Remotely sensed albedo and surface temperature of snow and ice: A contribution to estimation of the energy balance of snow and glaciers

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Two big observation problems in mountain hydroclimatology

- How much snow is there?
- At what rate does snow melt?

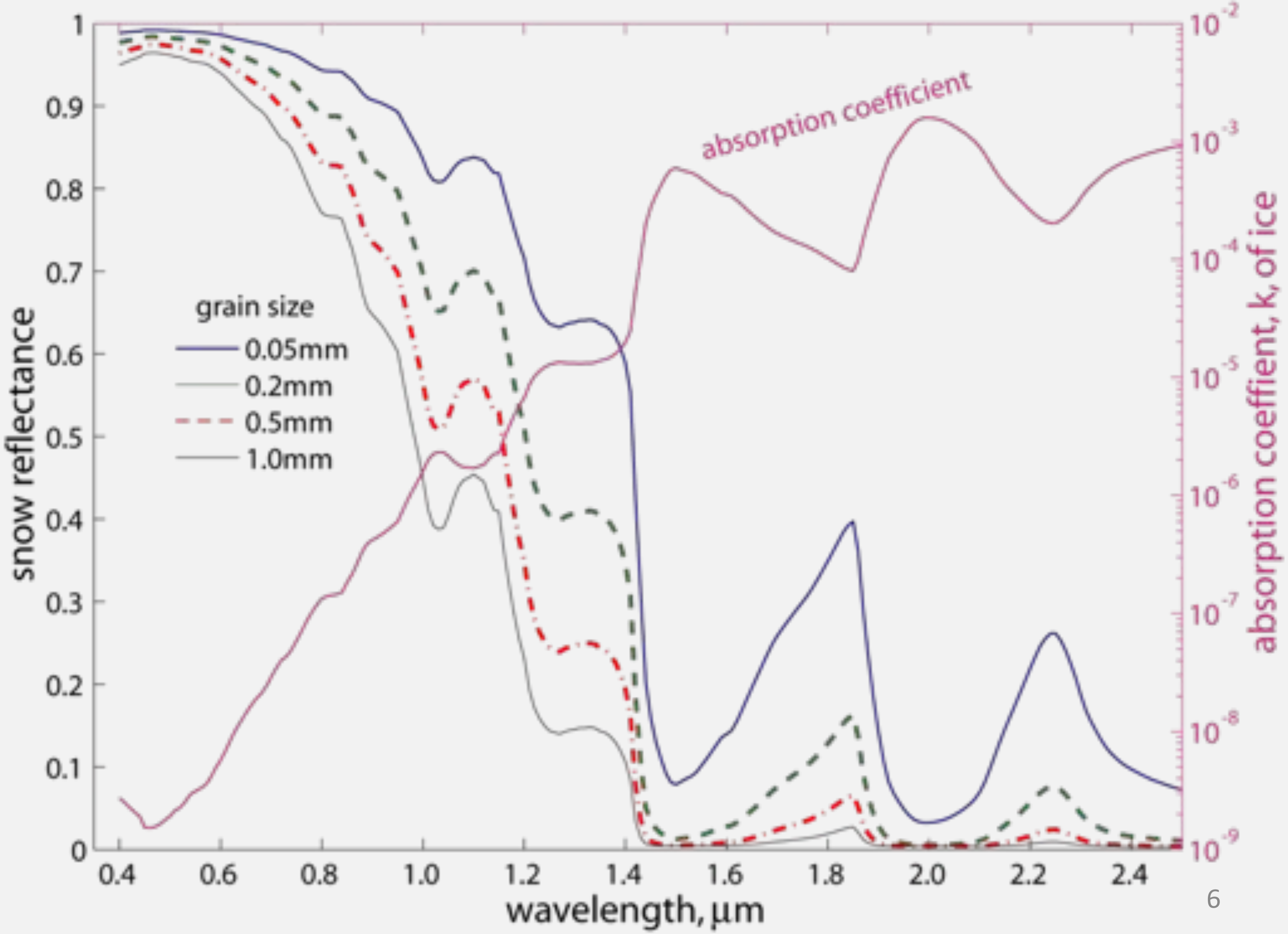
Two big observation problems in mountain hydroclimatology

- At what rate does snow melt?
  - Biggest driver is the radiation balance
  - Depends on the incoming solar and longwave radiation
    - Satellite missions like CERES can estimate
  - And on the spectral albedo and surface temperature
    - In the mountains, many pixels are mixed, with snow + soil and/or vegetation in the field of view
- How much snow is there?
  - *Topic for a different lecture*
  - Can be reconstructed from observing the date snow disappears

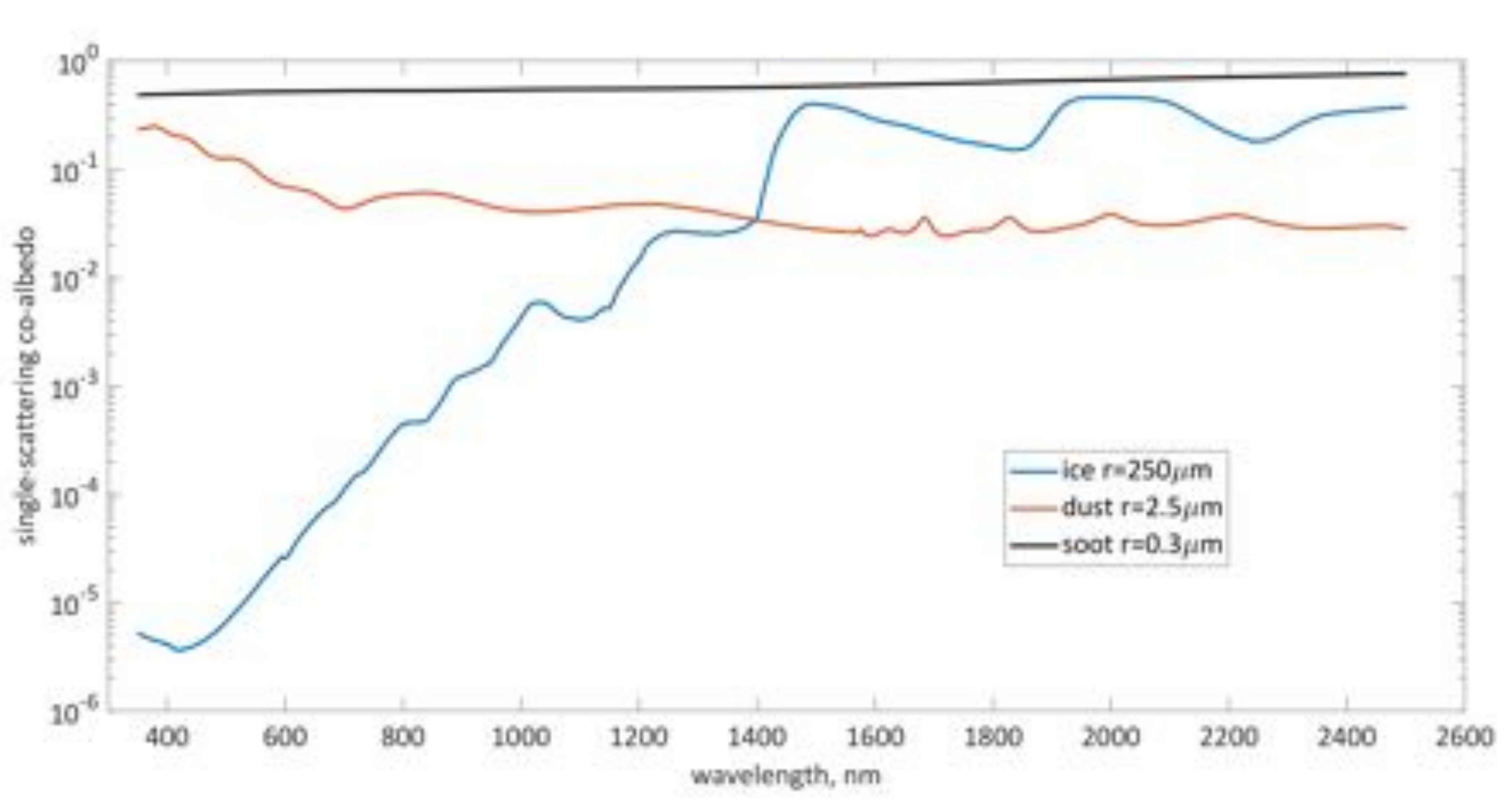
Part 1, Spectral albedo (and thus grain size and particulate concentration) of subpixel snow

Snow spectral albedo (reflectance) and absorption coefficient of ice

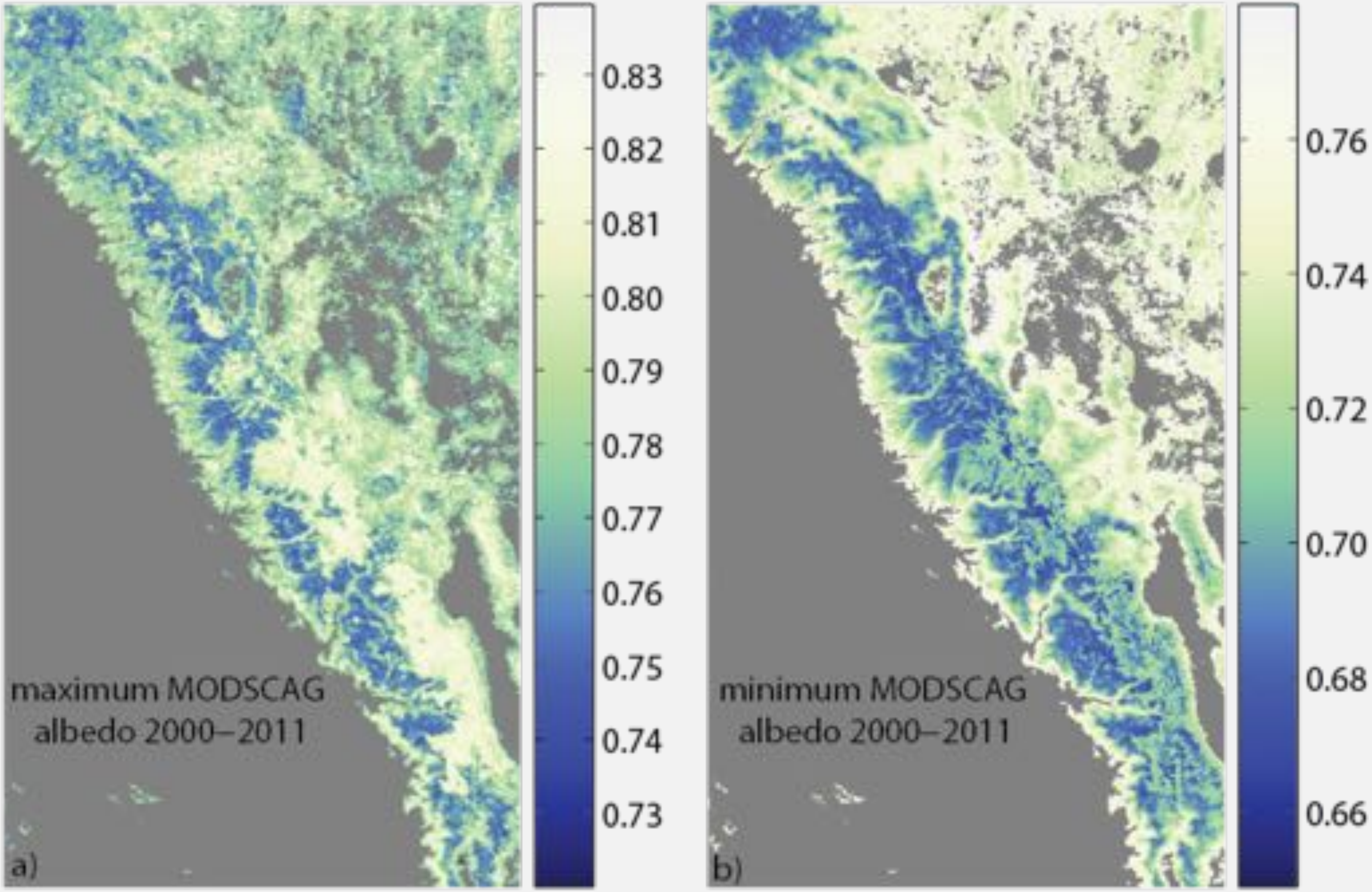
- Albedo of clean snow varies with grain size



Single-scattering co-albedo (1 – single-scattering albedo)



Remotely sensed albedo of fractional snow (too high along the boundary)



A new continuum approach with nonlinear least squares, **applied to an imaging spectrometer (AVIRIS-NG, 425 spectral bands, 5-6 nm resolution)**

