavelength	Complex Refractive Index
0.35	1.525-0.0018*i*
0.40	1.525-0.0016*i*
0.45	1.525-0.0013*i*
0.50	1.525-0.0011*i*
0.55	1.525-0.0009*i*
0.60	1.525-0.0008*i*
0.65	1.525-0.0007*i*
0.70	1.525-0.00067*i*
0.75	1.525-0.00064*i*
0.80	1.525-0.00062*i*
0.90	1.525-0.00063*i*
1.00	1.525-0.00059*i*
1.10	1.525-0.00057*i*
1.20	1.525-0.00054*i*
1.30	1.525-0.00052*i*
1.40	1.525-0.00055*i*
1.50	1.525-0.00052*i*
1.60	1.525-0.0005*i*
1.70	1.525-0.00048*i*

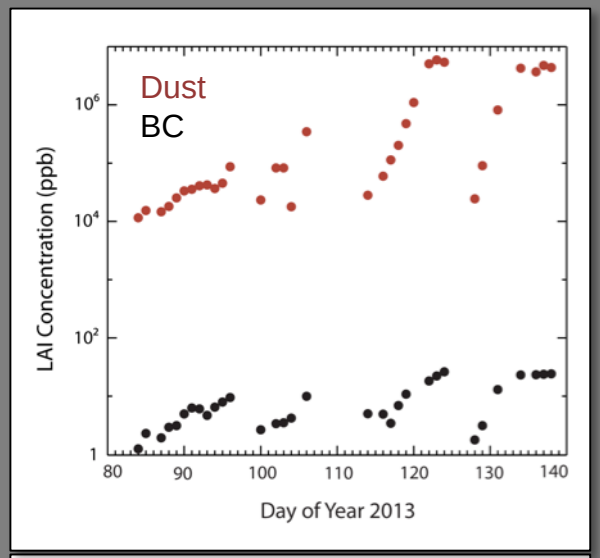


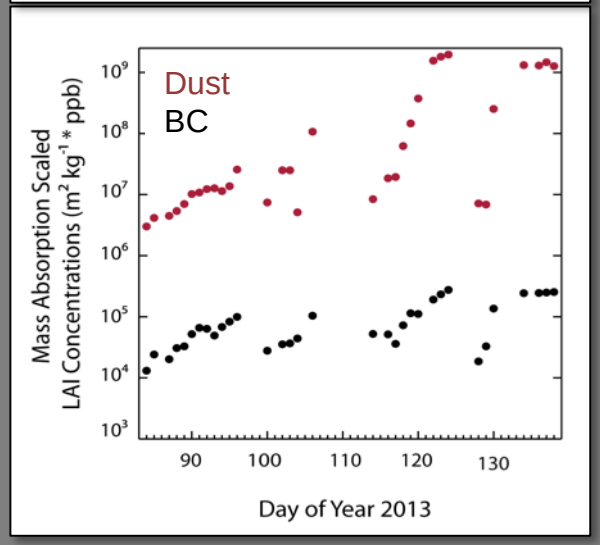
Updating dust in snow optical properties

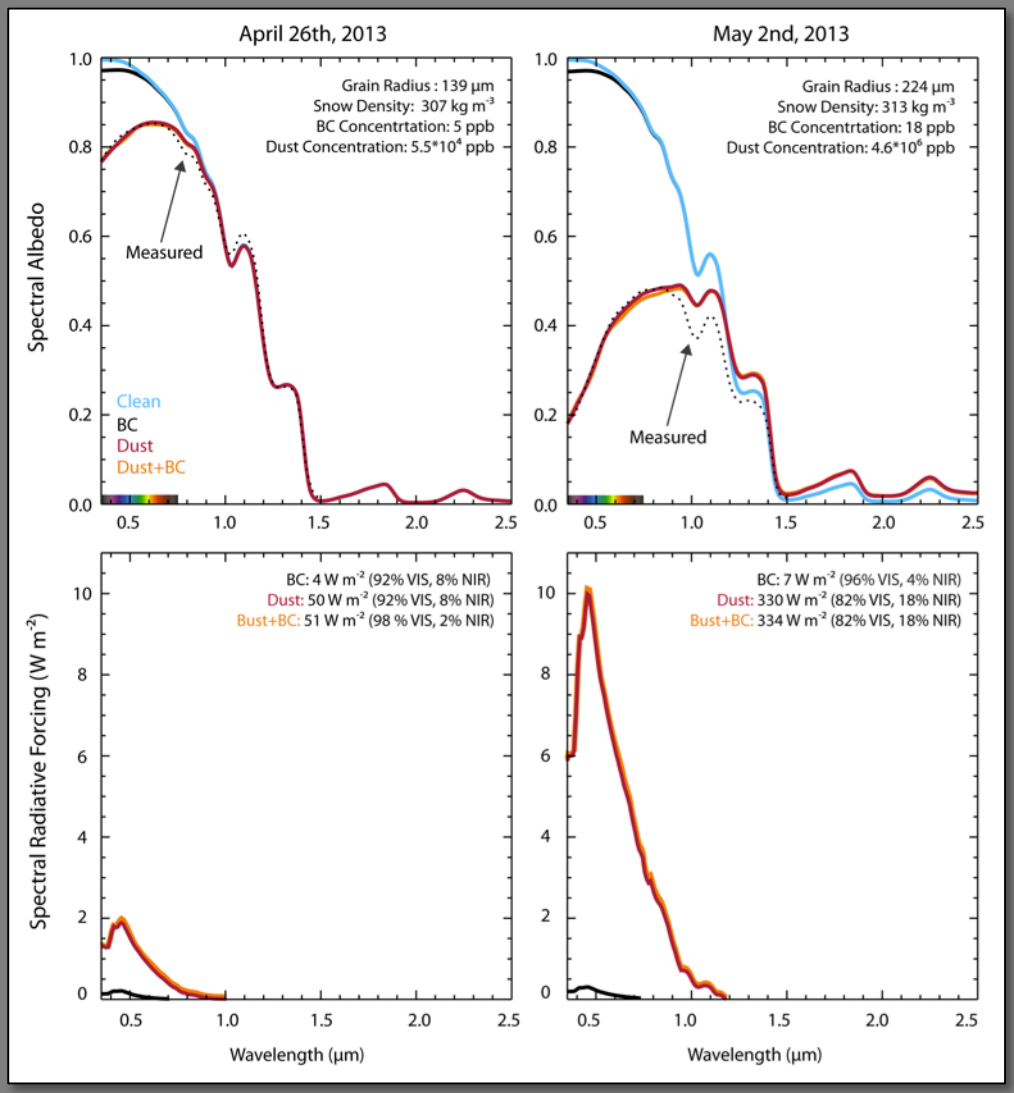


Using regionally specific dust optical properties improves modeling of net solar radiation by 70% in the visible wavelengths and 50% across the full range of snow reflectance

