10th EARSeL Workshop on Land Ice and Snow
Bern, 2023 Feb 6-8

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Retrieval of Subpixel Snow Albedo and Temperature from Visible through Thermal Infrared Sensing

Fractional coverage (f_{SCA})
Broadband albedo = f(grain size, LAP)
Snow temperature (melt state, energy balance)

Retrieval of albedo through spectroscopy (EnMAP, EMIT, CHIME, SBC)

Possible variables

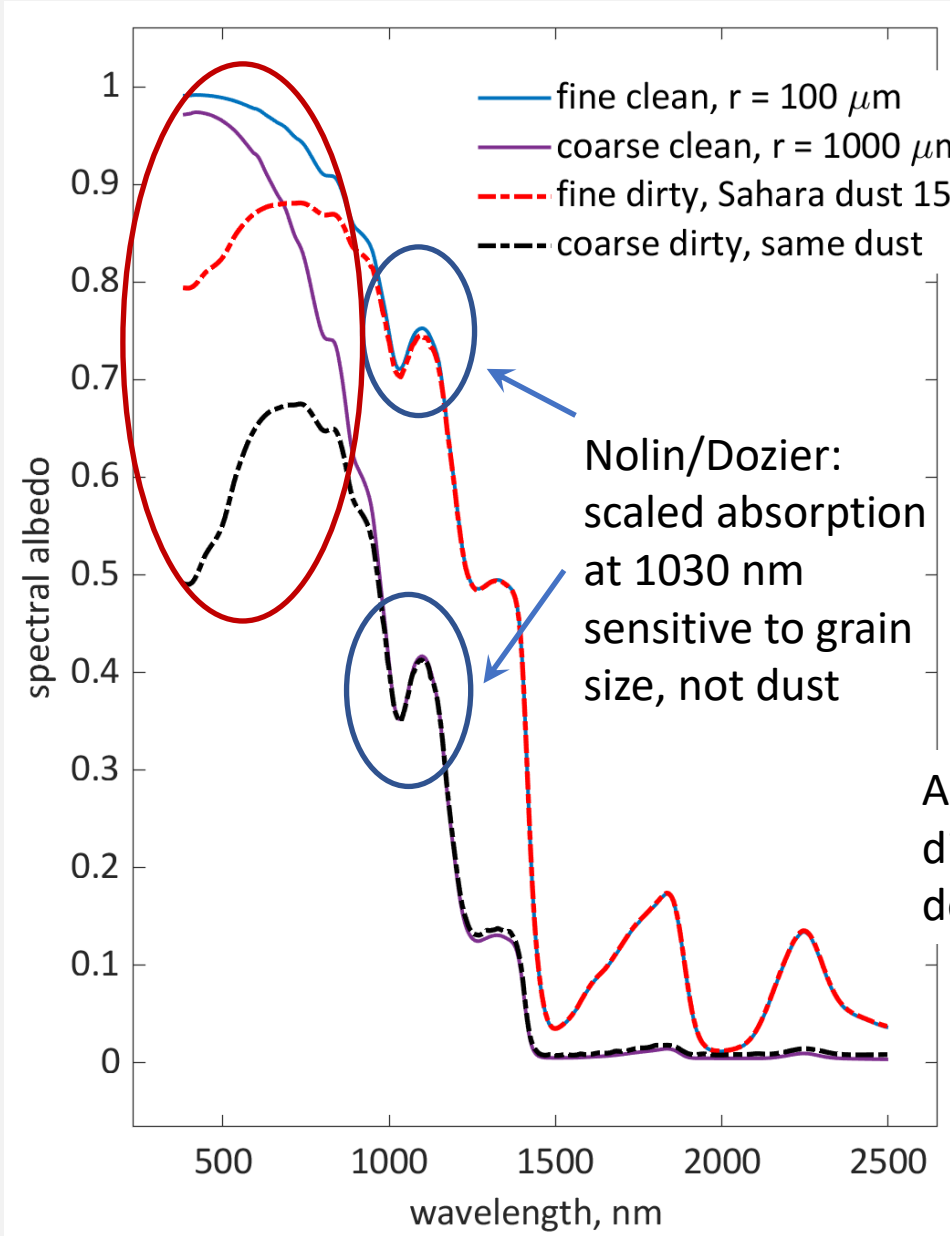
- To get f_{SCA} & broadband albedo
  - Grain size (or SSA, specific surface area)
  - LAP size or concentration, but not both
- Options
  - Multiple LAPs (algae, dust, black carbon)
  - LAP refractive index (f_{SCA}=1 and LAP size & concentration known)
  - SWE for shallow snow
  - Liquid water in surface layer

- Forward model
  - ➢ "intrinsic" reflectance (directional or hemispherical) of snow and of other surfaces in pixel
- Adjust for fractional coverages and for vegetation and terrain
  - ➢ "apparent" vs "intrinsic" reflectance
- Optimization to invert the model
  - ➢ Compare with atmospherically corrected reflectance

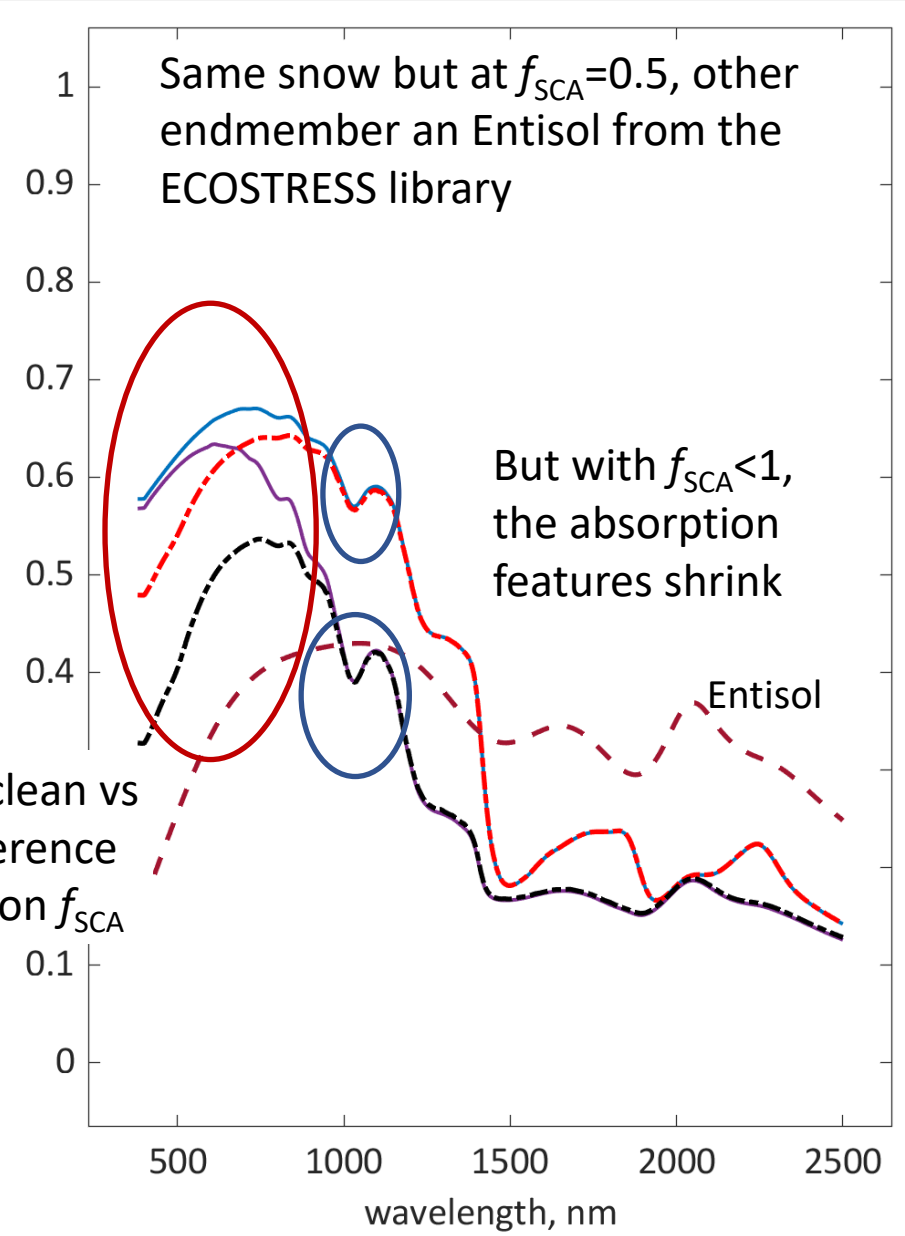
  Or
  - ➢ Propagate through atmosphere and compare with top-of-atmosphere reflectance
- In the optimization, what do you minimize?

Painter/Skiles: retrieve effect of LAP by comparing with modeled clean snow, difference depends on size

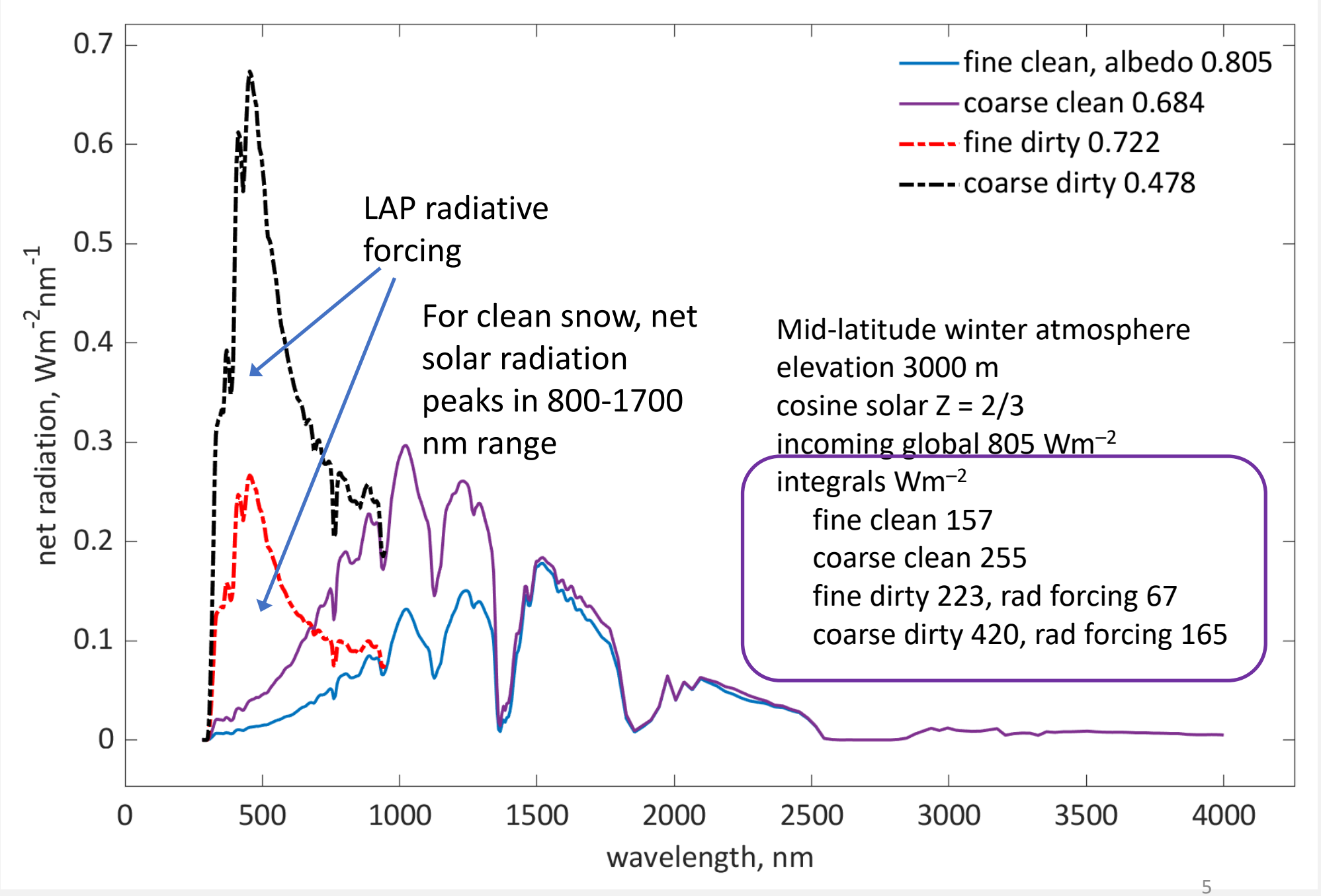
Retrieval of grain size, LAP (light-absorbing particles), and f_{SCA} must happen in tandem, not independently



