Constraining Physically-Based Modeling Of The Dwindling Cryosphere With Imaging Spectroscopy Of Snow And Ice

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Outline

- Energy balance of snow and ice
- Controls on accelerated melt and reduced accumulation
- Controls of grain size and radiative forcing on changes in albedo
- Spectroscopy to quantitative retrievals
- The Airborne Snow Observatory and moving to space
- Constraint on hydrologic and climate modeling
- This talk will produce a Science Traceability Matrix

Objectives for Cryosphere Missions

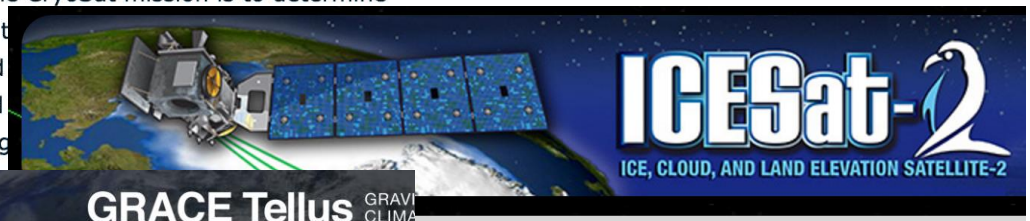
ΔMass

CRYOSAT – SCIENTIFIC OBJECTIVES

CryoSat's 'roof'

The aim of the CryoSat mission is to determine
variations in t
ice cover and
Antarctic and
contributing g

- the seasonal cycle and
- the variation in the thic



ESat-2: Science Objectives

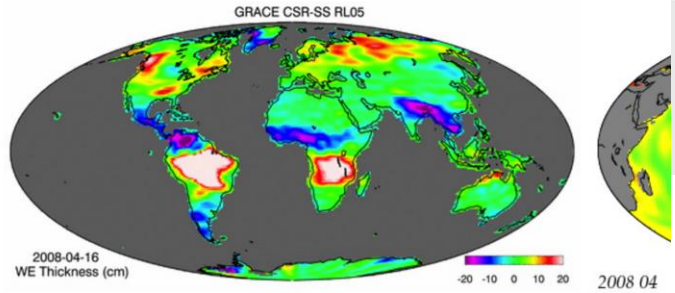
- Quantifying polar ice-sheet contributions to current and recent sea-level change, as well as ice-sheet linkages to climate conditions.
- Quantifying regional patterns of ice-sheet changes to assess what drives those changes, and to improve predictive ice-sheet models.
- Estimating sea-ice thickness to examine exchanges of energy, mass and moisture between the ice, oceans and atmosphere.
- Measuring vegetation canopy height to help researchers estimate biomass amounts over large areas, and how the biomass is changing.
- Enhancing the utility of other Earth-observation systems through supporting measurements.

Jet Propulsion Laboratory
California Institute of Technology

GRACE Tellus

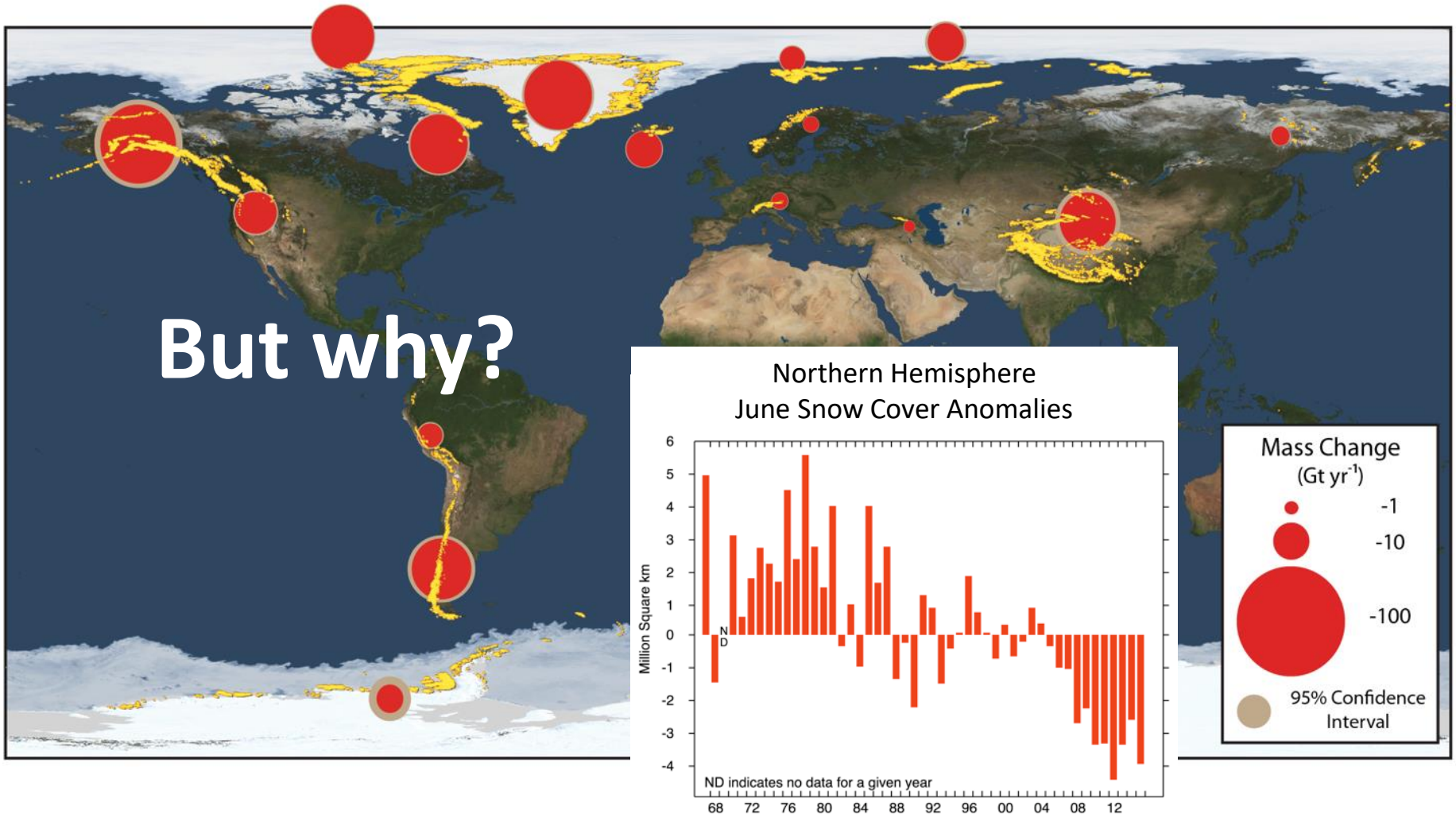
Mission | Data | Publications | Multimedia | Applicat

GRACE



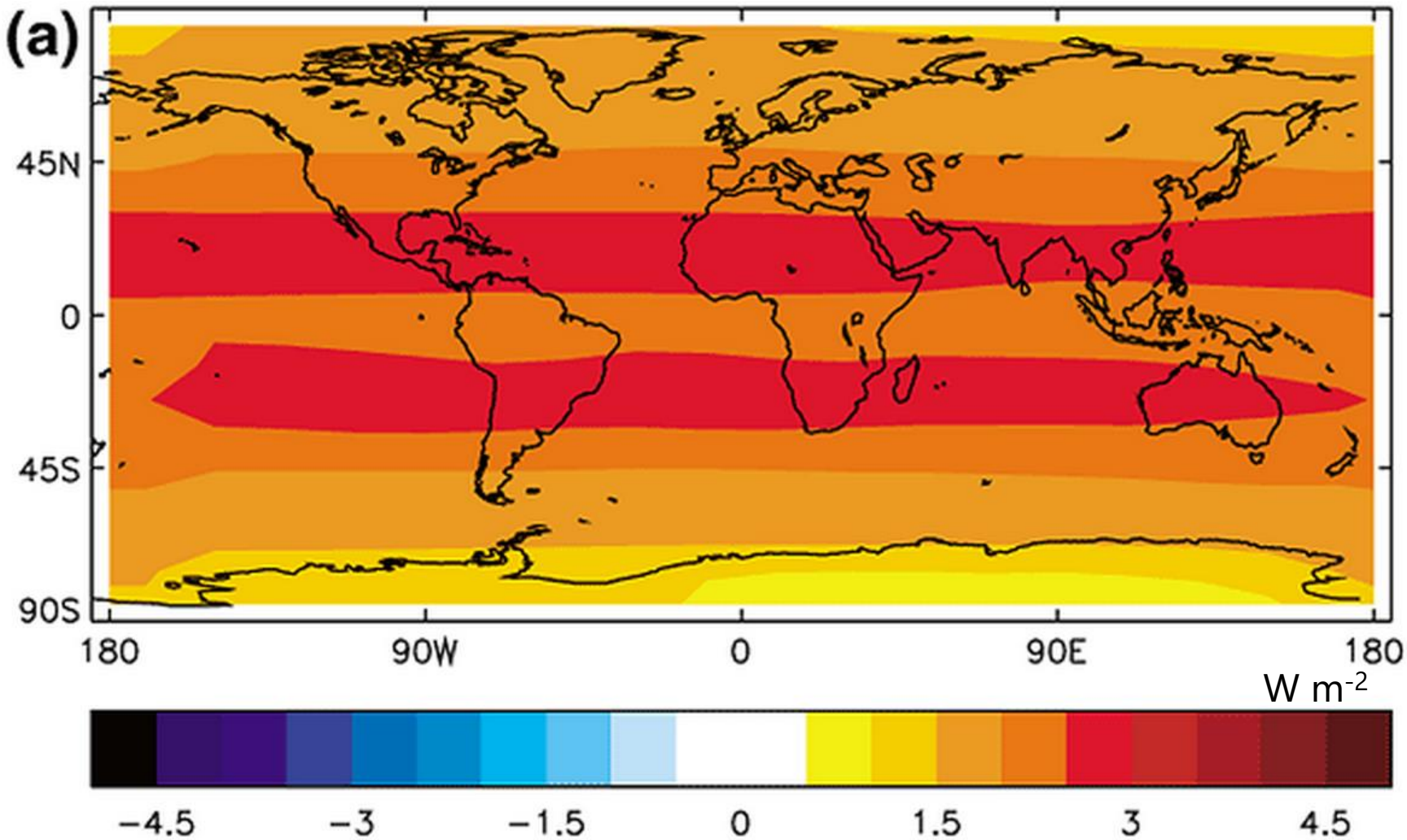
The GRACE twin satellites, launched 17 March 2002, are making detailed measurements of Earth's gravity field changes and revolutionizing investigations about Earth's water reservoirs over land, ice and oceans, as well as earthquakes and crustal deformations. The two GRACE satellites have completed more than 13 years of continuous measurements!