Partitioning the impacts from dust and black carbon

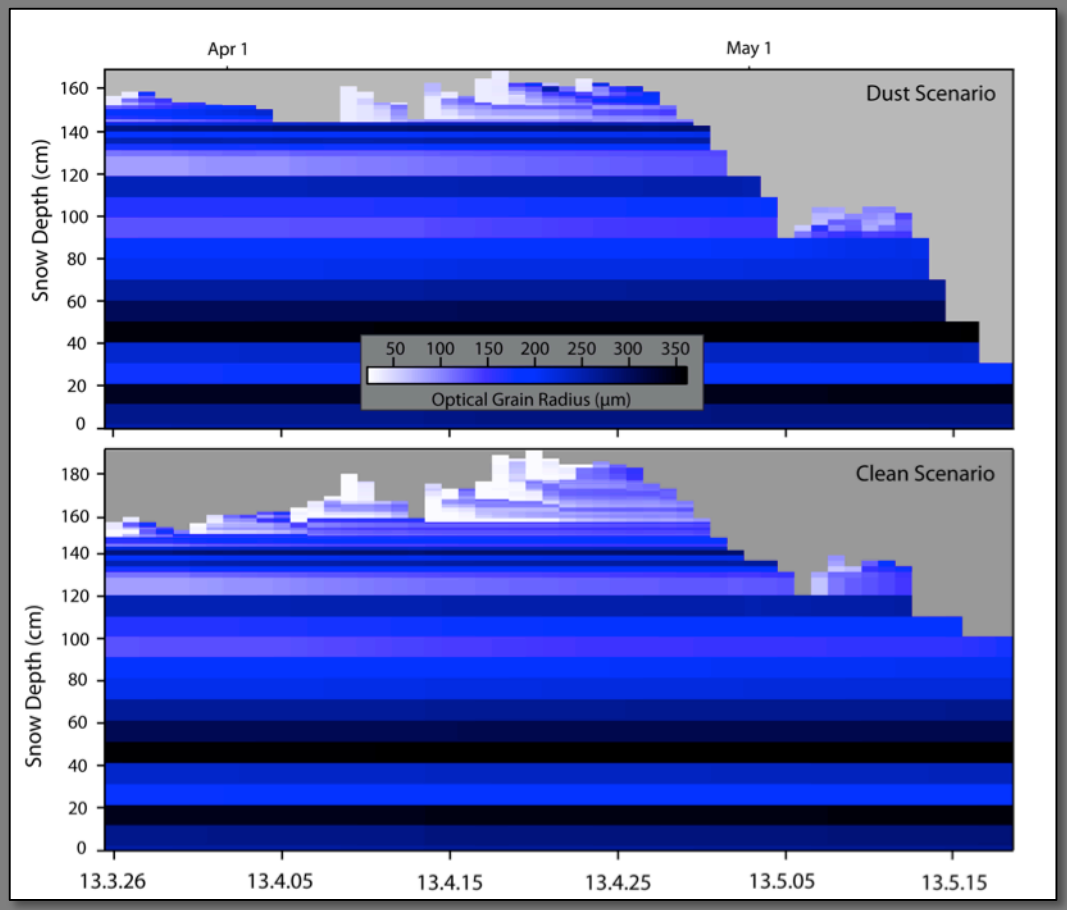


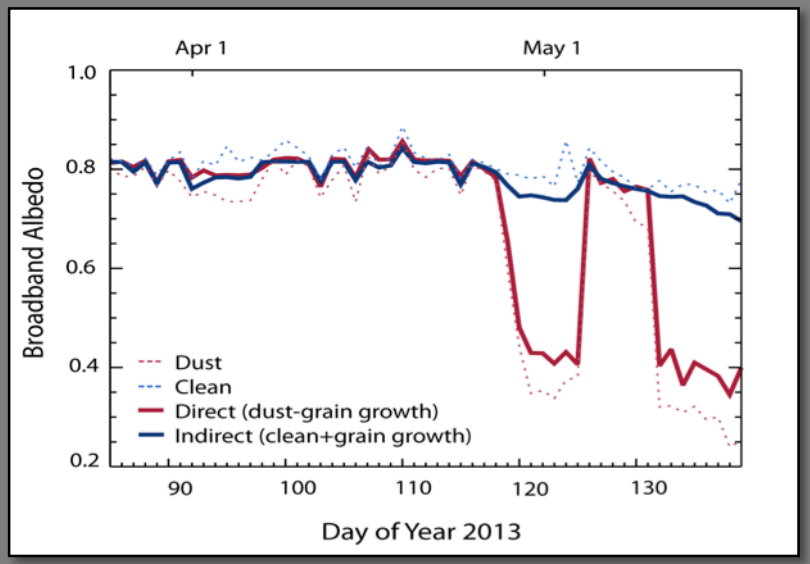


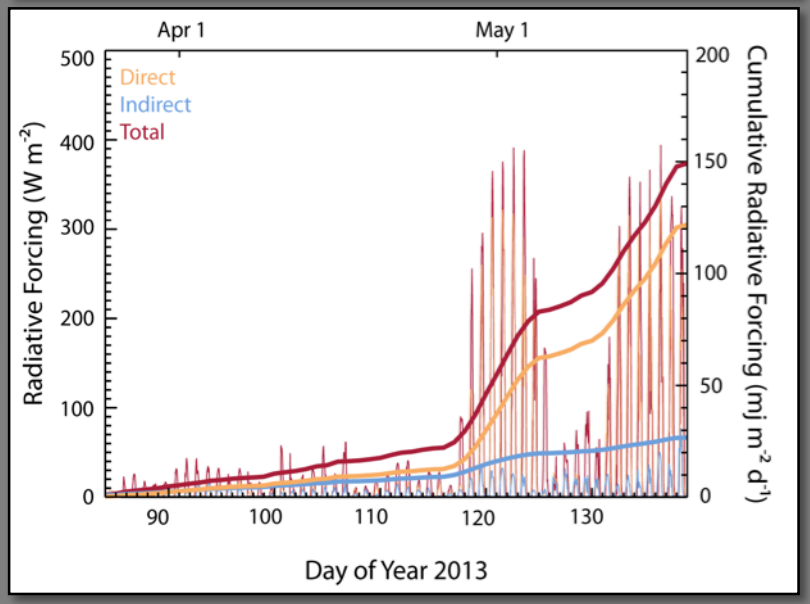


In this region, dust strongly dominates mass and absorption, accounting for <97% of radiative forcing

Partitioning the impacts from impurities and grain growth







Absorption by impurities is 80% of radiative forcing,
impurity enhanced grain growth is 20%

Ground Measurements

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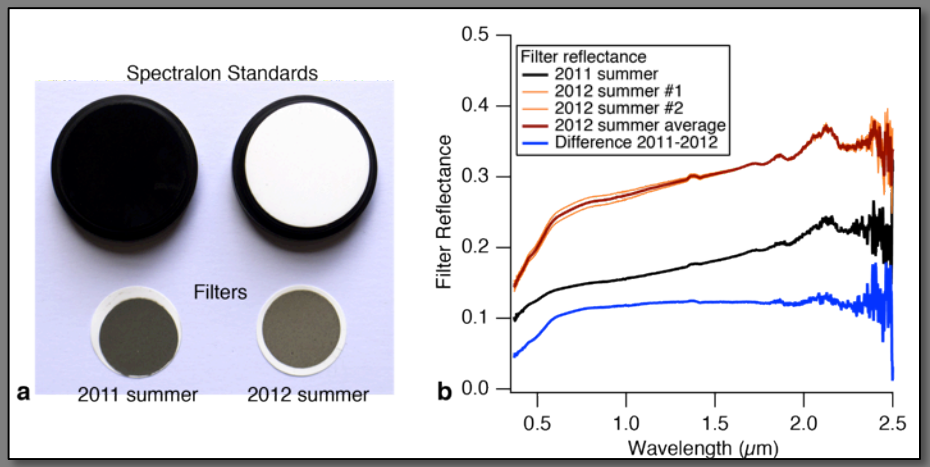
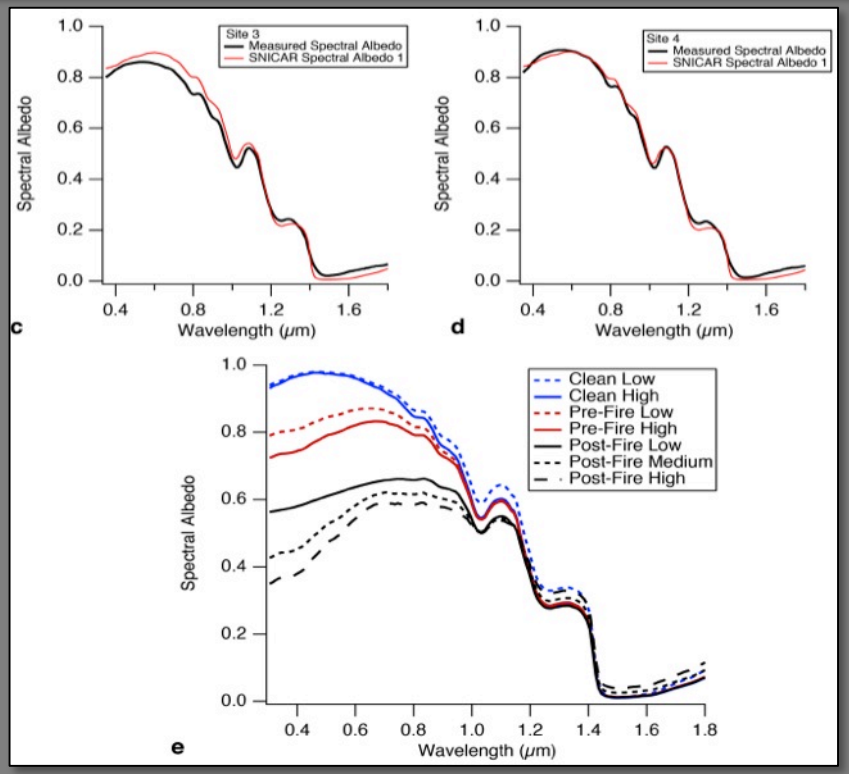
South Cascade Glacier, Cascade Mountains, WA