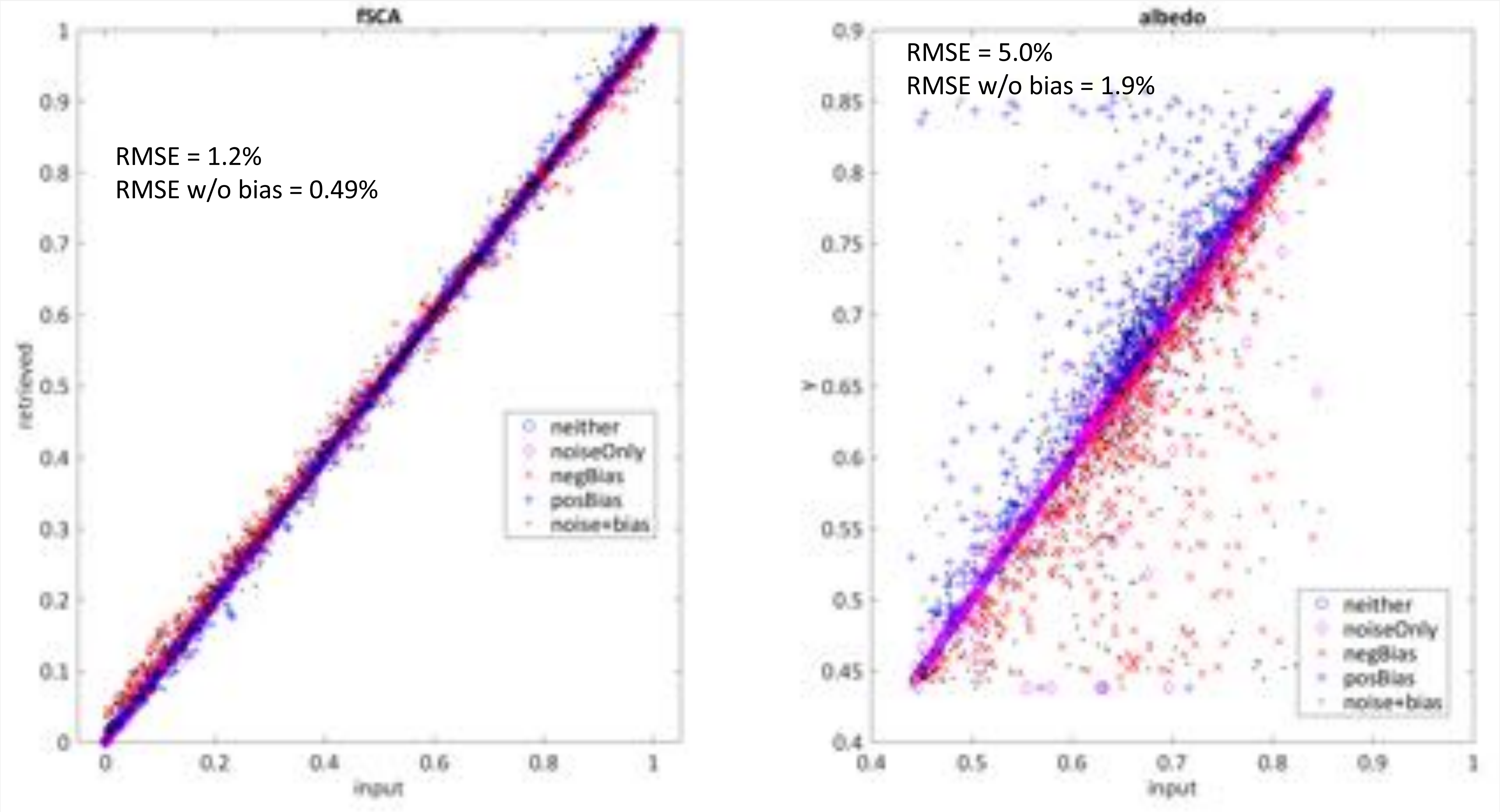
- Treat the snow as a single endmember at illumination angle θ with variable grain size r and contaminant concentration c, so $R_{\lambda,snow} = \mathrm{F}(\cos\theta, r, c)$, with estimated optical properties of dust or soot that could vary regionally
- Use snow-free imagery or adjacent pixels to estimate the background reflectance $R_{\lambda,back}$

$$R_{\lambda,model} = f_{SCA} R_{\lambda,snow} + (1 - f_{SCA}) R_{\lambda,back}$$

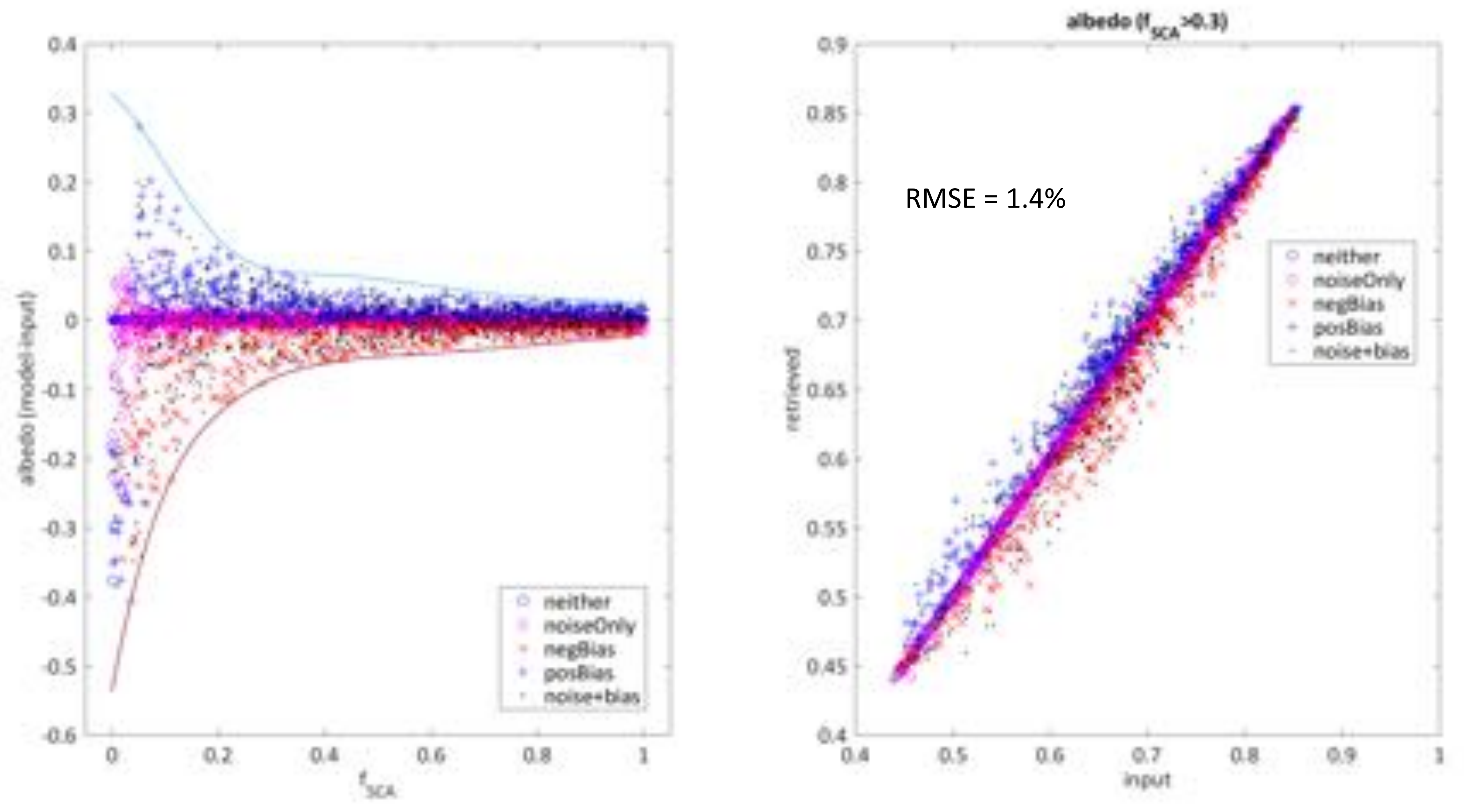
- Minimize, over 3 unknowns f_{SCA}, r, c, at multiple λ weighted by w_λ

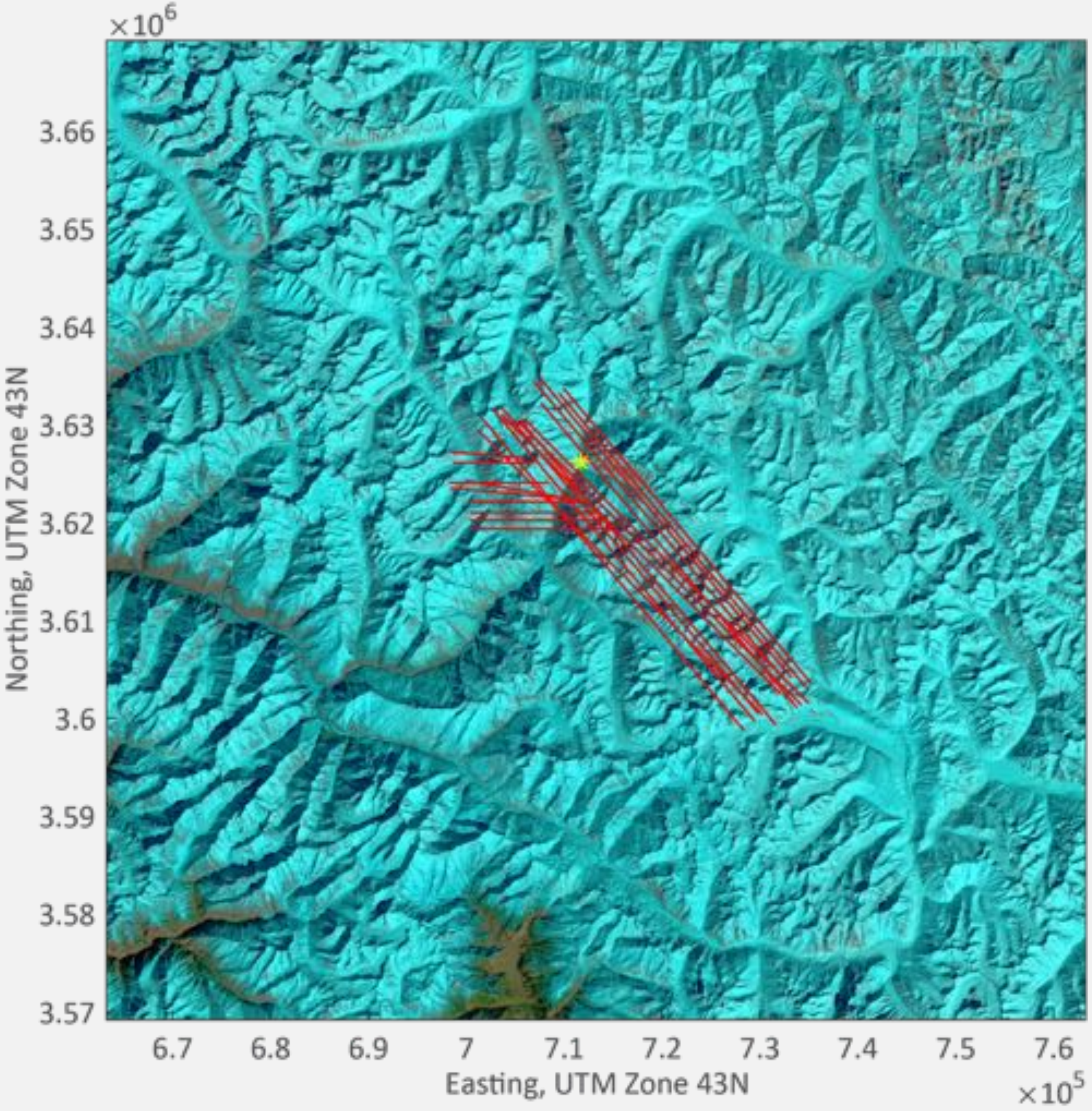
$$\sum_{\lambda} \left[w_\lambda \left(R_{\lambda,meas} - R_{\lambda,model} \right) \right]^2 \text{ or } \sum_{\lambda} \left[w_\lambda \left(\frac{R_{\lambda,meas} - R_{\lambda,model}}{R_{\lambda,meas} + R_{\lambda,model}} \right) \right]^2$$

Simulation tests: Fractional snow (f_{SCA}) and albedo, pale brown silt + grass



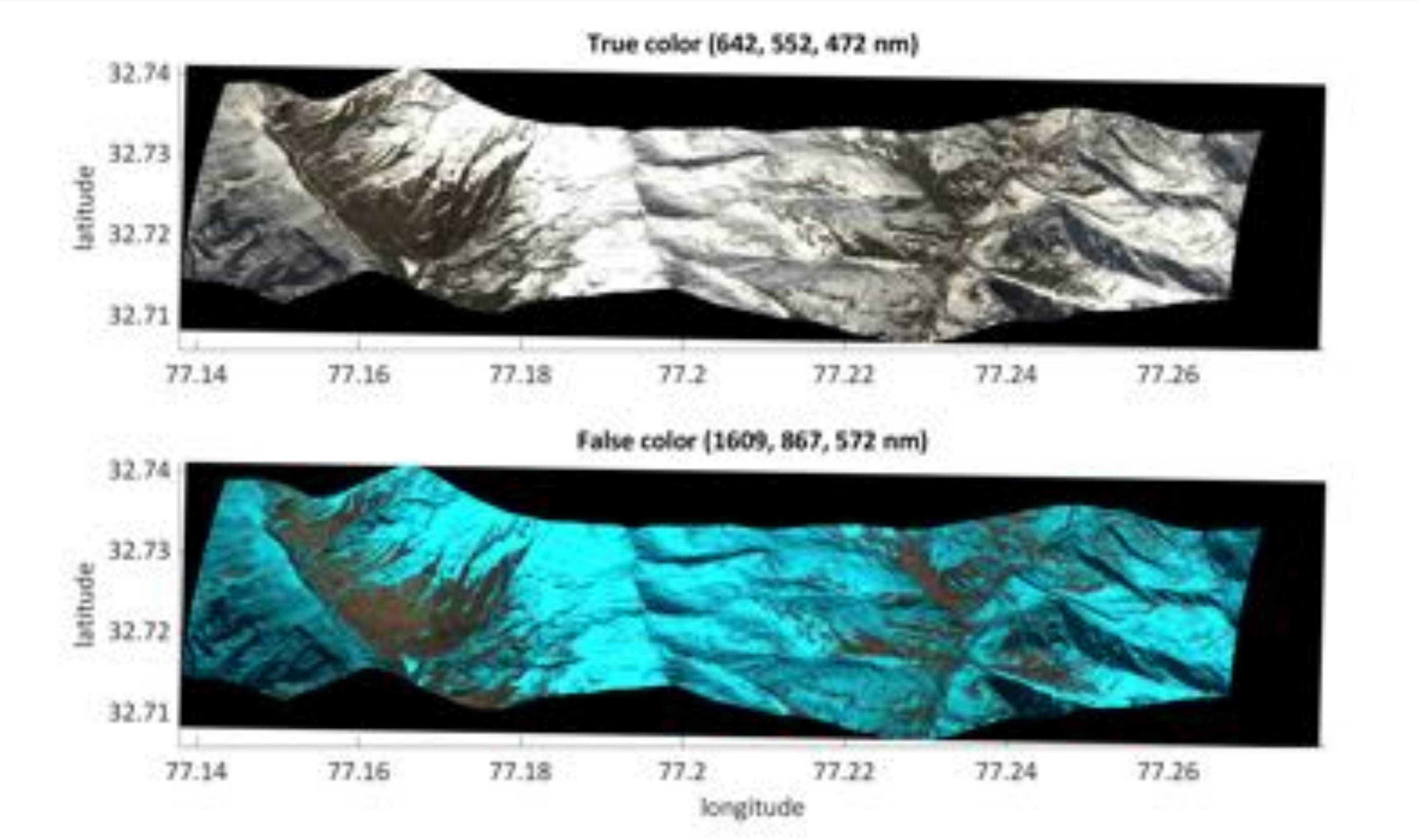
Restrict albedo calculation to pixels with f_{SCA}>0.3, grass+pale brown silt





