Interpretation and retrieval of snow properties from imaging spectroscopy, and its role in future Earth observing satellites

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Hydrology: Science and Applications Questions		Most Important Objectives
H1	**Coupling the Water and Energy Cycles.** How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?	H-1a. Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and close the water balance at Earth's surface and their interactions, daily at river basin scales.
		H-1b. Quantify rates of precipitation and its phase (rain and snow/ice) worldwide at convective and orographic scales suitable to capture flash floods and beyond.
		H-1c. Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide at scales driven by topographic variability.
H2	**Prediction of Changes.** How do anthropogenic changes in land use and water use interact and modify the water and energy cycles locally, regionally and globally and what are the short- and long-term consequences?	H-2c. Quantify how land-use and changes in land-cover related to agricultural activities, food production, and forest management affect water quality and especially groundwater recharge, threatening sustainability of future water supplies.

Two big observation problems in mountain hydrology

- In the middle and low latitudes, most of the snow is in the mountains

1. How much snow is there, throughout a drainage basin?
    - We can reconstruct the amount of snow from observing the dates it disappears over an area and estimating the energy required, but only after it has melted
    - so we want to measure directly the spatial distribution of **snow depth** and **water equivalent** (depth × density)?

We need the melt rate to do this

2. At what rate does snow melt, throughout a drainage basin?
    - Biggest driver is the radiation balance
    - which depends on the incoming solar and longwave radiation
    - and on the **spectral albedo** and **surface temperature,** which we need to measure

Designated observations address multiple water-… …es

Target Observable	Science/Applications Summary	…t
Aerosols	**Aerosol properties, aerosol vertical profiles, and cloud properties** to understand their effects on climate and air quality	E… …nel/ r… …naging r… …on the same p…
Clouds, convection, and precipitation	**Coupled cloud-precipitation state and dynamics** for monitoring global hydrological cycle and understanding contributing processes including cloud feedback	Radar(s), with multi-frequency passive microwave …
Mass change	**Large-scale Earth dynamics** measured by the changing mass distribution within and between the Earth's atmosphere, oceans, ground water, and ice sheets	S… …rement of g…
Surface biology and geology	**Earth surface geology and biology**, ground/water temperature, snow reflectivity, active geologic processes, vegetation traits and algal biomass	Imaging s… …and shortwave … imagery in …
Surface deformation and change	**Earth surface dynamics** from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction

Radiation balance drives evapotranspiration and snowmelt

… precipitation and snowfall

Ground water recharge

Snow albedo, evapotranspiration, water quality

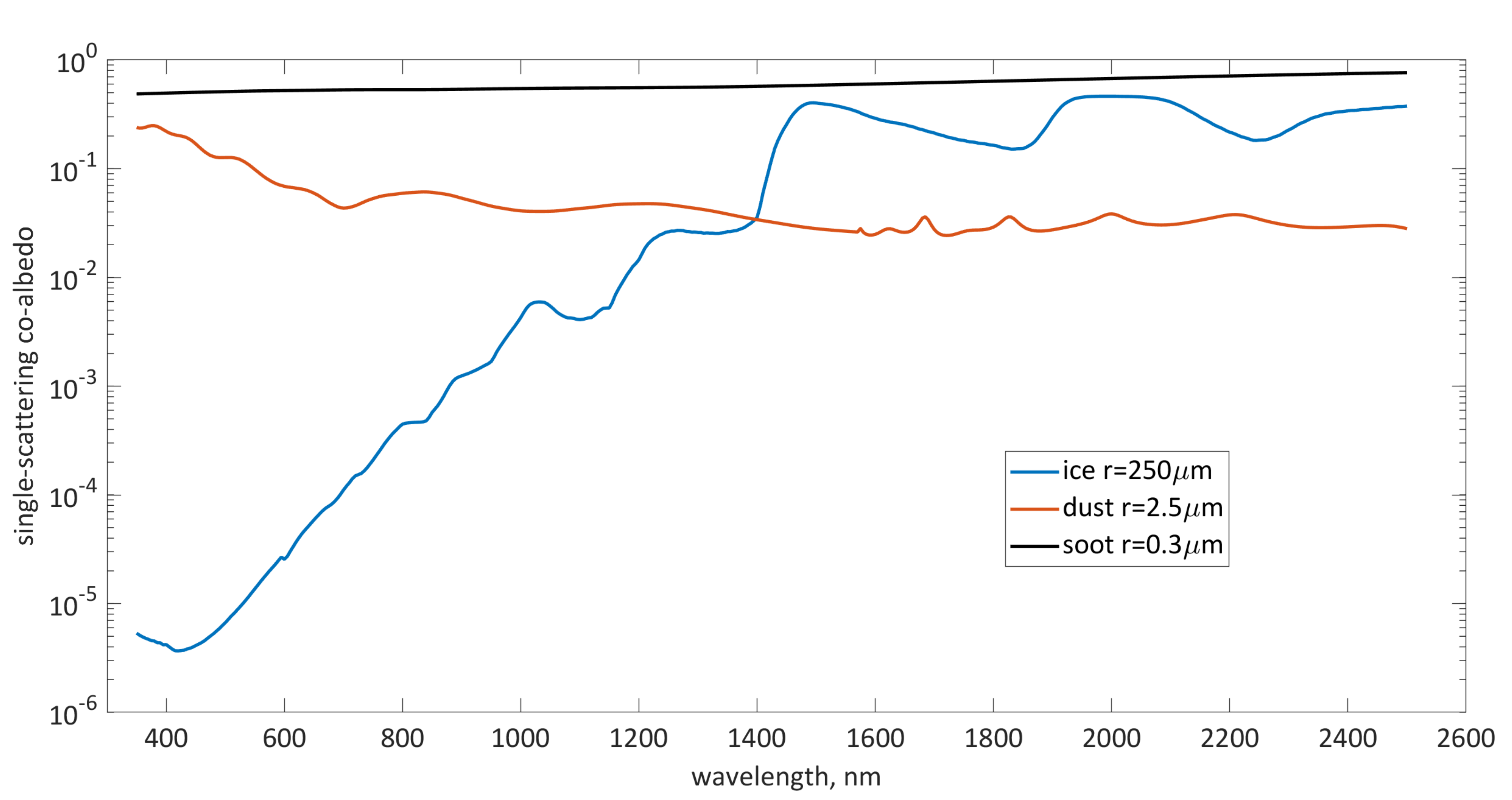
Potential path to snow density & water equivalent