Mera Peak, Himalaya, Nepal

Saddle, accumulation zone, Greenland

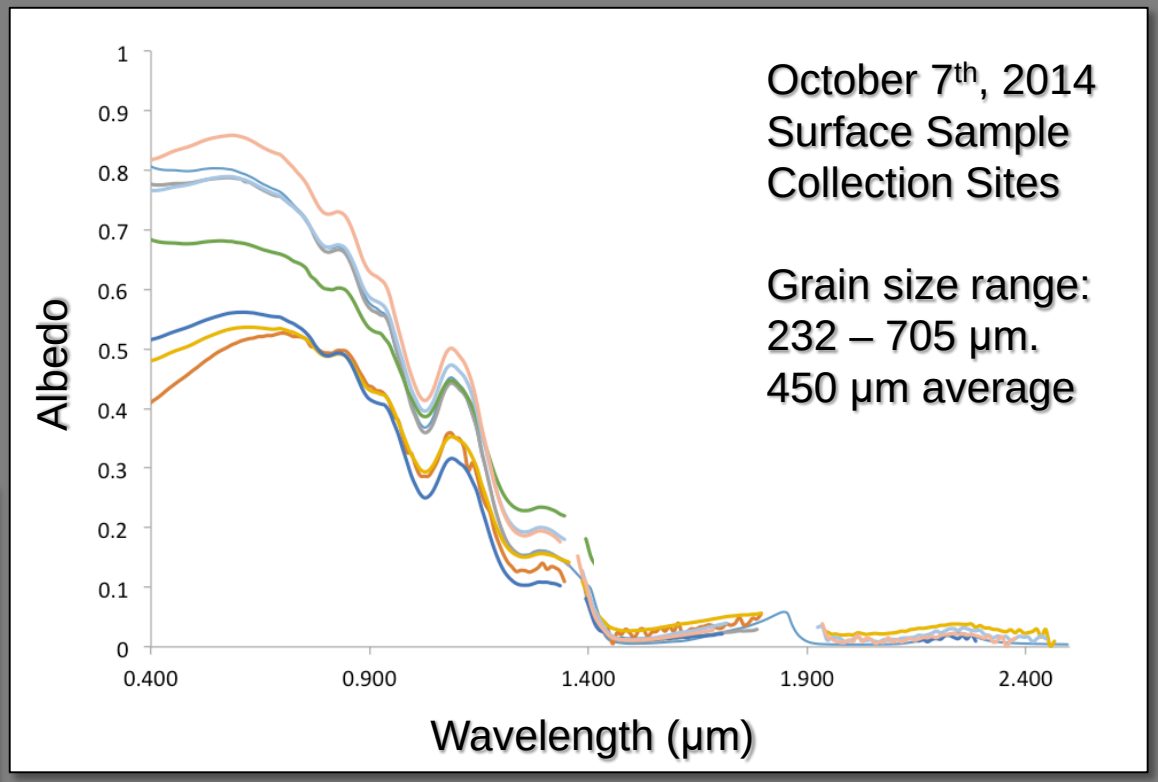
Snow Dome, Mt. Olympus, WA





Kaspari, Skiles, et al., 2015

South Cascade Glacier, WA



Kaspari, Skiles, et al., in prep

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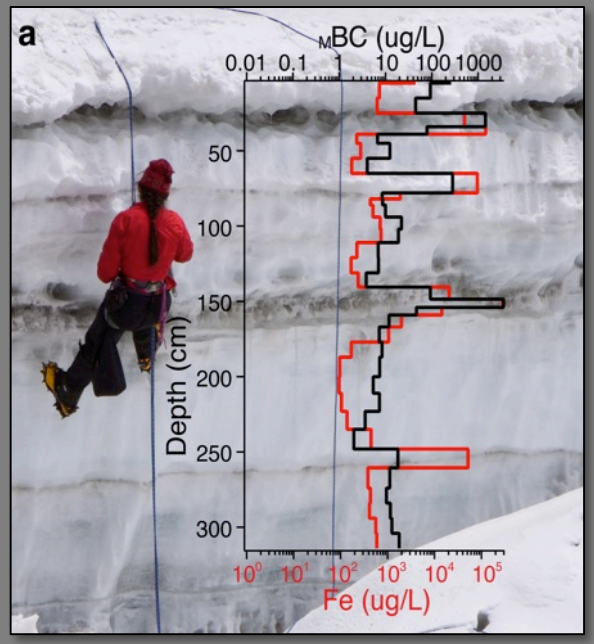

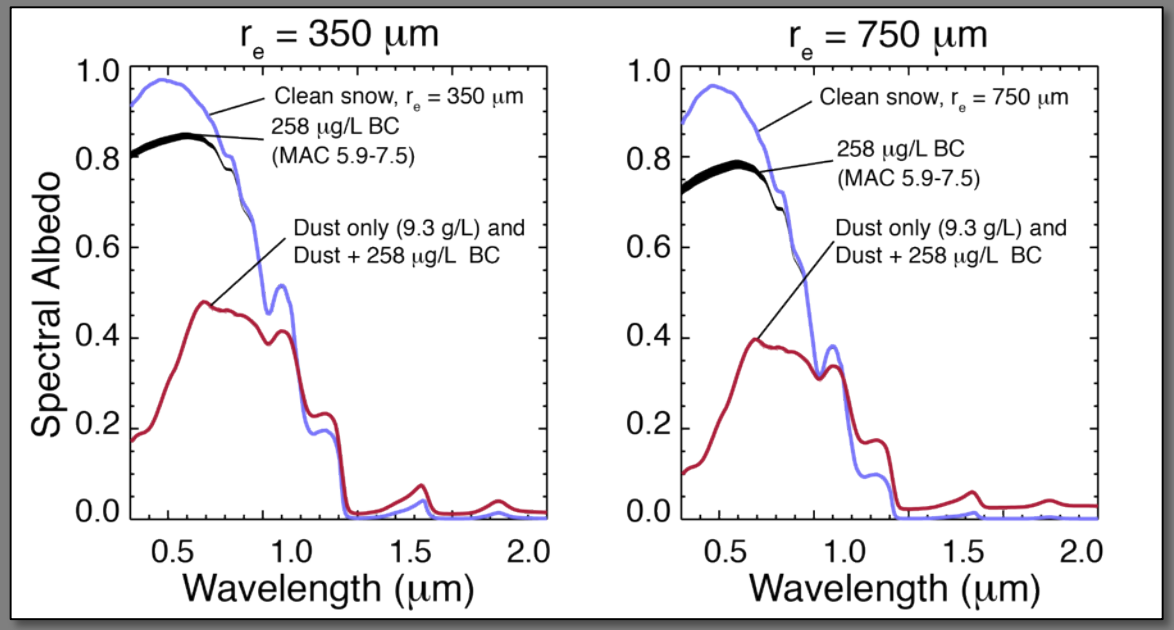

BC has long been the focus of impurity in snow research in the Himalaya

At Mera (south slope) radiative transfer modeling, constrained by the observational data, indicate that the albedo and radiative forcing of dust is considerably greater than BC