Mass change from GRACE and ICESat-1



Adapted from Gardner et al, 2013, *Science*

Physical Parameter Requirements



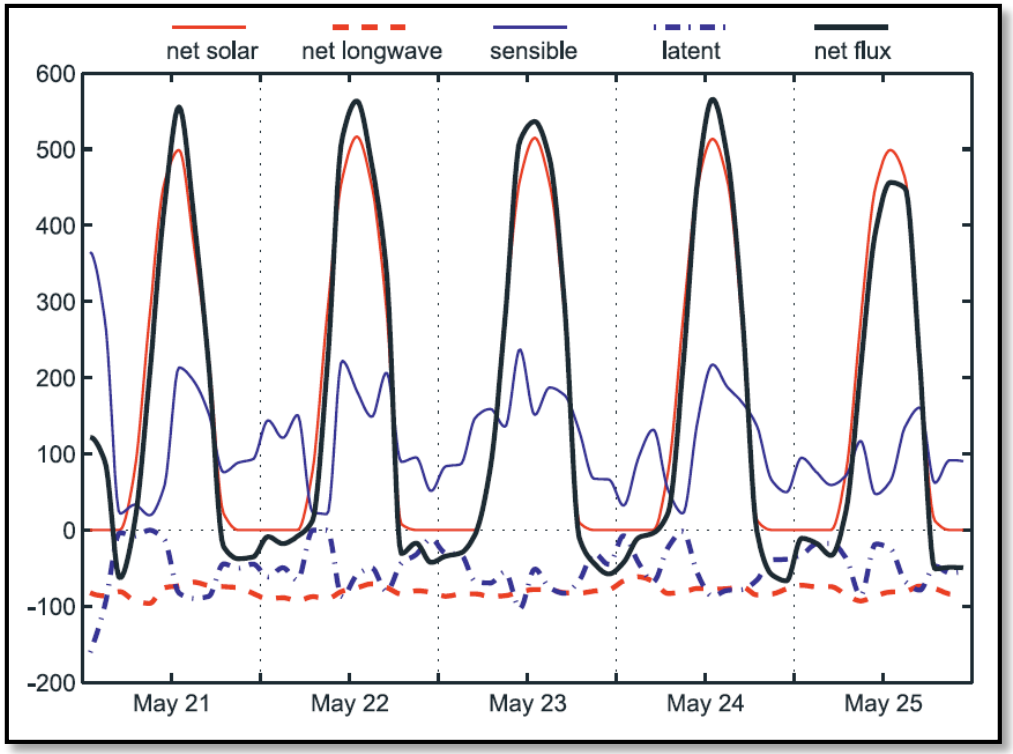
At-surface CO_2 radiative forcing

IPCC 5th AR, 2013

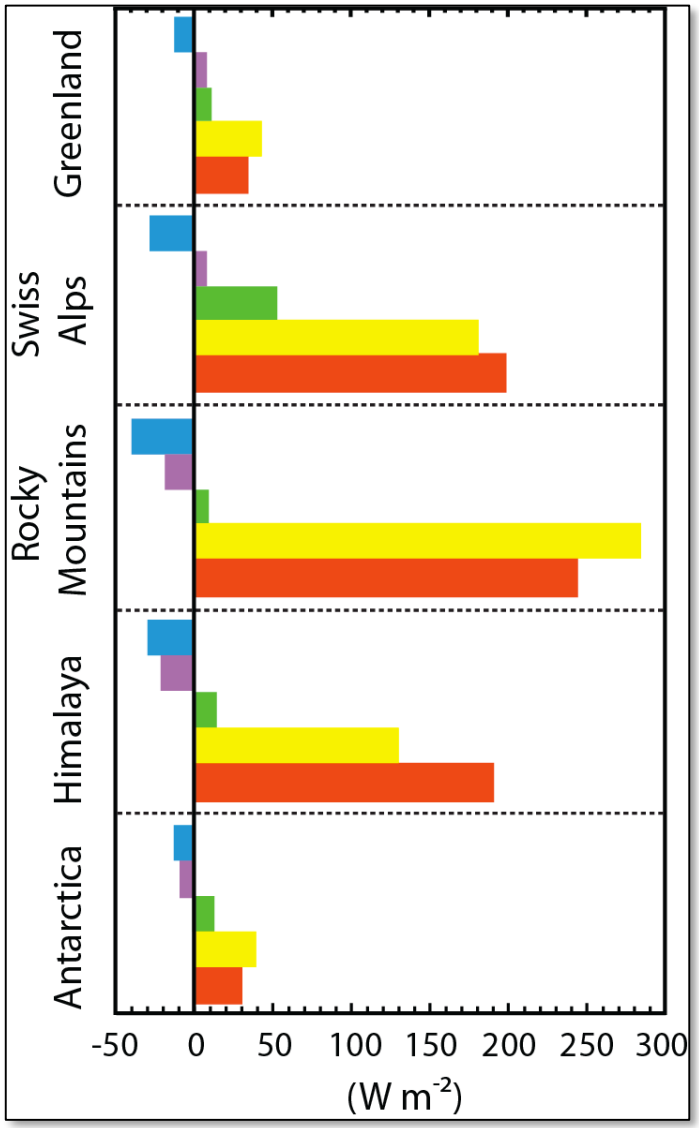
Snow energy balance – SW dominates

Net Flux | Net Solar | Net Longwave | Sensible Heat | Latent Heat

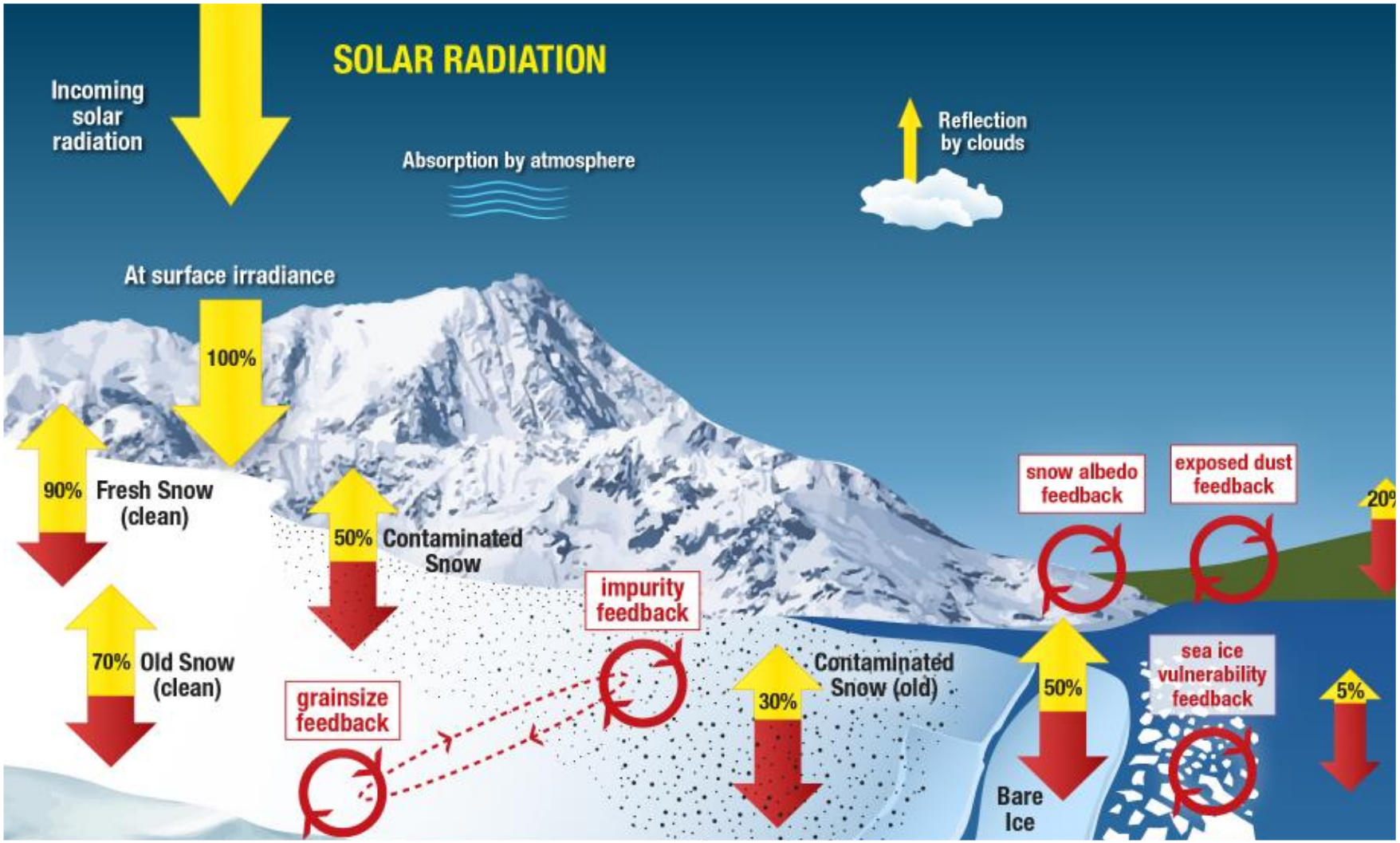
$$\frac{dU}{dt} + Q_m = (1-\alpha)S + L^* + Q_s + Q_v + Q_g$$



San Juan Mountains, Colorado, 2005



Cryosphere Energy Balance Components

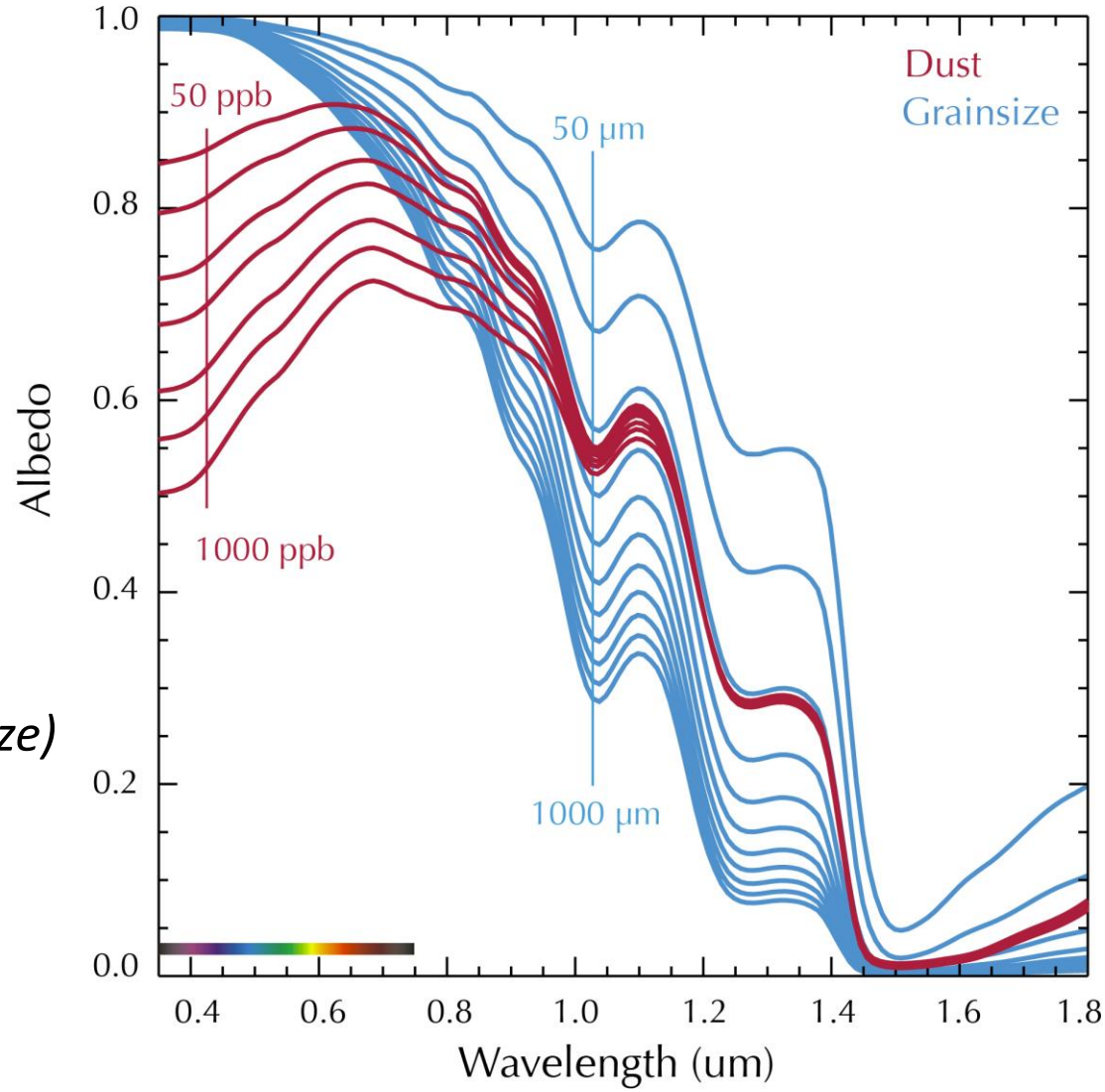


Controls of grain size and RF on α

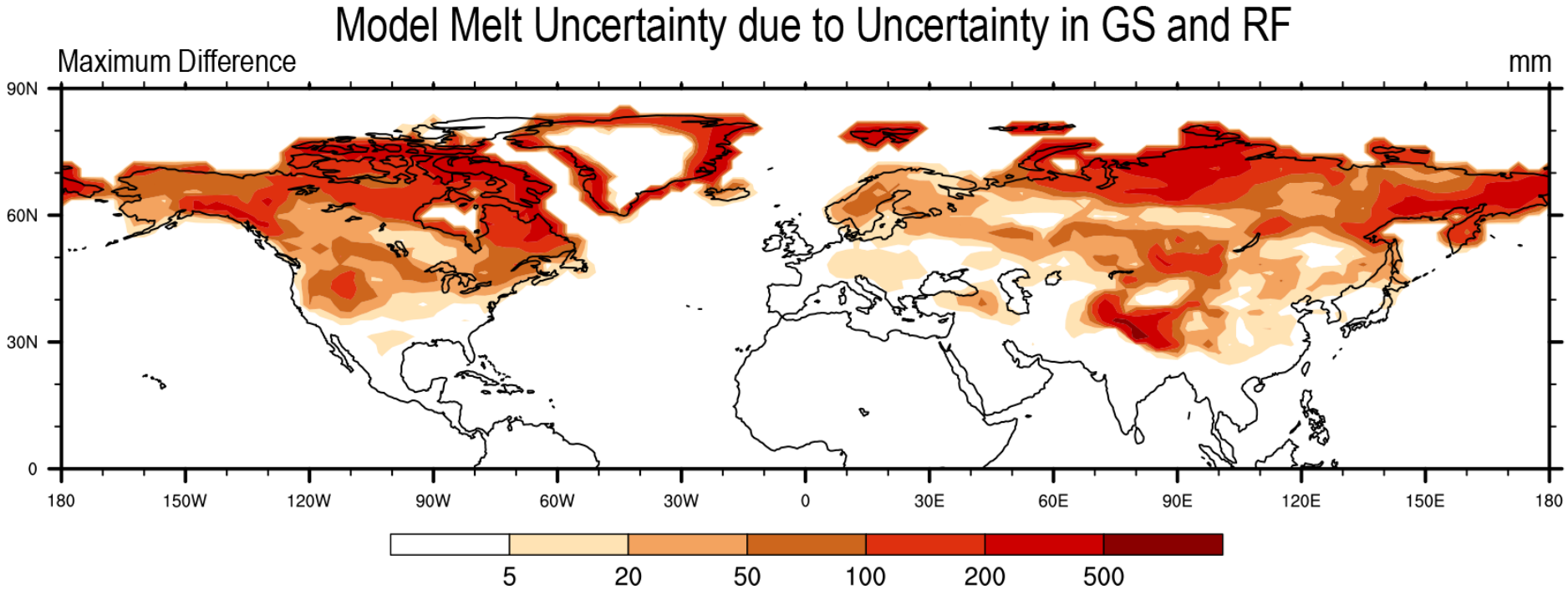
$$\alpha_t = f(GS_t, RF_t, \vartheta_0, E_\lambda)$$

$GS_t = g(\text{energy fluxes})$

$RF_t = h(\text{conc, GS, opt prop, part size})$

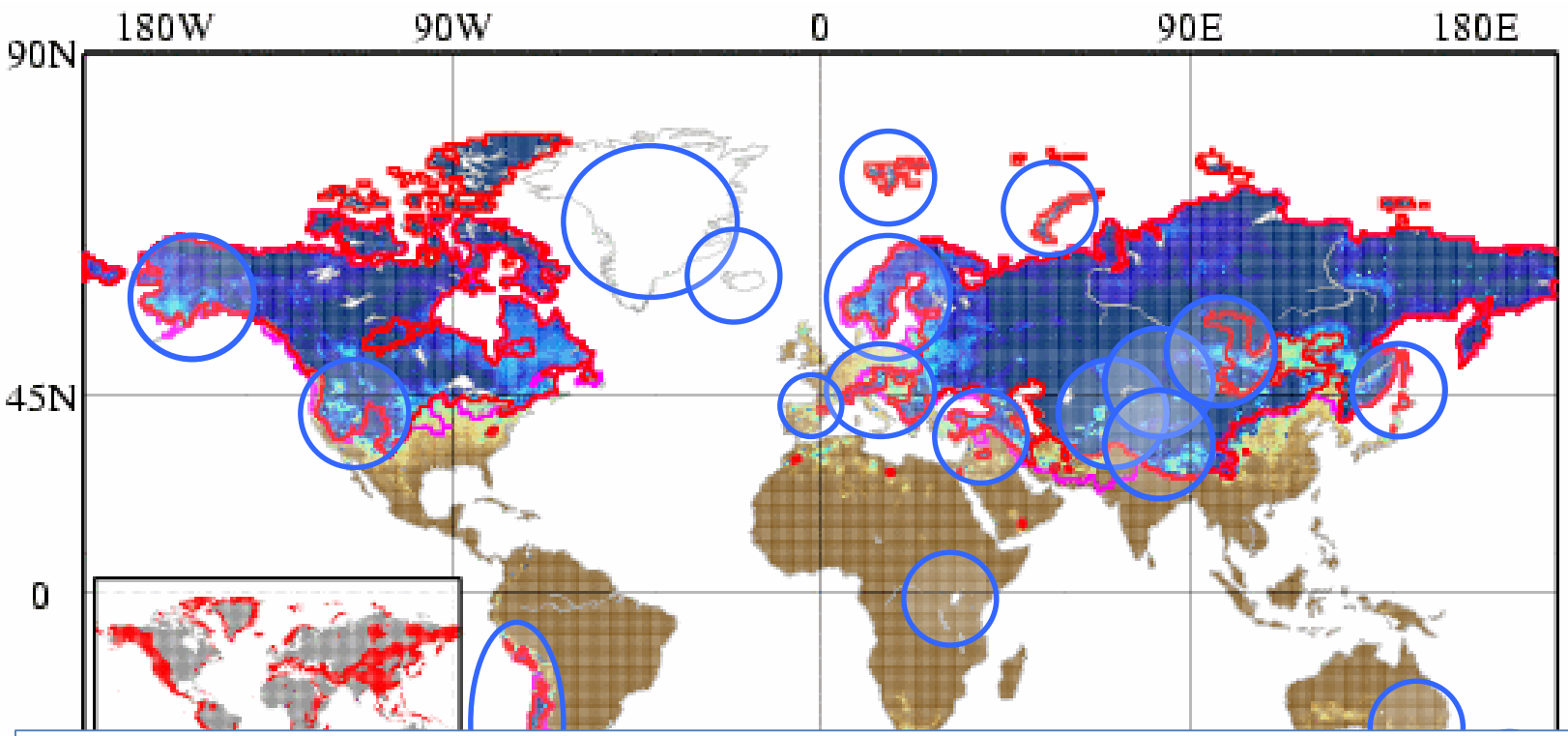


Melt uncertainties from ε(GS)+ε(RF)



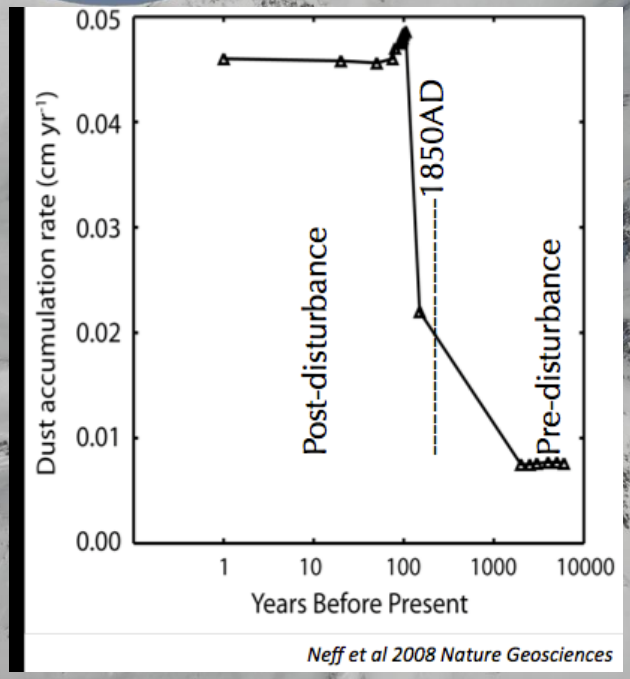
NCAR CESM + SNICAR, *Flanner pers. comm*

Where do we know that impurities are impacting snowmelt?