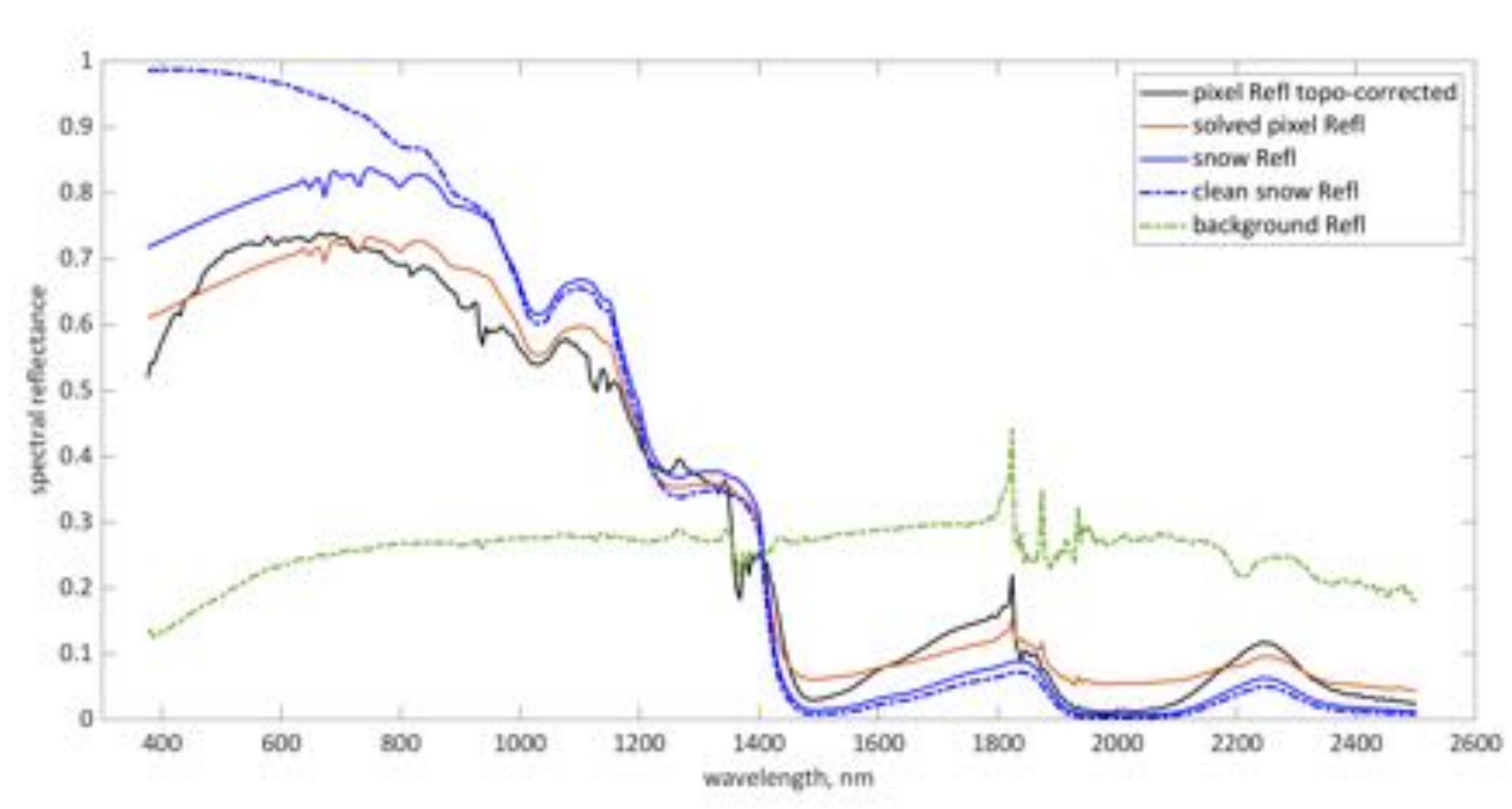
ISRO-NASA campaign: AVIRIS-NG flight lines on Landsat image, Himachal Pradesh, Feb 2016

AVIRIS-NG images, Himachal Pradesh 17 Feb 2016

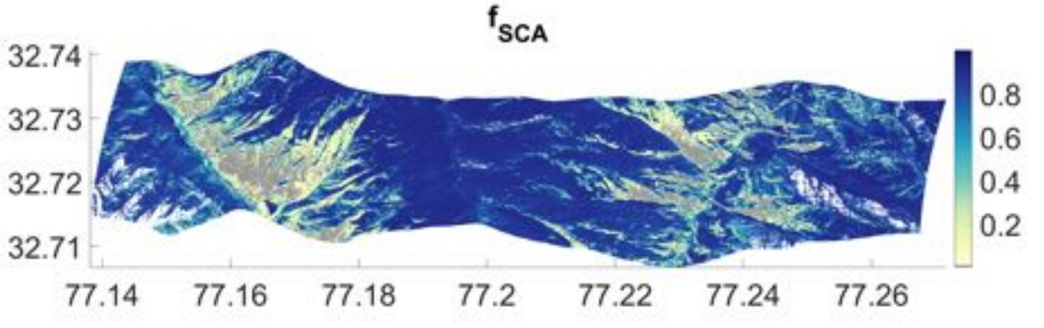


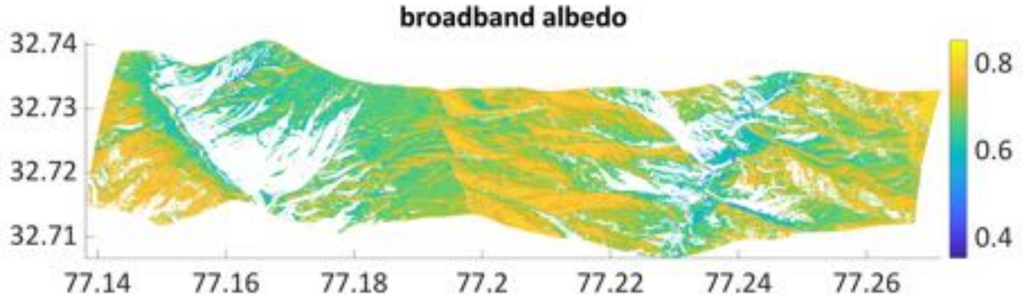
Typical solution for a pixel

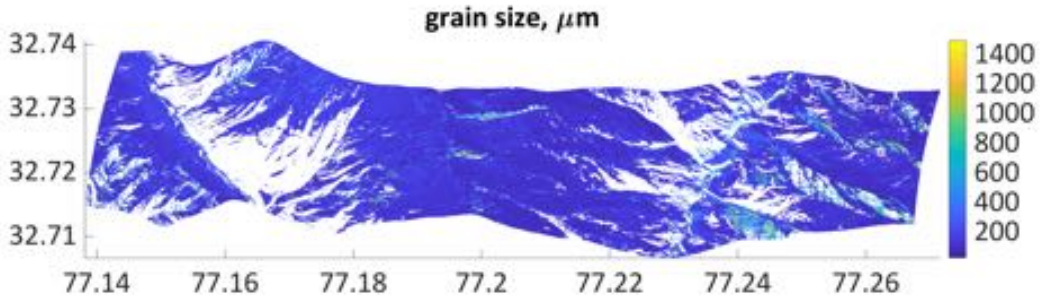
- f_{SCA} = 0.82
- Grain size (effective radius) = 212 μm
- Dust concentration = 4.3×10^{-4}
- Broadband albedo = 0.65 (clean 0.77)

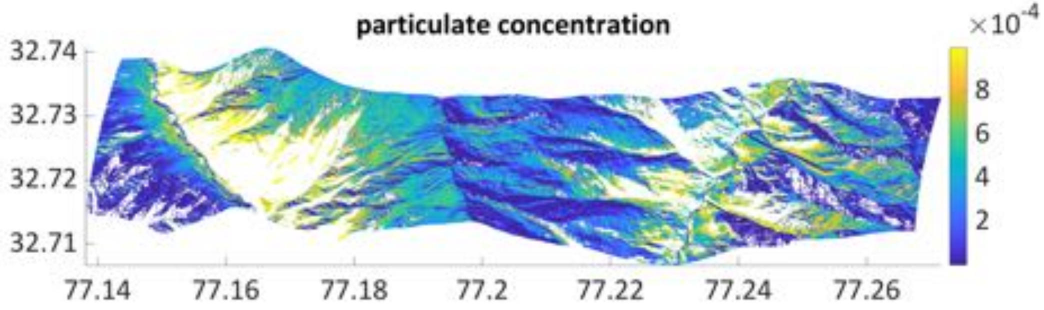


AVIRIS-NG results, 2016 Feb 17









Part 2, Learning to see in thermal infrared: Separating the temperatures of snow and trees

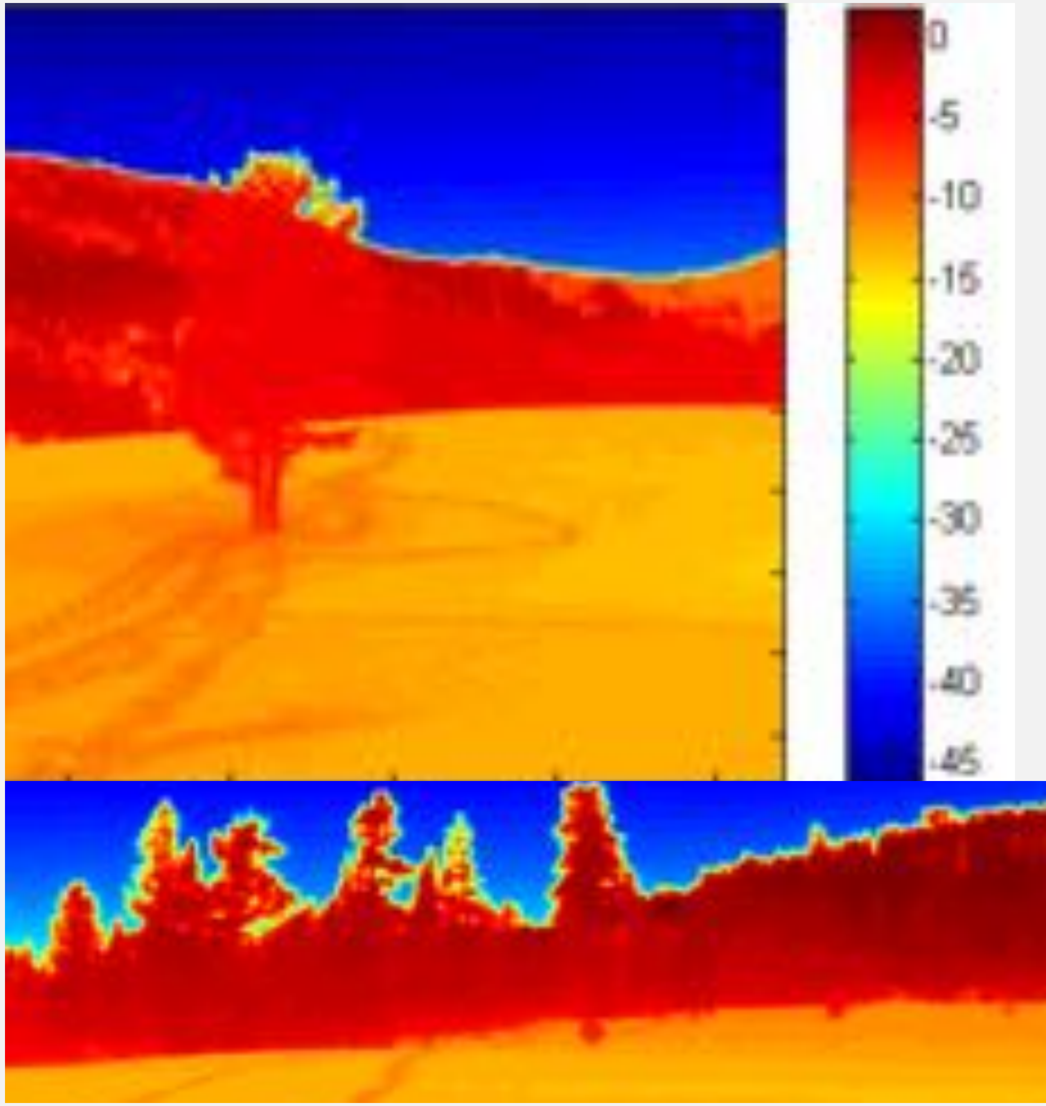
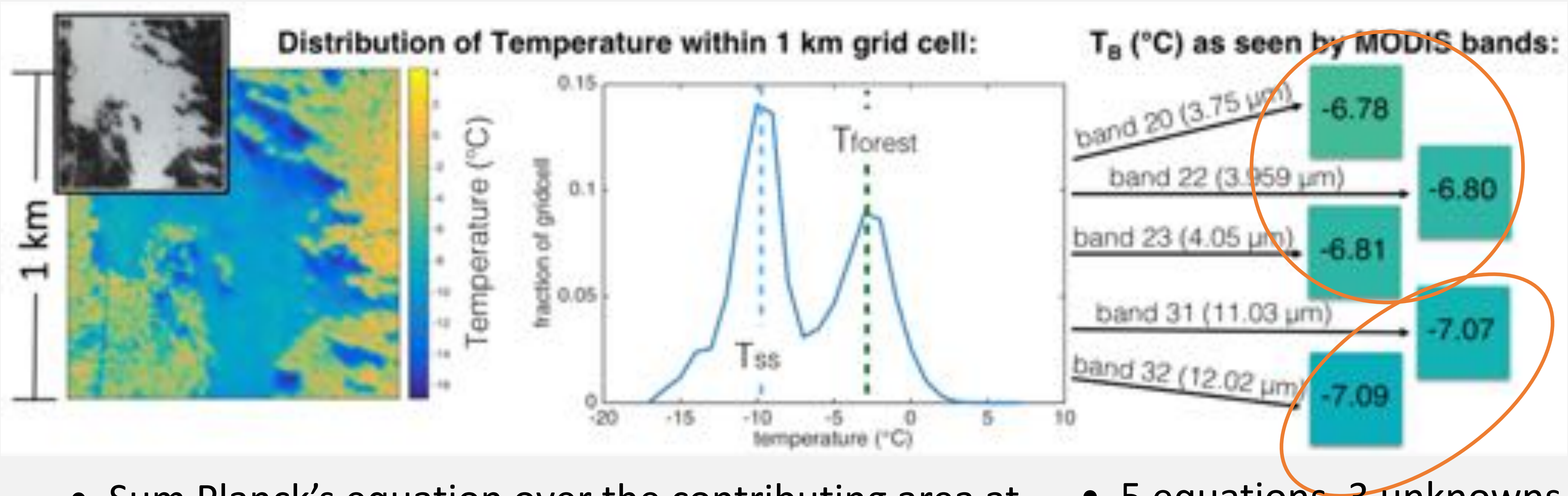