And the clean vs dirty difference depends on f_{SCA}

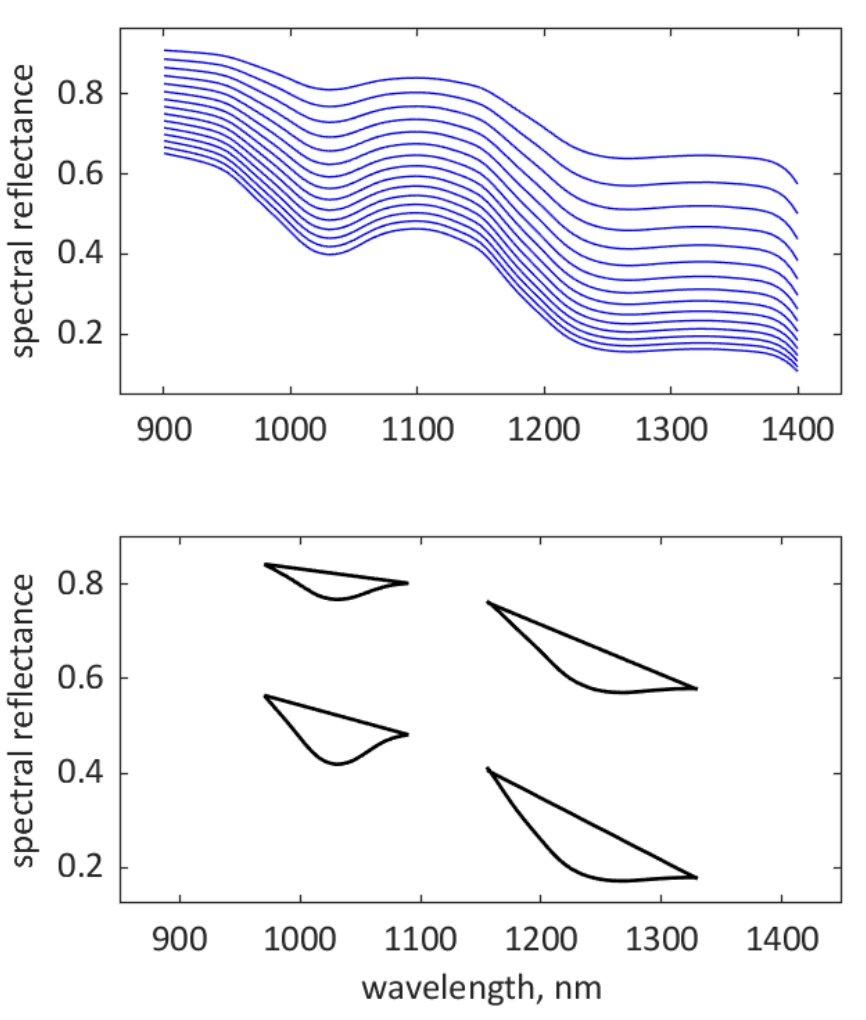


Effect on snow's net solar radiation



If f_{SCA}=1 (Greenland, Antarctica, plains, plateaus)

- Use Nolin/Dozier 1030 nm (and possibly 1260 nm too) absorption feature to estimate grain size
- Model clean snow reflectance
- Difference actual reflectance to clean snow to get radiative forcing
- Bohn et al. *RSE* 2021 solve for atmospheric variables at this step and estimate concentration of multiple LAP by optimal estimation



$$A_b = \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} \frac{R_{c\lambda} - R_{s\lambda}}{R_{c\lambda}} d\lambda$$

Nuances: different approaches when $f_{SCA} \neq 1$

- Intrinsic reflectance of snow and endmembers

$$\boldsymbol{R} = \begin{bmatrix} R_{\lambda_1}^{(snow)} & R_{\lambda_1}^{(veg)} & \cdots \\ R_{\lambda_2}^{(snow)} & R_{\lambda_1}^{(veg)} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}$$

- Fractional covers

$$\boldsymbol{f} = \begin{bmatrix} f_{SCA} \\ f_{veg} \\ \vdots \end{bmatrix}$$

- Measurements

$$\boldsymbol{m} = \begin{bmatrix} r_{\lambda_1} \\ r_{\lambda_2} \\ \vdots \end{bmatrix} = \boldsymbol{Rf}$$

- **Painter**: SCAG (MEMSCAG, MODSCAG, TMSCAG) precomputed library of $\boldsymbol{R}$ for various combinations of snow and endmembers

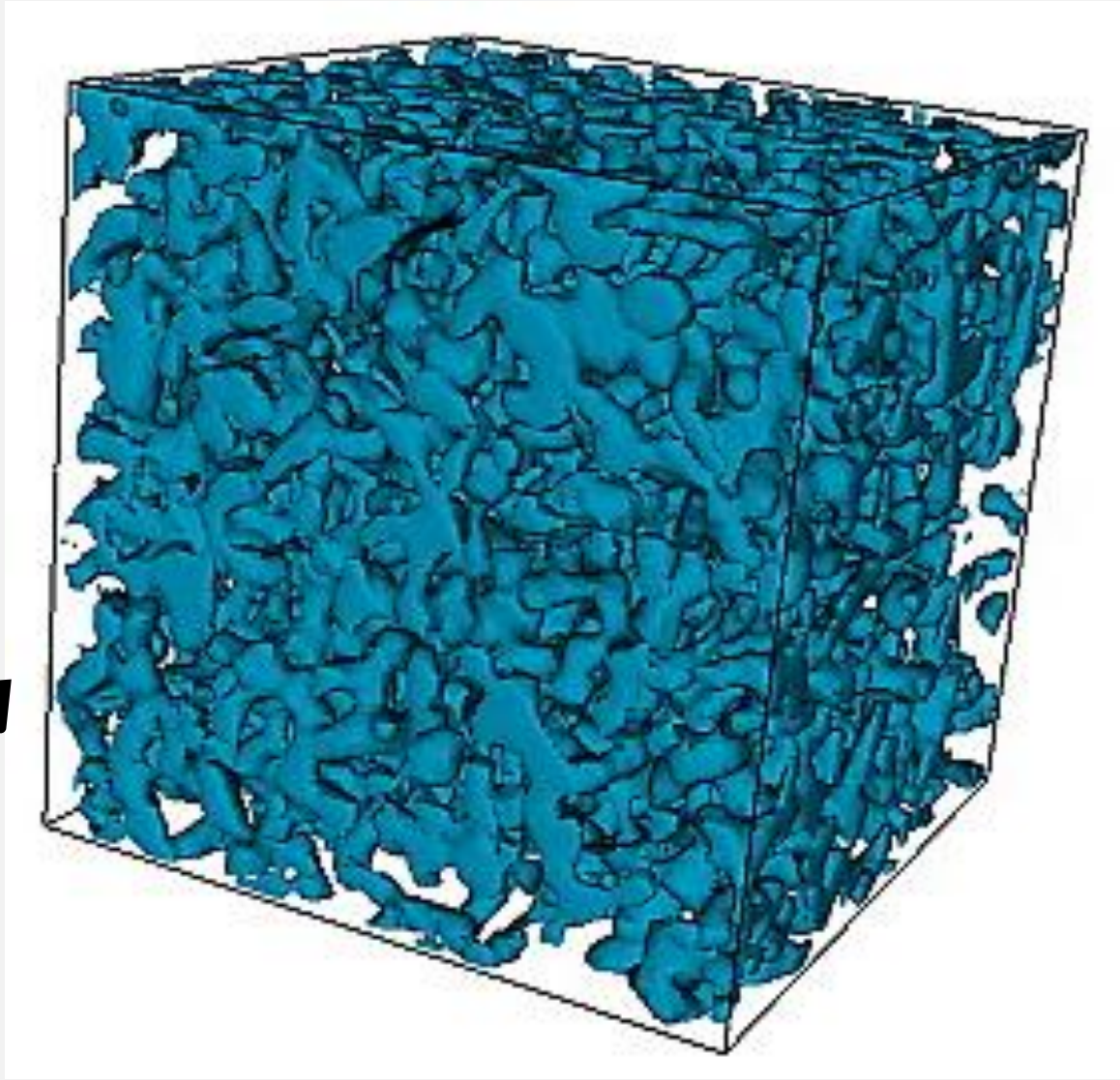
Solve $\boldsymbol{f} = \boldsymbol{R}^{-1}\boldsymbol{m}$ in the least-squares sense and find $\boldsymbol{R}^{(snow)}$ at $\min(\sum(1-f)^2)$ subject to constraint $0 \leq f \leq 1$

- **Dozier, Bair, Stillinger**: SPIReS

Consider f_{SCA}, f_{etc}, SSA, LAP concentration as bounded unknowns and constrained by $\sum f = 1$. Adjust for terrain. Minimize weighted sum of least squares, spectral angle, and absorption integrals. Get $\boldsymbol{R}$ for endmembers from non-snow pixels, but for SBG/CHIME, we can get endmembers from the timeseries