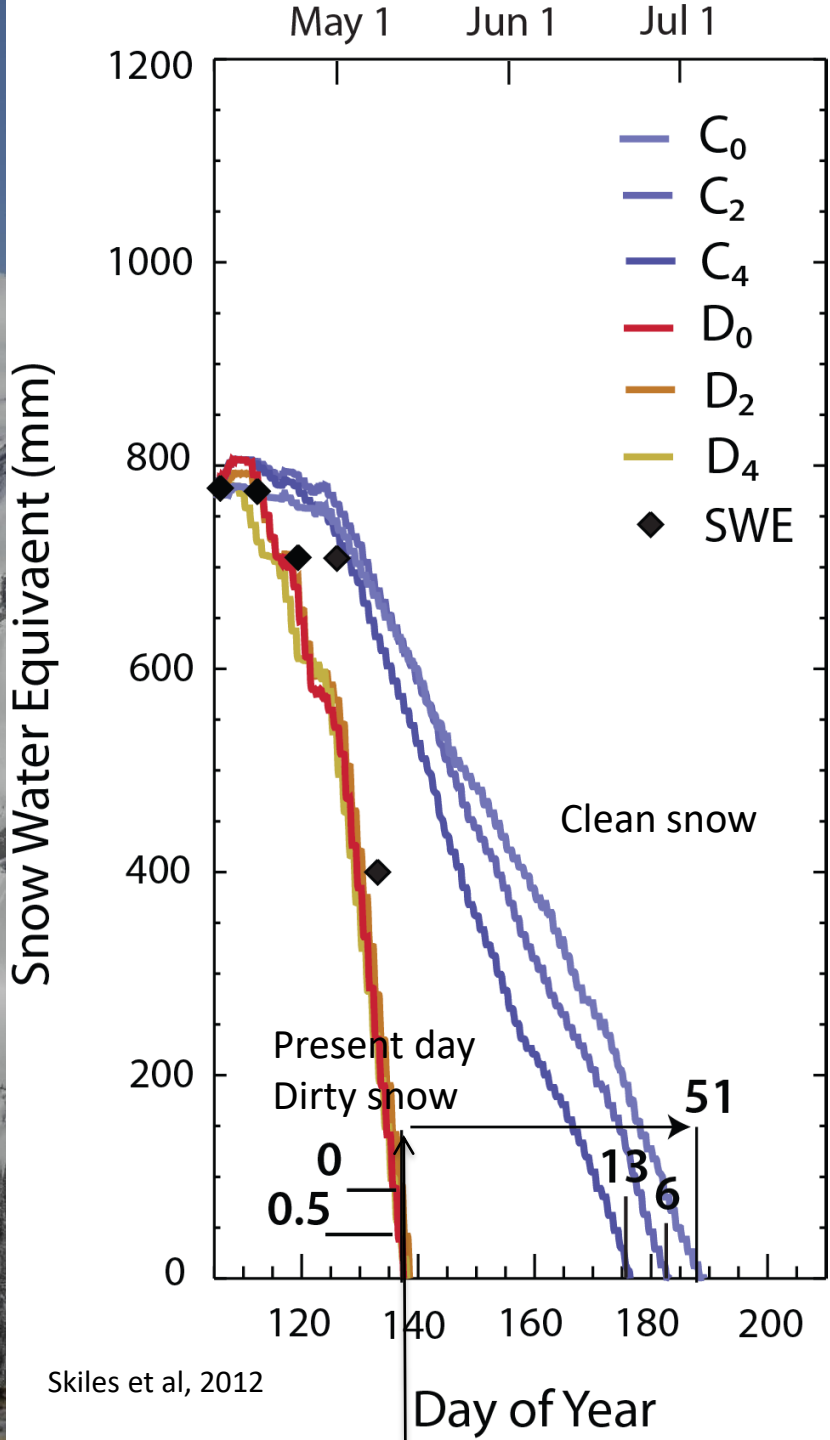


But by how much and how has this impact changed?

Colorado River Basin, USA

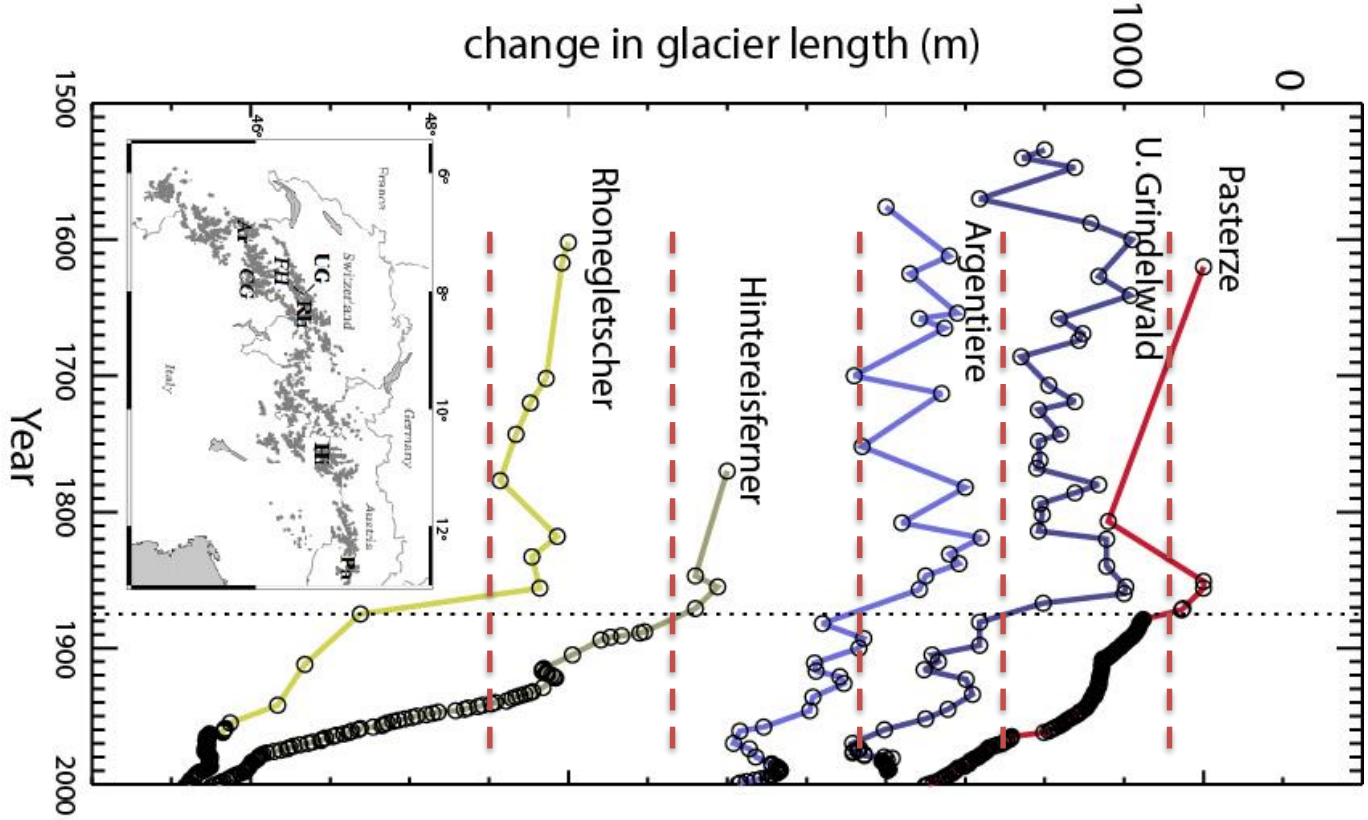


Photos courtesy Jeffrey Deems/University of Colorado, James Balog/Extreme Ice Survey, and NASA IDS project *Integrated Hydro Response*



Skiles et al, 2012

Glacial End of the Little Ice Age



Painter, T. H., M. Flanner, B. Marzeion, R. A. VanCuren, G. Kaser, and W. Abdalati, *PNAS,* 10.1073/pnas.1302570110.

Huybrechts et al (2009)

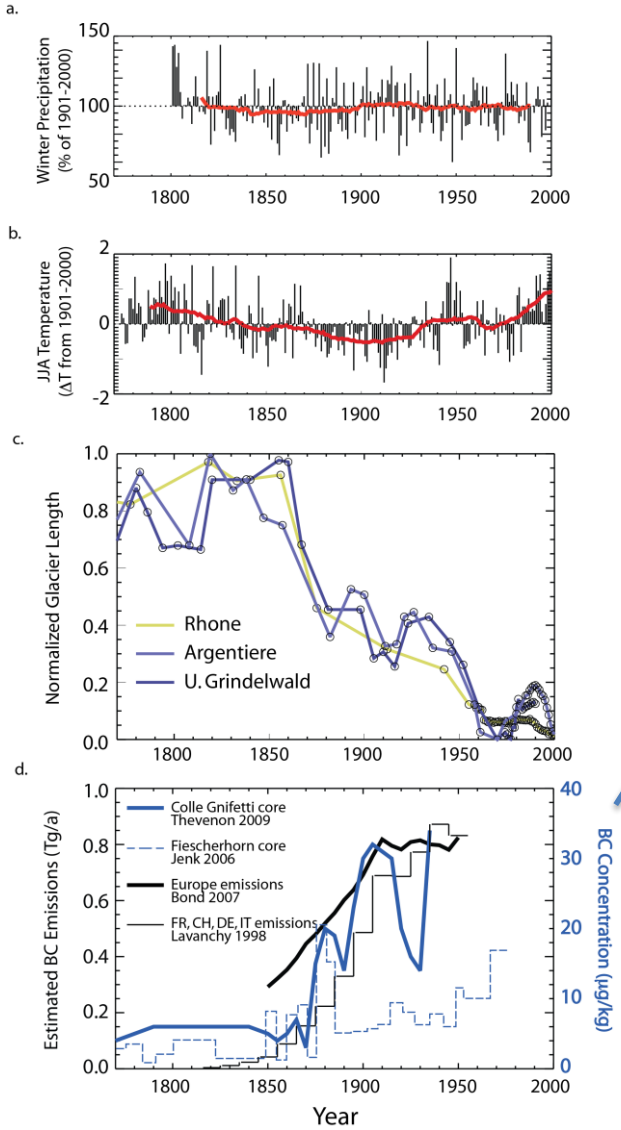
Δα?

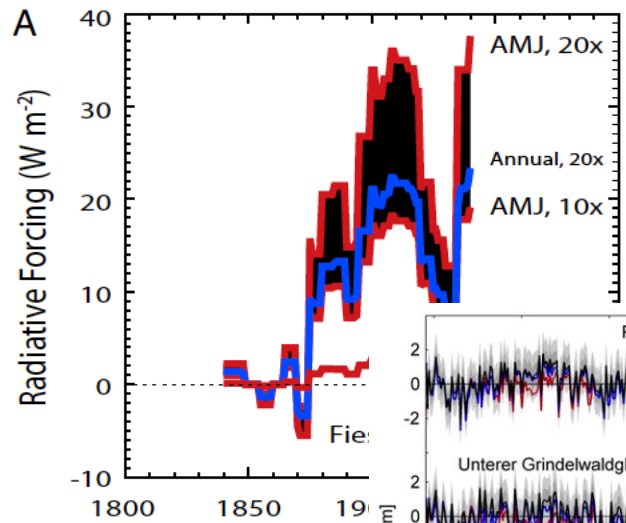
"Forcing the mass balance history [with summer and mean annual temperature anomalies] brought to light, that, in particular, the observed glacier retreat since about 1850 is not fully understood. This result and the improved model simulations that could be obtained while assuming an additional negative mass balance perturbation during roughly the last 150 y, seems to point to additional features affecting the glacier's mass balance that are not captured well in the ambient climatic records"

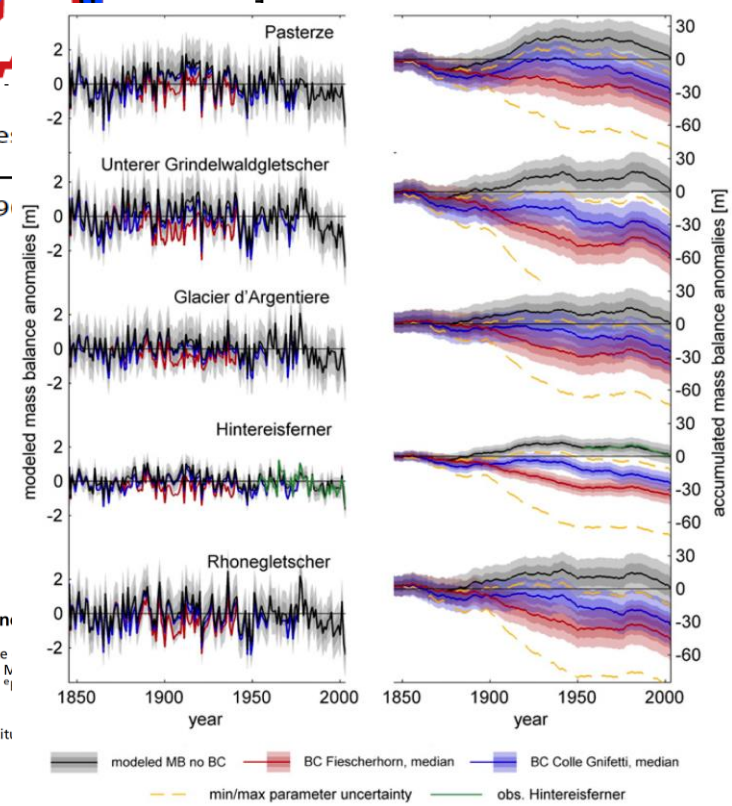
Huybrechts et al. (2009) modeling glacier-length record of Glacier d'Argentiere

Painter, T. H., M. Flanner, B. Marzeion, R. A. VanCuren, G. Kaser, and W. Abdalati, *PNAS,* 10.1073/pnas.1302570110.