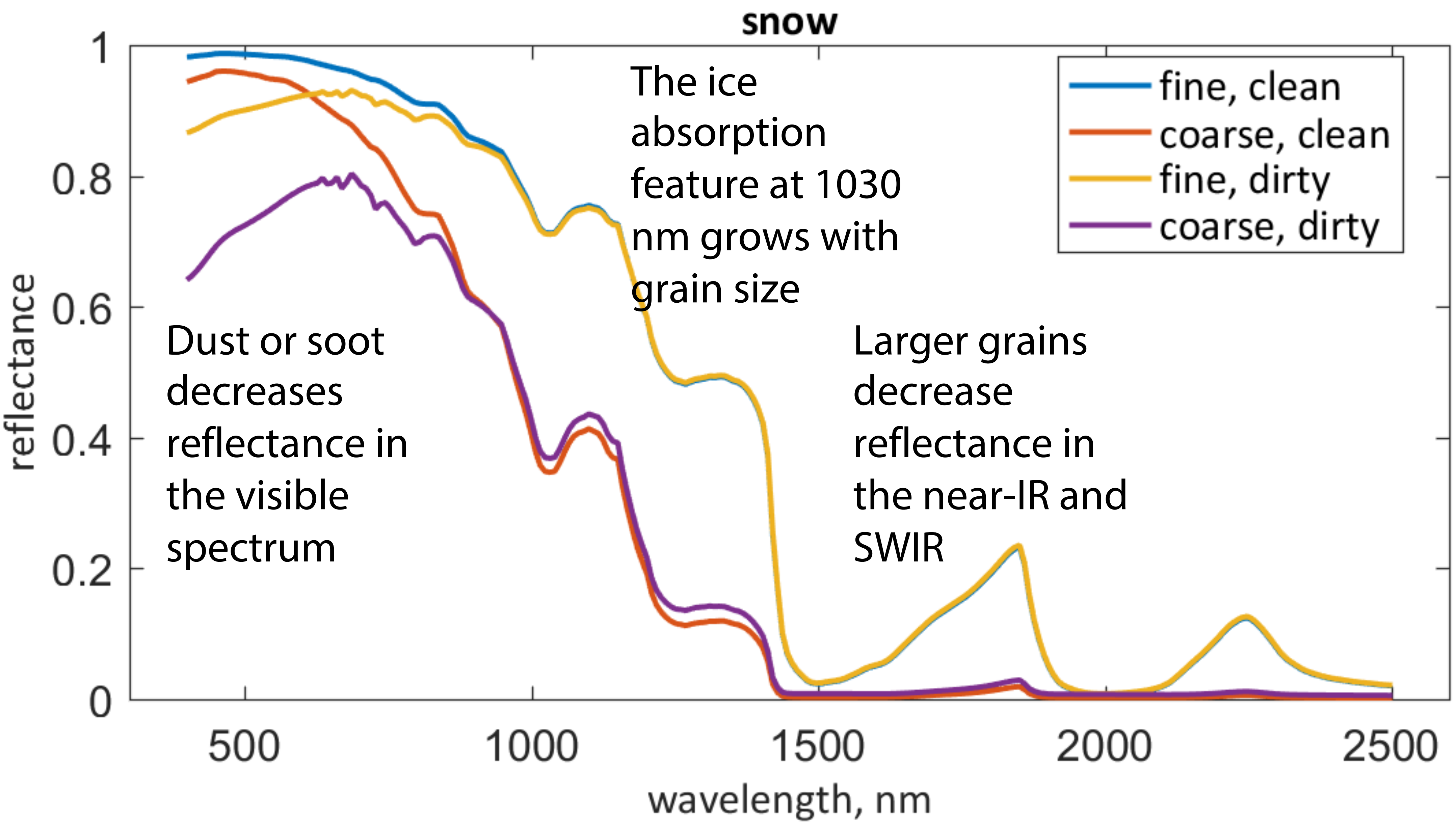
1. **At what rate does snow melt, throughout a drainage basin?**

A change in albedo causes a bigger relative change in absorption (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%

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





snow
fine, clean
coarse, clean
fine, dirty
coarse, dirty
The ice absorption feature at 1030 nm grows with grain size
Dust or soot decreases reflectance in the visible spectrum
Larger grains decrease reflectance in the near-IR and SWIR
reflectance
wavelength, nm
0
0.2
0.4
0.6
0.8
1
500
1000
1500
2000
2500

Continuum approach with nonlinear least squares, applied to AVIRIS-NG, 425 spectral bands, 5-6 nm resolution

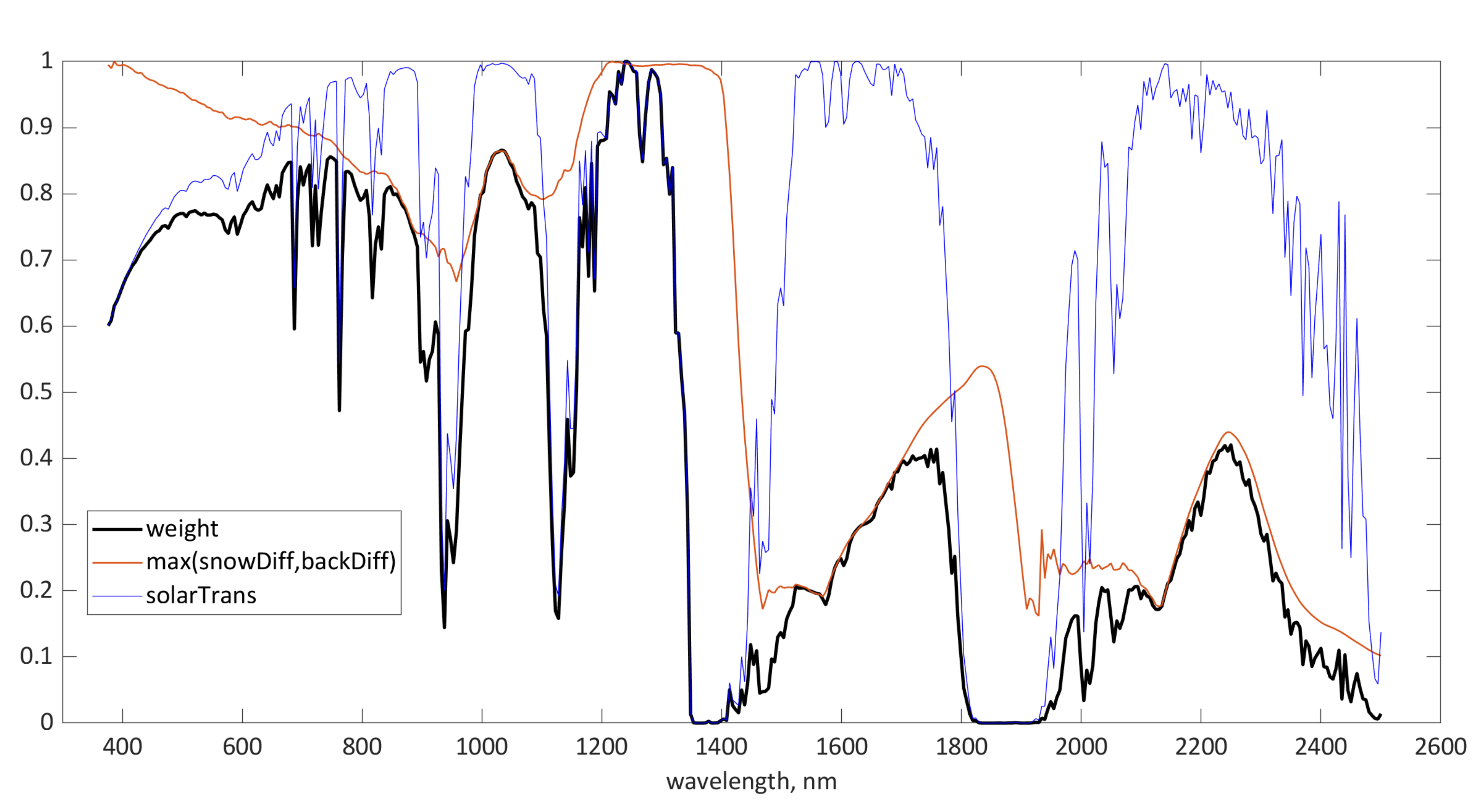
- Treat the snow as a single endmember at illumination angle θ with variable grain size r, particulate concentration c, particulate size r_c, so $R_{\lambda,snow} = \mathrm{F}(\cos\theta, r, c, r_c)$, with estimated optical properties of dust or soot that could vary regionally
- Use snow-free imagery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