Kaspari et al., 2014

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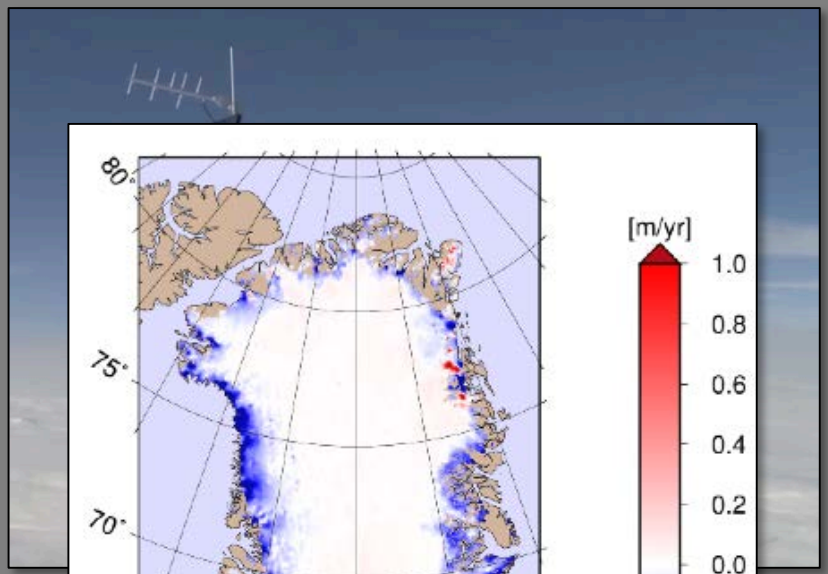
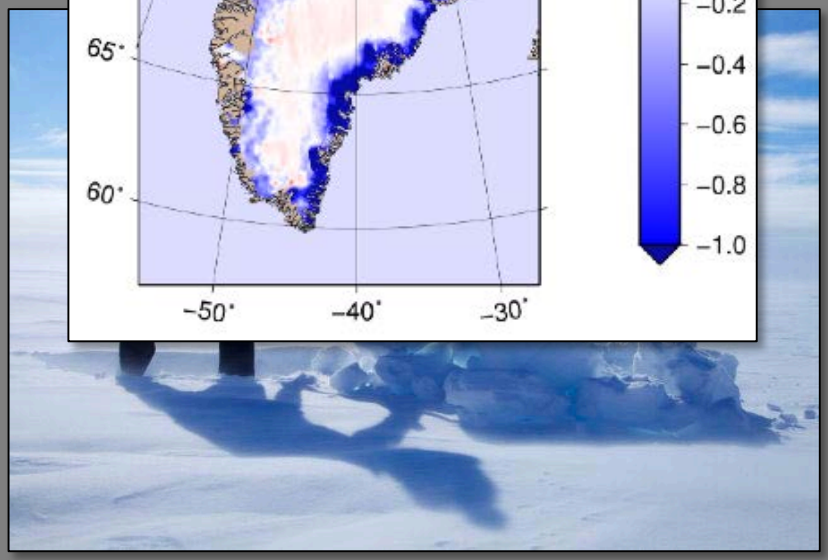
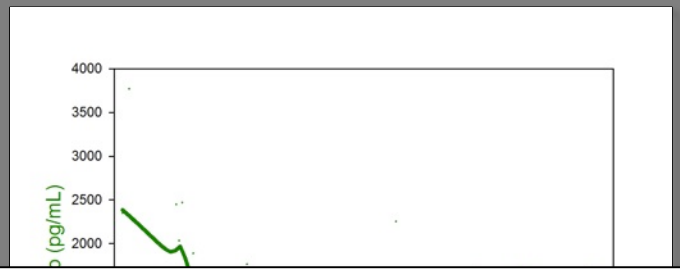
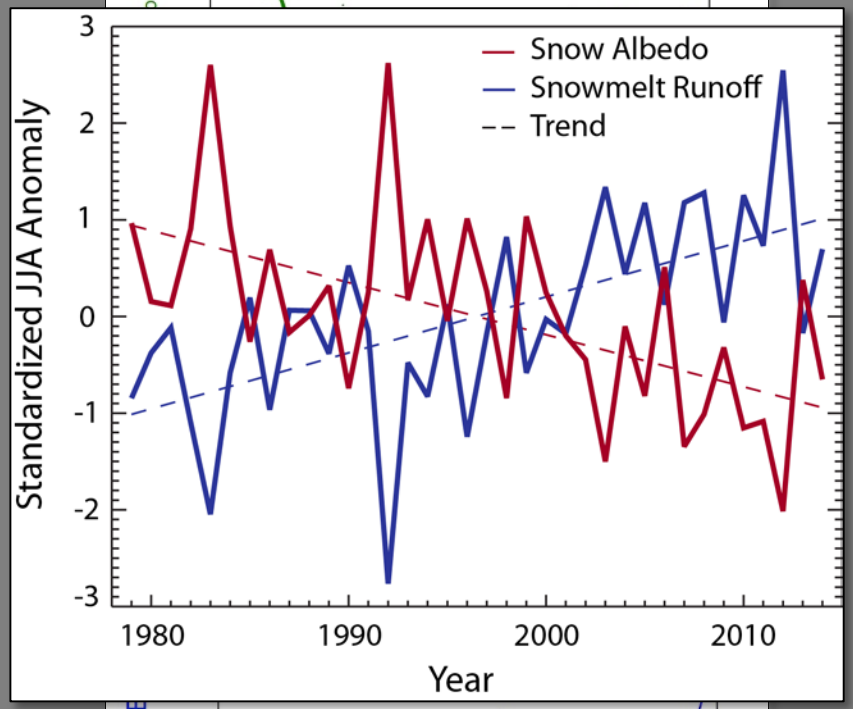
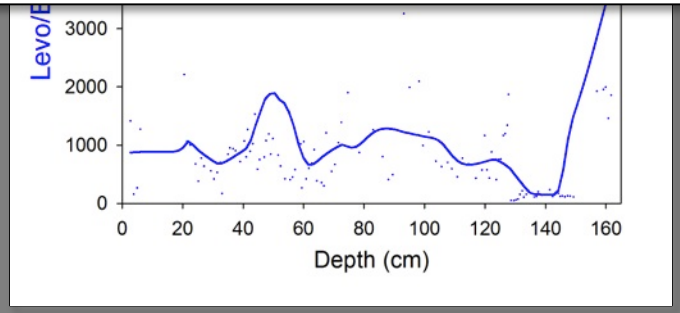










Skiles, et al., in prep

Ground Measurements: Summary and Concluding Thoughts

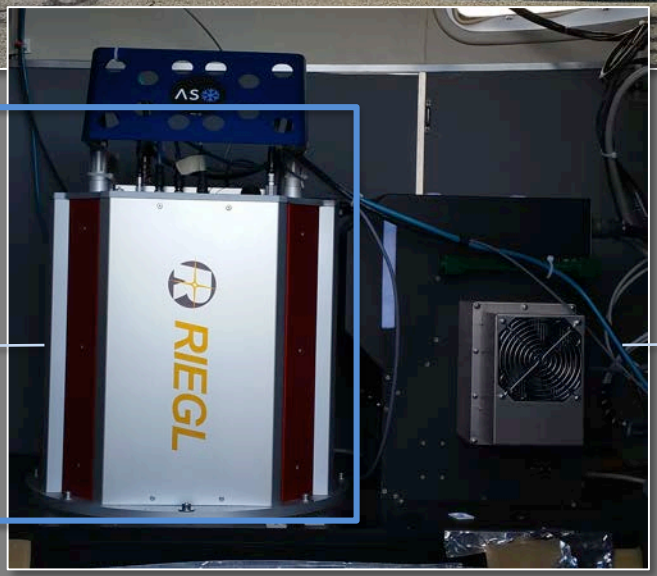
- Snow melt is driven by net solar radiation, itself controlled mainly by snow albedo
- Impurities in snow lower snow albedo in the visible wavelengths, directly increasing solar absorption
- Impurities enhance snow grain growth, lowering snow albedo in the near infrared wavelengths, and increasing absorption across the full range of snow reflectance
- This impact exhibits high variability in both space and time, and episodic events (dust emission, forest fires) can have a large impact
- Ground measurements alone are not sufficient to characterize these impacts on the scale of the global cryosphere