Photo by Ryan Currier

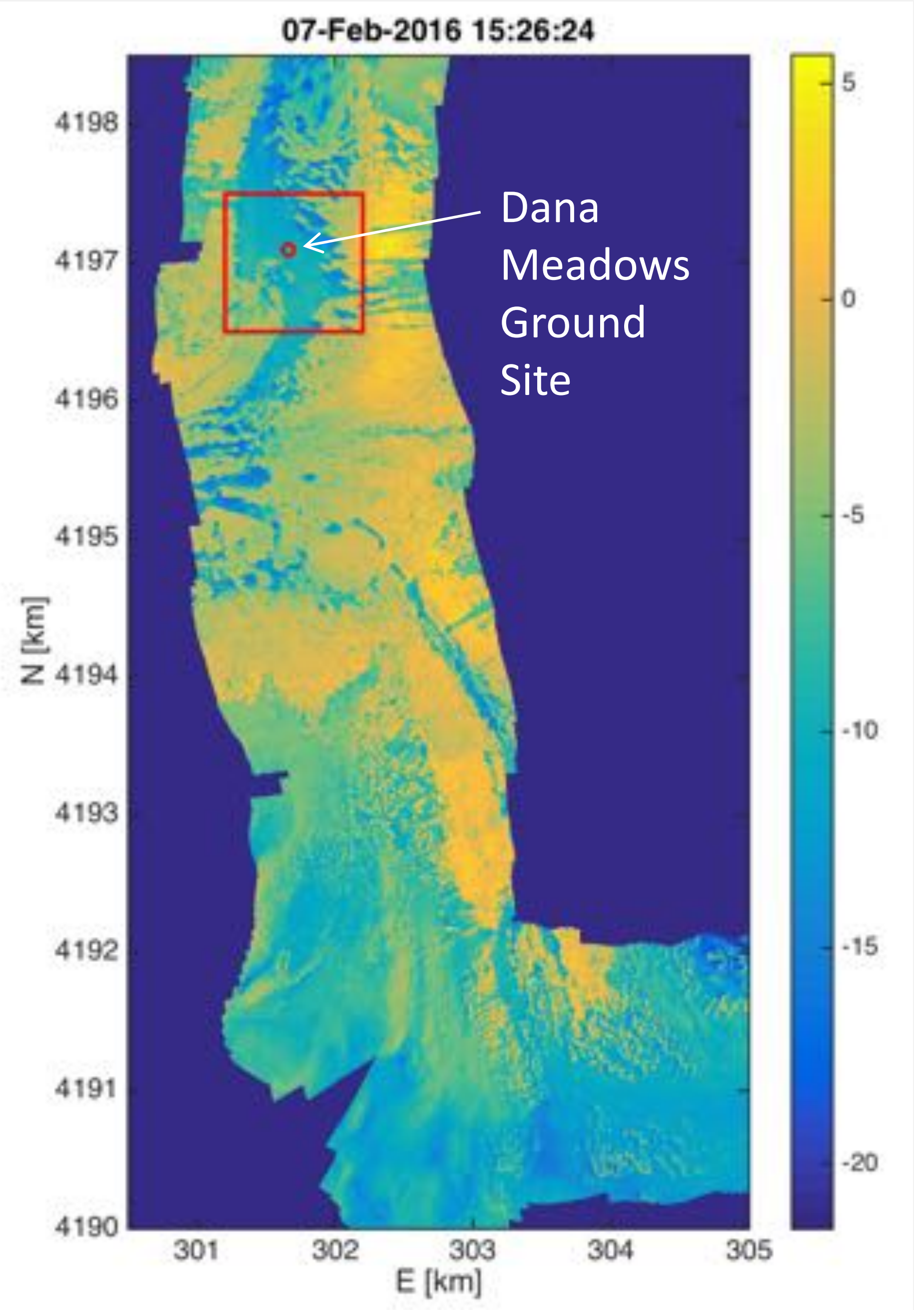
The disparate wavelengths enable separation of objects of different temperatures

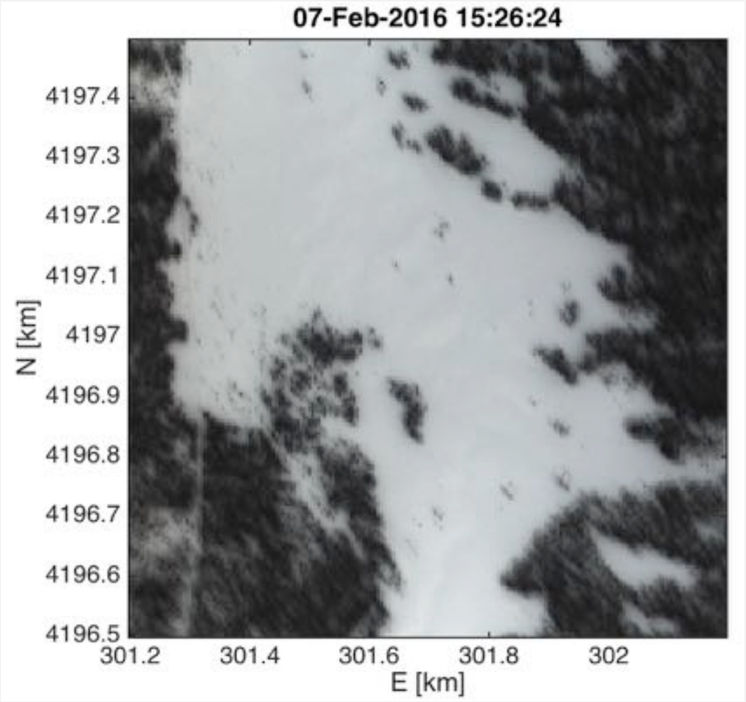
$$L[\lambda, T_b(\lambda)] = f_{SCA}\varepsilon_{snow}(\lambda)L(\lambda, T_{snow}) + (1 - f_{SCA})\,\varepsilon_{veg}(\lambda)L(\lambda, T_{veg})$$

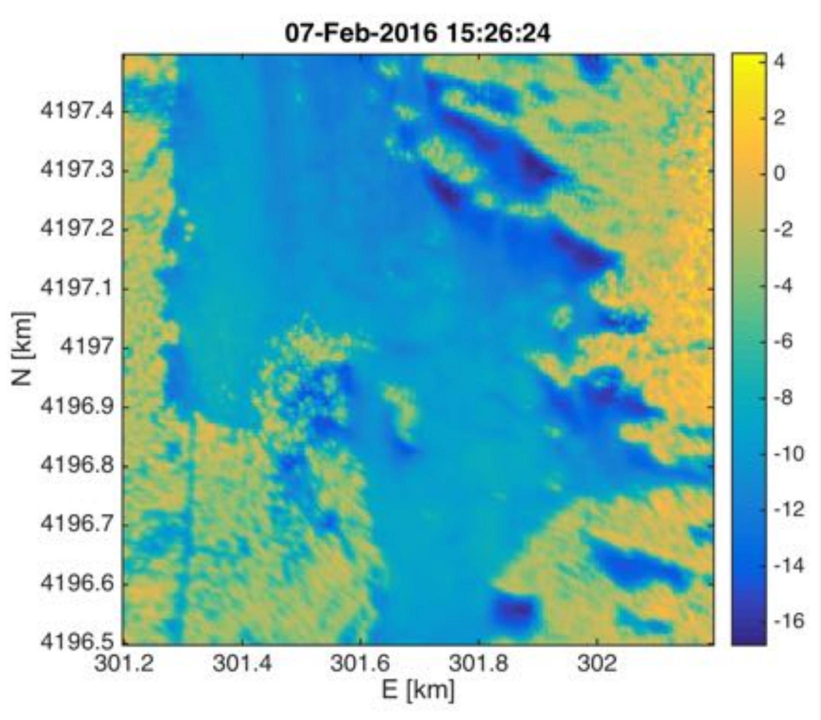


- Sum Planck's equation over the contributing area at each temperature and invert to get temperatures
- Use nonlinear optimization to fit two T values & f_{SCA}

- 5 equations, 3 unknowns
- ~~5 equations~~
- 2 equations, 3 unknowns

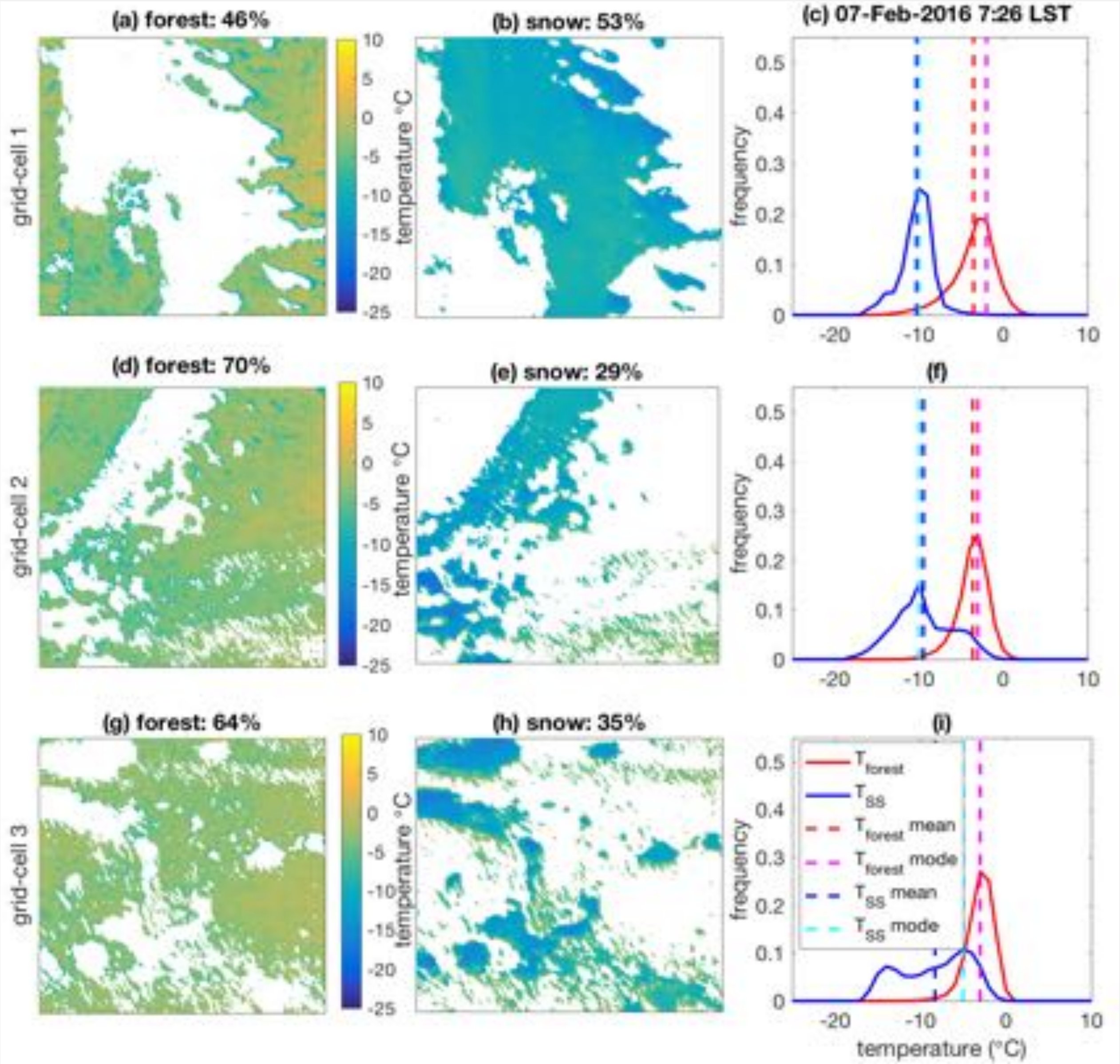






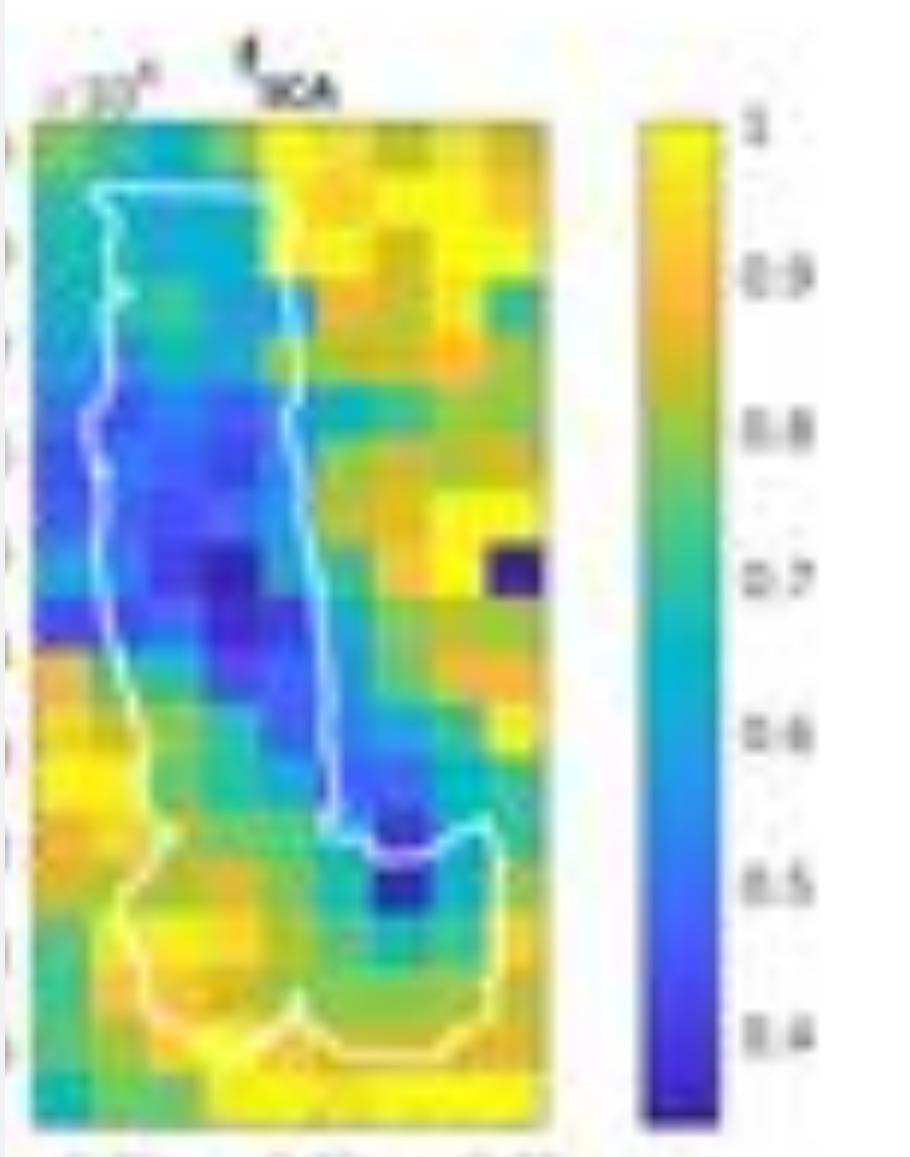
Showing 1 km x 1 km box (~ MODIS pixel size)

Night: While snow cover and local temperatures change rapidly in space, the median temperatures of trees and snow are similar in adjacent cells