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

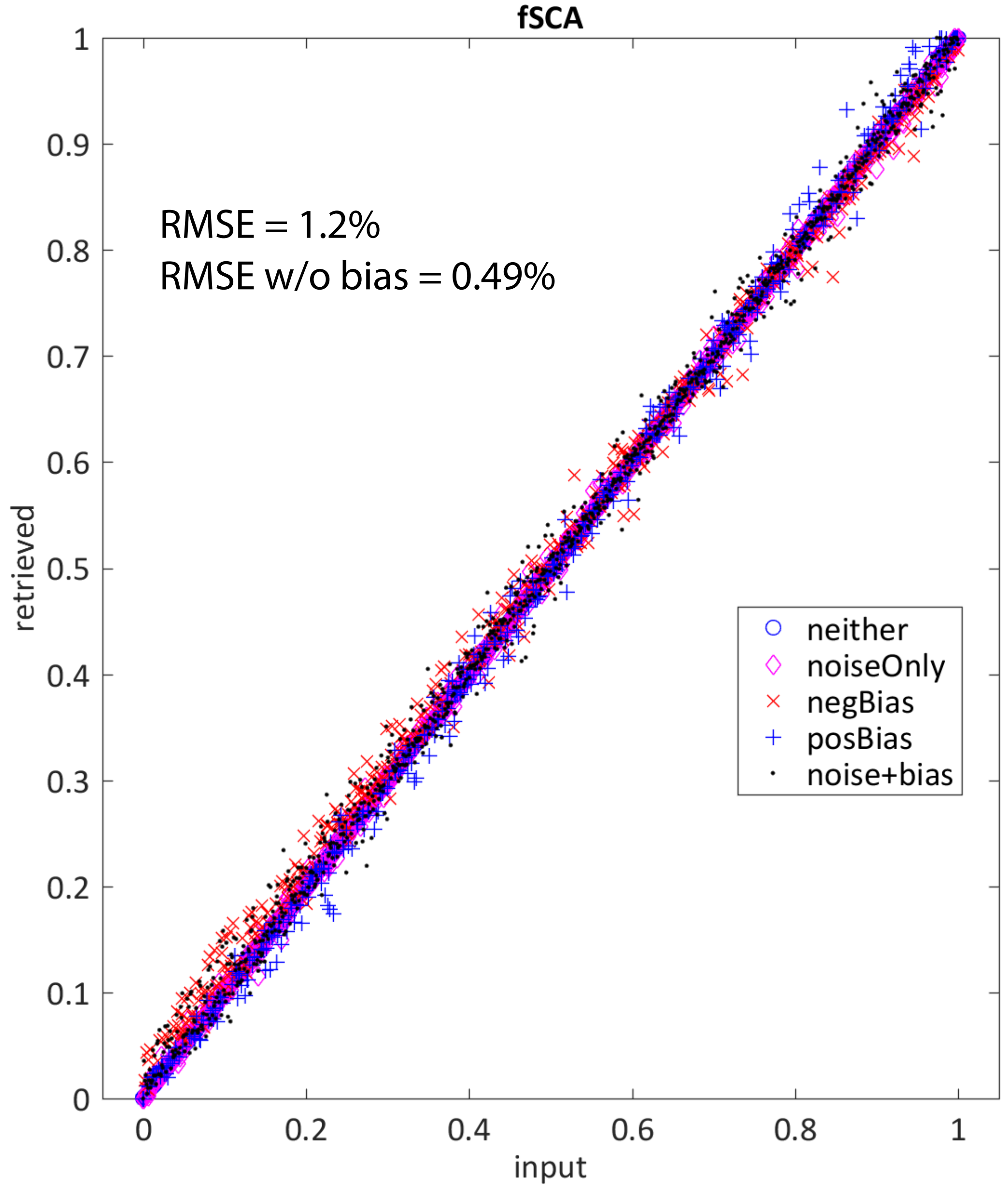
- Minimize, over up to 4 unknowns f_{SCA}, r, c, r_c at multiple λ weighted by w_λ, $R_{\lambda,meas}$ estimated from R_λ^{eff}

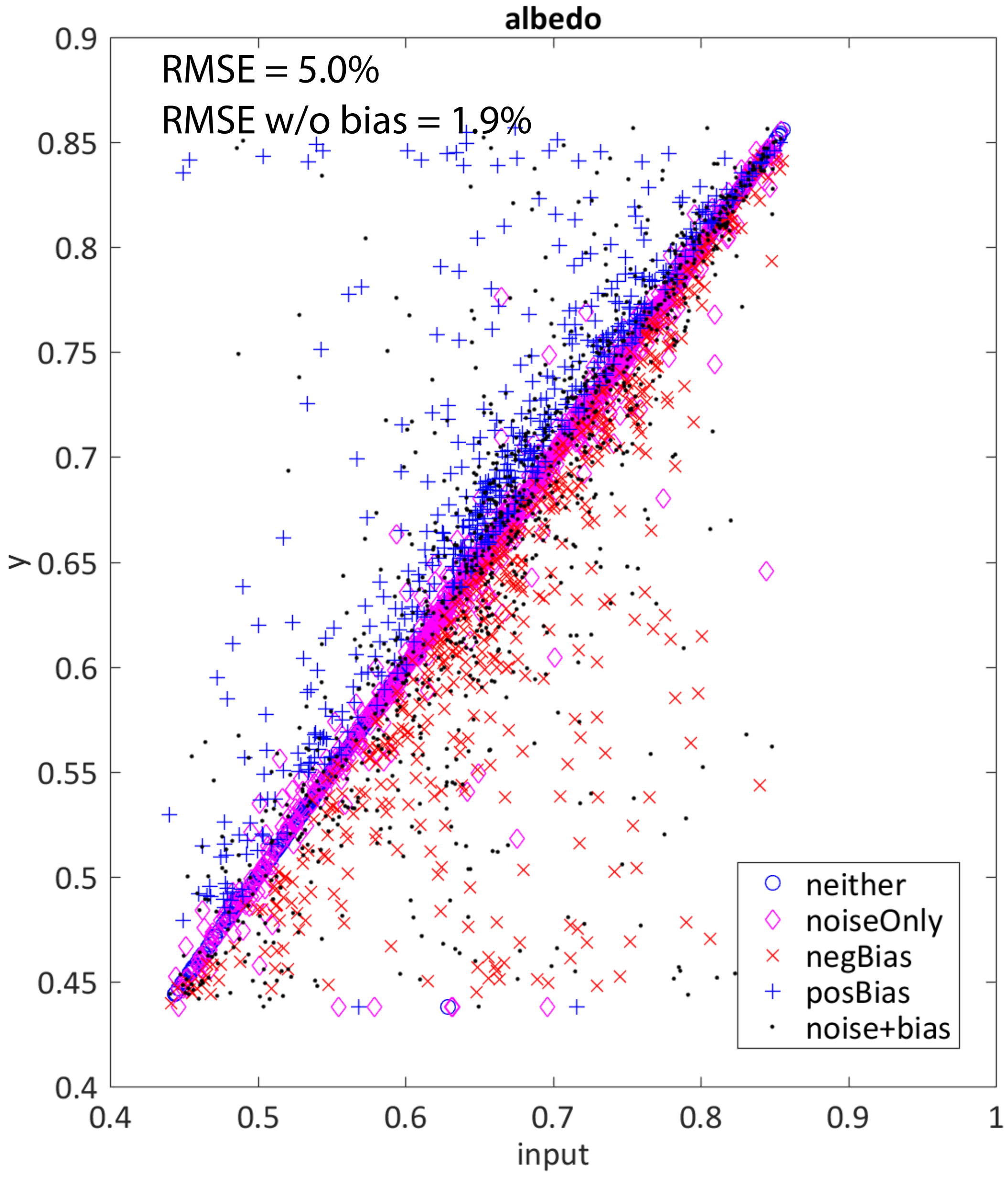
$R_{\lambda,\text{"}meas\text{"}} = R_\lambda^{eff} \dfrac{\cos\theta_0}{\cos\theta_s \cos S}$	$\sum_\lambda \left[w_\lambda \left(R_{\lambda,meas} - R_{\lambda,model}\right)\right]^2$