Airborne Measurements

Tuolumne River Basin, Sierra Nevada, CA

Upper Uncompahgre Watershed, Upper Colorado River Basin, CO

NASA Airborne Snow Observatory



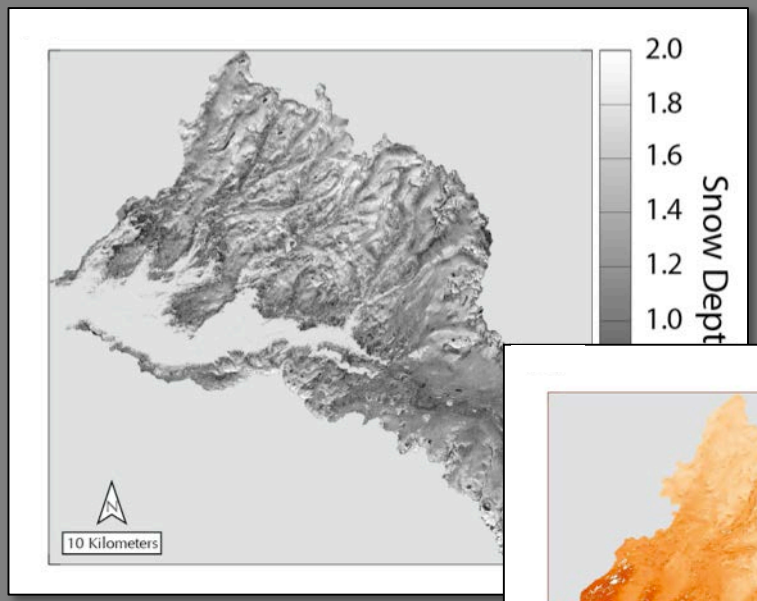
Snow Depth

- Riegl Q1560 dual laser scanning lidar
- 1064 nm
- Full-waveform
- 60° field of view

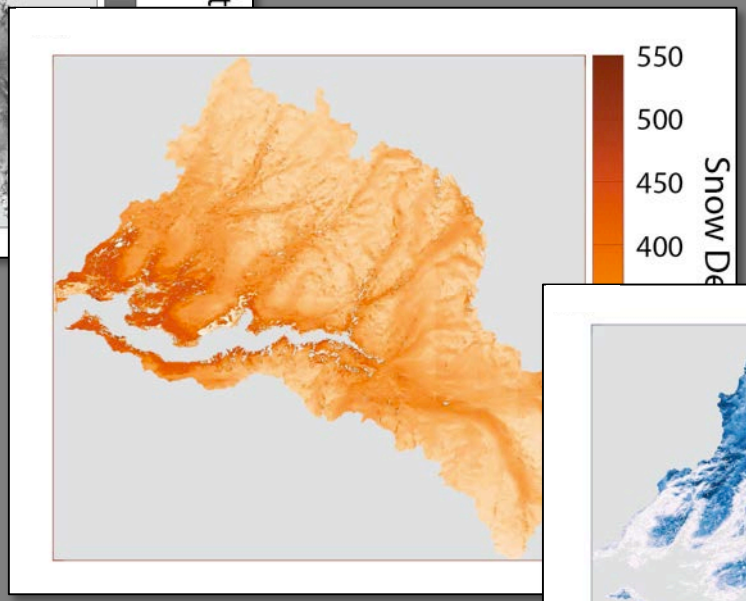
Snow Albedo

- CASI-1500 Imaging Spectrometer
- 72 bands between 0.35 and 1.05 µm
- 40° field of view