BC forced the End of the LIA in the Alps







PNAS

End of the Little black carbon

Thomas H. Painter[a,1], Mark G. Flann

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Michigan, Ann Arbor, MI 48109; [c]Institute of M
University of California, Davis, CA 95616; and [e]
CO 80309

Edited by Susan Solomon, Massachusetts Instit

Present Day in the Swiss Alps

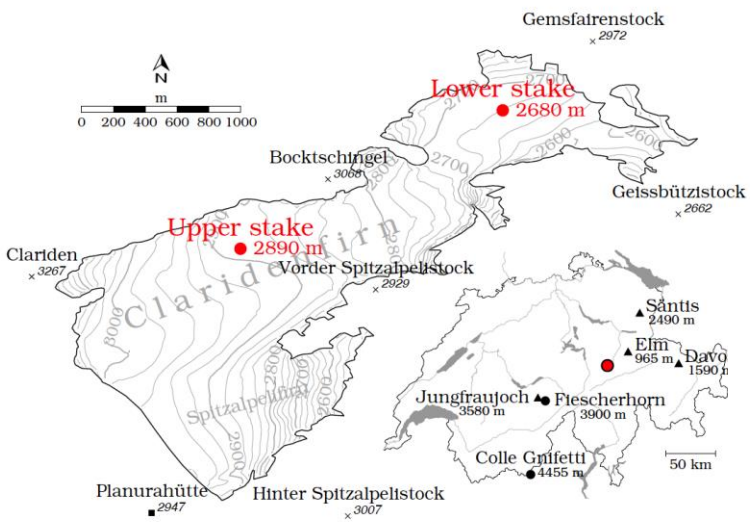
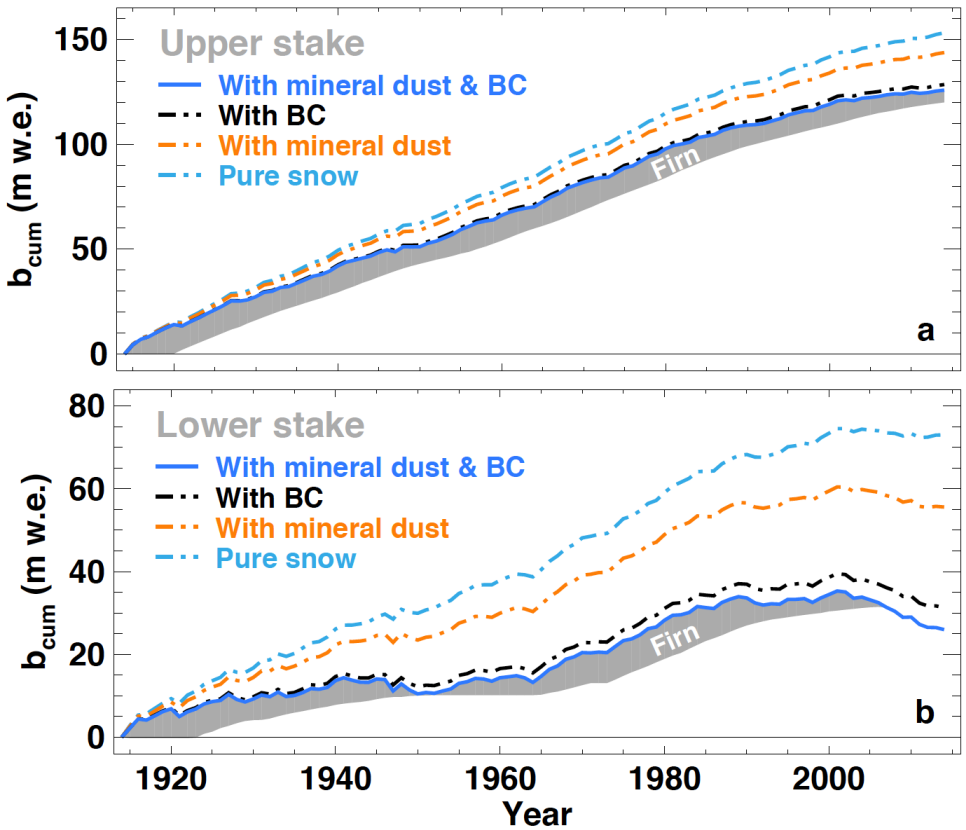


Figure 4.1: Study site overview. The red dots on Claridenfirn indicate the lower stake. The inset shows the location of the study site within Switzerland (red ice core sites Colle Gnifetti and Fiescherhorn (black dot) as well as of the aero station Jungfraujoch and of the weather stations used to derive meteorologic (black triangles).

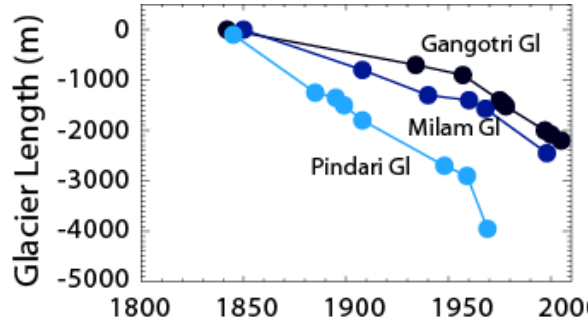


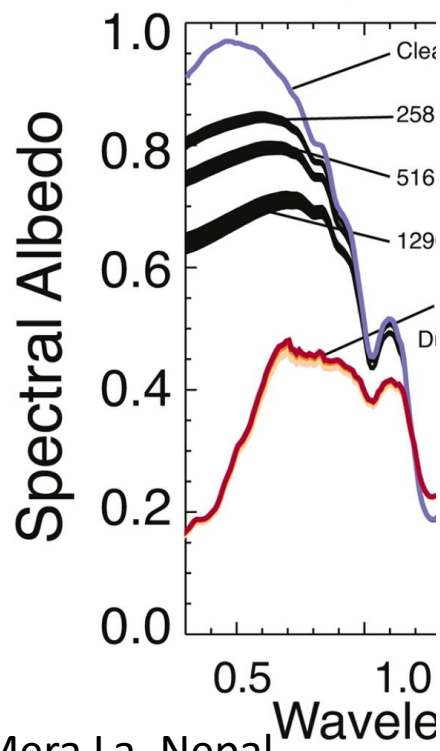
Dust RF daily max: 17.4–44.2 W m^{-2}

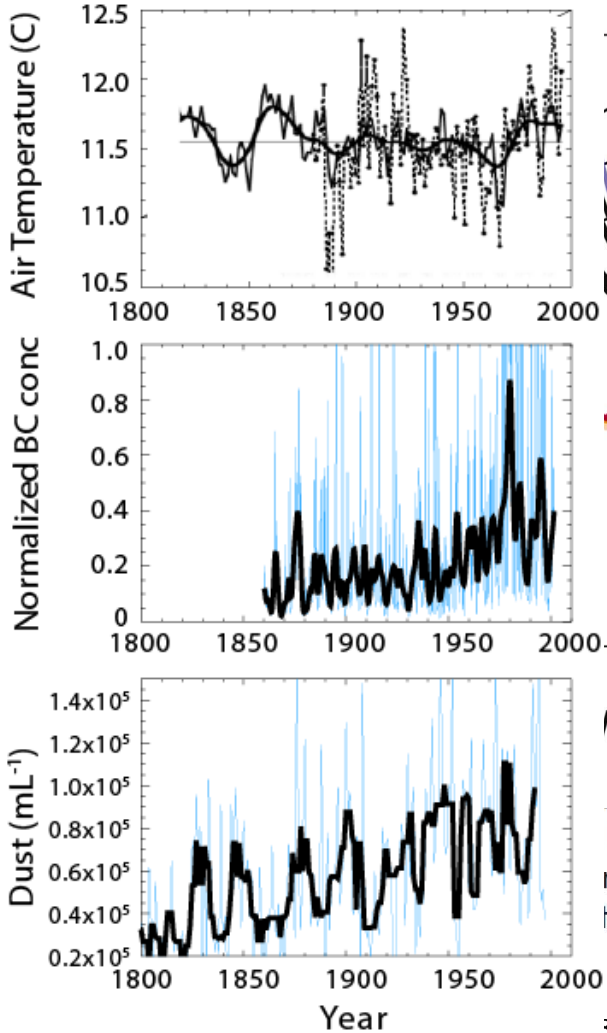
BC RF daily max: 42.6–65.5 W m^{-2}

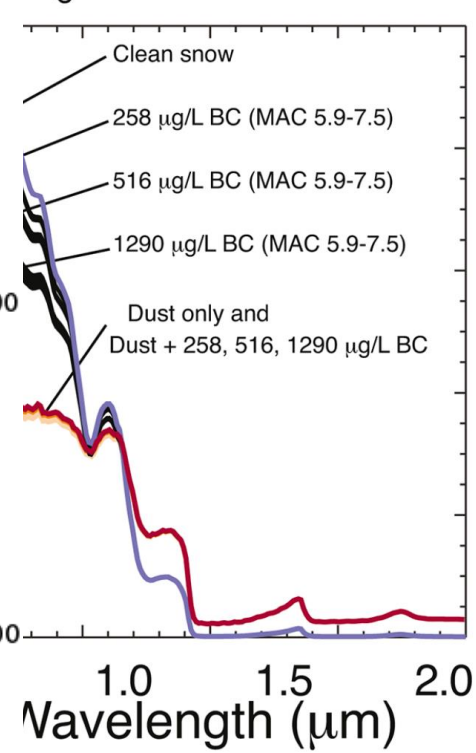
Gabbi et al, 2015, *The Cryosphere*

High rcing









Mera La, Nepal

Kaspari et al, 2014

FIGURE 2. (upper panels) and vertical distributions across the T horizontal scale shows latitude/longitude coordinates) show the deep and extended laye ngetic Plain and Himalayan foothills. Some aerosols can be detected over the top of the T tam et al. (2010); lower panel, Gautam et al. (2009b).

Kaspari, S., T. H. Painter, M. Gysel, M. Schwikowski, and S. 3103, 10.5194/acp-14-8089-2014.

DS RFI #2 Science Questions

Painter, Nolin, Seidel, and Skiles, Monitoring Cryospheric Albedo in a Changing World: Filling the knowledge void on a key climate parameter

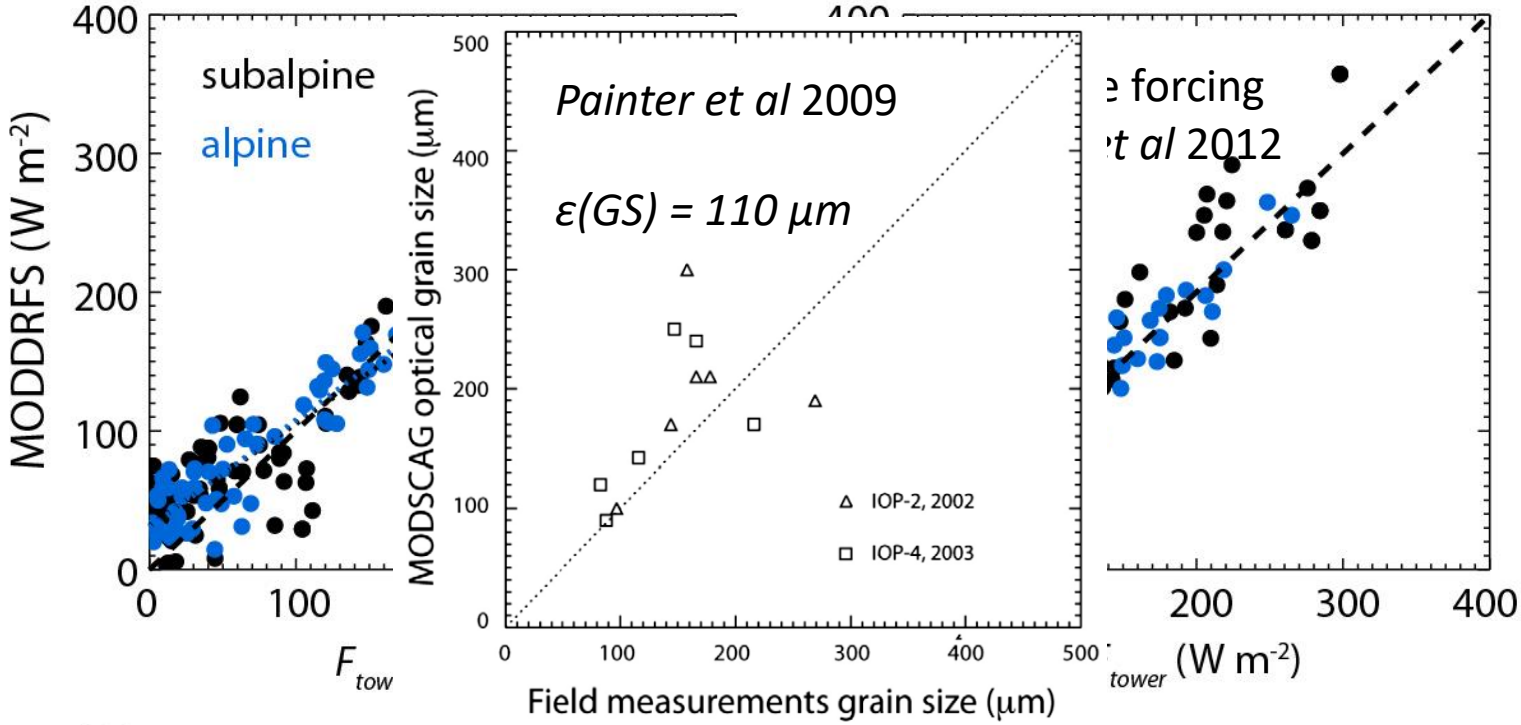
- What is the contribution of regional warming (including its influence on snow grain size growth) and radiative forcing by dust and black carbon to present day snow and ice melt?
- How will climate-driven and population-driven increases in desertification and forest fires lead to accelerated snow and ice melt and perturbation of the global water cycle and regional water supplies?
- How will perturbations of snow and ice albedo impact mountain and ice sheet glacier mass balance?
- For how long would reduction of radiative forcing by dust and BC mitigate against increased melt and sea level rise from climate warming?