Choose weights based on snow, background, and atmosphere

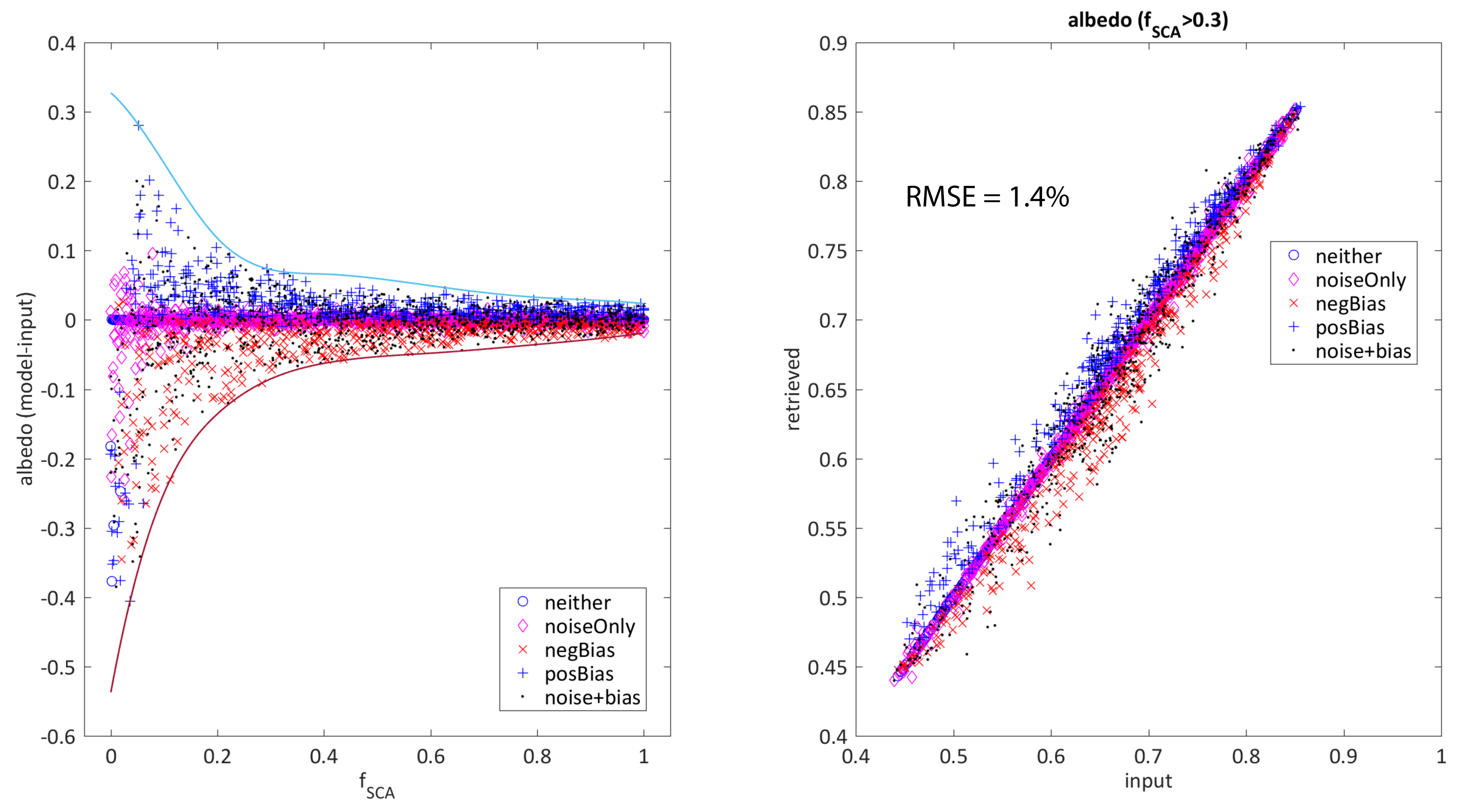


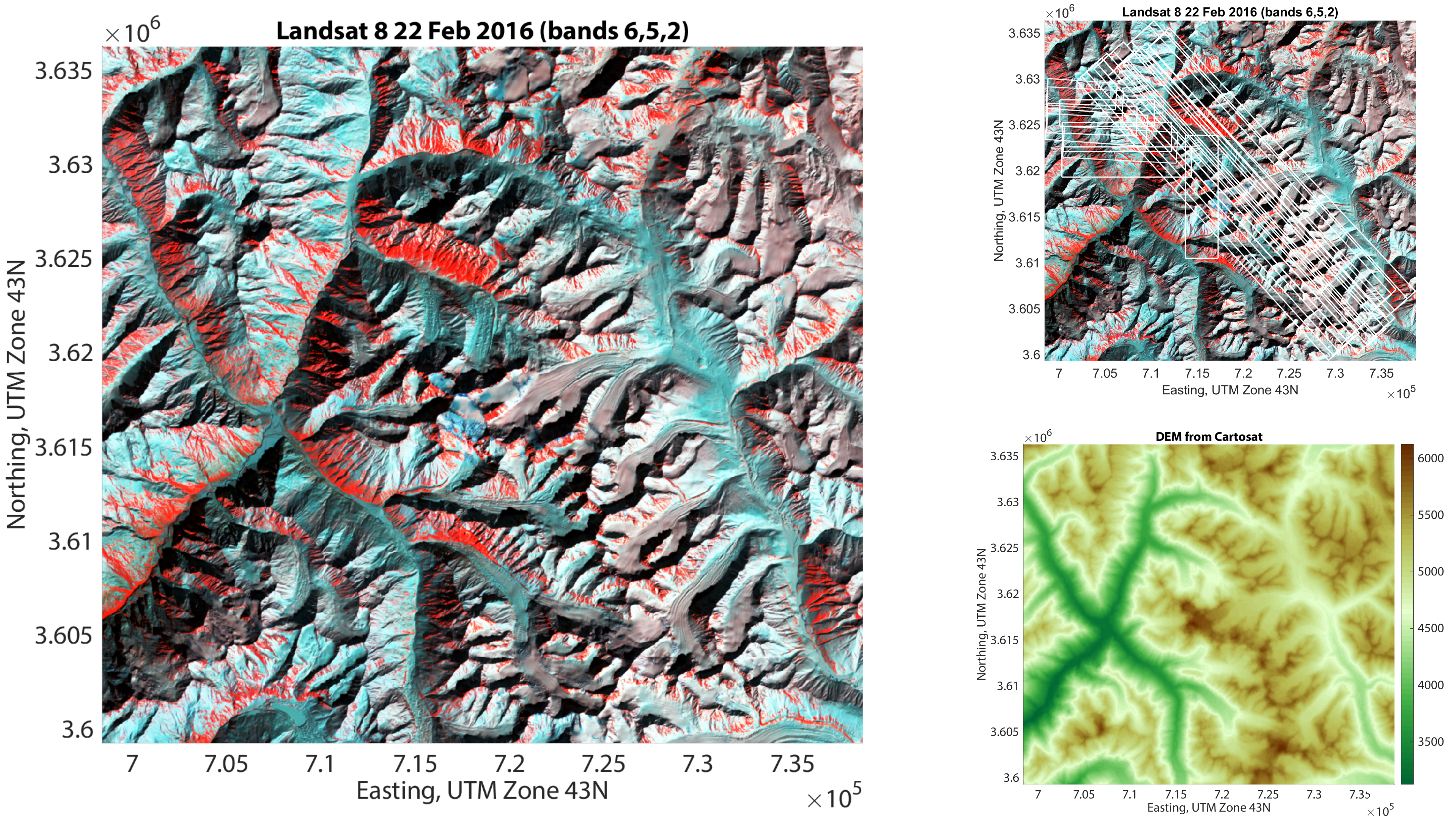
Simulation tests: Fractional snow (f_{SCA}) and albedo, pale brown silt + grass