Variety in forward modeling for snow

- Wiscombe & Warren (Bair & Dozier et al.)
  - δ-Eddington & Mie scattering
- Flanner et al. SNICAR
  - 2-stream model, huge algae library
- Painter et al. (Bohn et al.)
  - Nonspherical snow grains & DISORT for angular reflectance
- Kokhanovsky & Zege
  - Geometric optics & asymptotic radiative transfer
- Kaempfer et al.
  - 3D microstructure & photon tracking
  - (Ron Perla: “snow a structure, not a grain collection”)
- Larue et al.
  - Nascent model including snow roughness



Validation

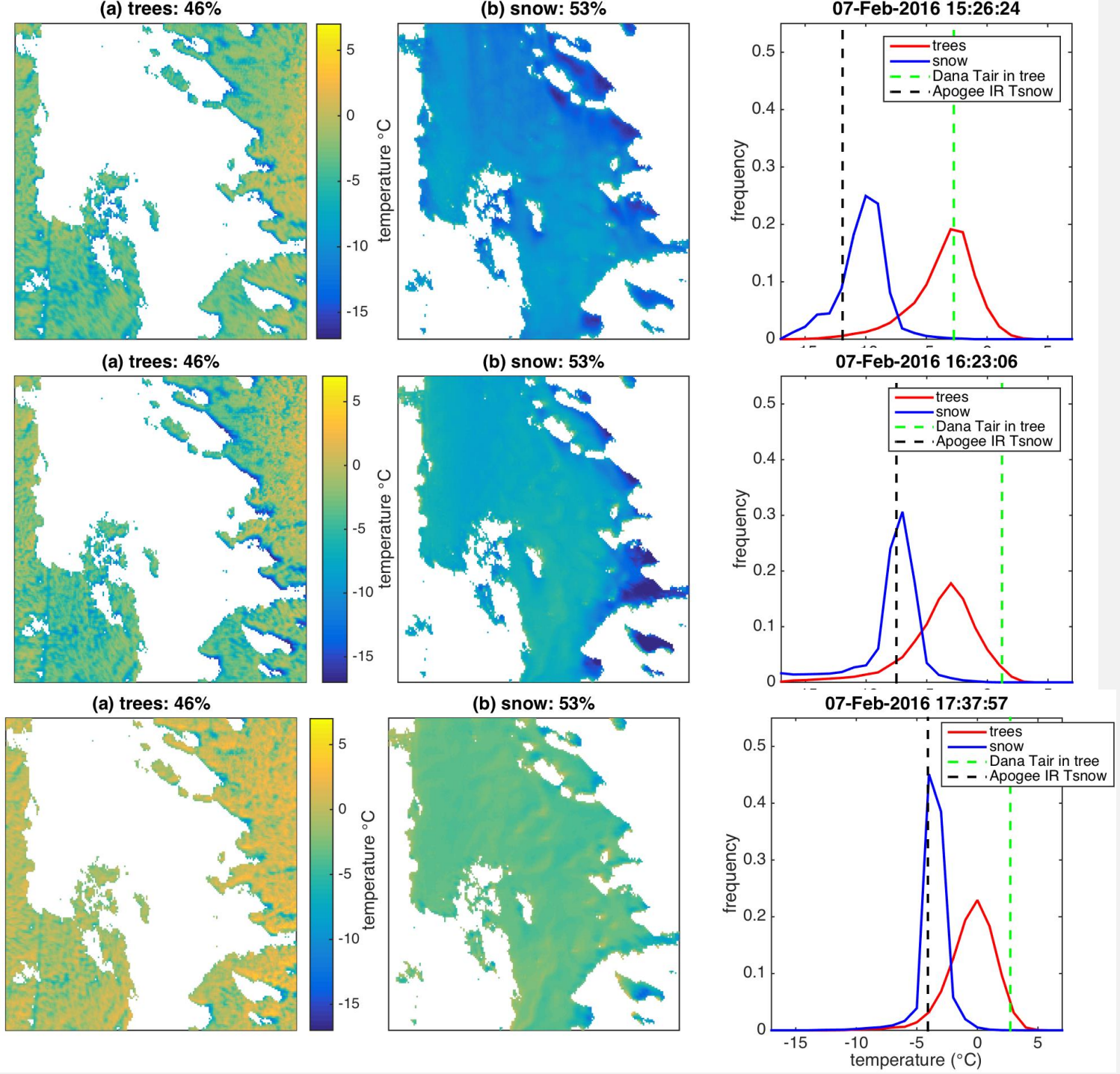
- f_{SCA} and reflectance: fine resolution imagery: satellite, airborne, or drone
  - AVIRIS-NG
  - Airborne Snow Observatories lidar and spectrometer at 3 m
  - Maxar (aka DigitalGlobe), Pan ½ m, 8-band multispectral 2 m, Available through EnhancedView for government-funded research
  - Planet, 3-band multispectral 3 m daily
- Continuous tower measurements of albedo
  - Mammoth Mtn, Senator Beck, Col du Lautaret
  - (must account for slope of snow surface beneath downlooking sensors)
- Field campaigns, especially to validate forward models
  - SnowEx, handheld spectroscopy and snow pit measurements of grain size and LAP (Gallet et al., *Cryosphere* 2009, Skiles & Painter, *JGlac* 2016)
- Simulation
  - Trust forward model, explore ability to invert

Snow temperature: detect melt state, constrain energy balance models

Before sun hits the meadow; warm wind from the N, coldest spots downwind of trees

Sun just hits the meadow; coldest spots in shadows northwest of trees

Sunny meadow; snow surface warms faster than trees



Bands on SBG-Heat (infrared, 60 m pixels)
(SBG-Light is the VSWIR spectrometer)

Band	Center wavelength, µm	Band width, µm
SWIR1 (not used)	1.6	0.25
MIR1	3.98	0.02
MIR2	4.8	0.20
TIR1	8.28	0.34
TIR2	8.63	0.36
TIR3	9.07	0.54
TIR4	11.33	0.54
TIR5	12.05	0.52

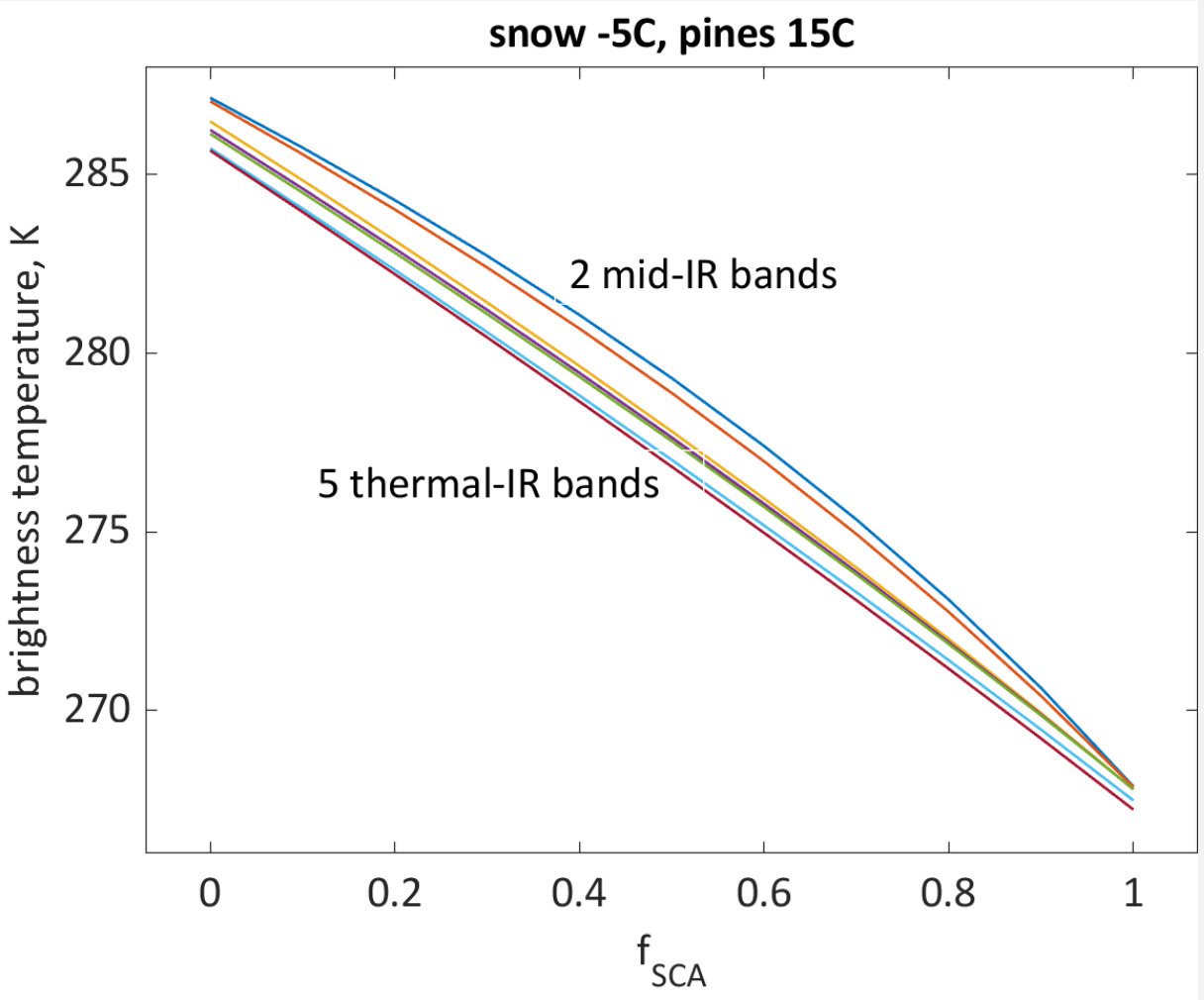
Problems to solve to get to a solvable problem

Nighttime	Daytime
It's dark	Signal from mid-IR bands contaminated by reflected sunlight (reflectance = 1–emissivity)
Swath of SBG-Heat wider than of SBG-Light so no independent estimate of f_{SCA}	