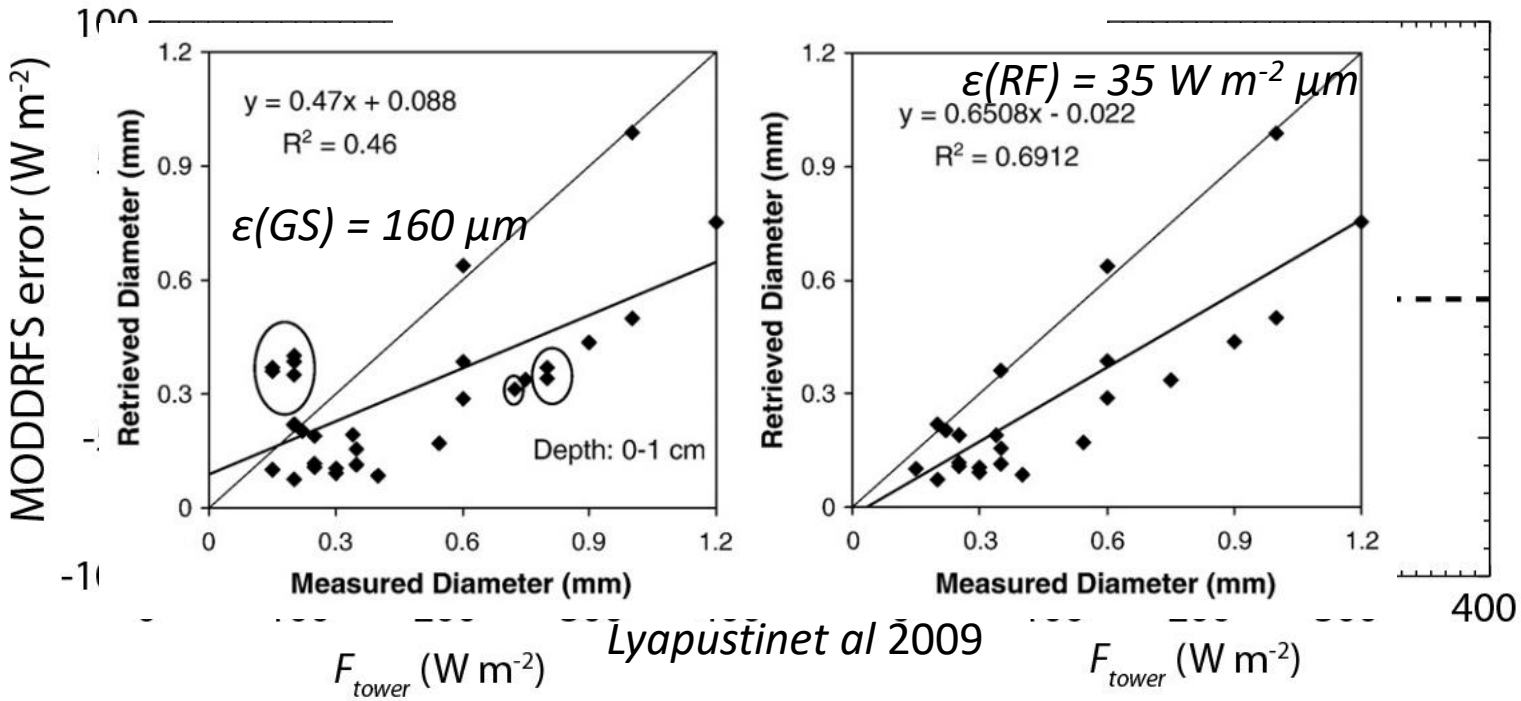
http://sites.nationalacademies.org/DEPS/esas2017/DEPS_170397

Science Traceability Matrix

NASA or ESA or ISSI or TOPC or … Science Goals	DS Science Objectives	Scientific Measurement
		Physical Parameters
	• What is the contribution of regional warming (including its influence on snow grain size growth) and radiative forcing by dust and black carbon to present day snow and ice melt? • How will climate-driven and population-driven increases in desertification and forest fires lead to accelerated snow and ice melt and perturbation of the global water cycle and regional water supplies? • How will perturbations of snow and ice albedo impact mountain and ice sheet glacier mass balance? • For how long would reduction of radiative forcing by dust and BC and sea level rise from climate warming?	Snow and ice spectral albedo in 400-2200 nm spectral range with 30 nm spectral resolution by 0.03 Spectrally-integrated snow albedo in the range 0.3–0.9 unitless, by 0.015 Snow grain radius: 50-2000 µm, by 20 µm Solar at-surface radiative forcing by dust/BC/organics by 3 W m^{-2}

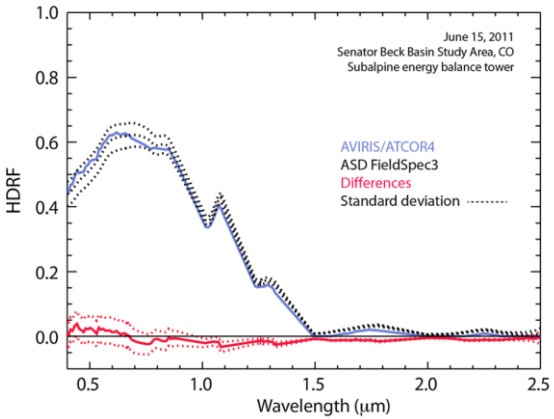
Science First, Spectroscopy Last

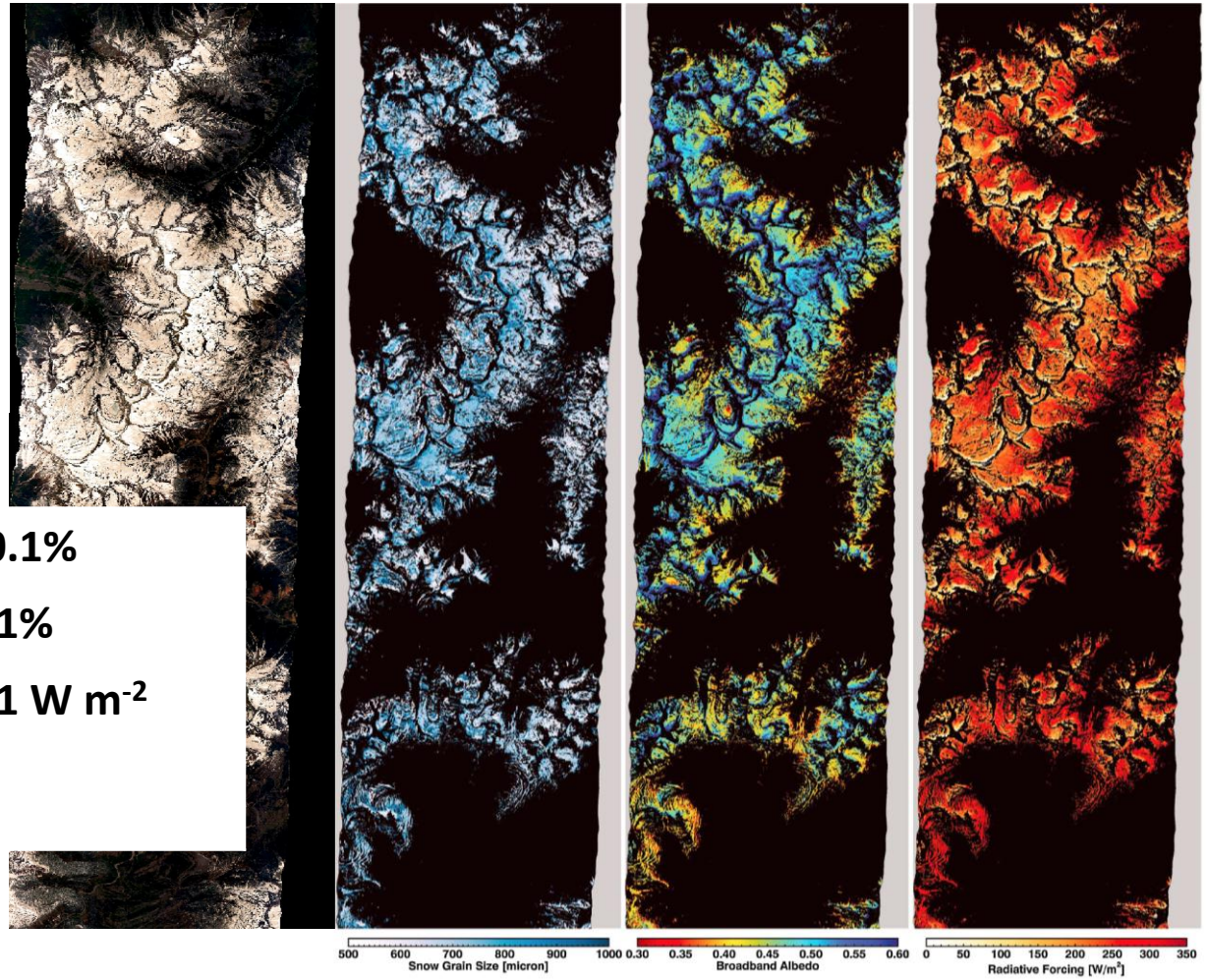




Lyapustinet al 2009

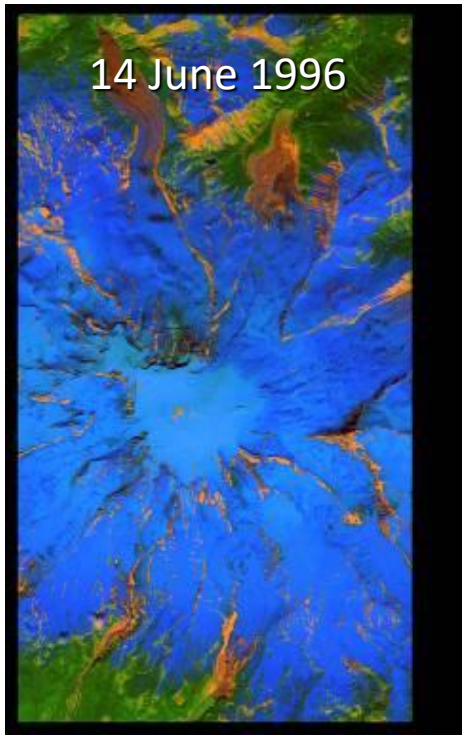
Snow property retrievals from AVIRIS



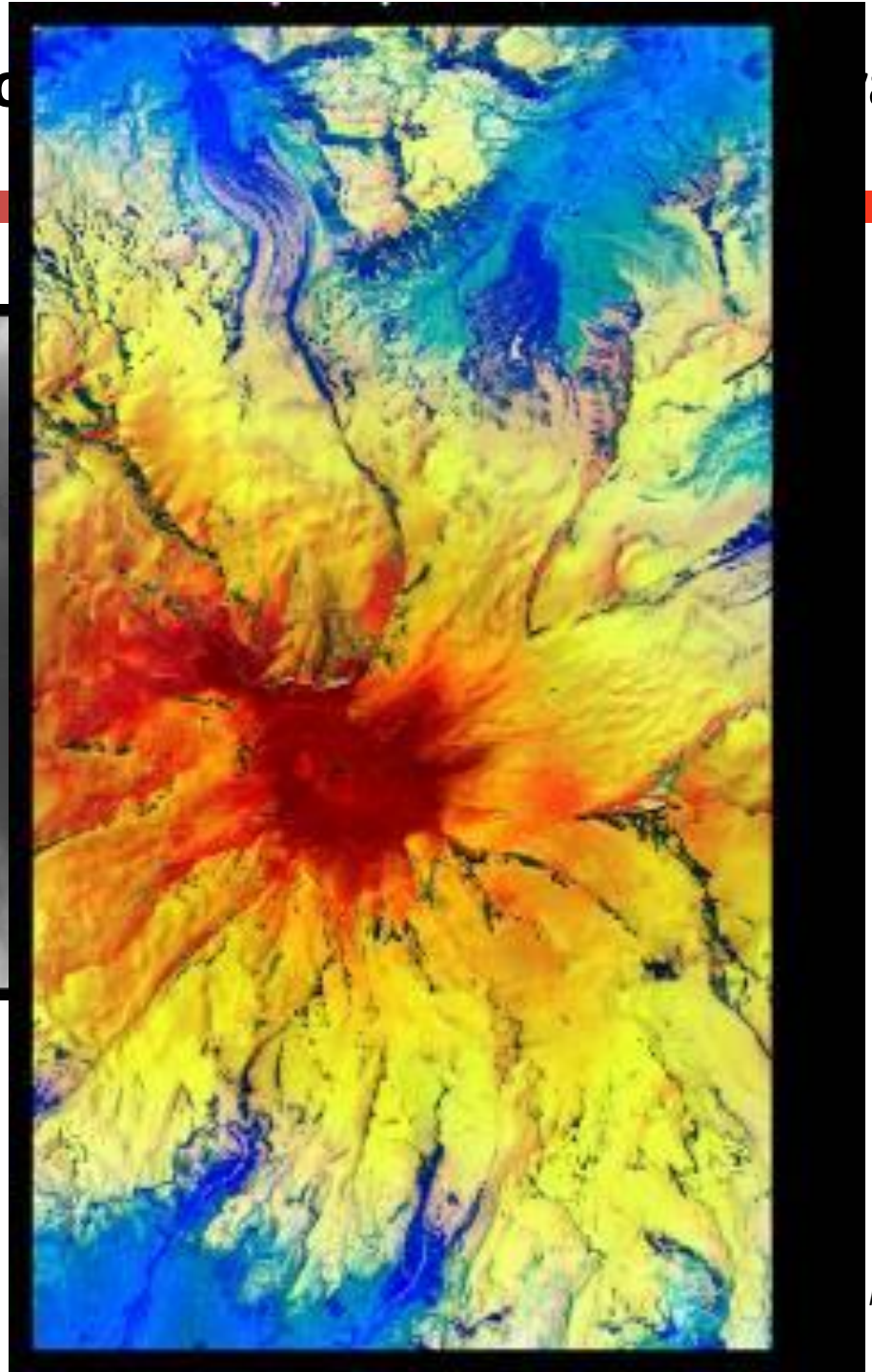


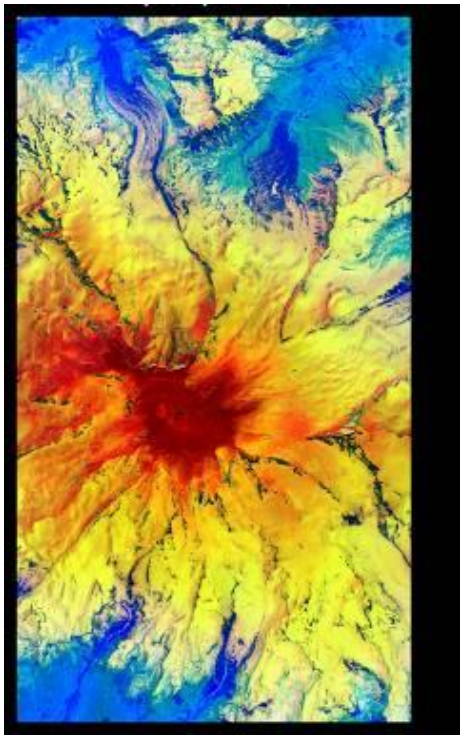
HDRF	**1.50±0.1%**
BB albedo	**0.0±0.1%**
Radiative forcing	**2.1±5.1 W m^{-2}**
Grain size	**25 µm**