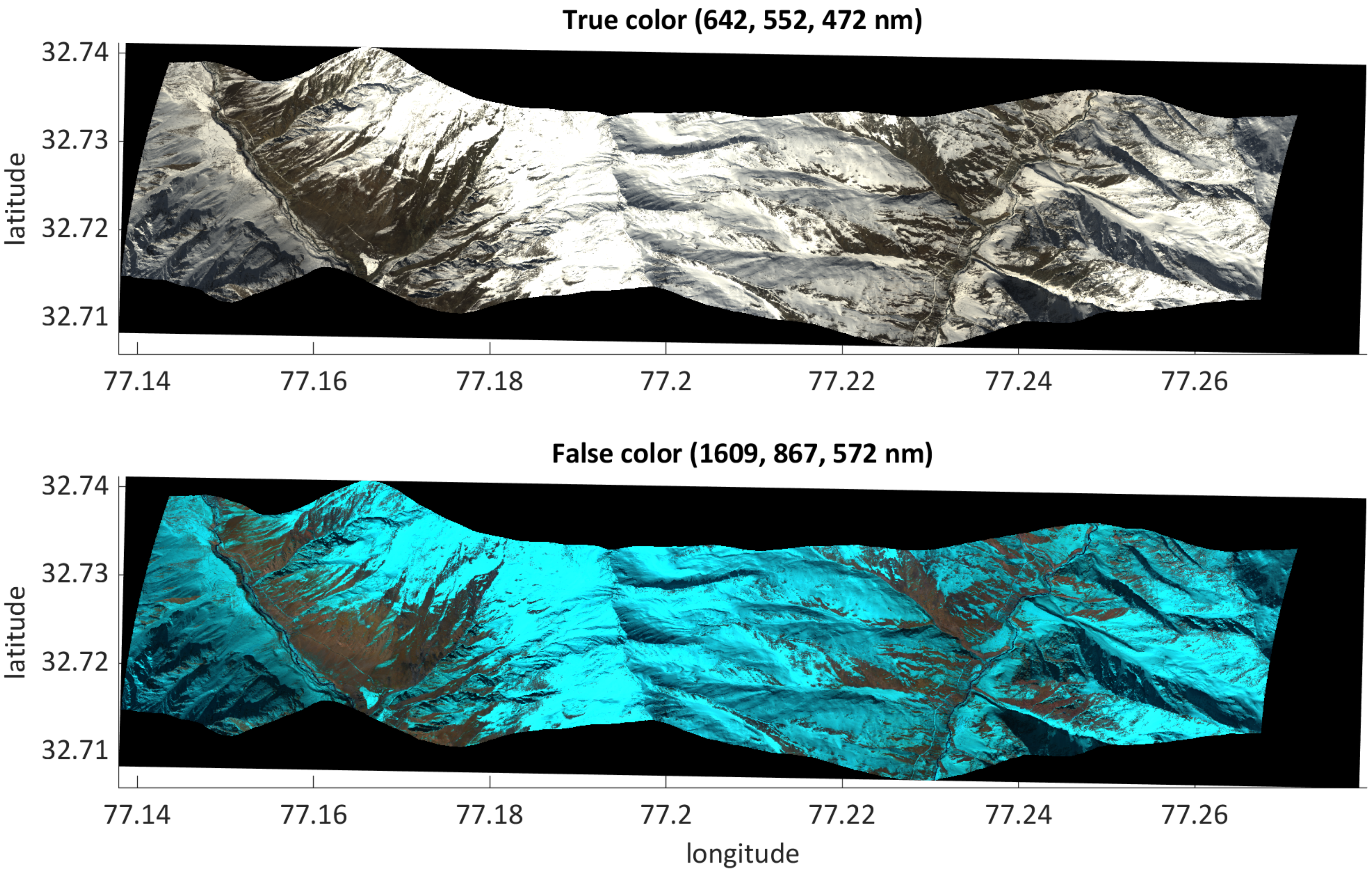
Restrict albedo calculation to pixels with f_{SCA}>0.3, grass+pale brown silt





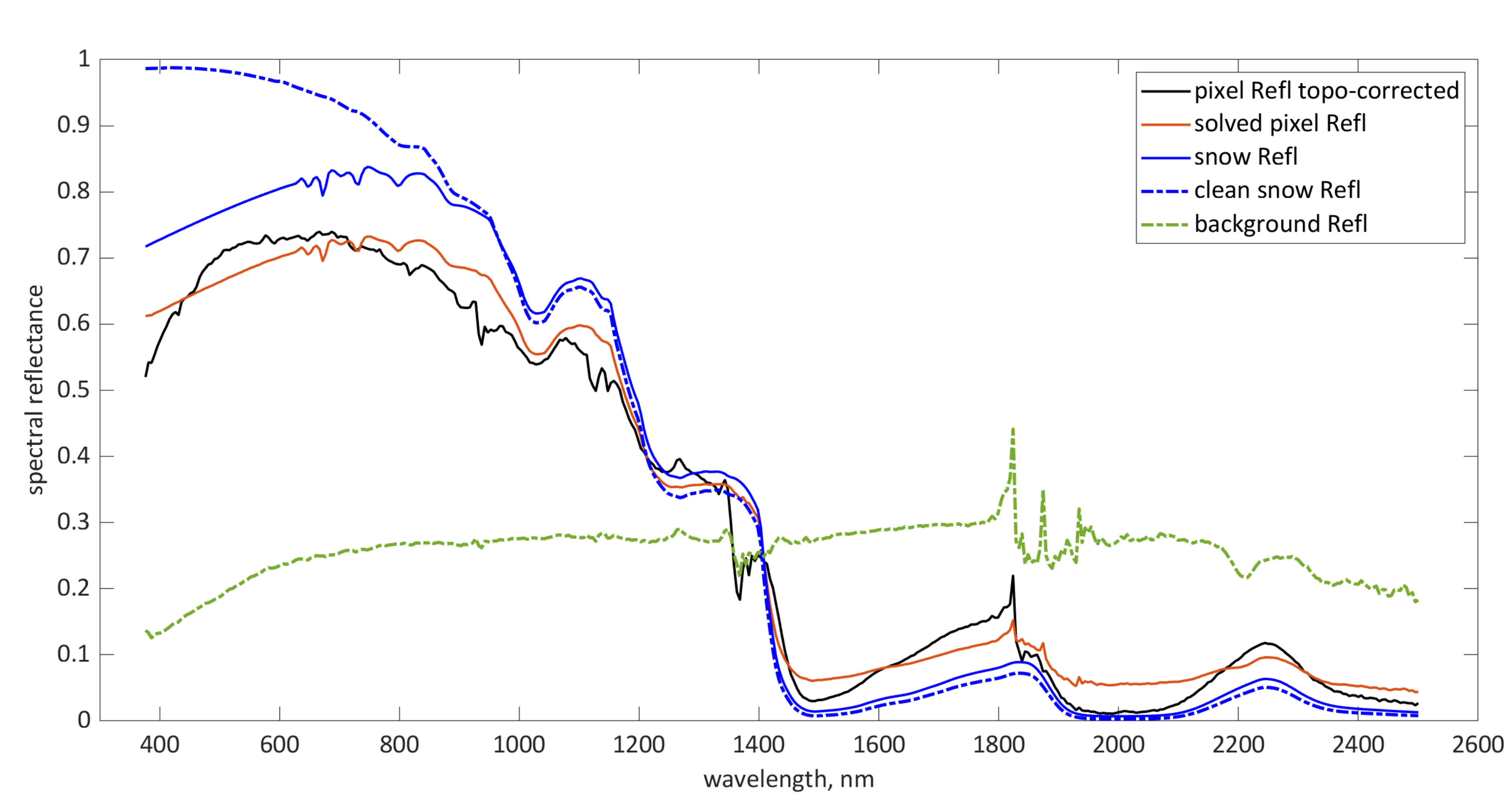
Landsat 8 22 Feb 2016 (bands 6,5,2)
×10^6
3.635
3.63
3.625
3.62
3.615
3.61
3.605
3.6
Northing, UTM Zone 43N
7
7.05
7.1
7.15
7.2
7.25
7.3
7.35
Easting, UTM Zone 43N
×10^5
Landsat 8 22 Feb 2016 (bands 6,5,2)
DEM from Cartosat
6000
5500
5000
4500
4000
3500