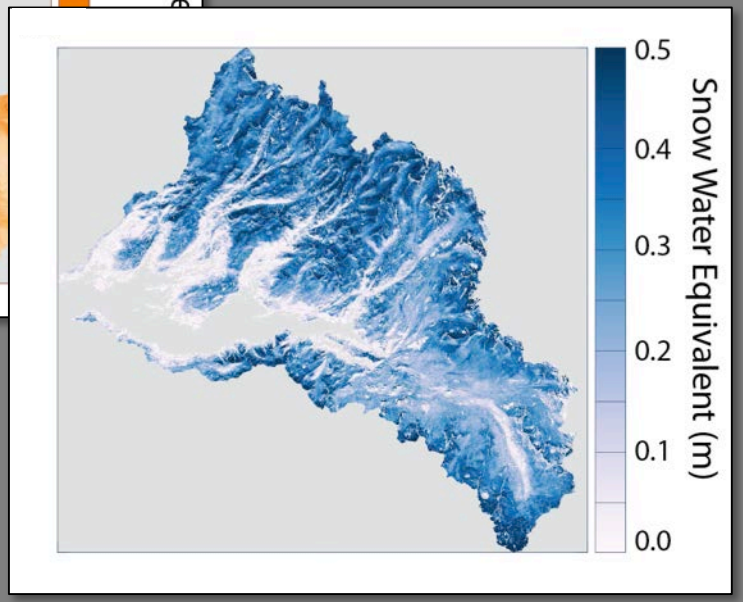
ASO Core Lidar Products



Snow Depth
- ASO Measured

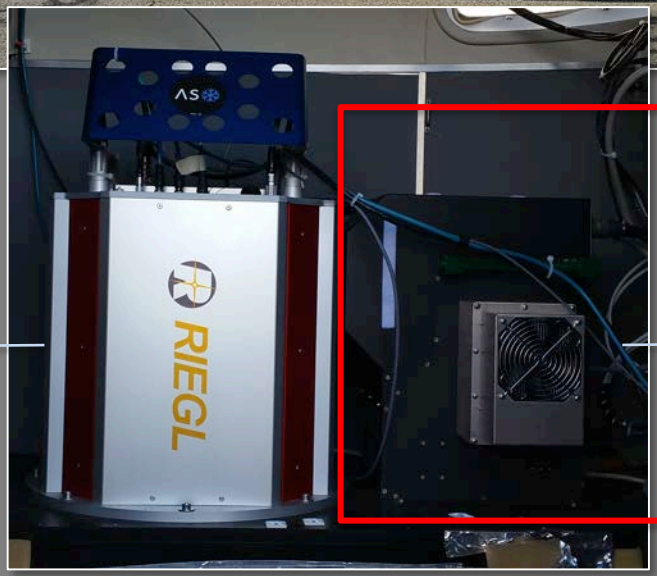


Snow Density
- iSNOBAL modeled



Snow Water Equivalent
- Fusion of measured and modeled

NASA Airborne Snow Observatory



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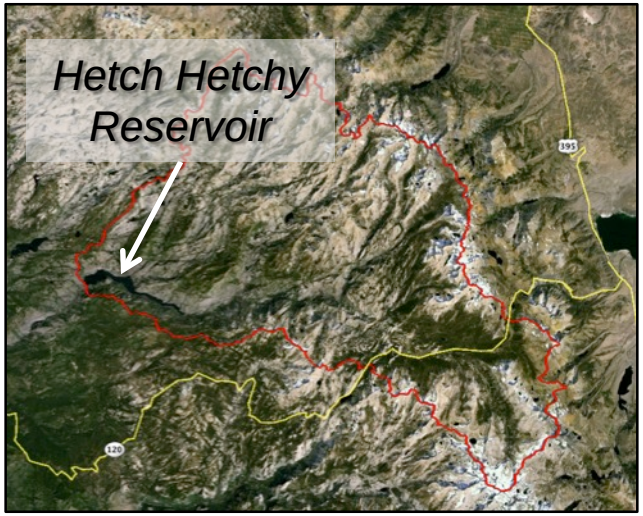
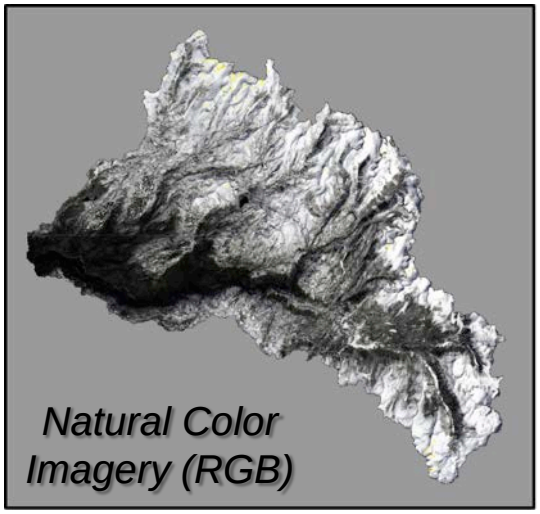
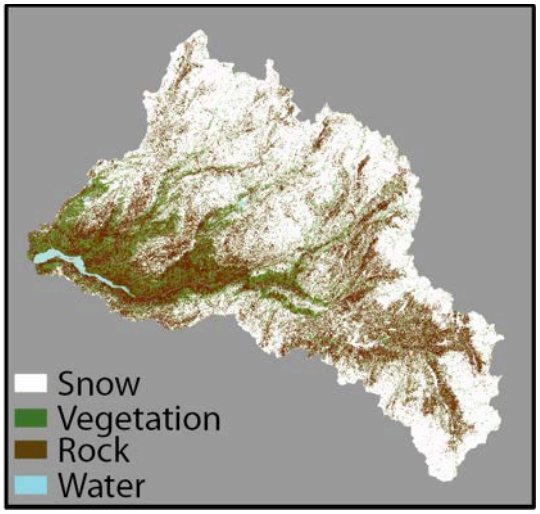
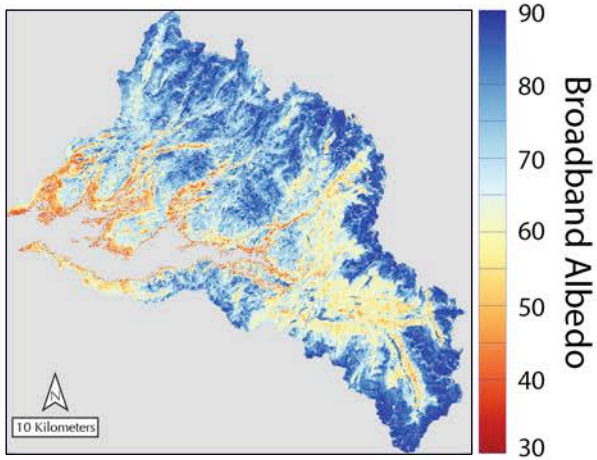
ASO Imaging Spectrometer Products

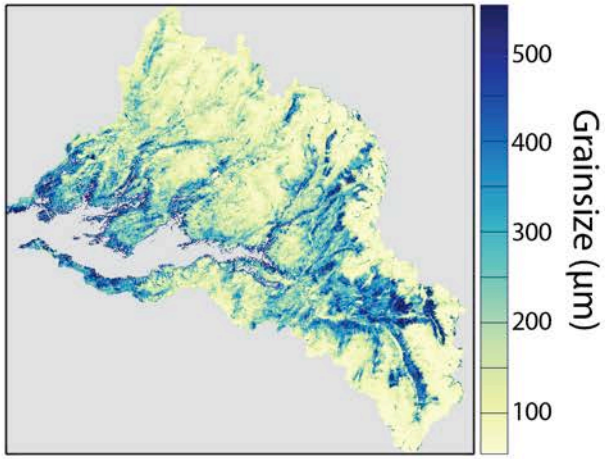
Tuolumne, CA (1300 km^2)