Sno al



AVIRIS image, 409, 1324, 2269 nm

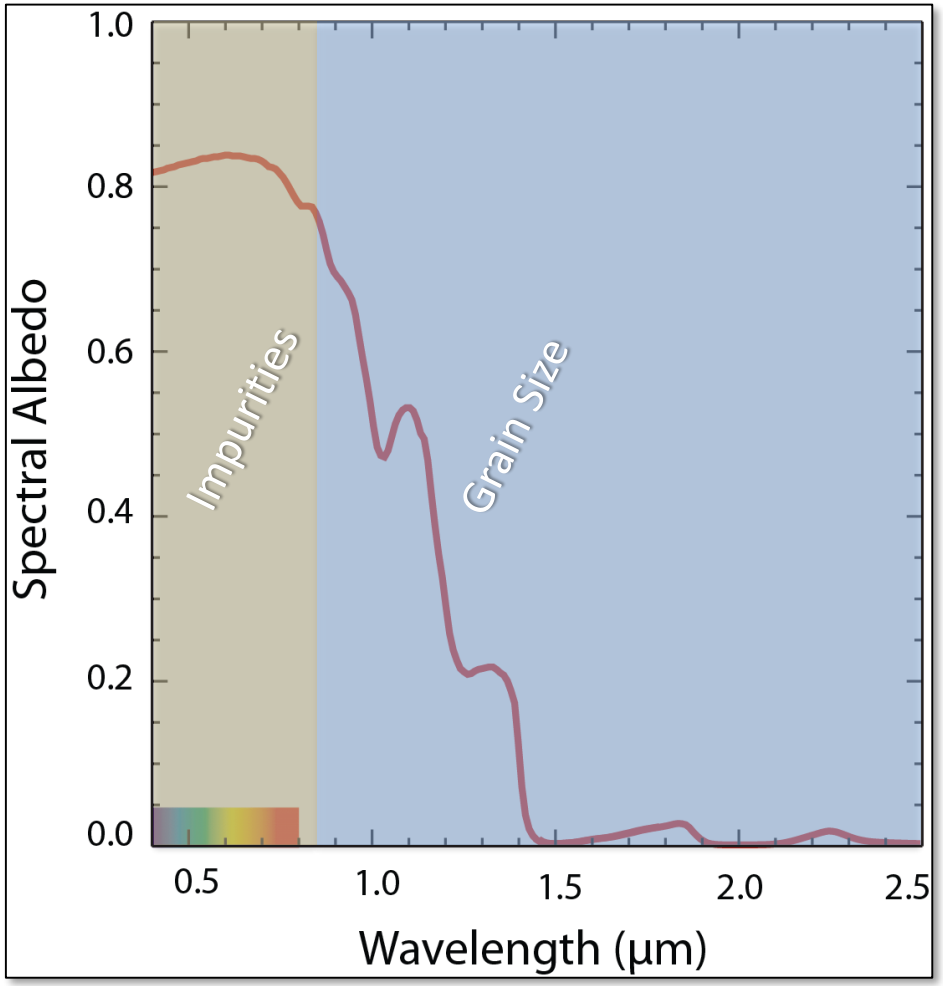


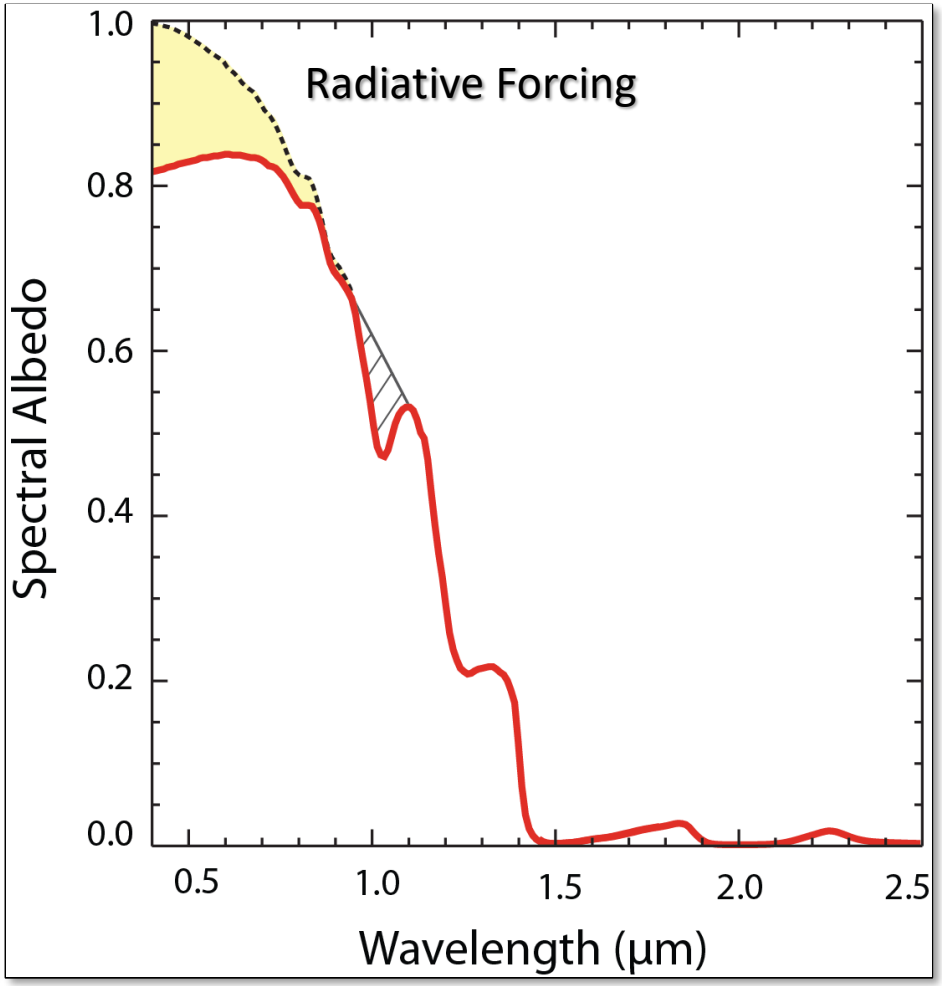


vapor, liquid, ice (BGR)

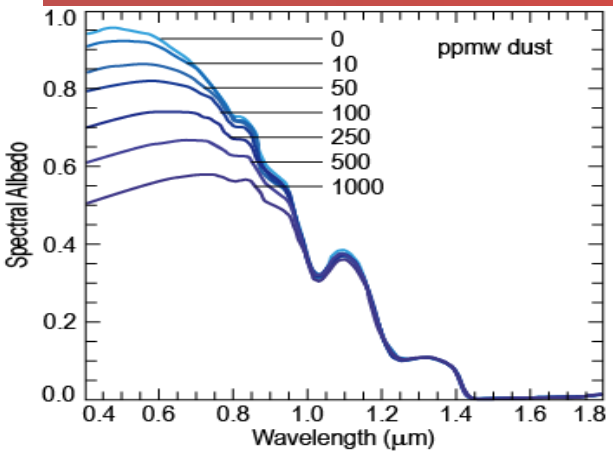
Research, doi: 10.1029/2005WR004509.