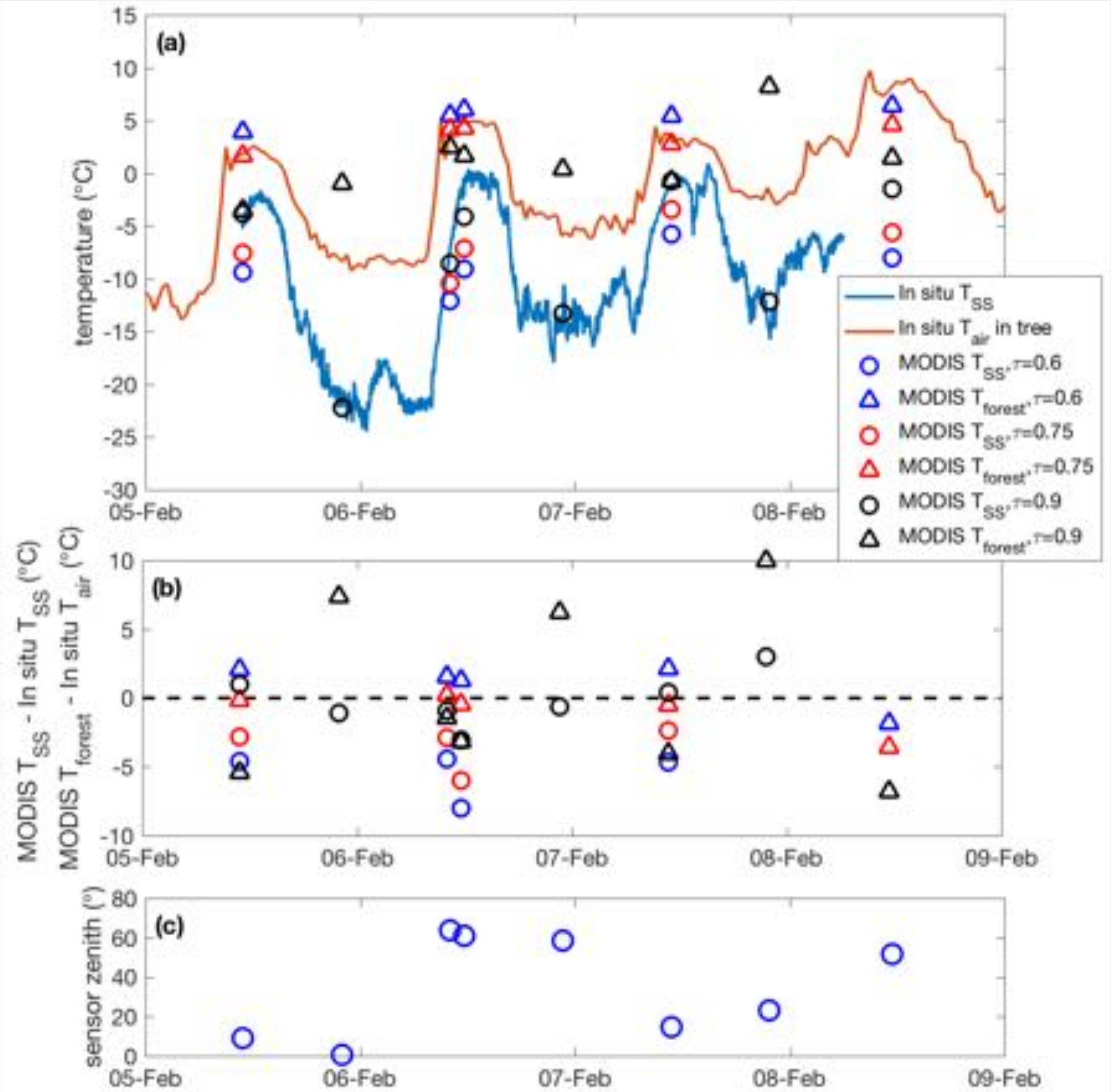


So, we take a 3 × 3 matrix of ~1 km cells, and solve for T_{snow}, T_{forest}, and 9 values of f_{SCA}
(45 equations, 11 unknowns)

Day



1) Reproject MODSCAG (Painter et al. *RSE*, 2009) f_{SCA} to the MODIS Level 1B geolocated grid
2) Use this f_{SCA} and the solar angles relative to the surface (and surface solar radiation observations if available) to calculate the expected radiance from reflected sunlight in the midwave IR bands
3) Subtract this from observed midwave radiance
4) Either use MODSCAG f_{SCA} to eliminate one unknown, and get pixel-by-pixel T_{snow} and T_{veg}.
5) Or use MODSCAG f_{SCA} as first guess and limits to the f_{SCA} fit to correspond with nighttime analysis



MODIS Results at Dana Field Site

1) At night, we can separate T_{snow} and T_{veg} at 1 km scale and match surface T_{snow} obs within ±1 °C
2) During the day, the method is sensitive to assumptions regarding the amount of solar radiation (τ) available for reflection in the midwave IR

Implications for the Third Pole: Observations from remote sensing

- Currently there is no spaceborne imaging spectrometer, but the recent U.S. Decadal Survey for Earth Science and Applications recommends one
  - Terrestrial and aquatic ecology would also benefit from such observations
- Surface temperature could be measured through diurnal cycle from small satellites
  - Useful in estimating evapotranspiration also
- Remotely sensing snow depth and water equivalent from satellite in the mountains is an unsolved problem
  - Significant results with aircraft using lidar with NASA's Airborne Snow Observatory, but that technology is difficult to move to space

Implications for the Third Pole: Policy

- Deposition of dust and especially black and brown carbon are easier to reduce than carbon dioxide and other greenhouse gases
- Glaciers integrate snowfall and melt of snow ice over decadal scales, hence their health identifies climate fluctuations over such time scales
- Melt from glaciers provides water in the mountains themselves, but overall most of the water comes from rain and melt of seasonal snow so forecasts would help manage water for competing uses of hydropower, irrigation, and maintenance of aquatic habitat

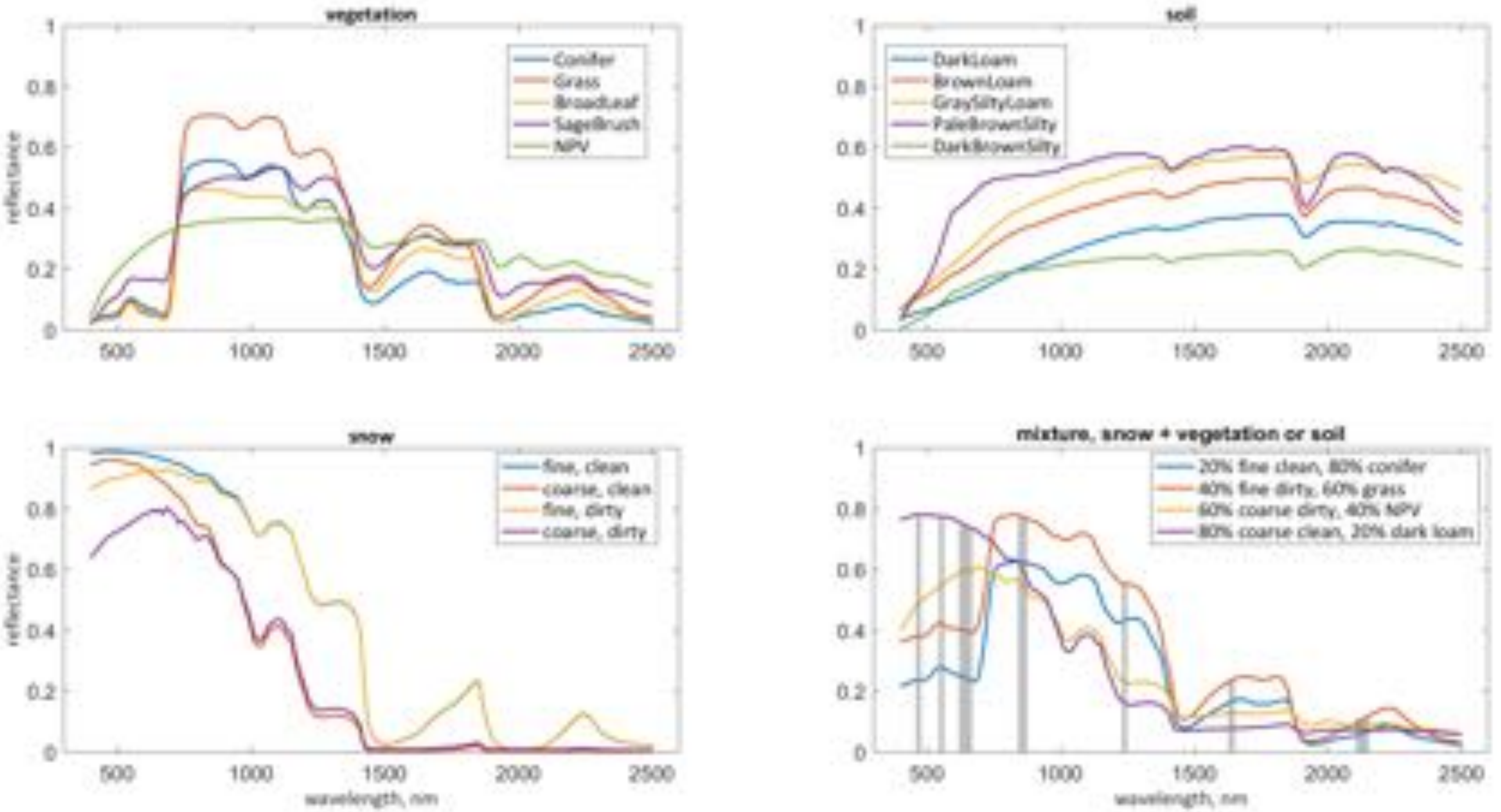
Details and backup slides, albedo

A change in albedo causes a bigger relative change in (1–albedo)

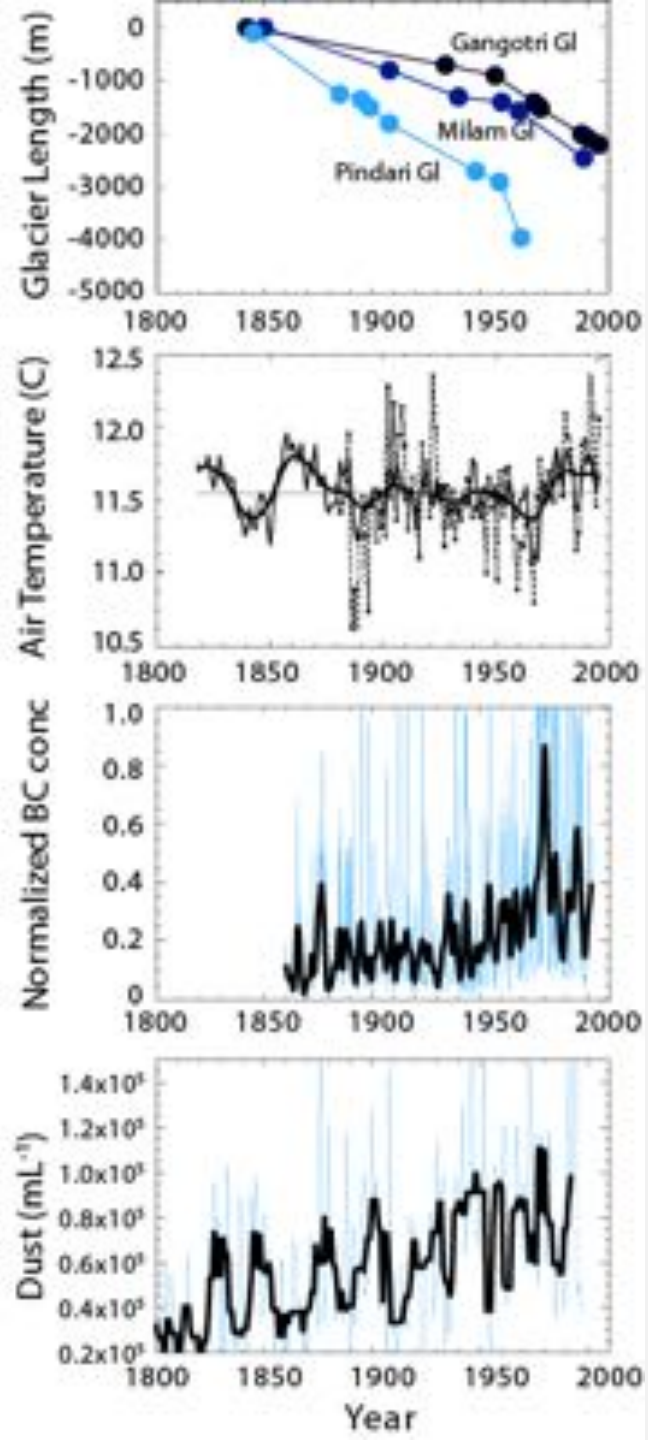
	albedo	Fraction absorbed (1–albedo)	
Start with	0.80	0.20	
Lower it by 20%, you get	0.64	0.36	An increase of 80%

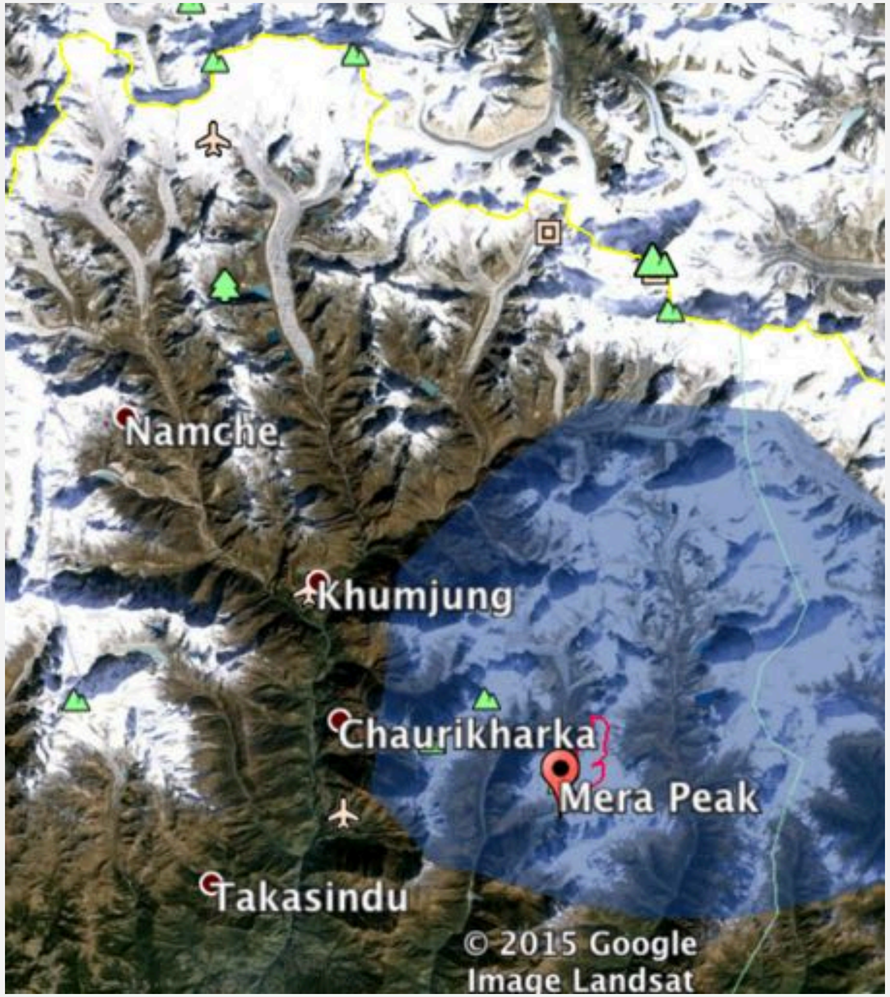
Problem & heritage: Measure the snow-covered fraction of a pixel, and the albedo of that snow