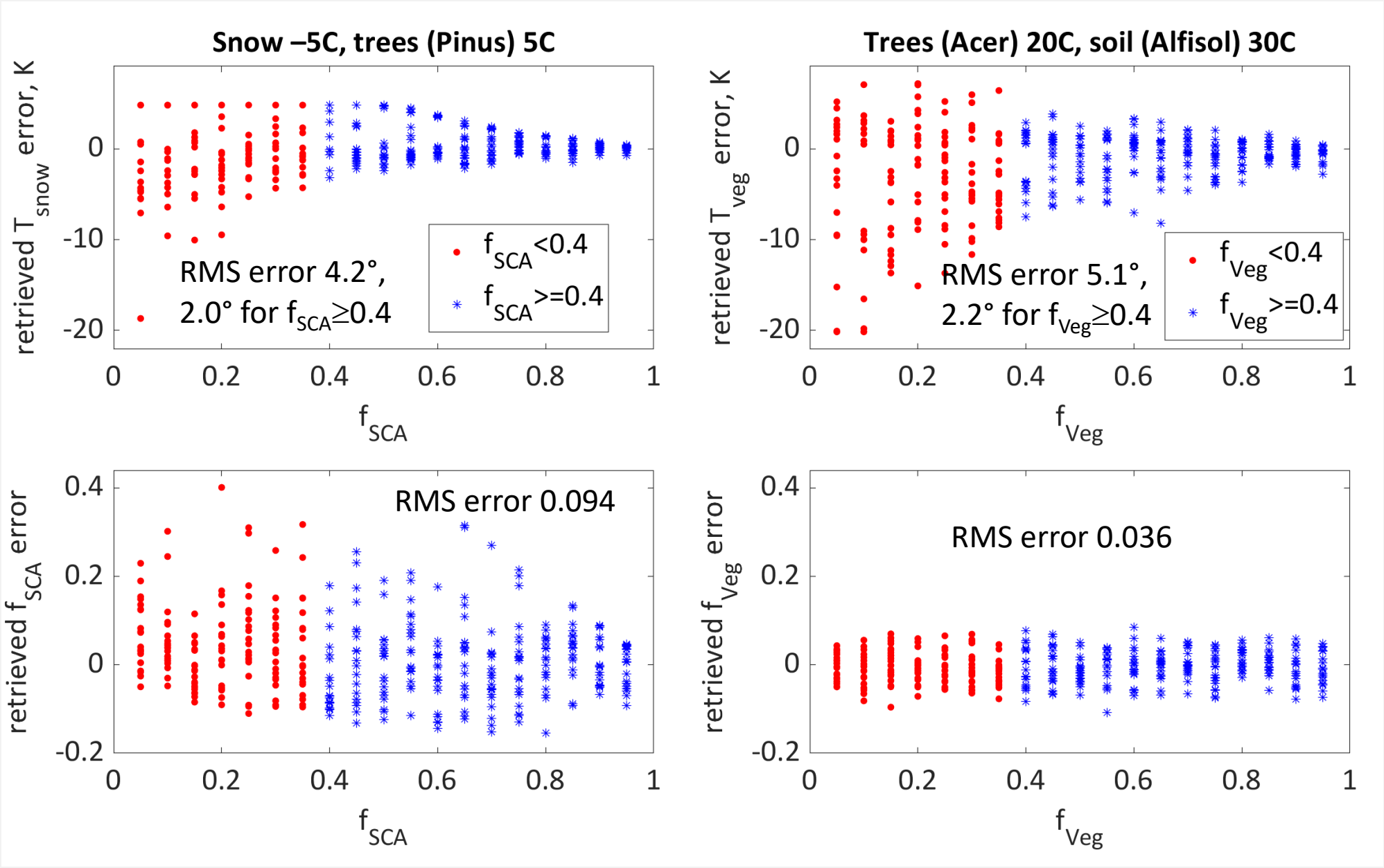
AGU Chicago December paper:
Spectral Unmixing in the Middle- and Thermal-Infrared Can Retrieve Separate Temperatures of Vegetation and Soil or Snow in Mixed Pixels (Jeff Dozier, Anamika Shreevastava, Glynn Hulley)

With SBG-Heat (thermal infrared), can we separate subpixel temperatures? (snow vs trees, or vegetation vs soil)

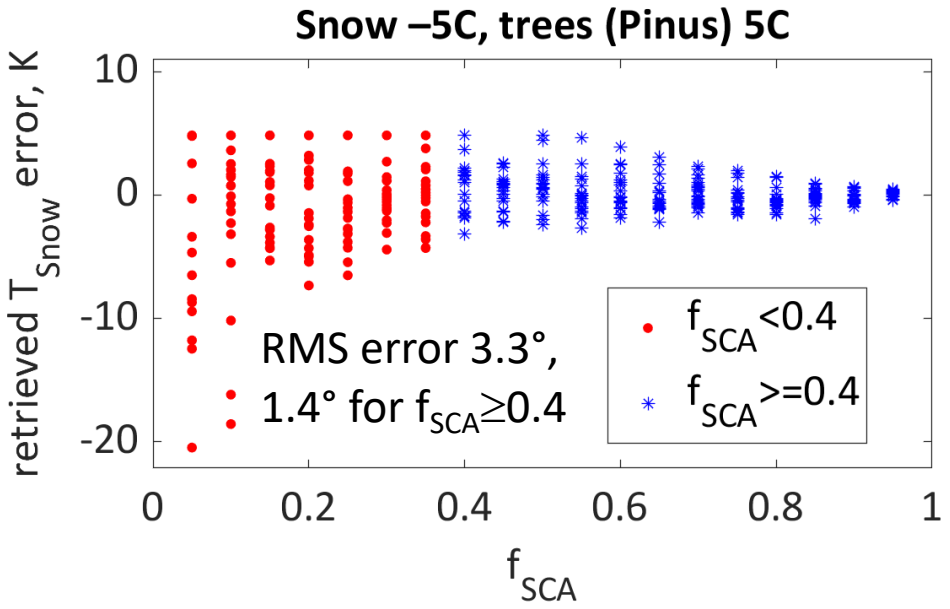
- L (radiance) $= \varepsilon_\lambda \beta(\lambda, T)$
  emissivity × Planck equation
- Mixed pixel target (t) & background (b), $f_t + f_b = 1$
- $L(\lambda) = f_t \varepsilon_\lambda^{(t)} \beta(\lambda, T_t) + (1 - f_t) \varepsilon_\lambda^{(b)} \beta(\lambda, T_b)$
- $T_B(\lambda) = \beta^{-1}[L(\lambda)]$
- 3 unknowns T_t, T_b, f_t
- Reduce to 2 unknowns if either T or f is known

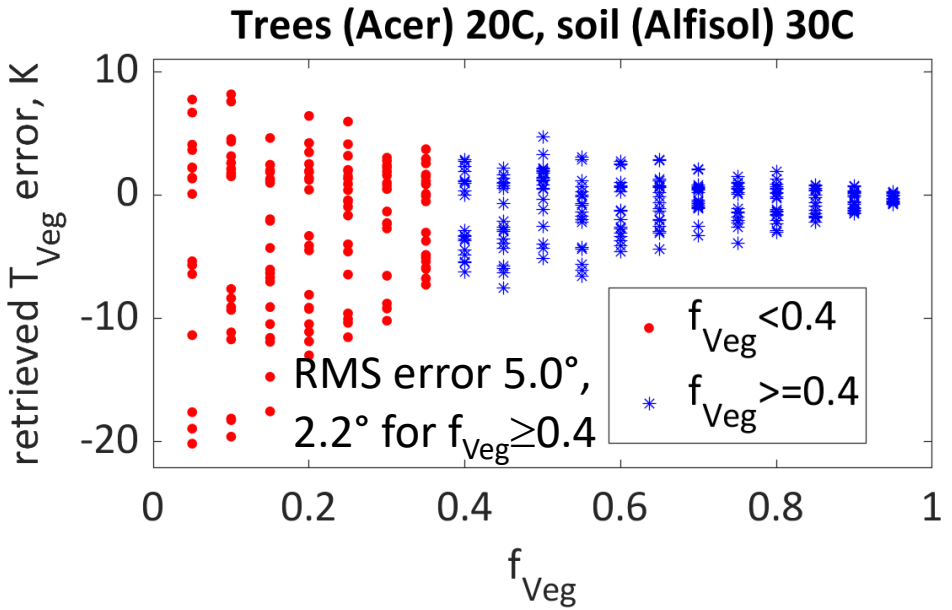


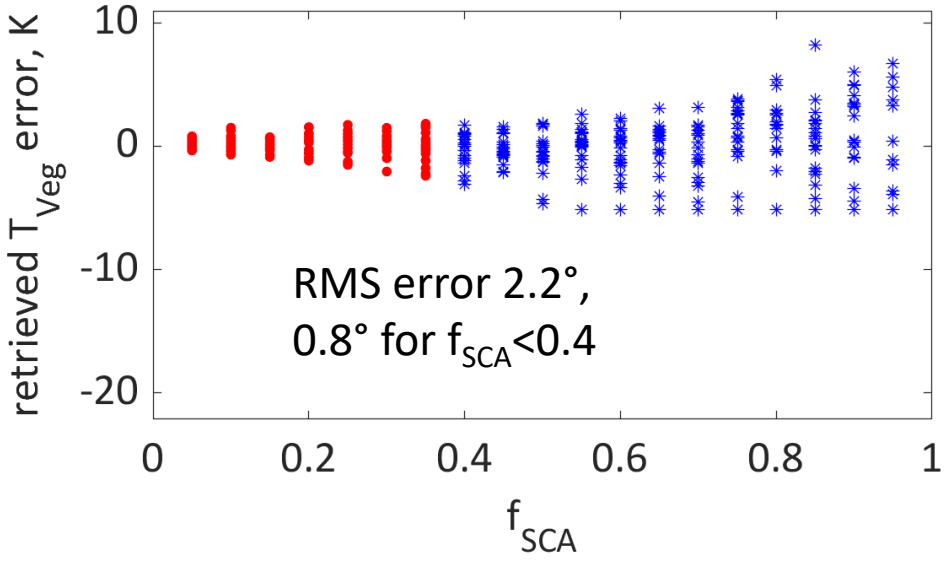
Retrievals for 3 unknowns with 0.2° noise in brightness temperature (including solar reflection)

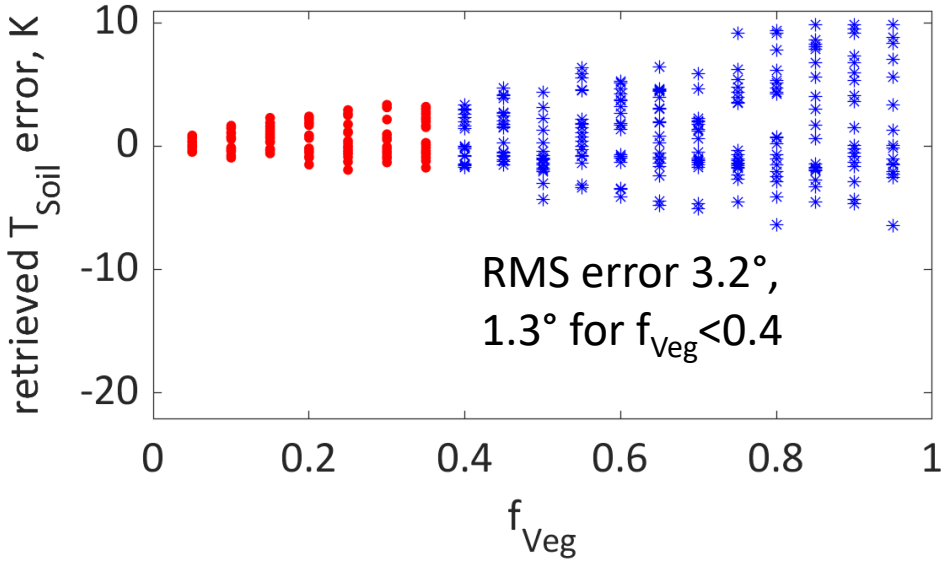


Retrieval of temperatures, fractions known, with 0.2° noise in brightness temperatures