AVIRIS-NG images, Himachal Pradesh 17 Feb 2016

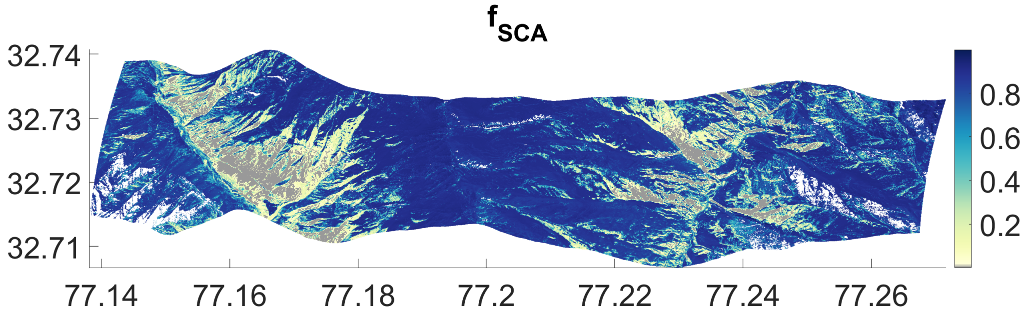


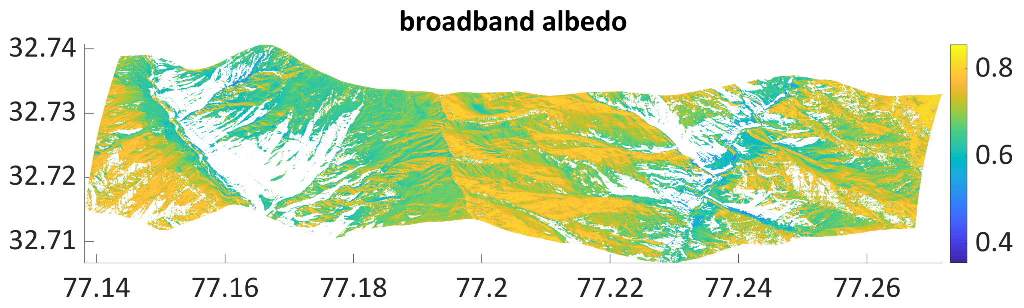
Typical solution for a pixel

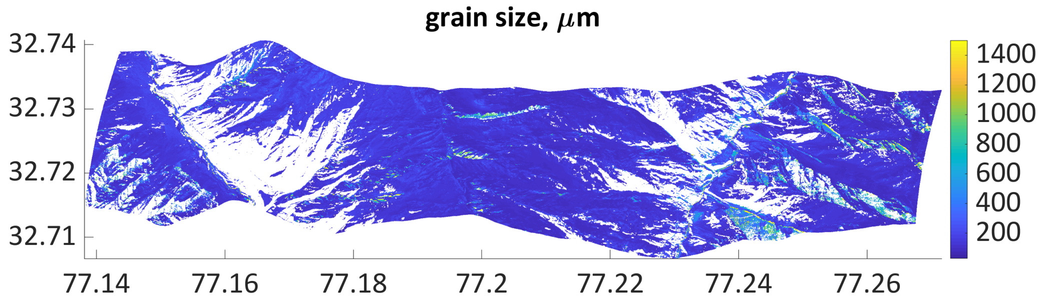
- $f_{SCA} = 0.82$
- Grain size (effective radius) = 212 µm
- Dust concentration = 4.3×10^{-4}
- Broadband albedo = 0.65 (clean 0.77)

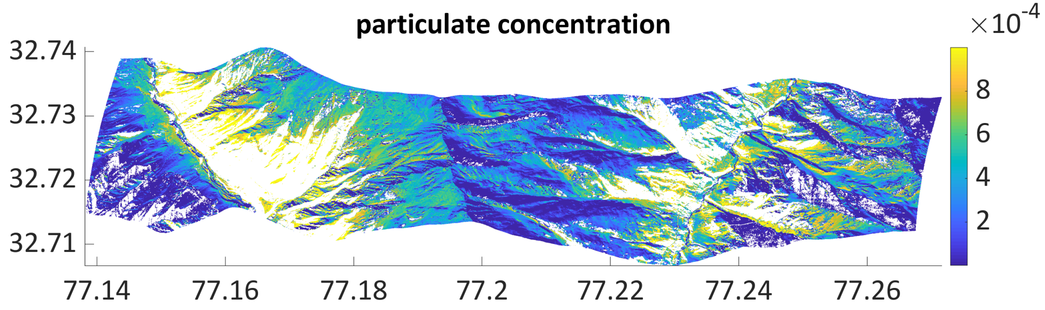


AVIRIS-NG results, 2016 Feb 17

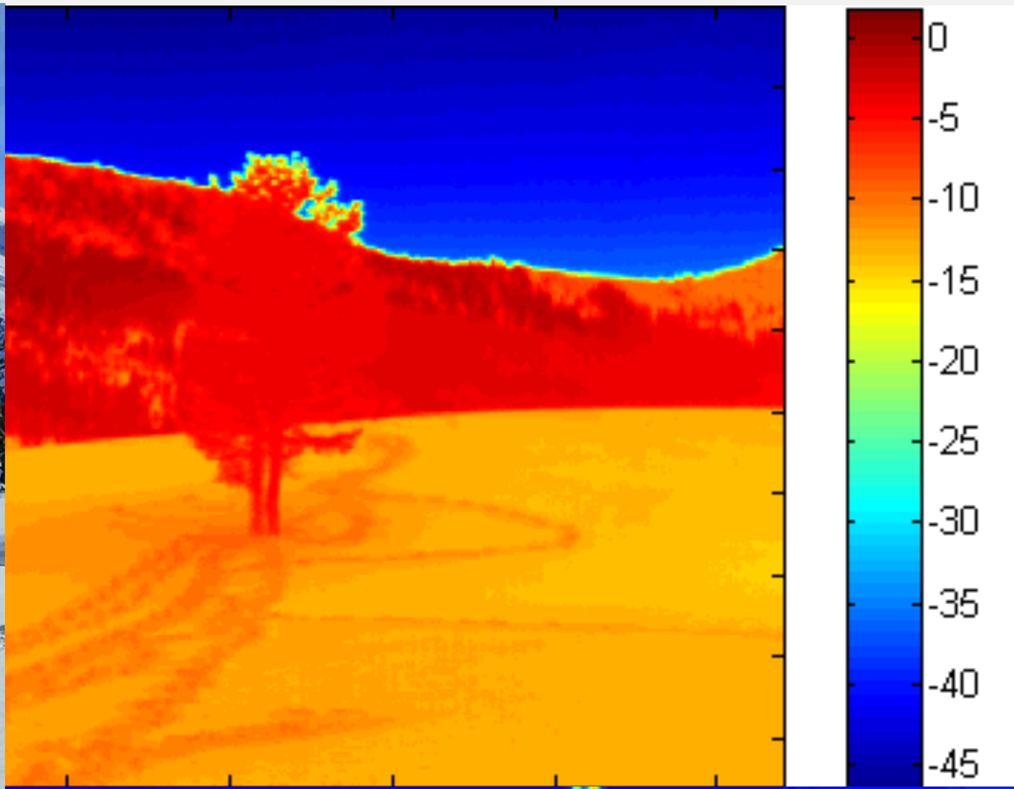


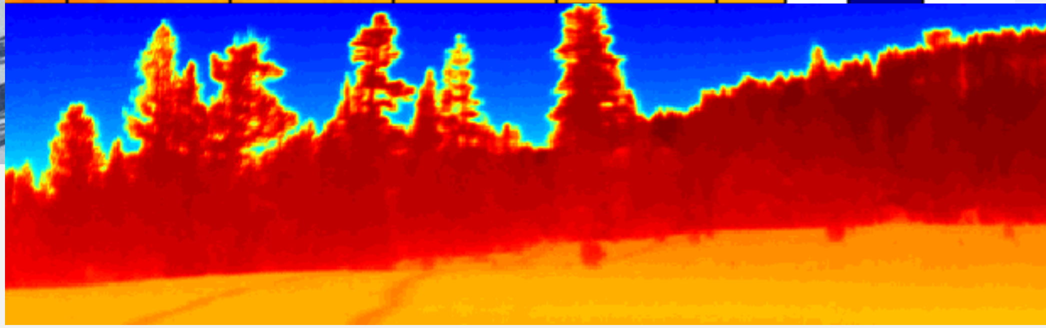






Surface temperature: trees and rocks are warmer than the snow





- Snow temperature gives us emitted radiation, and also helps calibrate energy balance calculations