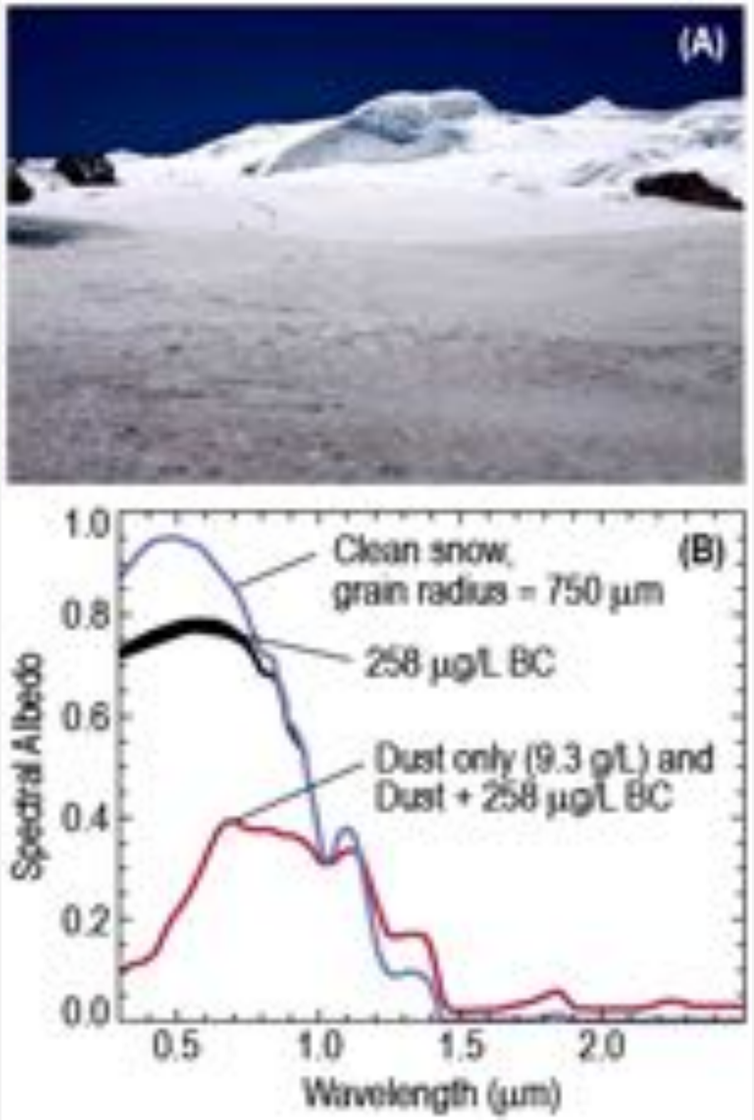
- Multiple endmember spectral mixture analysis (MESMA)
  - Mapping chaparral vegetation in the Santa Monica Mountains [Roberts et al., *Remote Sens Environ* 1998]
- Snow grain size of 100% snow-covered pixels from spectrum around ice absorption feature at 1030 nm
  - Model albedo of clean snow over whole spectrum once grain size is known [Nolin & Dozier, *Remote Sens Environ* 2000]
- Multiple endmember snow-covered area and grain size (MEMSCAG)
  - Consider snow endmembers of different grain size, combine with multiple vegetation and soil endmembers [Painter et al., *Remote Sens Environ* 2003]
- Adapted to 7 spectral bands of MODIS (MODSCAG)
  - [Painter et al., *Remote Sens Environ* 2009; Sirguey et al. *Remote Sens Environ* 2009]
- Quantifying effect of light-absorbing impurities from spectroscopy and multispectral remote sensing (MODDRFS)
  - [Painter et al., *Geophys Res Lett* 2012, *J Geophys Res* 2013]


vegetation
Conifer
Grass
Broadleaf
SageBrush
NPV
reflectance
soil
DarkLoam
BrownLoam
GraySiltyLoam
PaleBrownSilty
DarkBrownSilty
snow
fine, clean
coarse, clean
fine, dirty
coarse, dirty
wavelength, nm
mixture, snow + vegetation or soil
20% fine clean, 80% conifer
40% fine dirty, 60% grass
60% coarse dirty, 40% NPV
80% coarse clean, 20% dark loam

What forces glacier to melt?





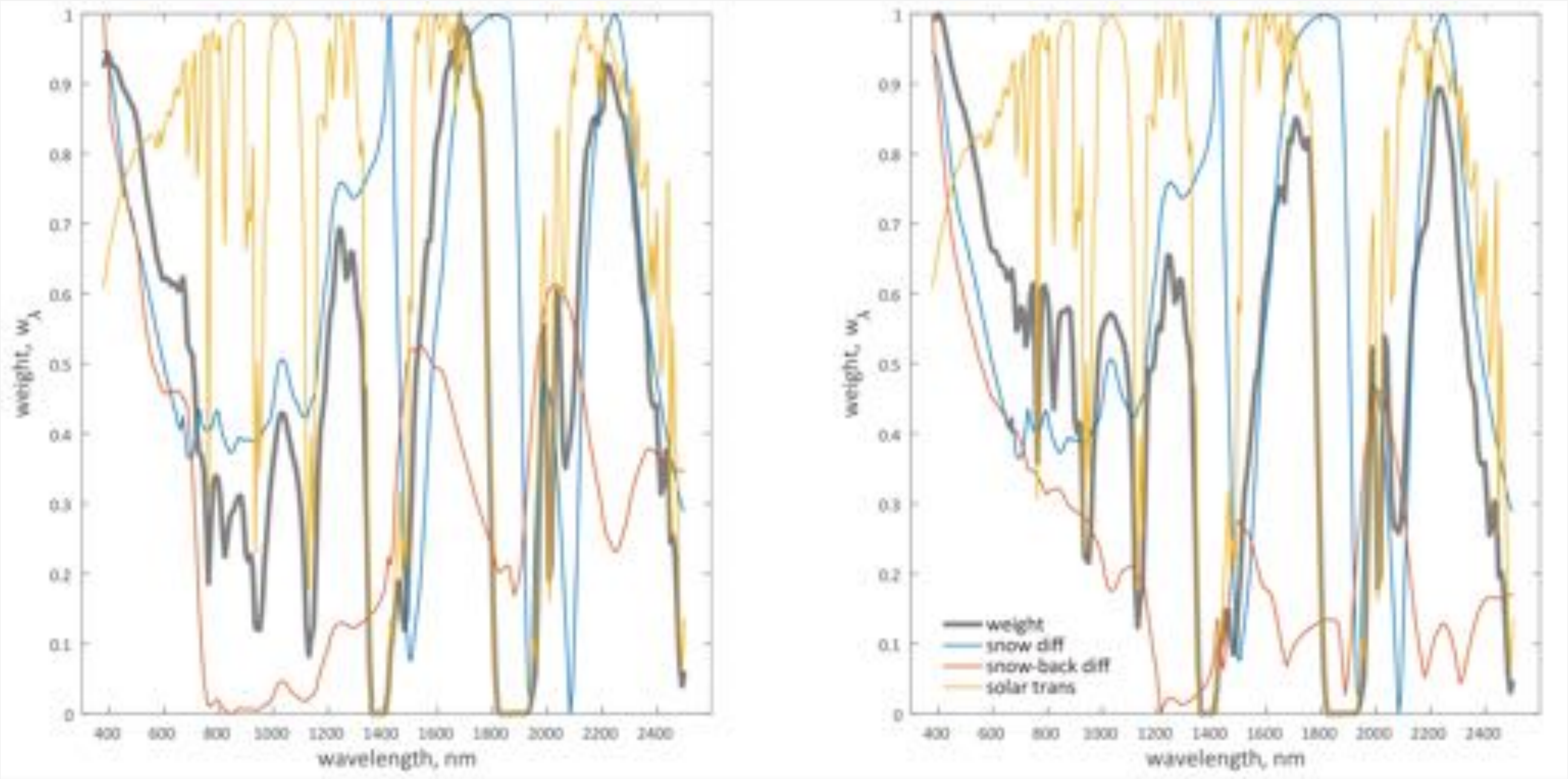


[Kaspari et al, 2014]