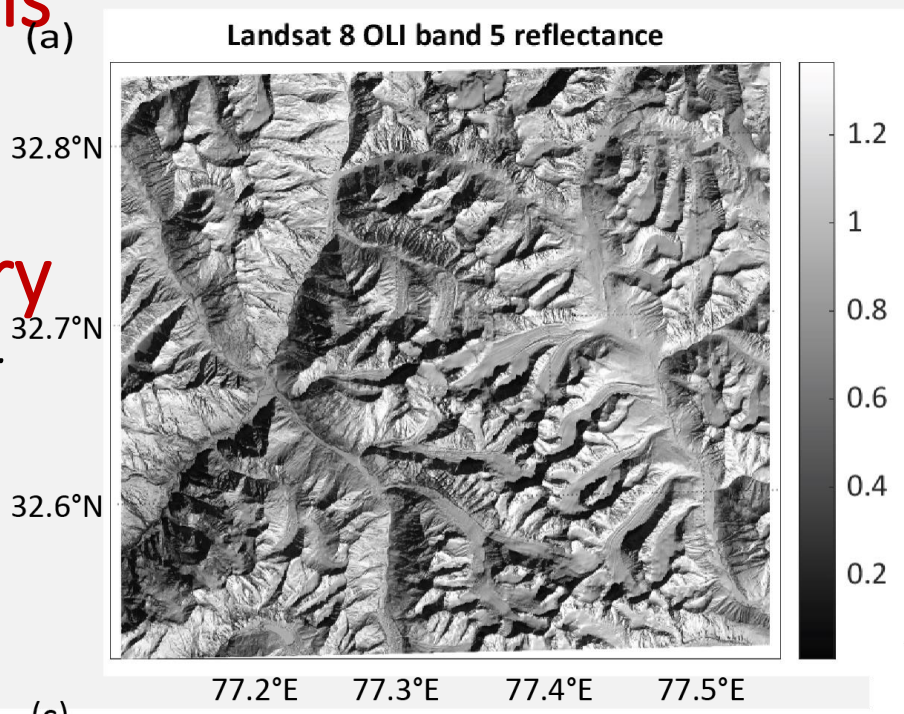


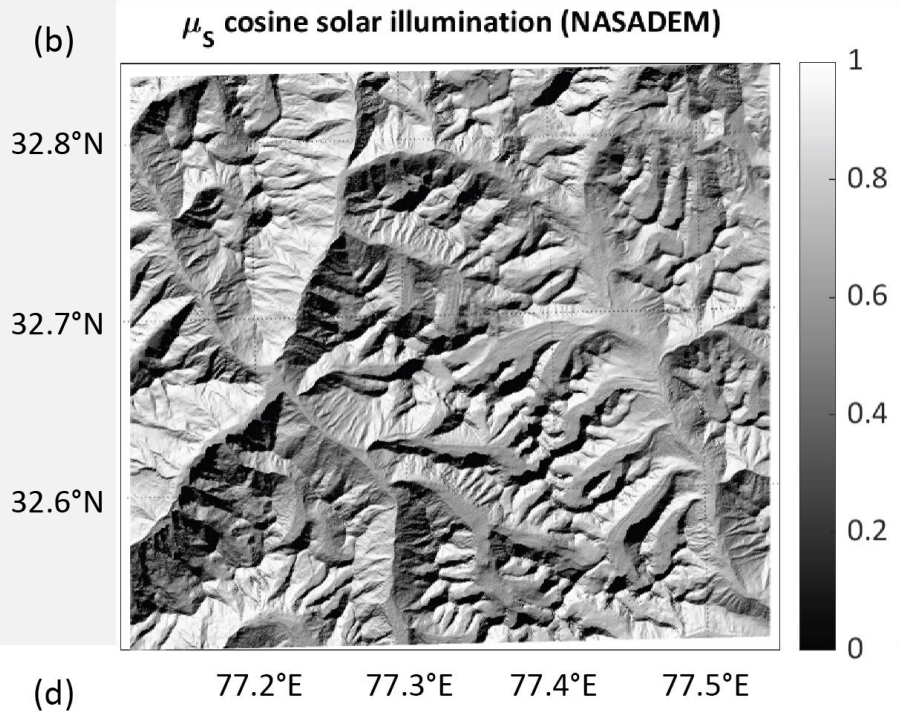


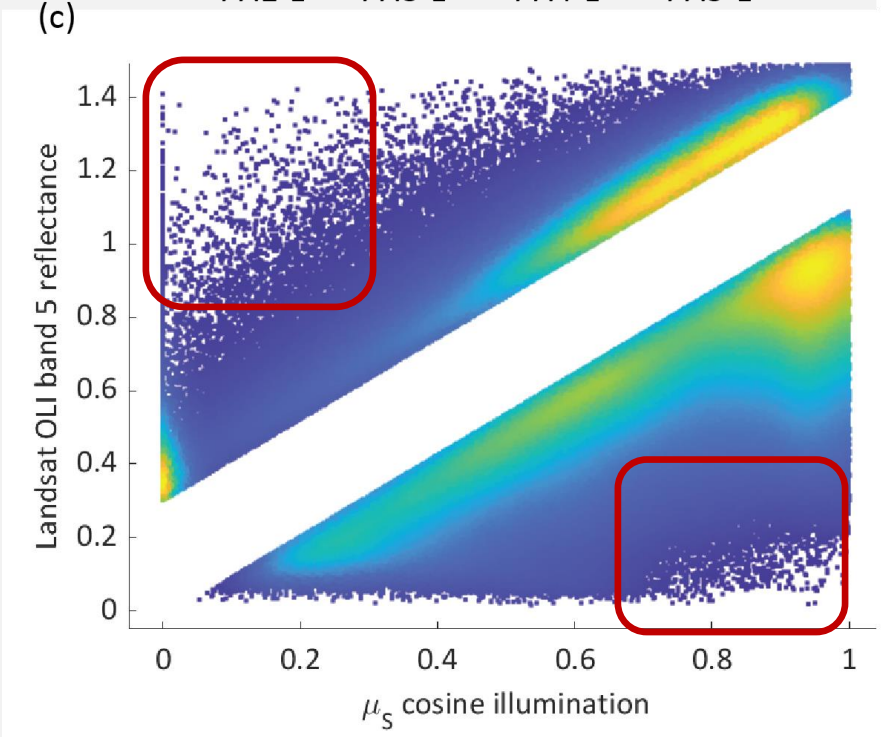
Topography: lots of mid-latitude snow in the mountains

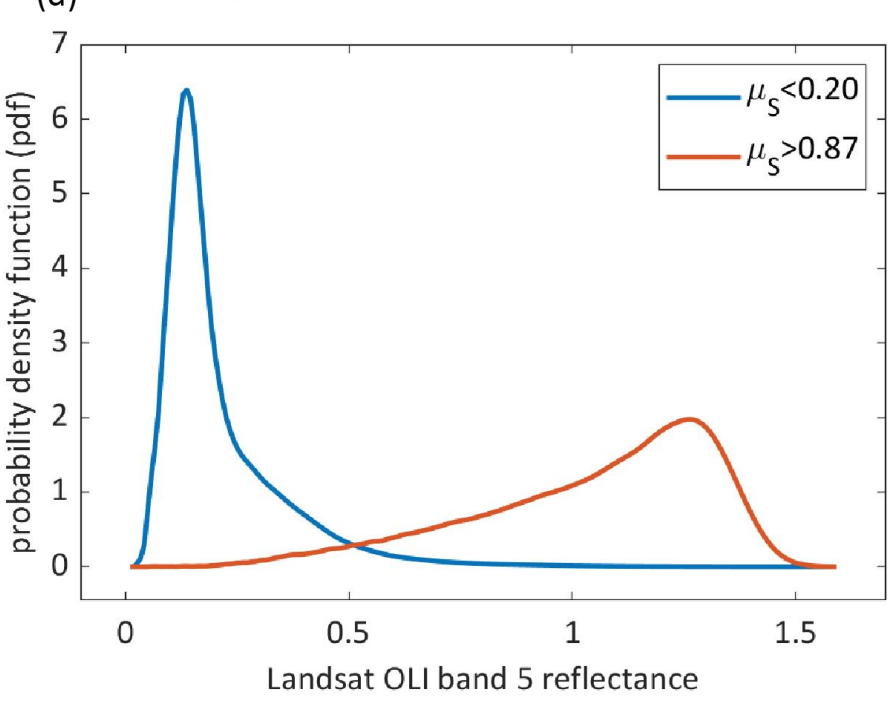
available DEMs have errors in calculation of solar geometry (Dozier et al., *JGR-Biogeo* 2022)

Perhaps possible to solve for illumination angle w spectroscopy (Carmon et al., accepted in *RSE,* "Shape from spectra")