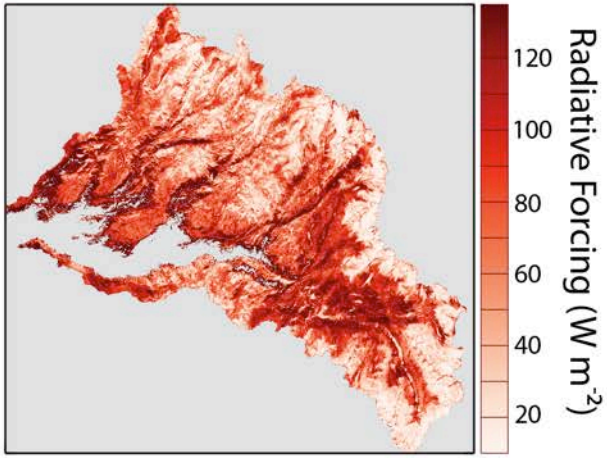




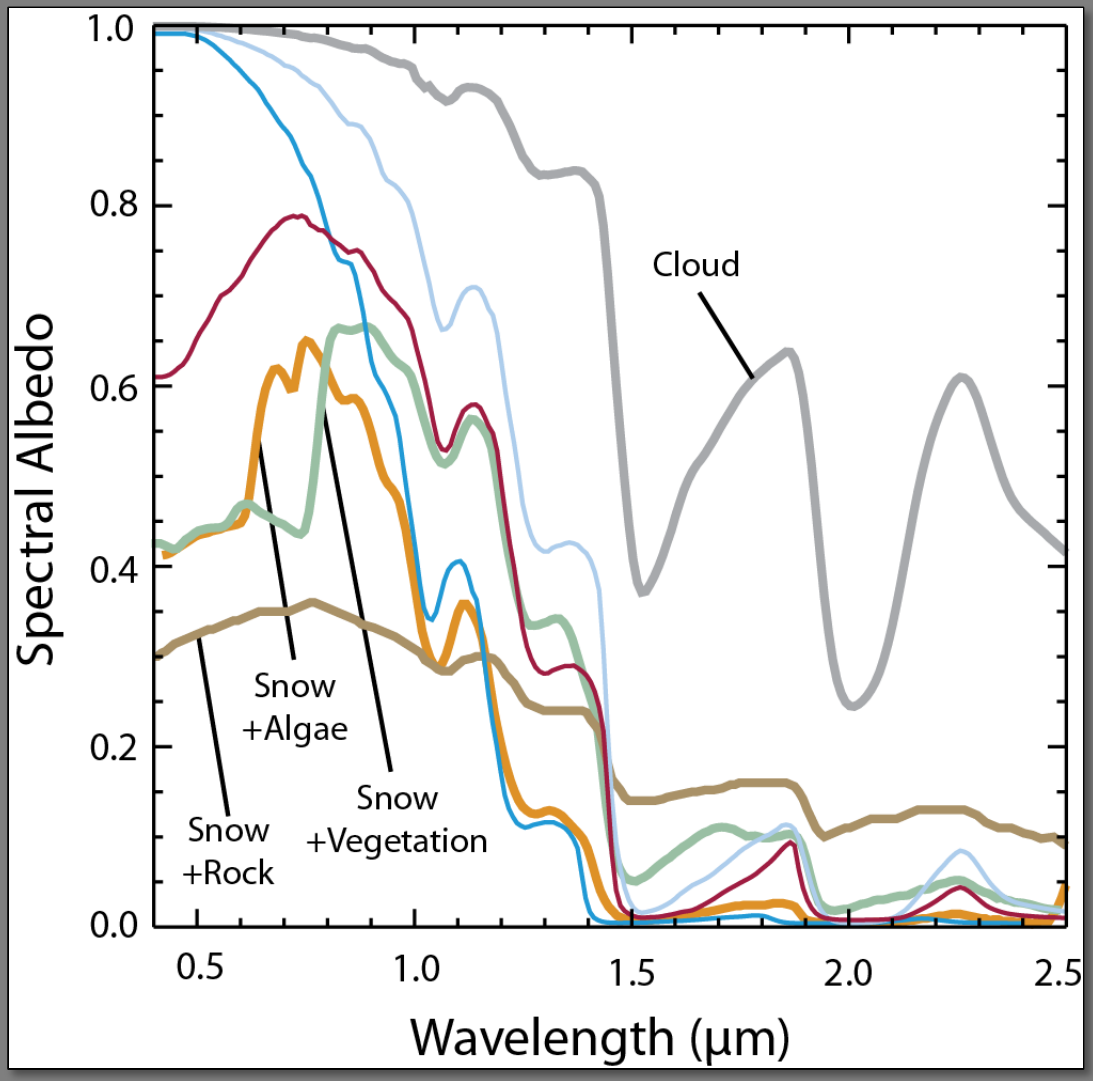




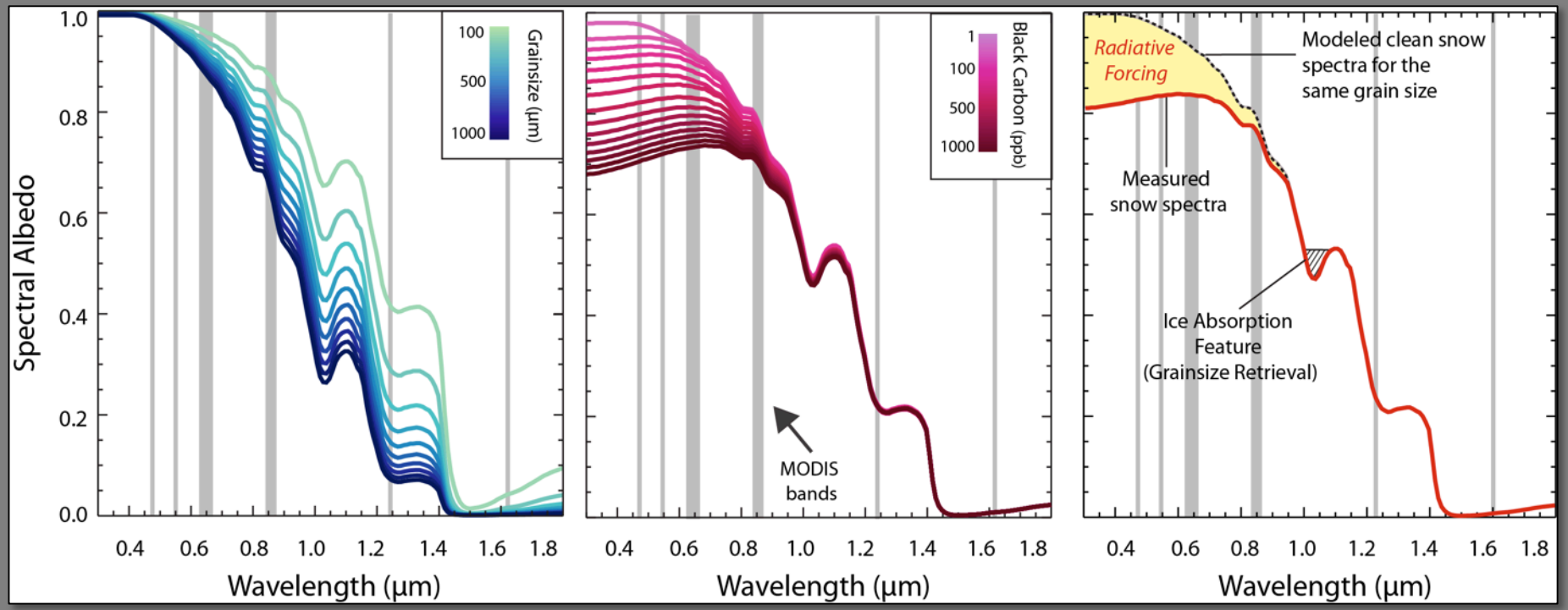


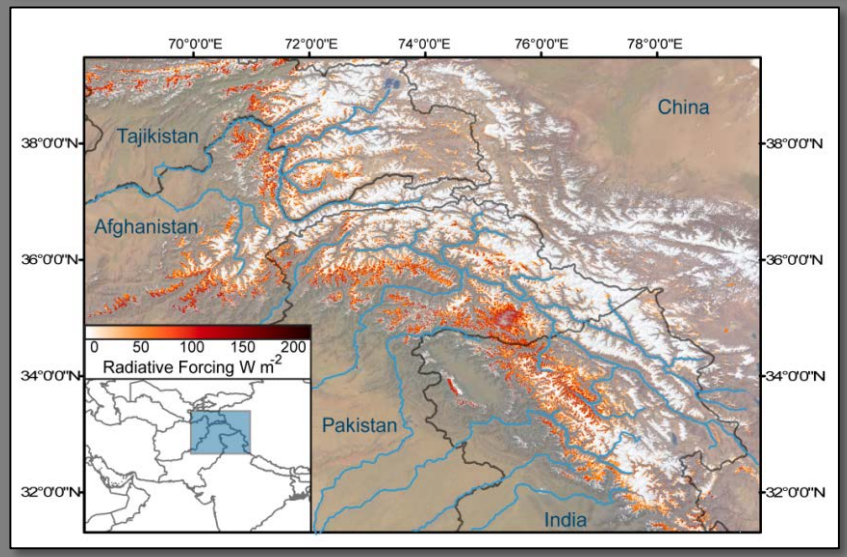


Detecting Snow/Spectral Unmixing



Why not MODIS?