Choose weights based on snow, background, and atmosphere

snow, grass, pale brown silty

snow, NPV, dark brown silty

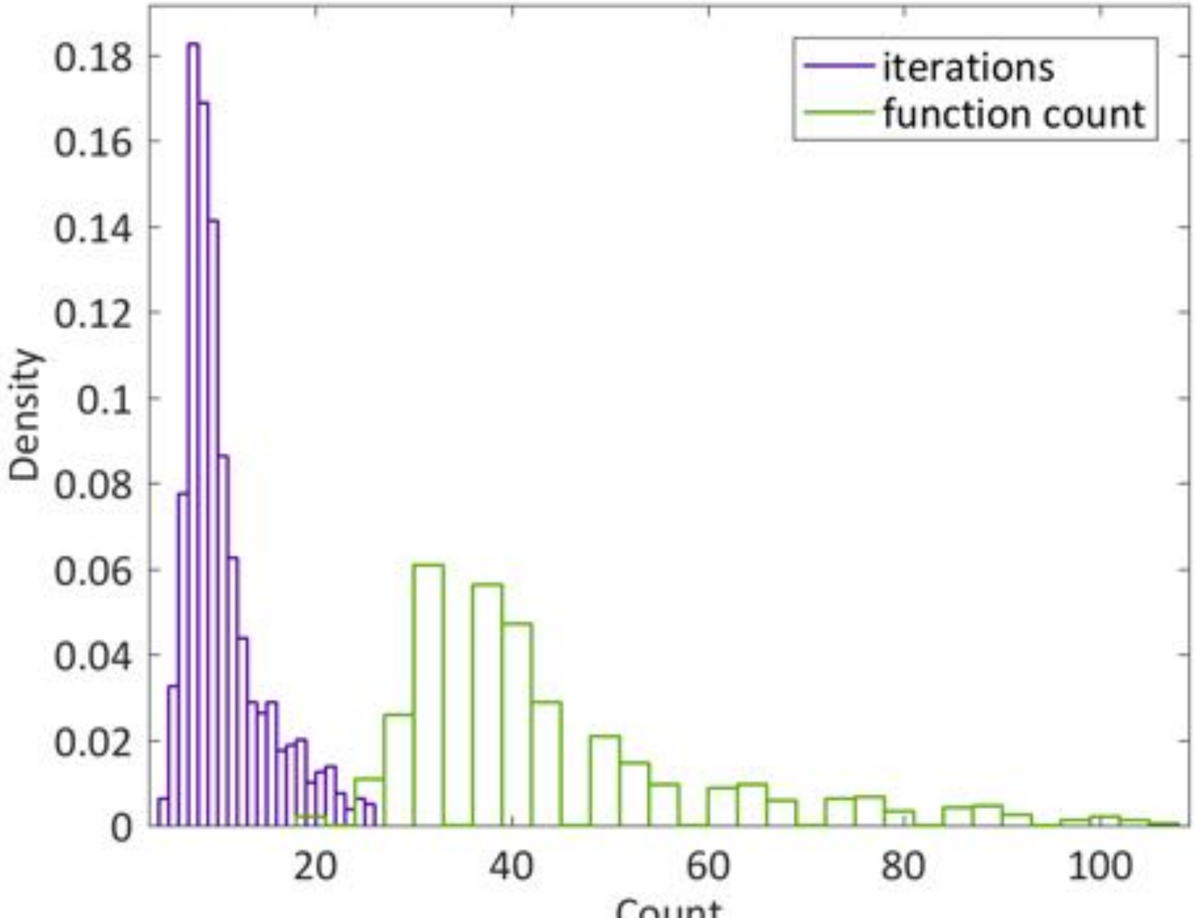


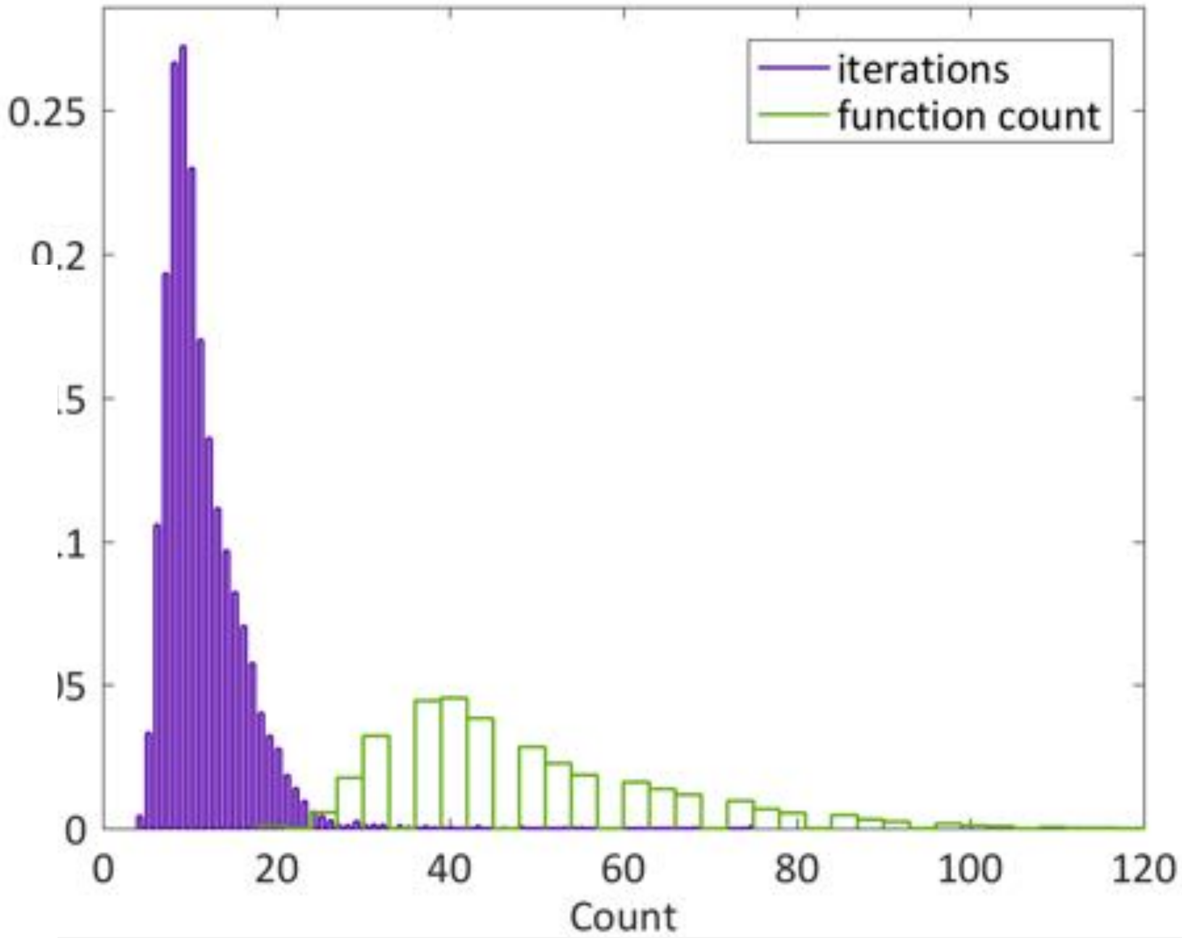
Calculations

- Mie scattering
  - For small Mie parameter $\left(\frac{2\pi r}{\lambda} < \sim 20\right)$ Bohren-Huffman code
    - Available from MATLAB File Exchange as MatScat, by J-P Schäfer
  - Else, Nussenzveig-Wiscombe complex angular momentum approximation
    - I've coded this in MATLAB, runs only a little faster than the Fortran version
  - Adjusted for dirty or sooty snow according to the absorption and scattering cross-sections
  - Sizes r_{dust}=1µm, r_{soot}=10nm, complex refractive indices from a presentation by Charlie Zender
- Radiative transfer
  - For directional-hemispherical reflectance, two-stream approximation based on the Meador-Weaver formulation
  - For BRDF, use DISORT

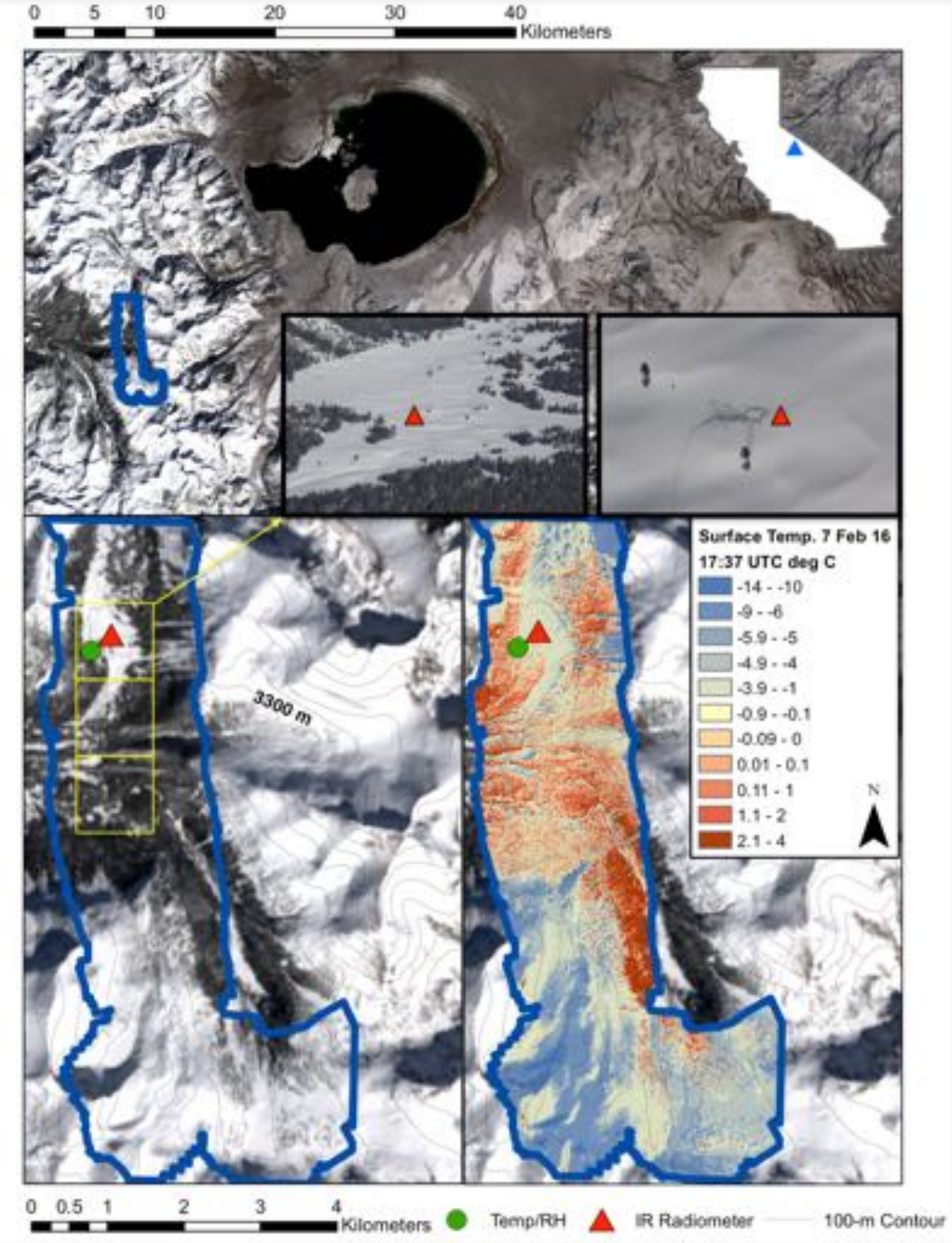
Calculations, cont.

- Minimizing least squares
  - Usually the MATLAB lsqnonlin function





Details and backup slides, snow temperature



Field Experiment

5-8 Feb 2016

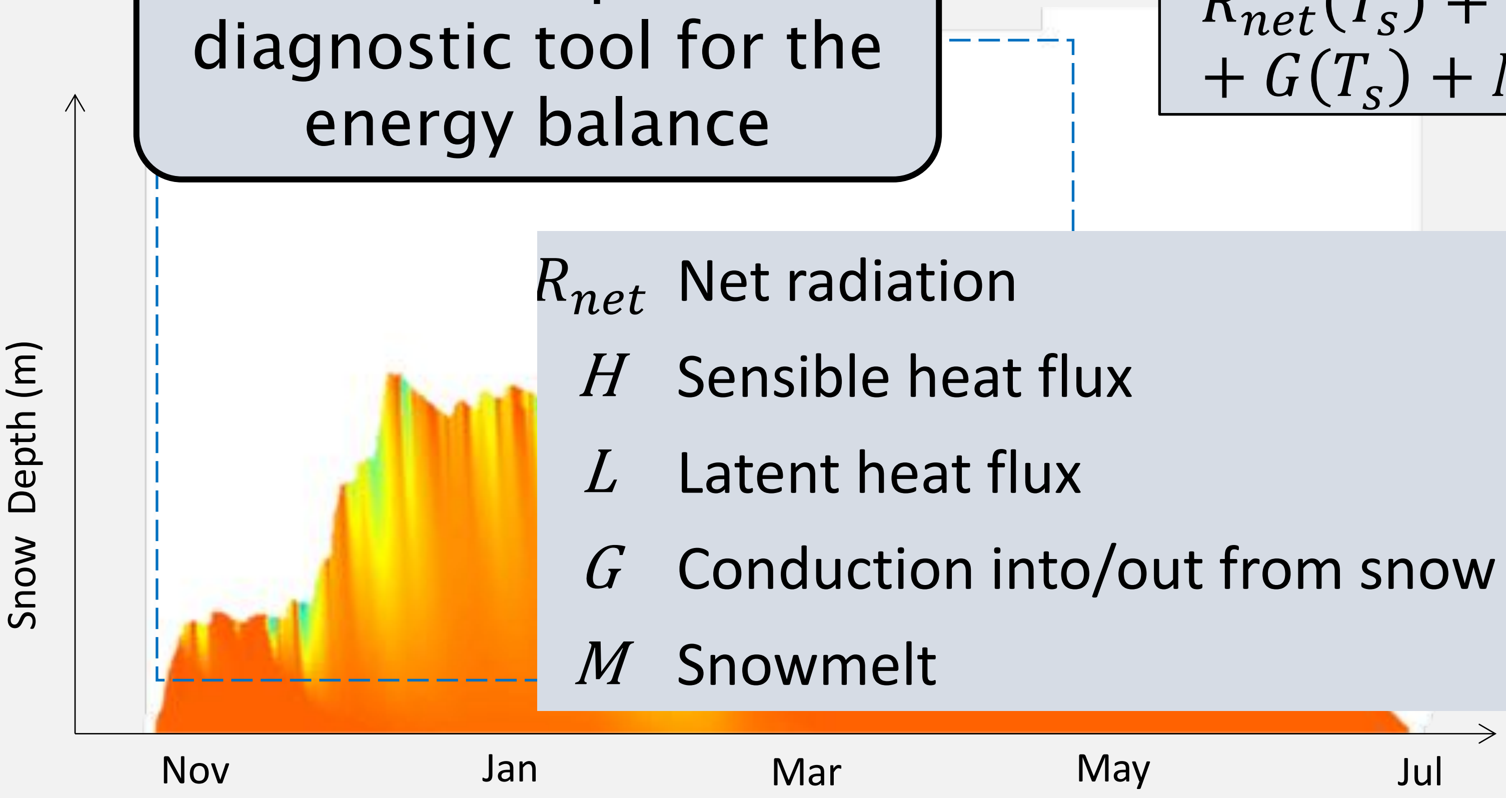
Dana Meadows, Yosemite National Park

Why infrared?

- Already measured remotely (lots of sensors, MODIS, VIIRS, Landsat TIRS, ASTER, etc., but not on Sentinel-2ab)
- IR cameras can be mounted on an airplane
- Use T_s to assess model energy balance during non-melt periods (Raleigh et al. *WRR* 2013; Lapo et al. *WRR* 2015; Pomeroy et al. *J Hydromet* 2016) and identify times wh

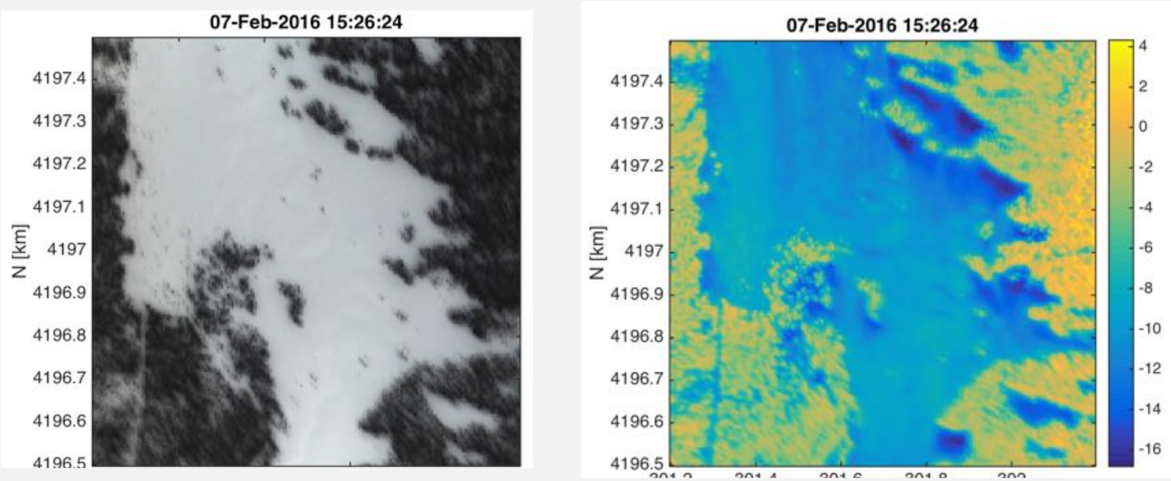
Surface Temperature: diagnostic tool for the energy balance

$$R_{net}(T_s) + H(T_s) + L(T_s) + G(T_s) + M(T_s) = 0$$

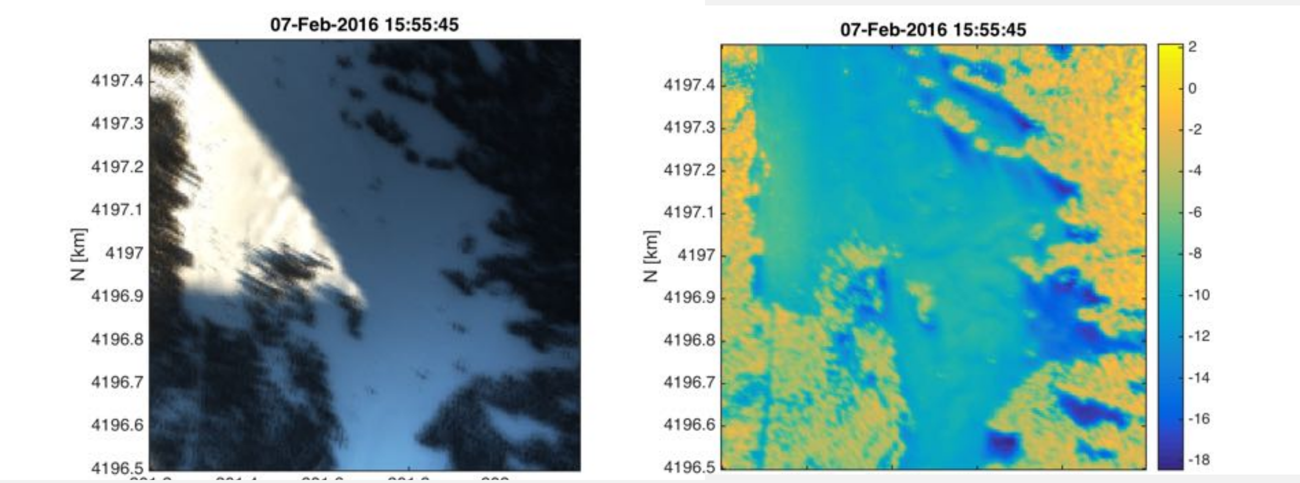


R_{net}	Net radiation
H	Sensible heat flux
L	Latent heat flux
G	Conduction into/out from snow
M	Snowmelt