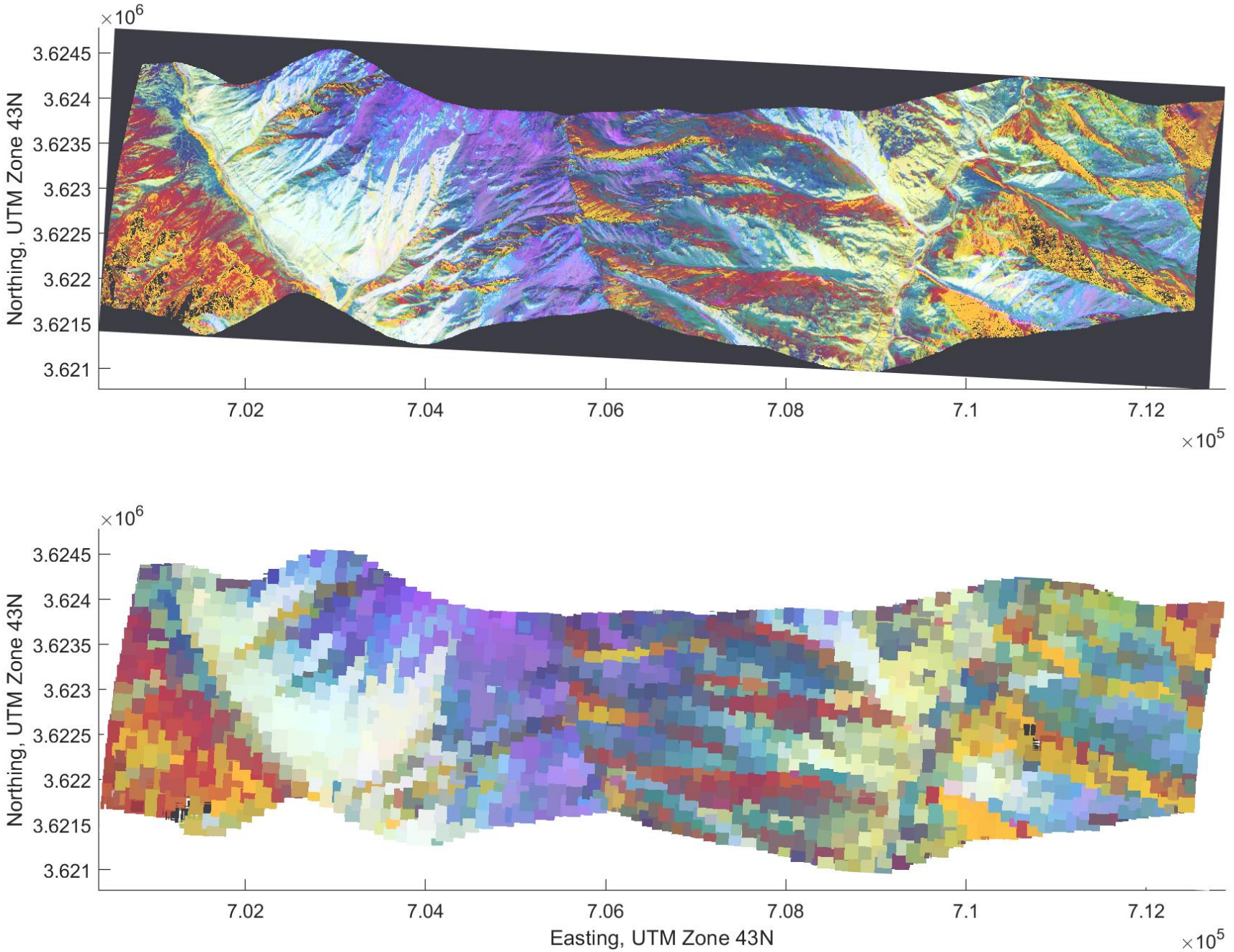
State of the practice 2023

- Parallel, independent work by different research groups has led to robust results from imaging spectroscopy of snow
- If CHIME or SBG were to launch next year, we would know what to do
- The various scientists would disagree about details, but we could make an ensemble product available right away
- Issue: topographic compensation with uncertain solar geometry from DEMs
- Issue: what lies beneath the trees?

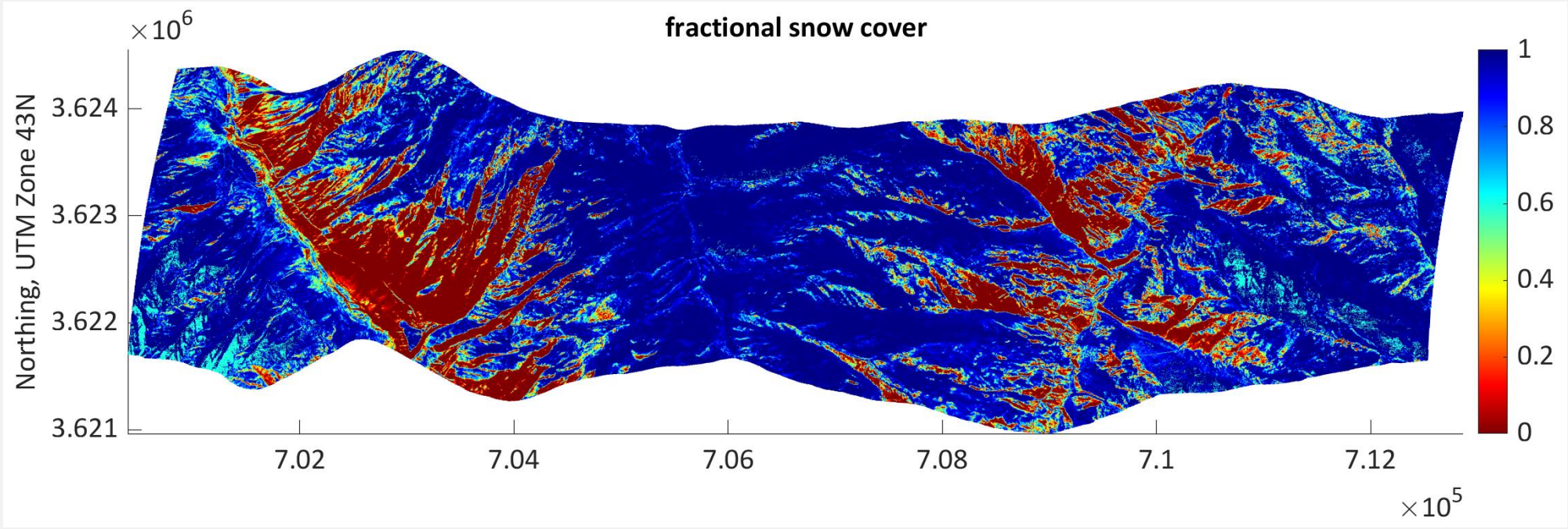
Machine learning to speed up computation

Train on a sample of pixels

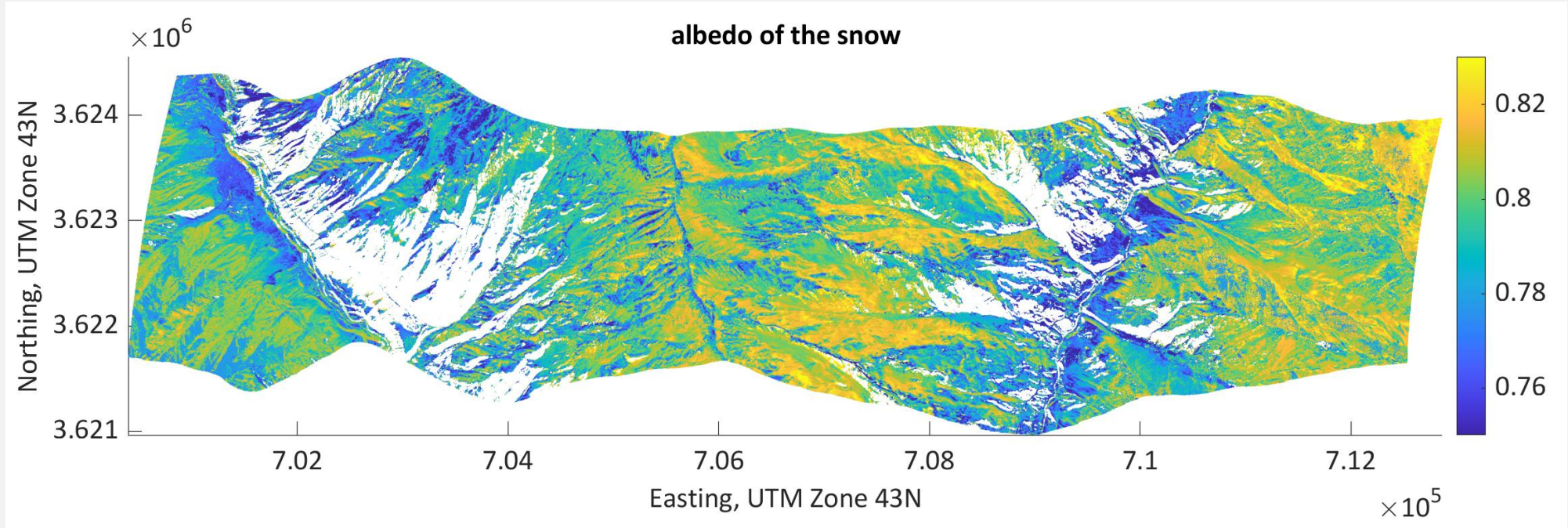
- Superpixels to sample the image (0.1% sample)
  - Or use “uniquetol” to identify similar pixels
- For each sample element, invert reflectance model to estimate properties of interest
- Use those to train a machine learning model
- Improve over time with subsequent images



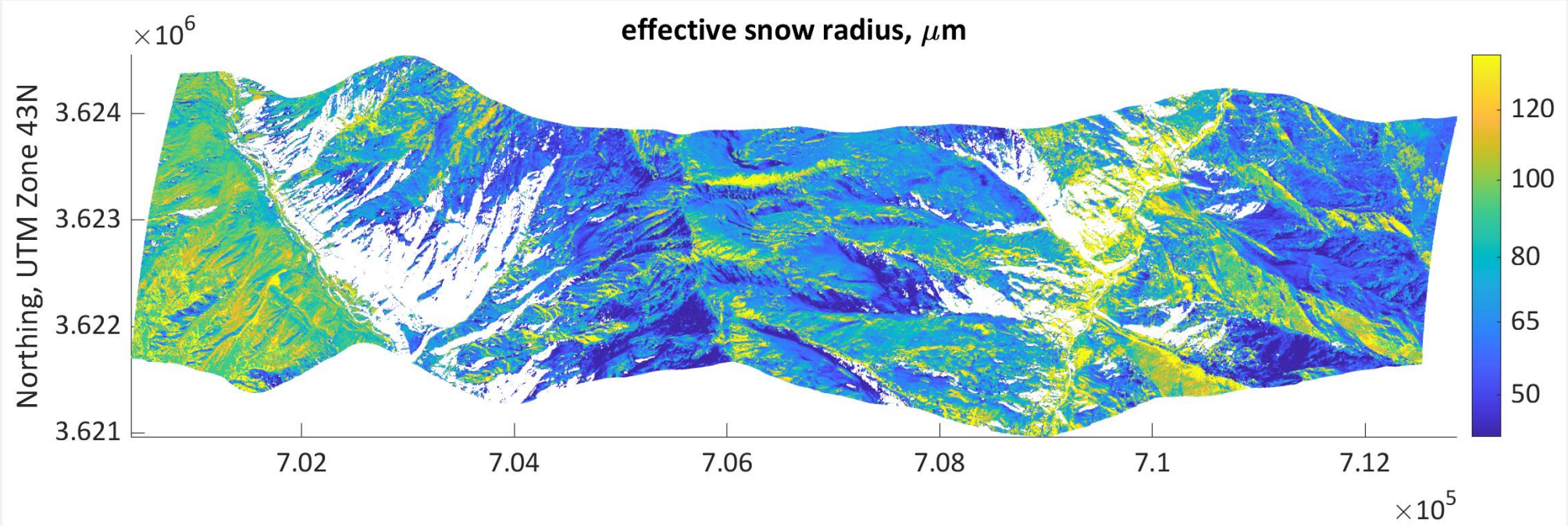
f_{SCA} and snow albedo, Indian Himalaya, Feb 17 2016