Photo by Ryan Currier

Wavelengths around 4 µm and 11 µm enable spectral mixing in the thermal infrared

REMOTE SENSING OF ENVIRONMENT 11 221–229 (1981) 221

A Method for Satellite Identification of Surface Temperature Fields of Subpixel Resolution

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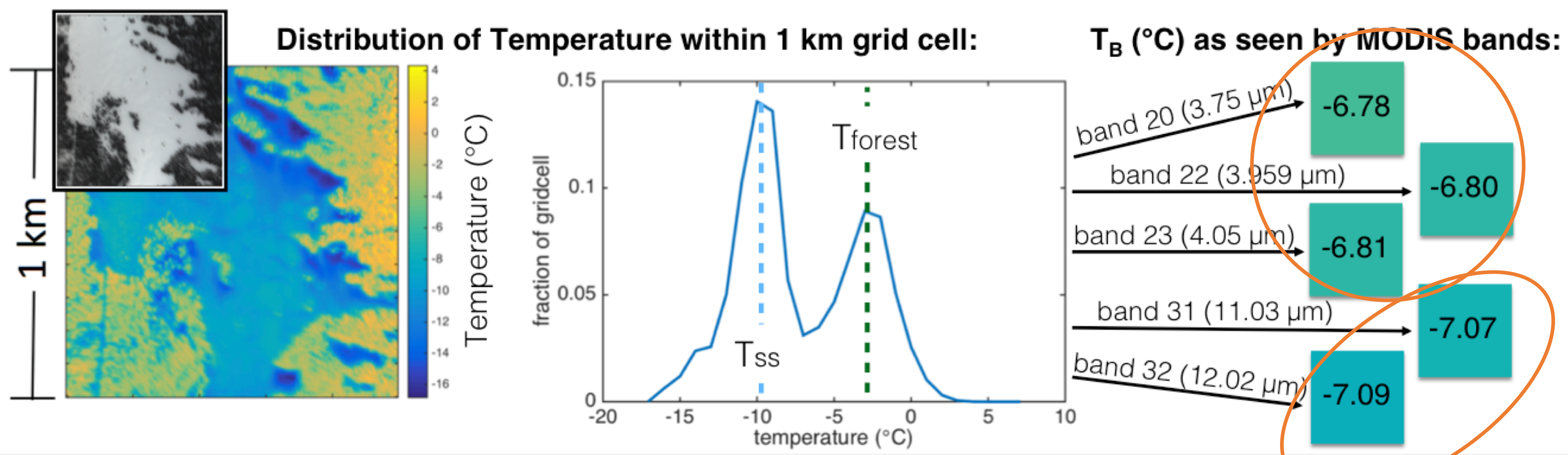
Wavelengths around 4 µm and 11 µm enable separation of snow from other

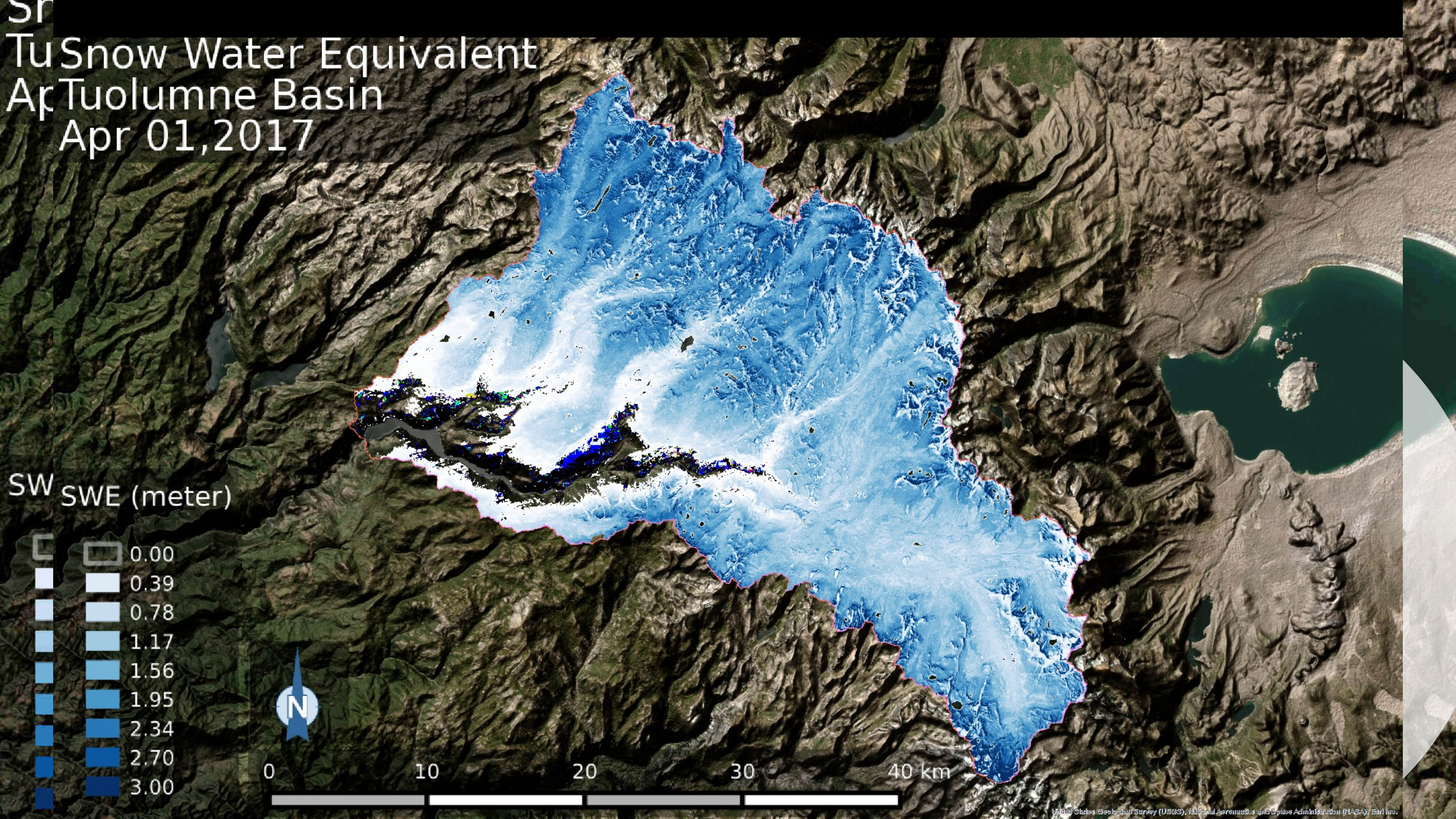
$$L[\lambda, T_b(\lambda)] = f_{SCA}\varepsilon_{snow}(\lambda)L(\lambda, T_{snow}) + (1 - f_{SCA})\,\varepsilon_{veg}(\lambda)L(\lambda, T_{veg})$$