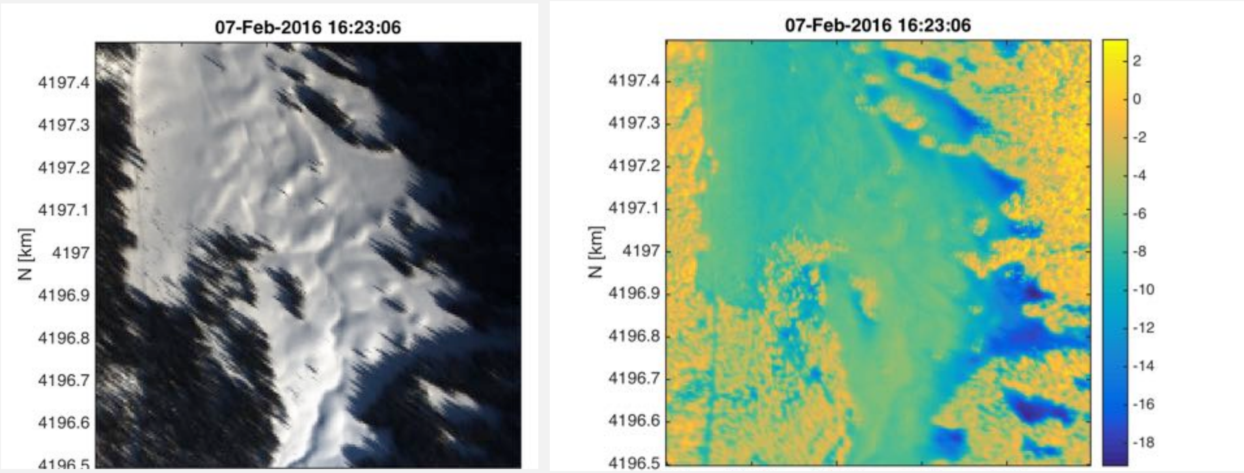
Before sun hits the meadow



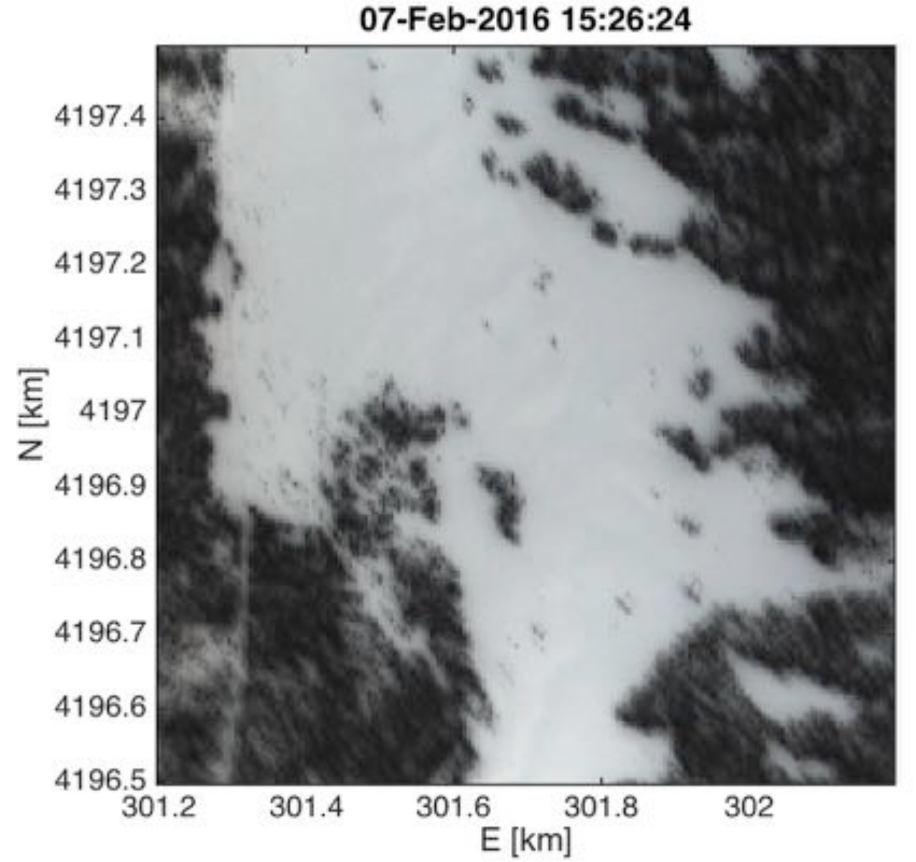
Sun just hits the meadow

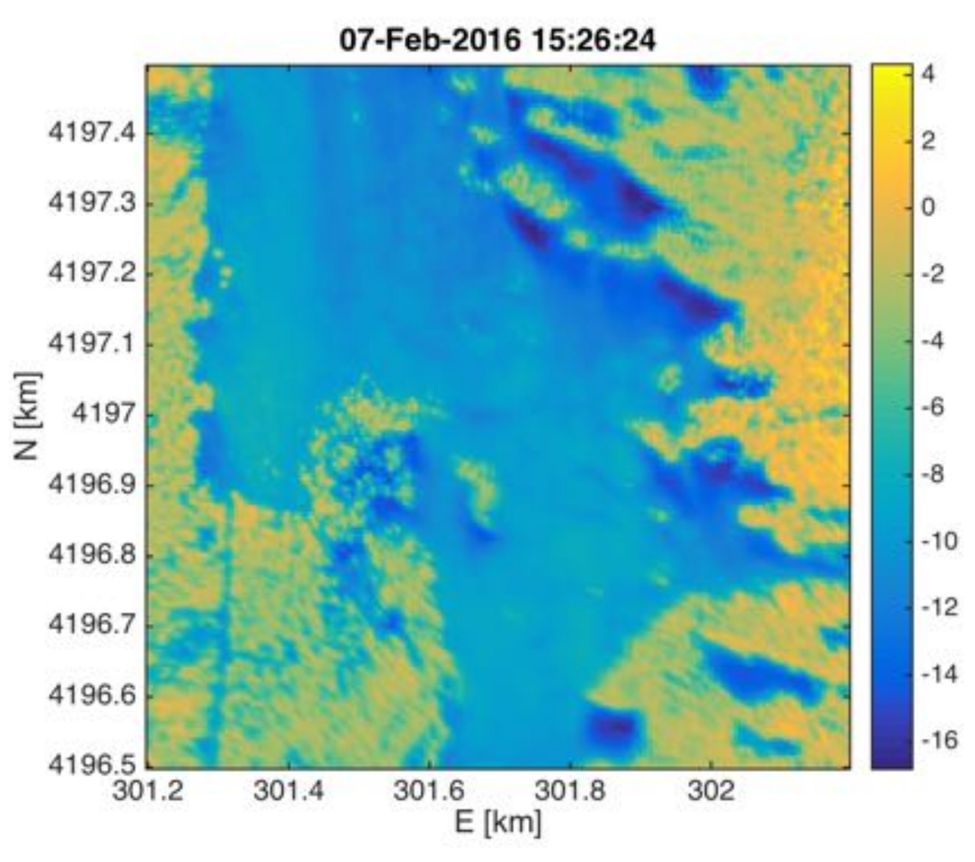


Sunny meadow with shadows



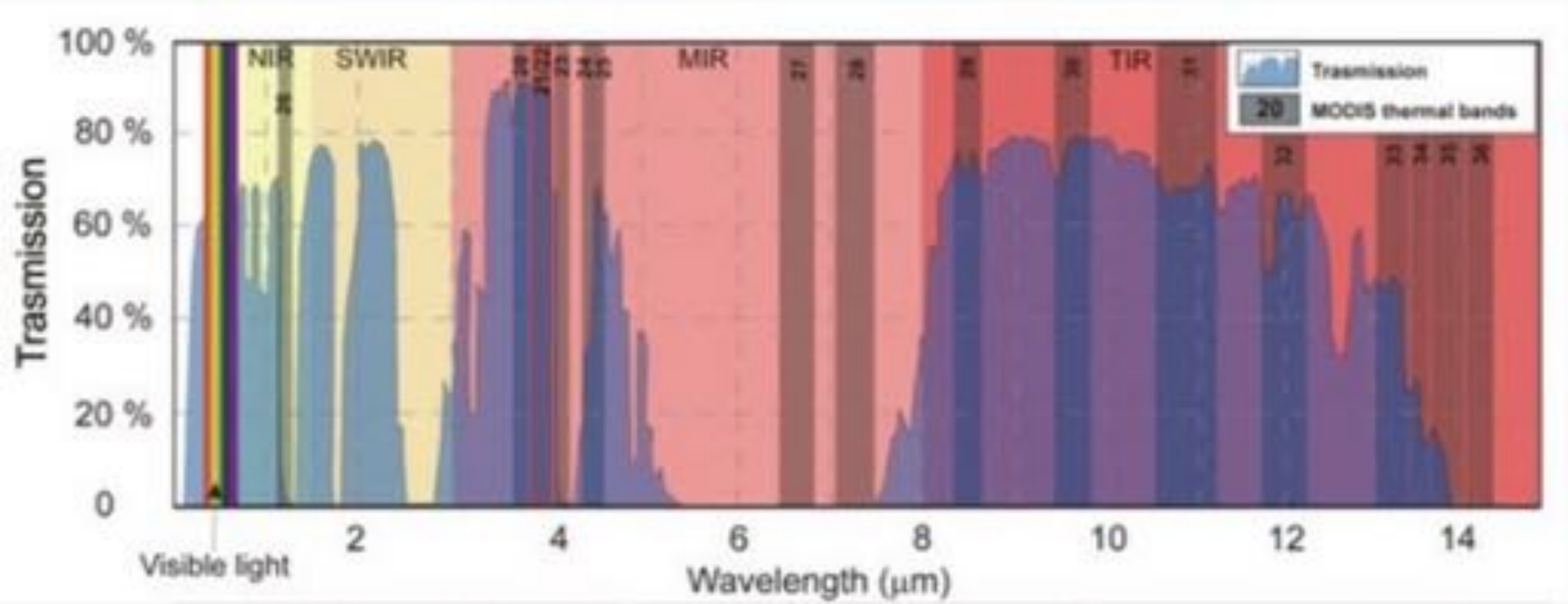
Looking at a 1 km grid cell (a MODIS pixel at nadir):





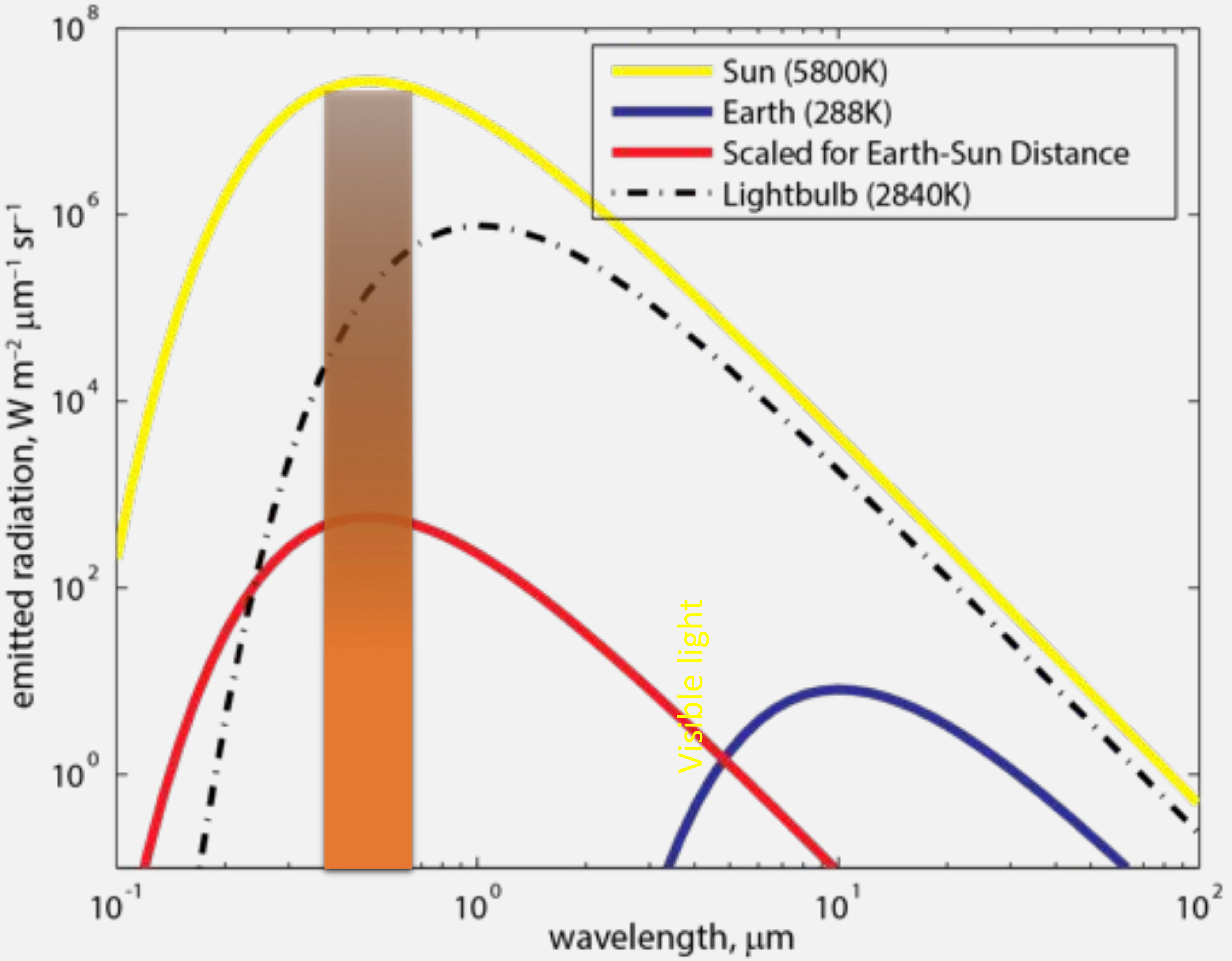
- In the mountains especially, nearly all pixels are "mixed," so the infrared signal incorporates temperatures of snow and "other" (here, trees), with their differences in temperature often exceeding 5 K

Atmospheric infrared "windows" around 4 μm and 11 μm



- Original purpose (NOAA AVHRR, 1978) was to enable atmospheric correction for sea-surface temperature measurements
  - Water vapor absorption slightly greater at 11 μm than at 4 μm

Planck equation for Sun and Earth



$$L(\lambda, T) = \frac{2hc^2}{\lambda^5 \left(e^{hc/k\lambda T} - 1\right)}$$

- c Speed of light
- h Planck constant
- k Boltzmann constant
- T Temperature (K)
- λ Wavelength, m