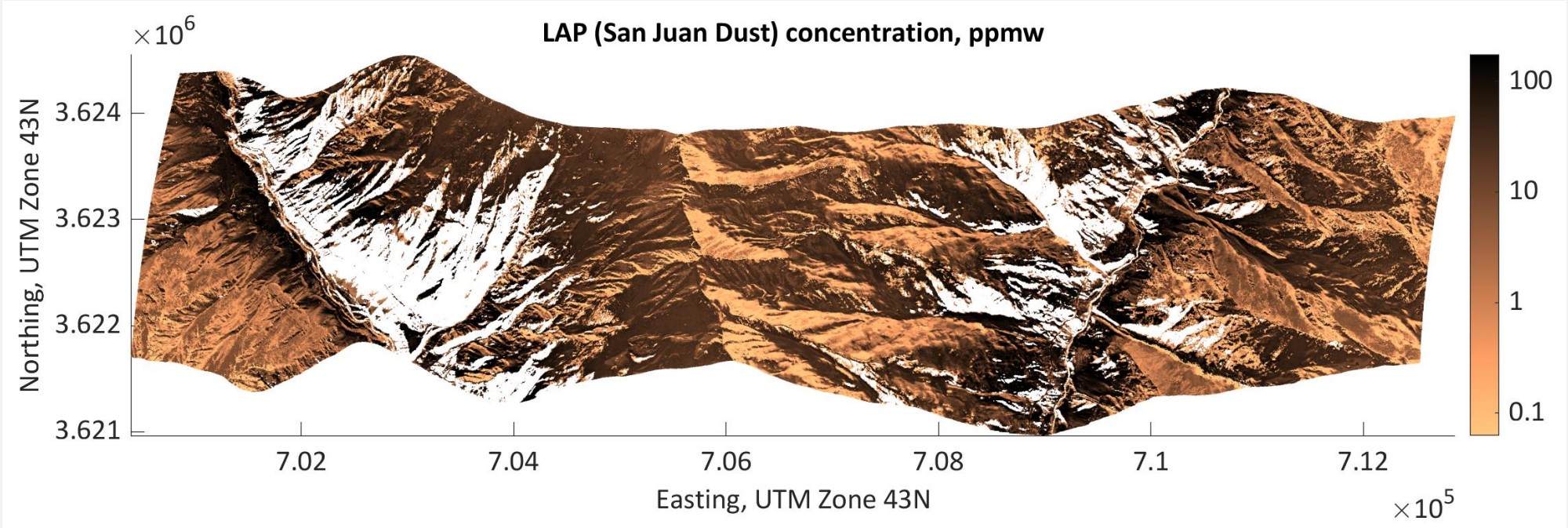


(albedo range display from 5th to 95th percentile)



Snow grain size (µm) and LAP concentration (ppmw), Feb 17 2016





Implications for Applications

- Deposition of dust and especially black and brown carbon are easier to reduce than carbon dioxide and other greenhouse gases
- Glacier melt depends on the duration, and therefore the melt rate, of the overlying snow
- Forecasts of daily-scale snowmelt runoff depend on albedo
- Effect of air temperature is probably most important in controlling the phase of the precipitation and the elevation of the rain-snow transition







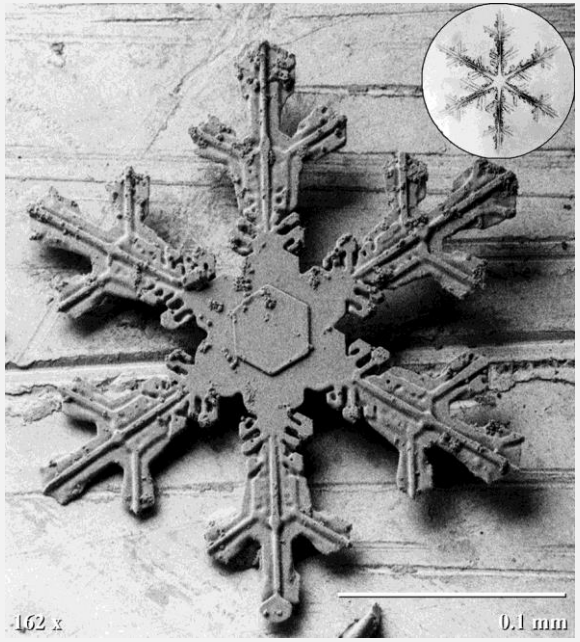
Backup Slides

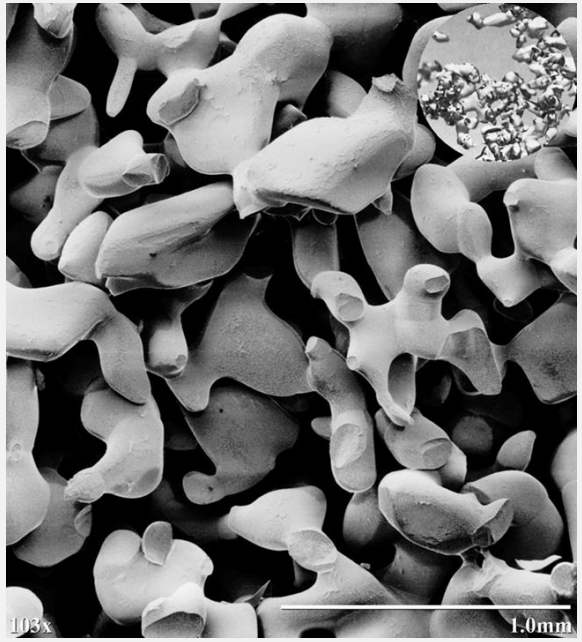
Issues and caveats

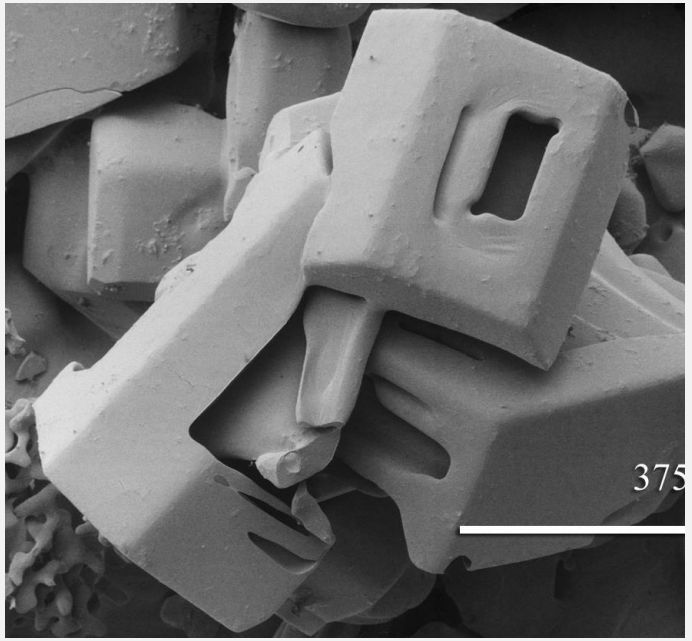
- Forests
  - Raw f_{SCA} shows the observable snow
  - What's beneath the trees?
- Not all dust is the same
  - Regional variability of optical properties
  - Learn from EMIT!
- How important are angular variations?
  - Illumination and view angles uncertain at 30 m resolution
  - Surface roughness introduces backscatter, reducing forward peak of reflectance
- Glaciers
  - Applying the snow model with a big grain size doesn't match measurements of the crystals
  - Whicker et al. 2022 SNICAR for glacier ice
- Low light in the high latitudes

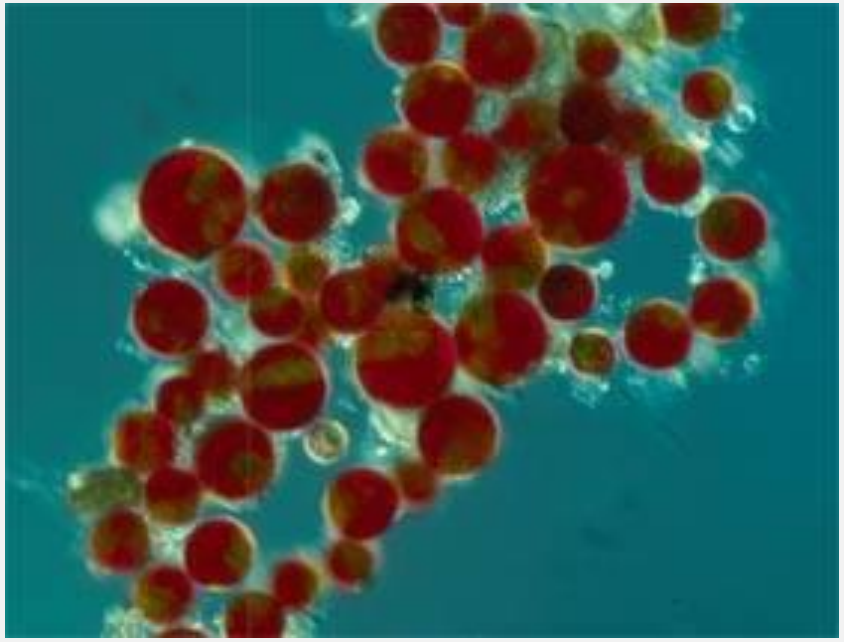
New with CHIME and SBG

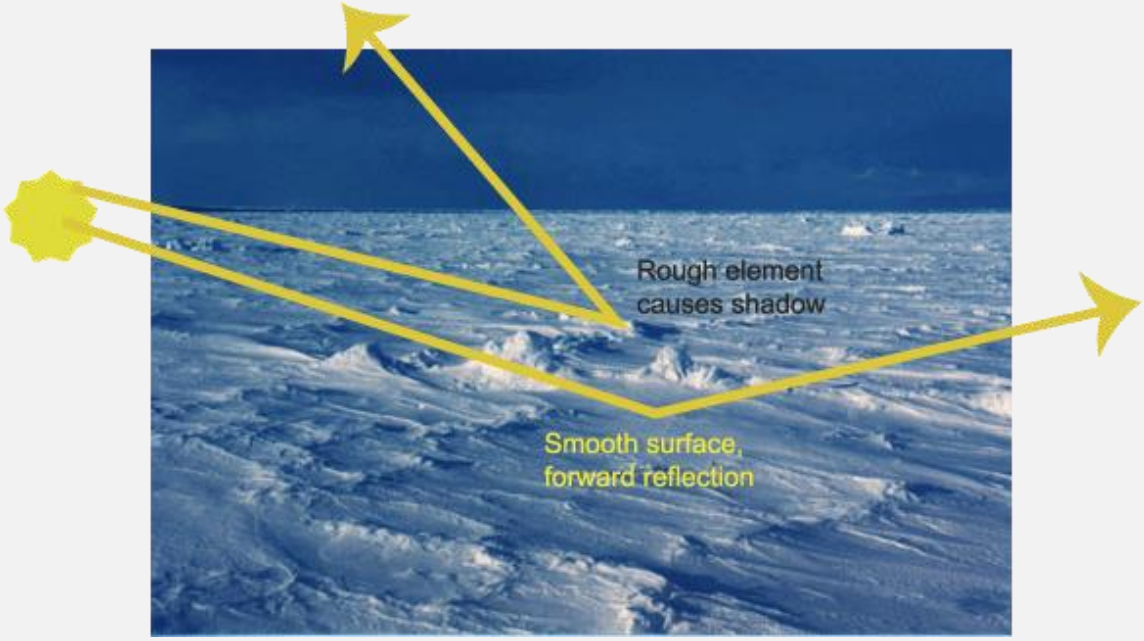
- Spatial time series!
  - Identification of endmembers when the pixel is snow-free
  - Opportunity for Bayesian approaches to retrieval of snow properties
- Global variability of snow albedo
  - Sources of LAP? (Oaida et al. *JGR* 2015)
  - Can albedo increase during metamorphism?
- Don't optimize too early
  - Solving the wrong equations faster not a way to progress
- Analyses integrated with Sentinel and Landsat to identify the rapid changes