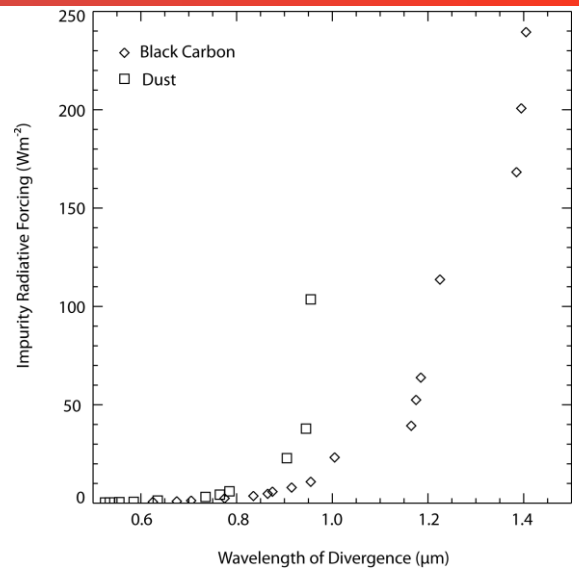
Snow Property Retrievals from IS

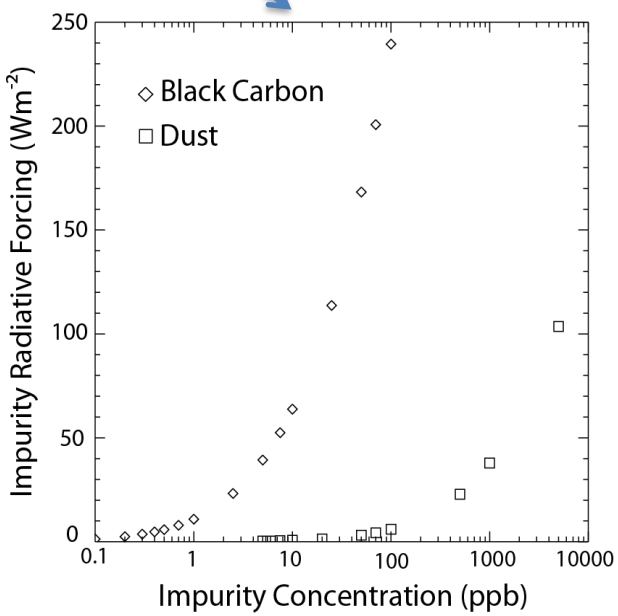


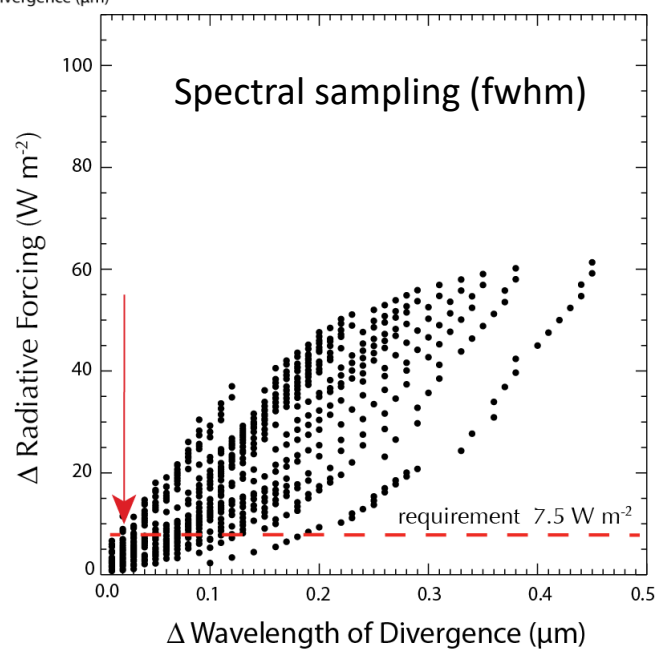


Continuity requirements





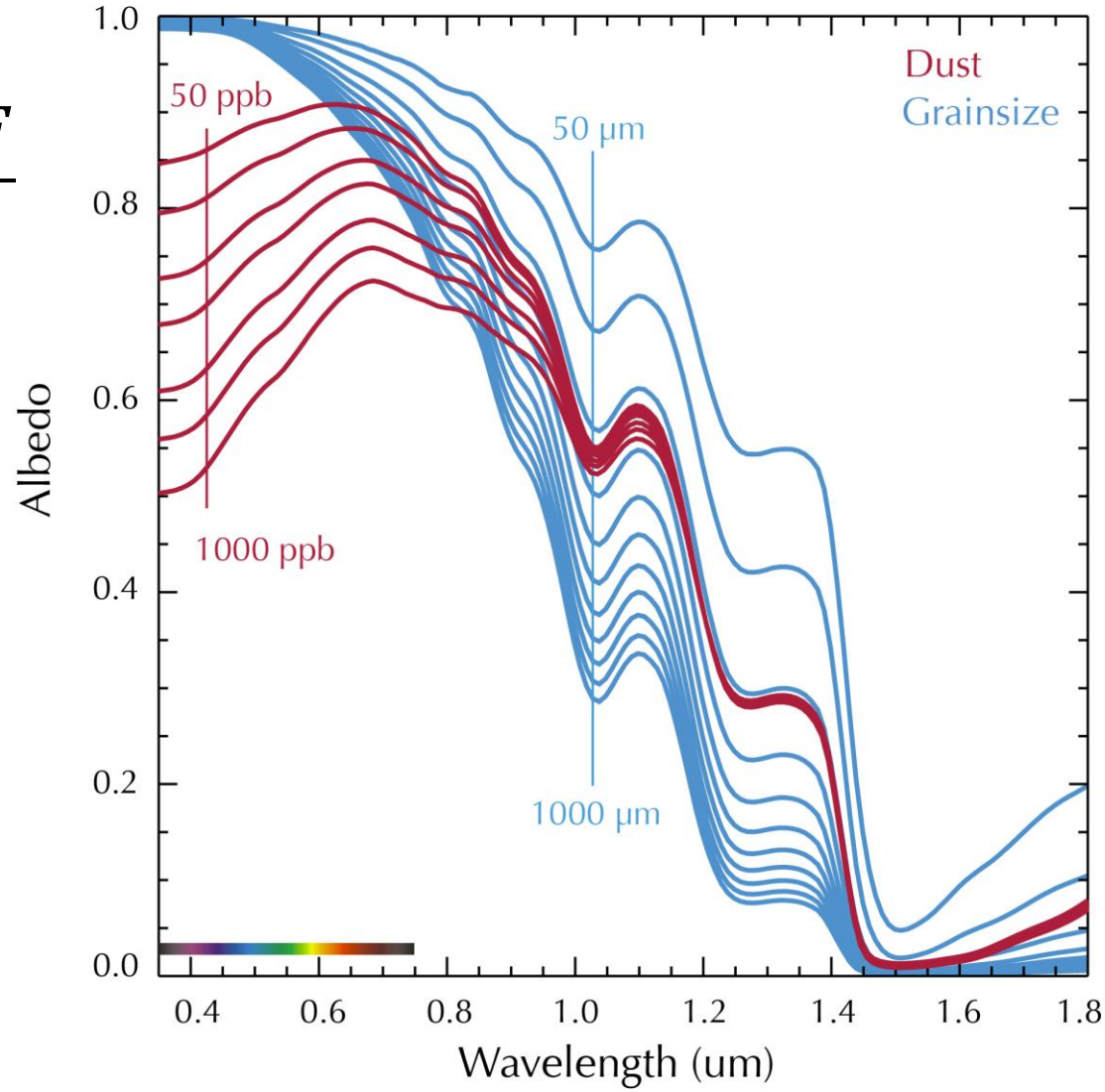




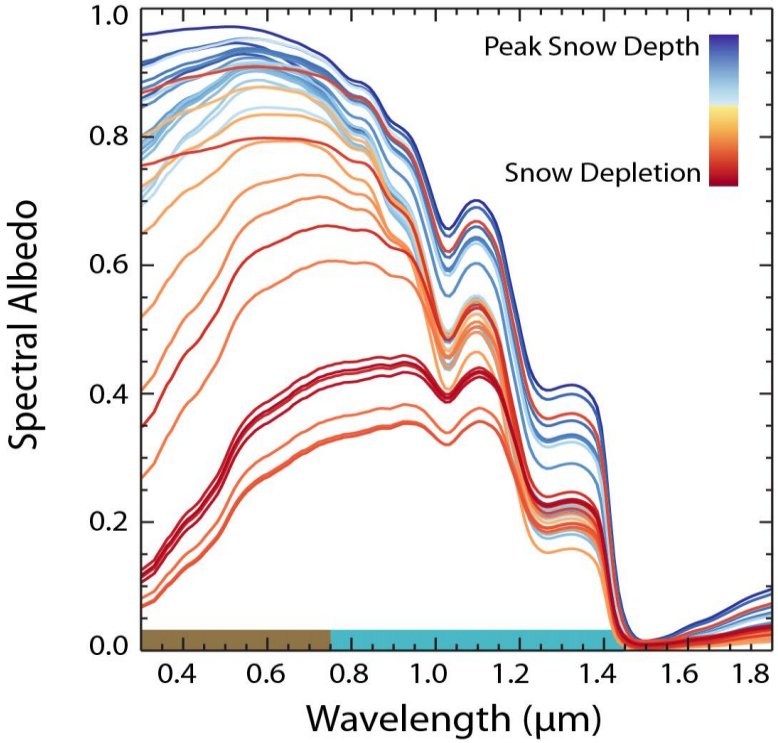
Changes in grain size and RF on α

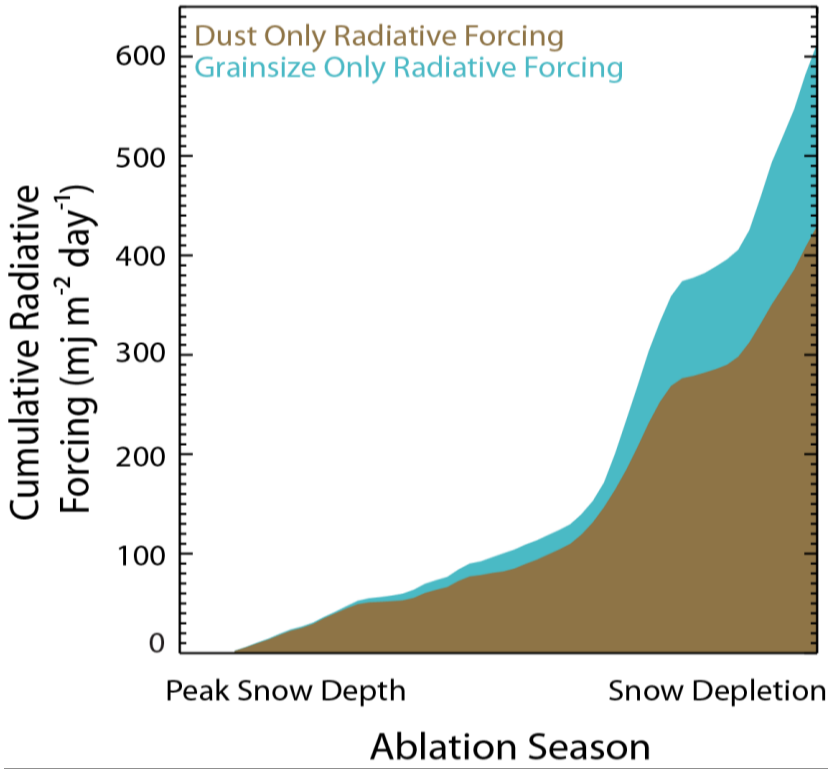
$$\frac{da}{dt} = \frac{\P a}{\P GS}\frac{\P GS}{\P t} + \frac{\P a}{\P RF}\frac{\P RF}{\P t}$$

for a fixed solar zenith angle and spectral irradiance



Measurement needs





Circa weekly acquisition

(Skiles, 2014; Skiles and Painter, in prep)

Science Traceability Matrix

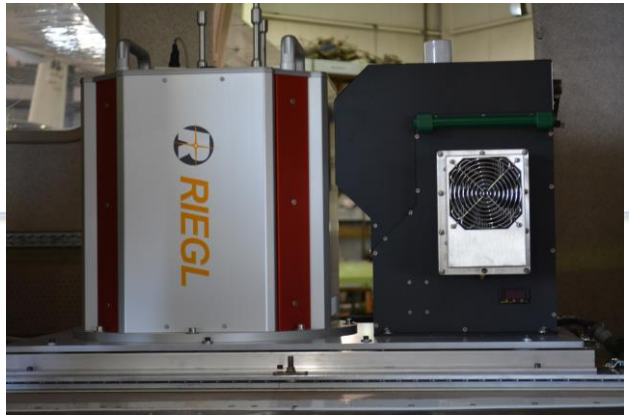
NASA or ESA or ISSI or TOPC or … Science Goals	DS Science Objectives	Scientific Measurement Requirements		Mission Requirements	
		Physical Parameters	Observable	Parameter	Performance
	• What is the contribution of regional warming (including its influence on snow grain size growth) and radiative forcing by dust and black carbon to present day snow and ice melt? • How will climate-driven and population-driven increases in desertification and forest fires lead to accelerated snow and ice melt and perturbation of the global water cycle and regional water supplies? • How will perturbations of snow and ice albedo impact mountain and ice sheet glacier mass balance? • For how long would reduction of radiative forcing by dust and BC mitigate against increased melt and sea level rise from climate warming?	Snow and ice spectral albedo in 400-2200 nm spectral range with 30 nm spectral resolution by 0.03 Spectrally-integrated snow albedo in the range 0.3–0.9 unitless, by 0.015 Snow grain radius: 50-2000 µm, by 20 µm Solar at-surface radiative forcing by dust/BC/organics by 3 W m^{-2}	**Visible shortwave infrared (VSWIR) radiance spectra, 400-2200 nm:** 40 nm precision at 400-900 nm for radiative forcing due to dust and BC 30 nm precision at 980–1070 nm for snow grain size 10 nm precision at 740–780 nm for oxygen A-band atmospheric correction 10 nm precision at 860–1020 nm and 1050–1250 nm for water vapor corrections	Spectral range	**350-2500nm**
				Spectral resolution	**< 9 nm**
				SNR	**> 100 (Vis)** **> 200 (NIR)**
				Radiometric range	**1.9× Lambertian**
				Spatial resolution	
				Swath	**38 km, nadir @ 500 km min altitude**
				Calibration:	

NASA/JPL AIRBORNE SNOW OBSERVATORY – FINALLY DISTRIBUTED SWE

Airborne Snow Observatory

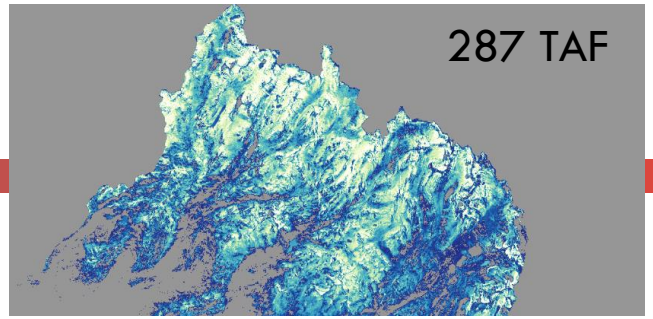
Snow Depth

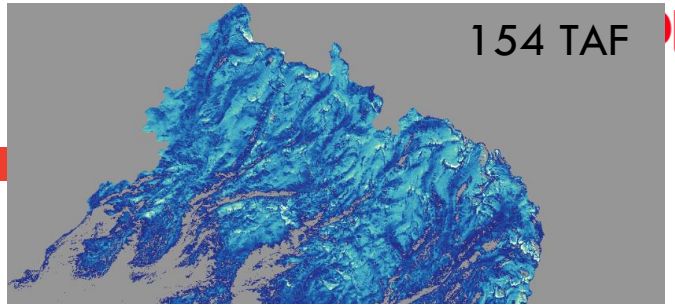
- Riegl Q1560 dual laser scanning lidar
- 1064 nm
- Full-waveform
- 60° field of view