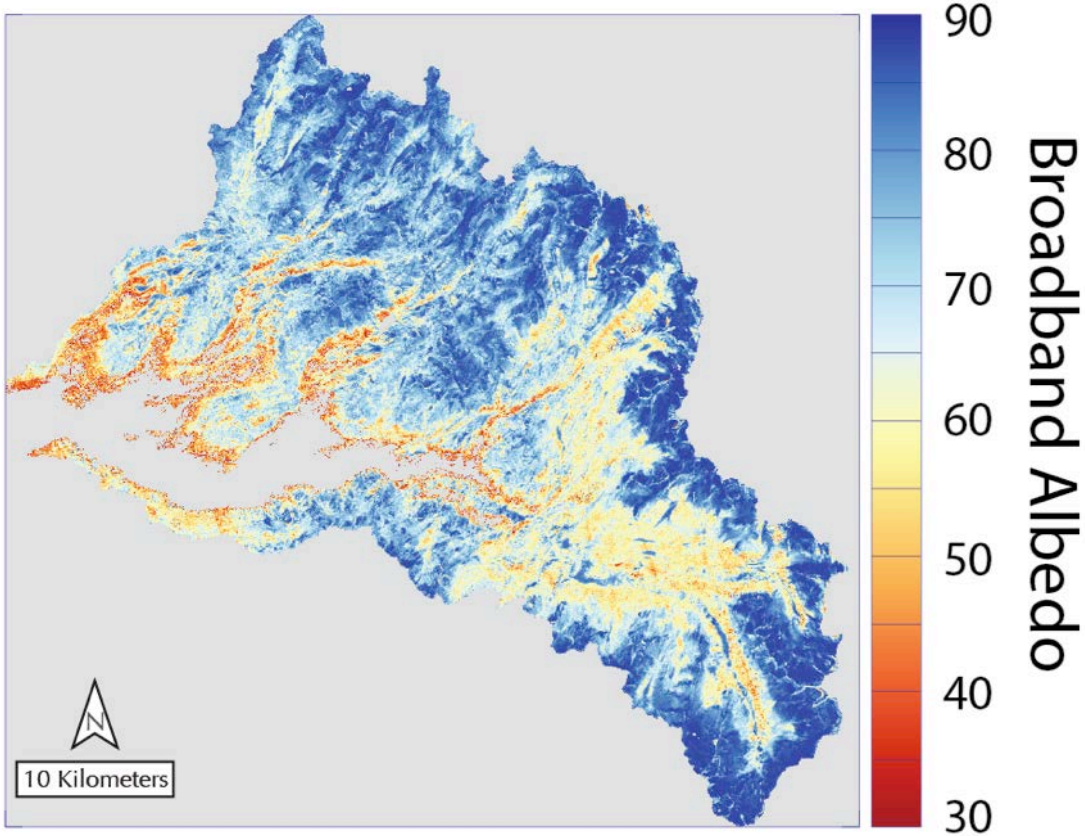




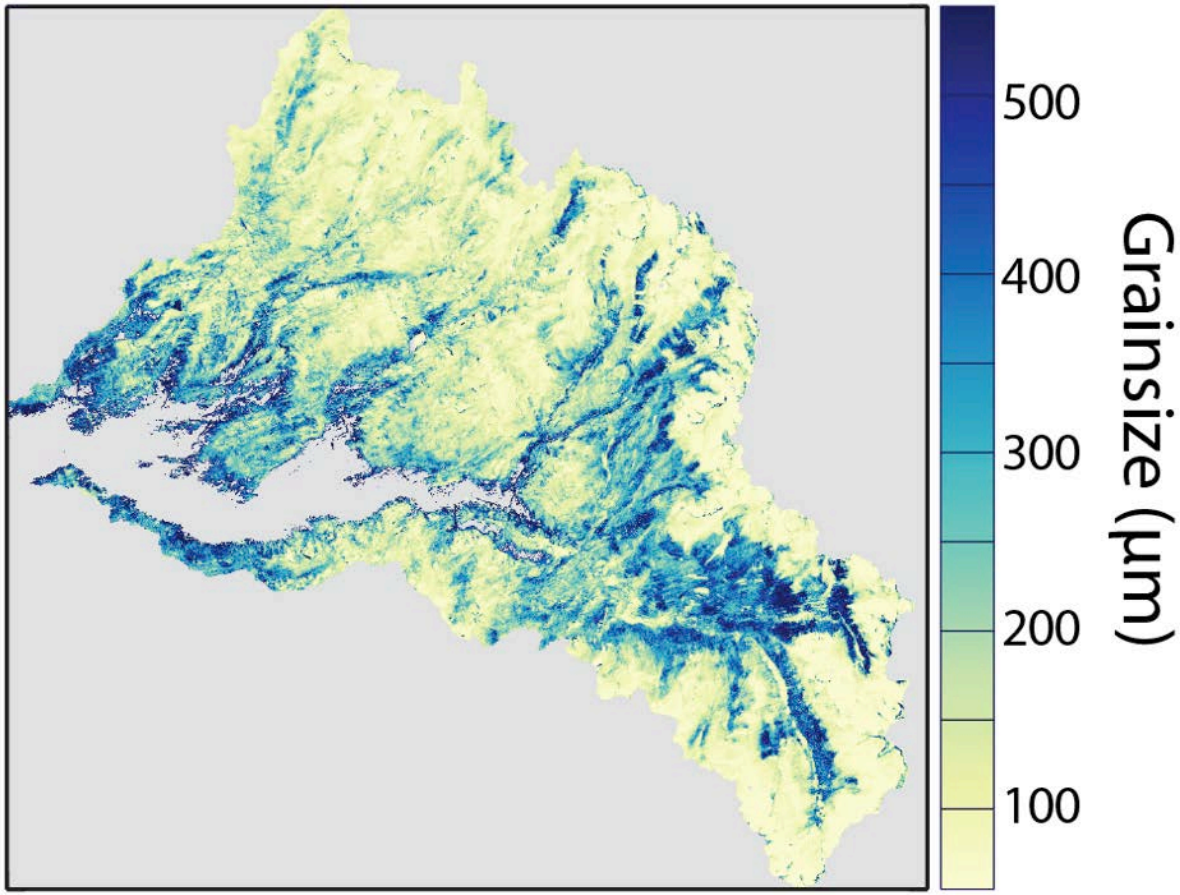
MODIS spectral and spatial resolution limit the ability to accurately retrieve snow properties in mountainous terrain

The MODDRFS product (JPL snow data server) provides a MODIS RF products, but with relatively large errors (34 W m^{-2}) limiting use to impurity laden regions

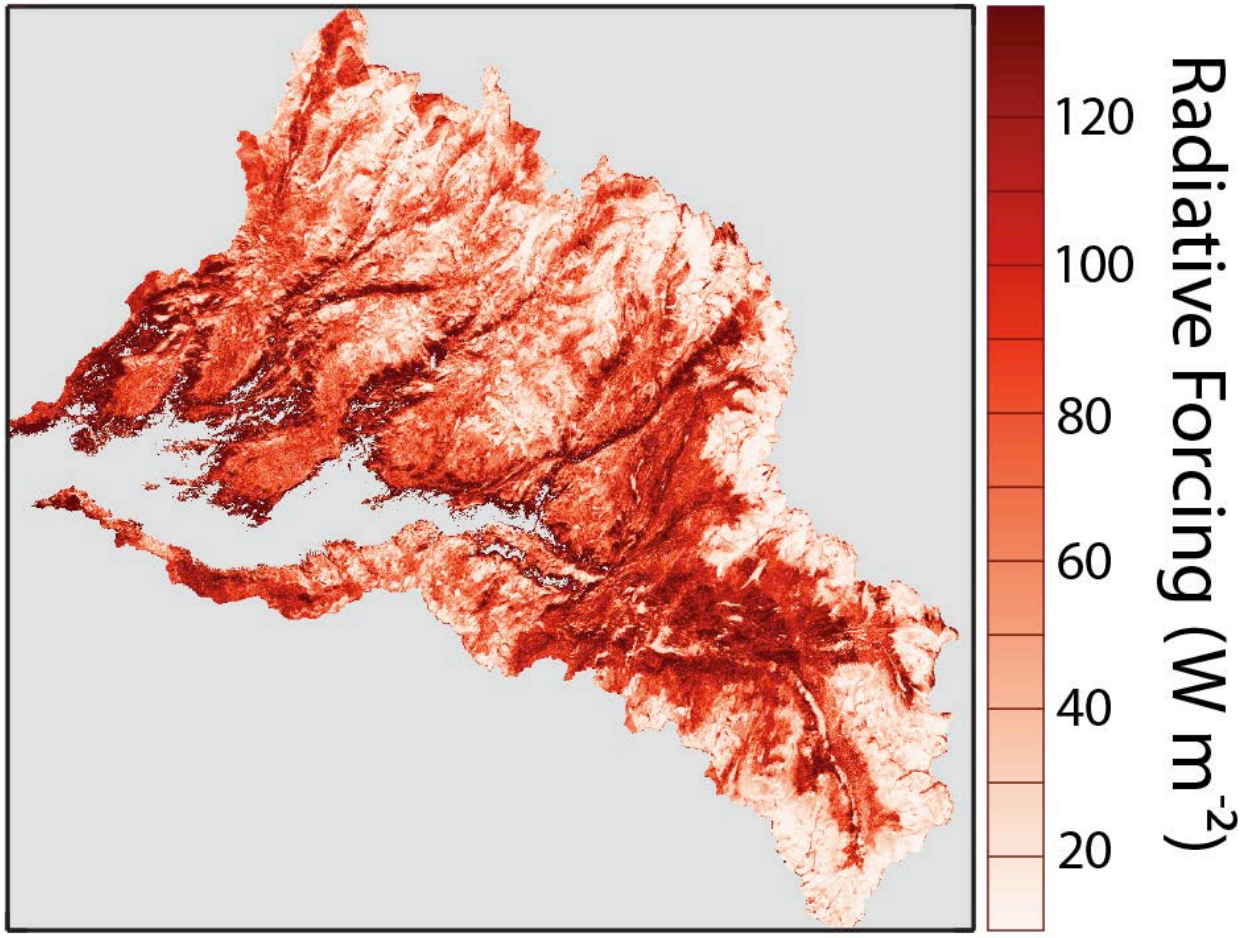
Snow Albedo



Snow Grain Size



Radiative Forcing



Questions or Comments?

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