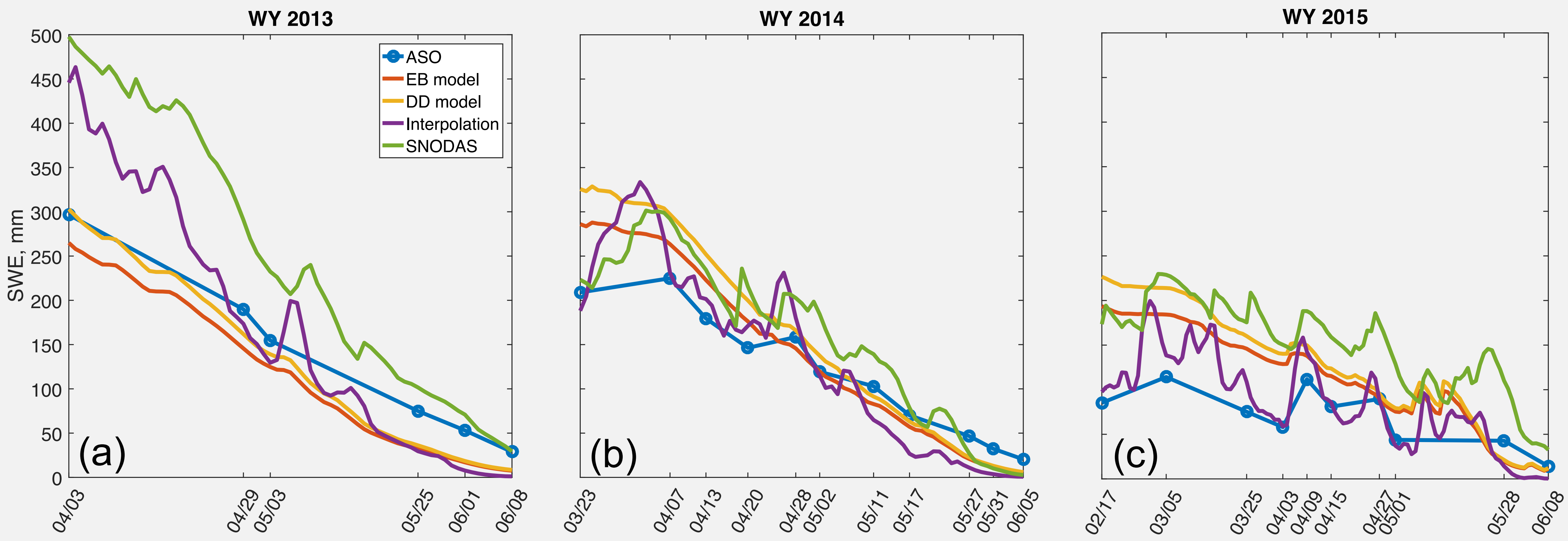


- Sum Planck's equation over the contributing area at each temperature and invert to get temperatures
- Use nonlinear optimization to fit two *T* values & f_{SCA}

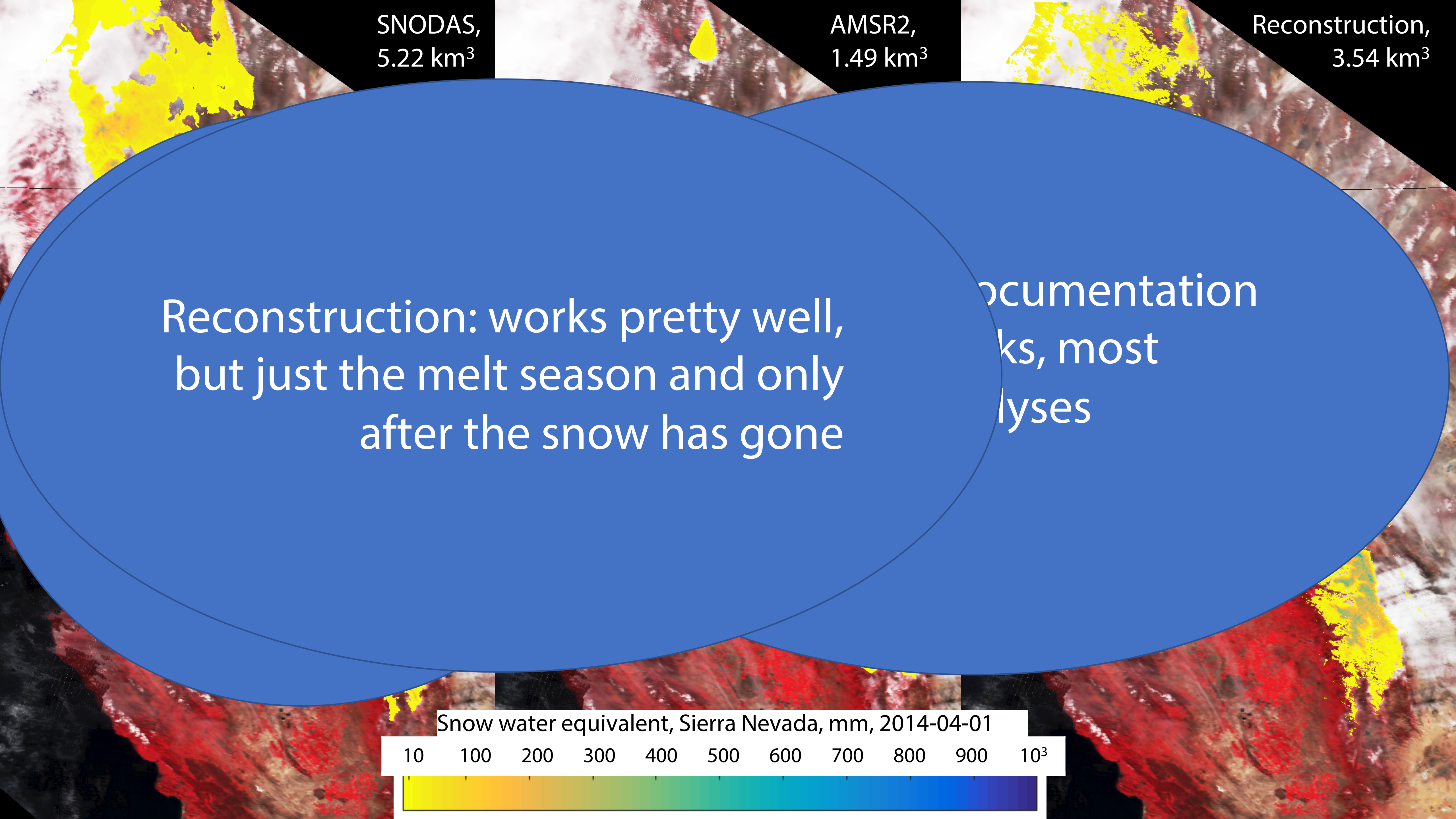
- 5 equations, 3 unknowns
- ~~5 equations~~
- 2 equations, 3 unknowns

2. How much snow is there, throughout a drainage basin?


Snow Water Equivalent
Tuolumne Basin
Apr 01,2017
SWE (meter)
0.00
0.39
0.78
1.17
1.56
1.95
2.34
2.70
3.00
N
0
10
20
30
40 km



Basin average ASO SWE compared to: Full Energy Balance (EB) Reconstruction; Net radiation/degree-day (DD) Reconstruction; Snow Pillow Interpolation (Interpolation), and the Snow Data Assimilation System (SNODAS) for the Upper Tuolumne



SNODAS,
5.22 km³
AMSR2,
1.49 km³
Reconstruction,
3.54 km³
Reconstruction: works pretty well, but just the melt season and only after the snow has gone
ocumentation
ks, most
lyses
Snow water equivalent, Sierra Nevada, mm, 2014-04-01
10
100
200
300
400
500
600
700
800
900
10³

Implications: Observations from remote sensing

- A spaceborne imaging spectrometer would best enable measurement of variables to drive snow albedo, along with calibration of multispectral sensors with more comprehensive coverage
  - Terrestrial and aquatic ecology would also benefit from such observations
  - Observing strategy should integrate with more frequent, wider swath or finer spatial resolution, multispectral measurements
- Surface temperature should be measured through diurnal cycle
  - Spectral unmixing of surfaces of different temperatures in the same pixel requires bands around 4 μm and 11 μm
  - Need not be simultaneous with VSWIR measurements
- Precipitation models and remotely sensed measurements of snow water equivalent can be validated by comparison to reconstructed SWE, whose accuracy depends partly on getting the albedo right

Implications: 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
- Forecasts of weekly-scale snowmelt runoff depends 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