162 x
0.1 mm


103x
1.0mm

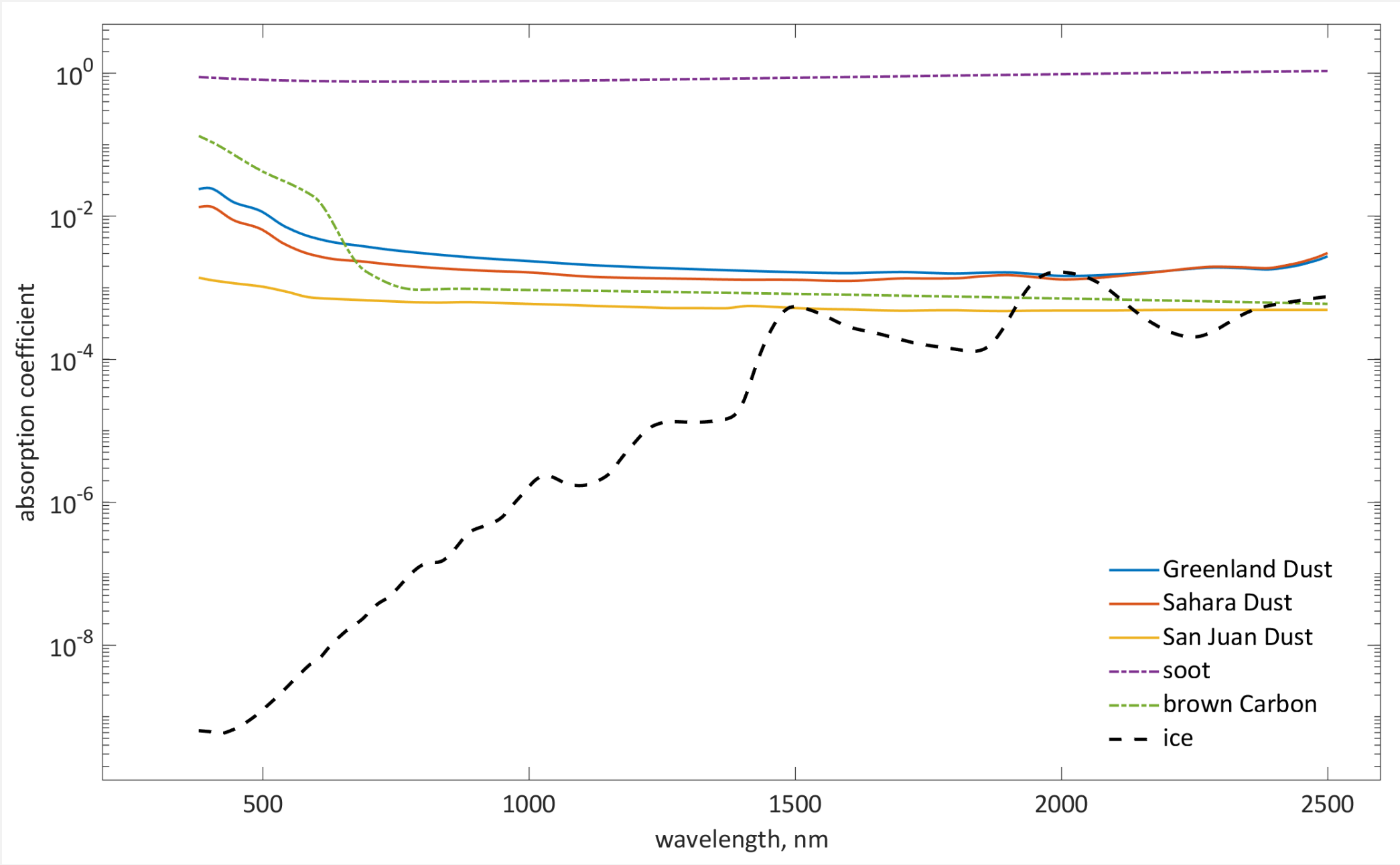

375



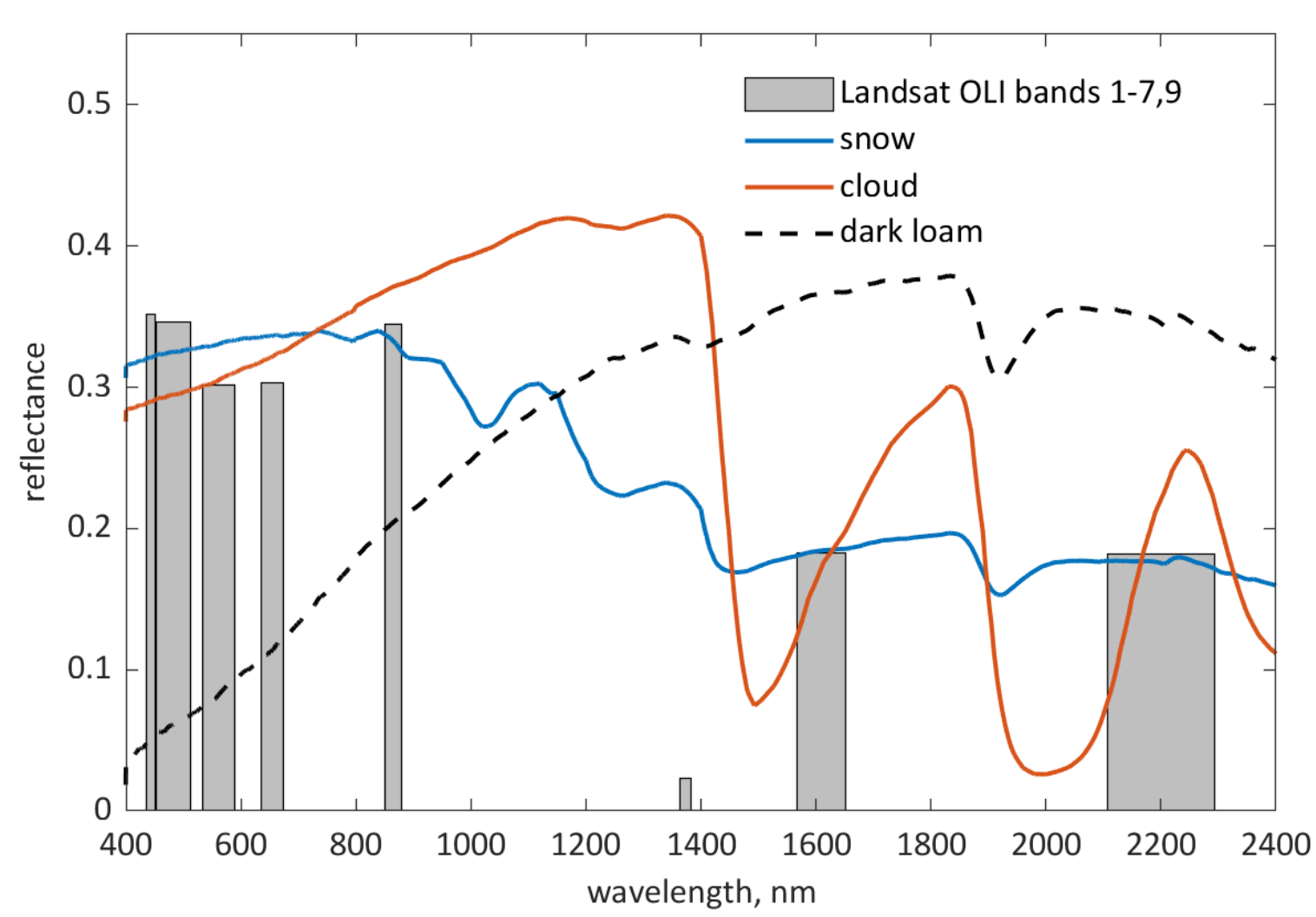

Rough element
causes shadow
Smooth surface,
forward reflection



Absorption coefficients (imaginary part of refractive index) of dust, black/brown carbon, ice



Snow and cloud can be too similar when viewed with a multispectral sensor



- Snow: clean, radius 346 µm, f_{SCA} 30%, 49.5% dark loam, 20.5% photometric shade
- Ice cloud: radius 36 µm, water equivalent 0.25 mm, above dark loam surface

Heritage Literature (through 2000)

- Jones *MWR* 1913, early paper on dust in snow
- Giddings & LaChapelle *JGR* 1961, radiation as a diffusion process
- Bohren & Barkstrom *JGR* 1974, geometric optics, albedo independent of snow density
- Wiscombe & Warren *JAS* 1980 and Warren *RevG* 1982, Mie scattering, radiative transfer, effect of light-absorbing particles
- Dozier *WRR* 1981, qualitative retrieval of grain size (and SWE of shallow snow) from AVHRR
- Dozier *RSE* 1981, subpixel temperature retrieval
- Nolin et al. *RSE* 1993 and *AnnGlac* 1993, grain size, f_{SCA} from AVIRIS, used DISORT for angular reflectance
- Painter et al. *RSE* 1998, grain size, f_{SCA} from AVIRIS, extensive validation, multiple endmembers
- Nolin & Dozier *RSE* 2000, scaled absorption feature for grain size

After 2000

- Green et al. *WRR* 2006, absorption from ice, liquid water, and water vapor
- Painter et al. *PNAS* 2010, effect of dust on runoff timing and magnitude, radiative forcing concept
- Lundquist et al. *RSE* 2018, subpixel snow temperature from MODIS