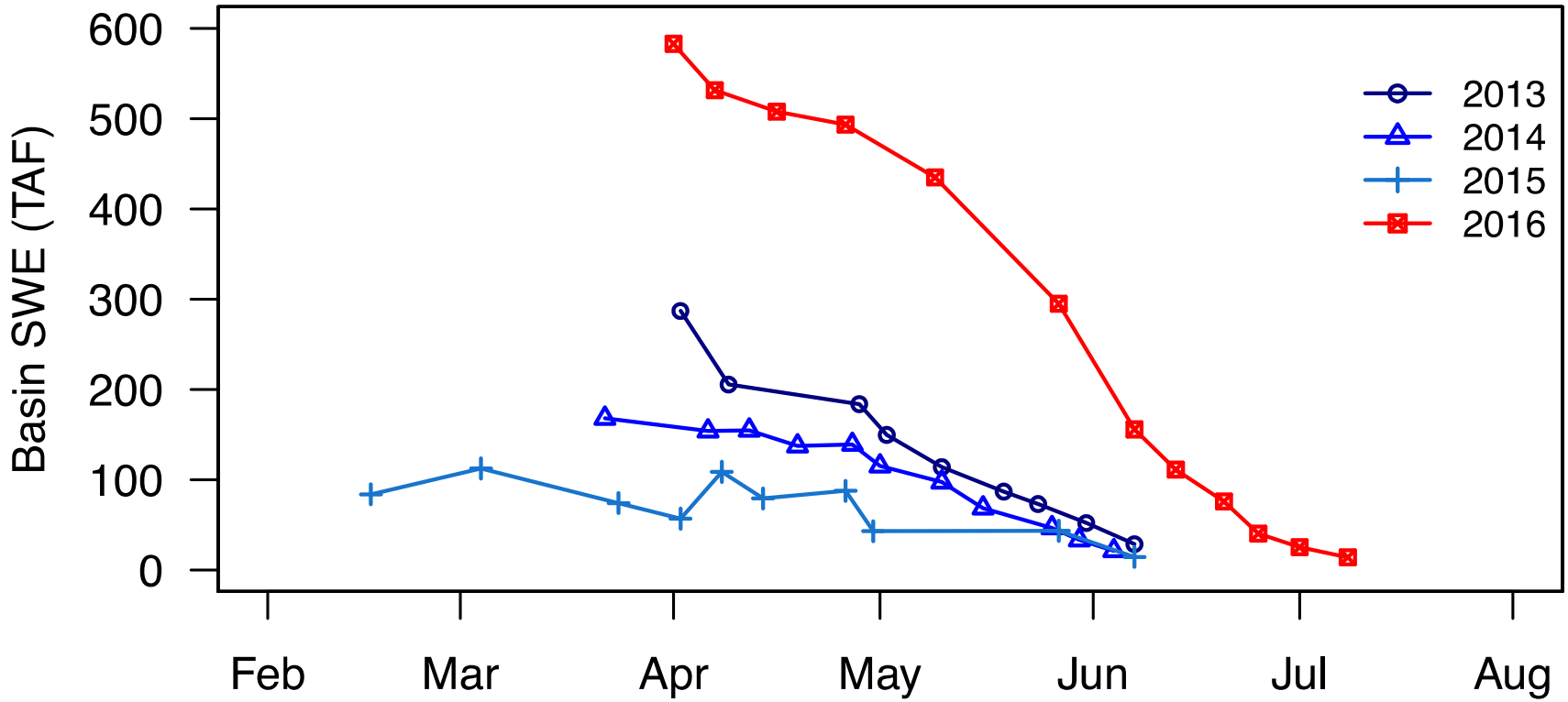


Snow Albedo

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

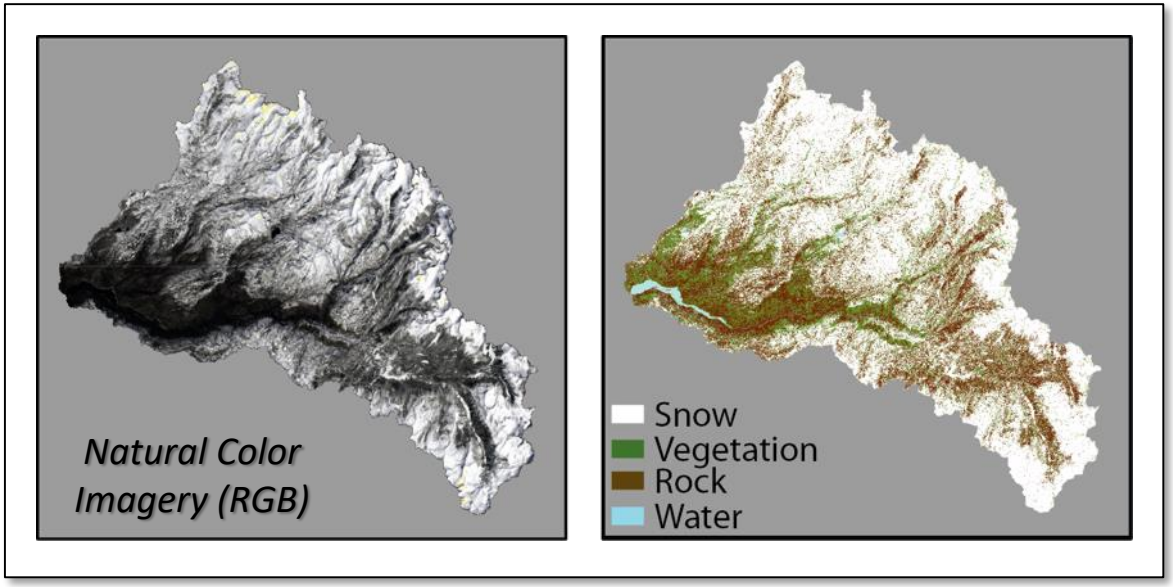


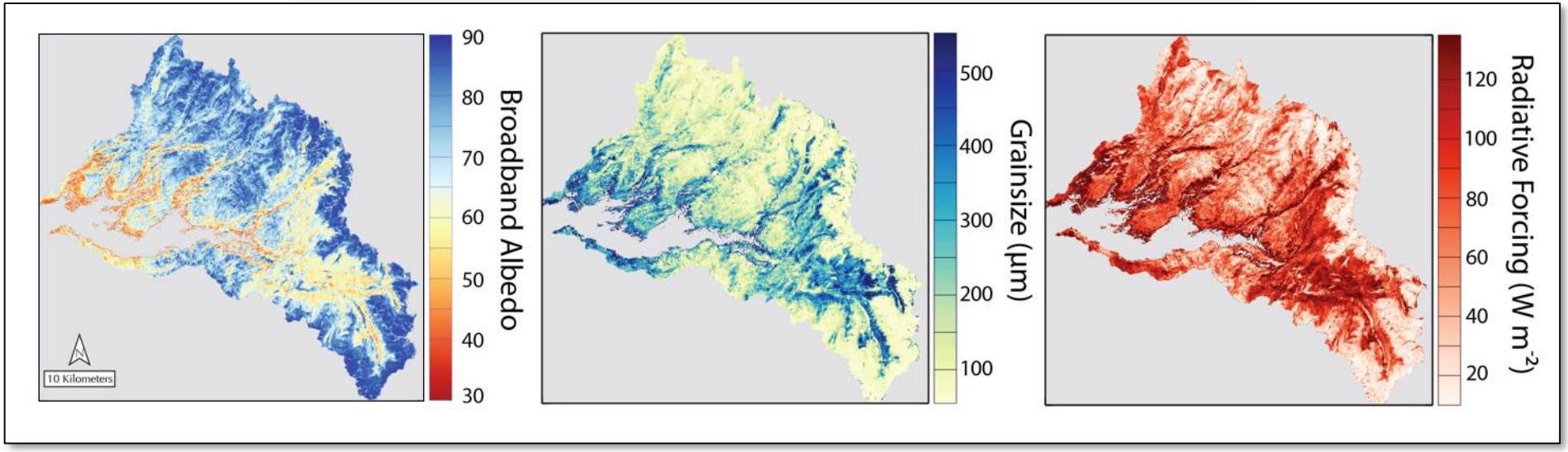




TAF = thousand acre-feet

ASO Imaging Spectrometer Products



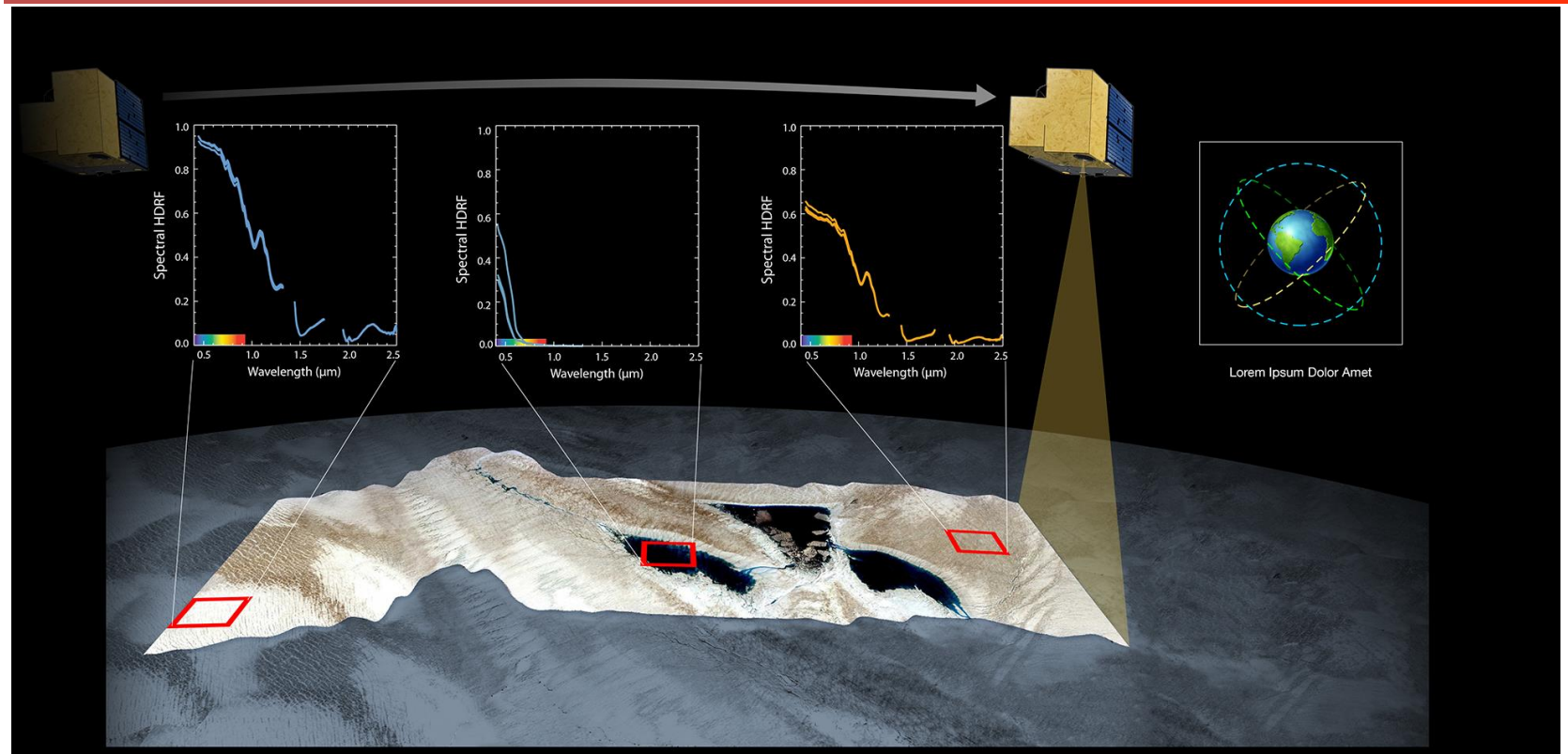


Painter et al., 2013

Science Traceability Matrix

NASA or ESA or ISSI or TOPC or … Science Goals	DS Science Objectives	Scientific Measurement Requirements		Mission Requirements			
		Physical Parameters	Observable	Parameter	Performance	Requirement	Performance
	• What is the contribution of regional warming (including its influence on snow grain size growth) and radiative forcing by dust and black carbon to present day snow and ice melt? • How will climate-driven and population-driven increases in desertification and forest fires lead to accelerated snow and ice melt and perturbation of the global water cycle and regional water supplies? • How will perturbations of snow and ice albedo impact mountain and ice sheet glacier mass balance? • For how long would reduction of radiative forcing by dust and BC mitigate against increased melt and sea level rise from climate warming?	Snow and ice spectral albedo in 400-2200 nm spectral range with 30 nm spectral resolution by 0.03 Spectrally-integrated snow albedo in the range 0.3–0.9 unitless, by 0.015 Snow grain radius: 50-2000 µm, by 20 µm Solar at-surface radiative forcing by dust/BC/organics by 3 W m^{-2}	**Visible shortwave infrared (VSWIR) radiance spectra, 400-2200 nm:** 40 nm precision at 400-900 nm for radiative forcing due to dust and BC 30 nm precision at 980–1070 nm for snow grain size 10 nm precision at 740–780 nm for oxygen A-band atmospheric correction 10 nm precision at 860–1020 nm and 1050–1250 nm for water vapor corrections	Spectral range	**350-2500nm**	**TBD**	**LEO** **11:00 LT; nodal drift over mission < 30 min**
				Spectral resolution	**< 9 nm**	**TBD**	
				SNR	**> 100 (Vis)** **> 200 (NIR)**	**TBD**	
				Radiometric range	**1.9× Lambertian**	**TBD**	**Etc.**
				Spatial resolution		**TBD**	
				Swath	**38 km, nadir @ 500 km min altitude**	**TBD**	
				Calibration:		**TBD**	

Global spectroscopy to understand process controls on melting cryosphere



Collect global spectra

SIRFA's accurate frequent-repeat measurements will collect globally-distributed spectra throughout the Earth's cryosphere.

Map snow grain size and impurity (BC/dust) loading

These key spectral features captured throughout a melt season provide regional characterizations needed to separate the physical processes that have contributed to accelerated melting

Inform current snow and ice models

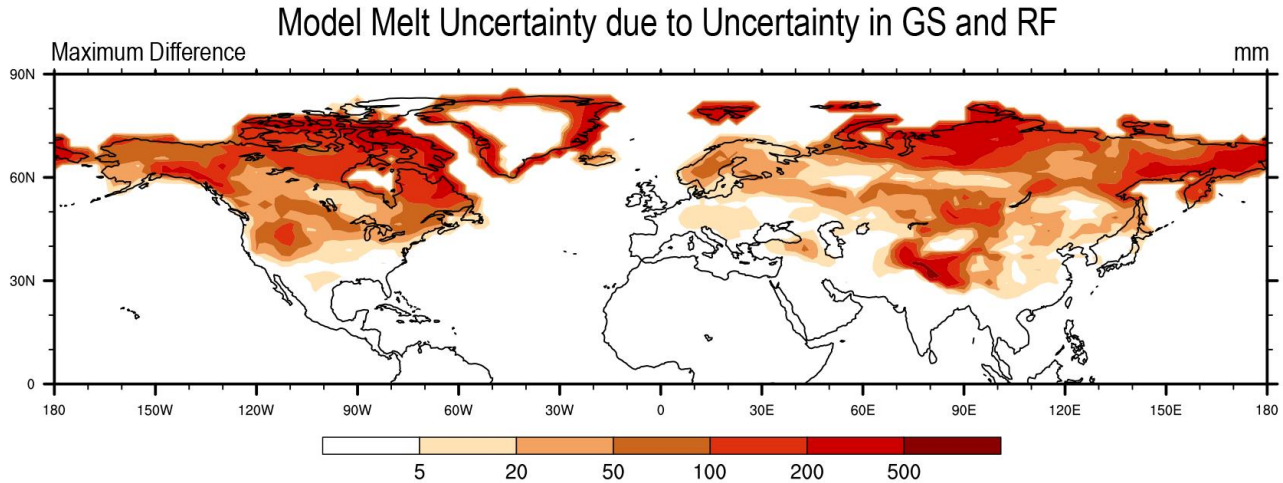
SIRFA's physical data will "replace" current empirical data filling an unknown error gap leading to more accurate modeling of melt

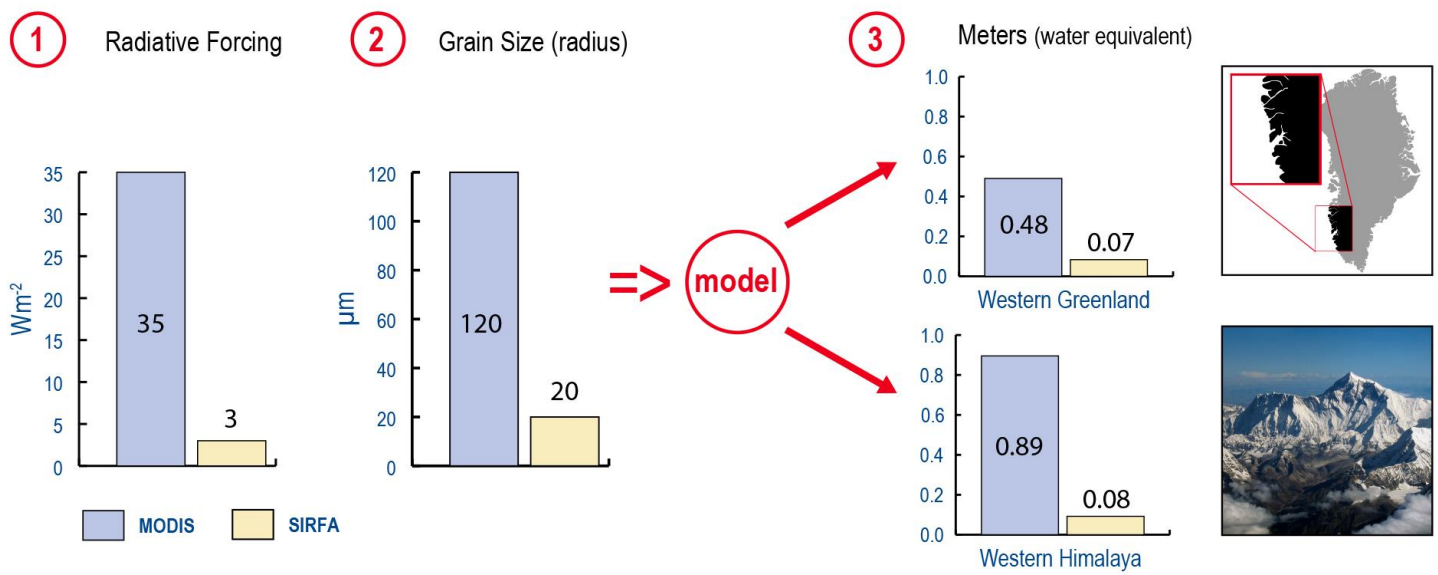
Better understanding of processes accelerating cryospheric melt

SIRFA determines and communicates what processes are controlling global snow and ice melt allowing the scientific community to better project how they will melt in the future

F010

Getting down to answers to "Why?"





Measurement Uncertainty Improvement

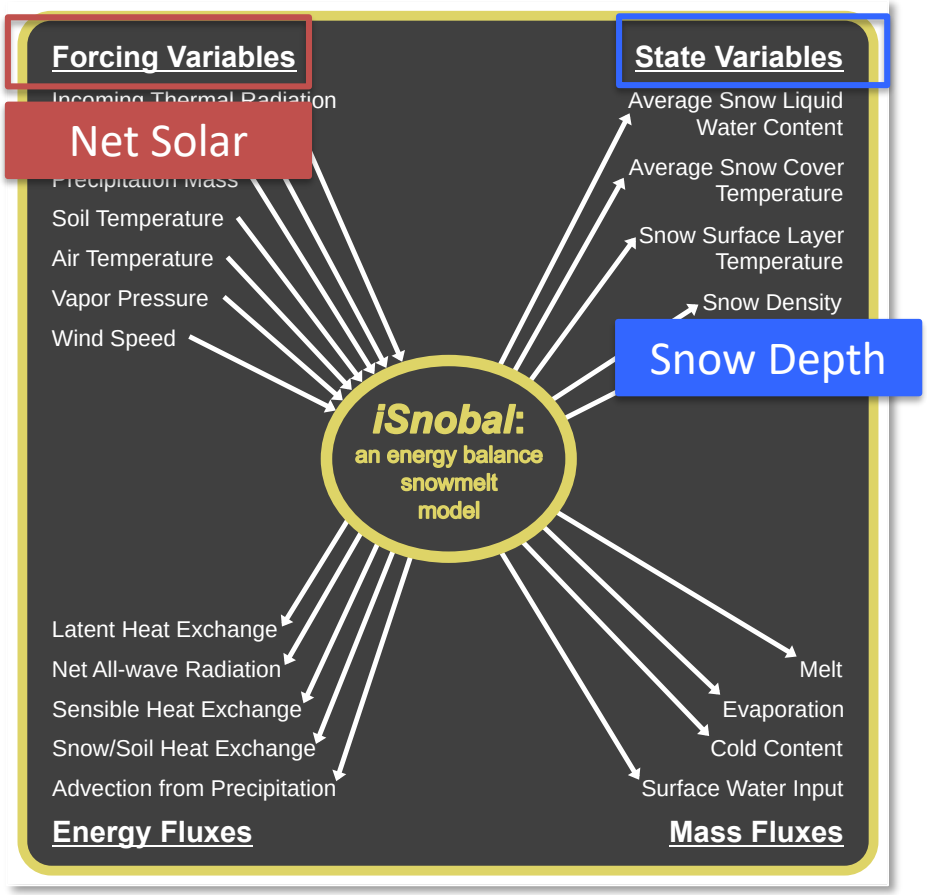
Modeling Uncertainty Improvement

Where are we now?

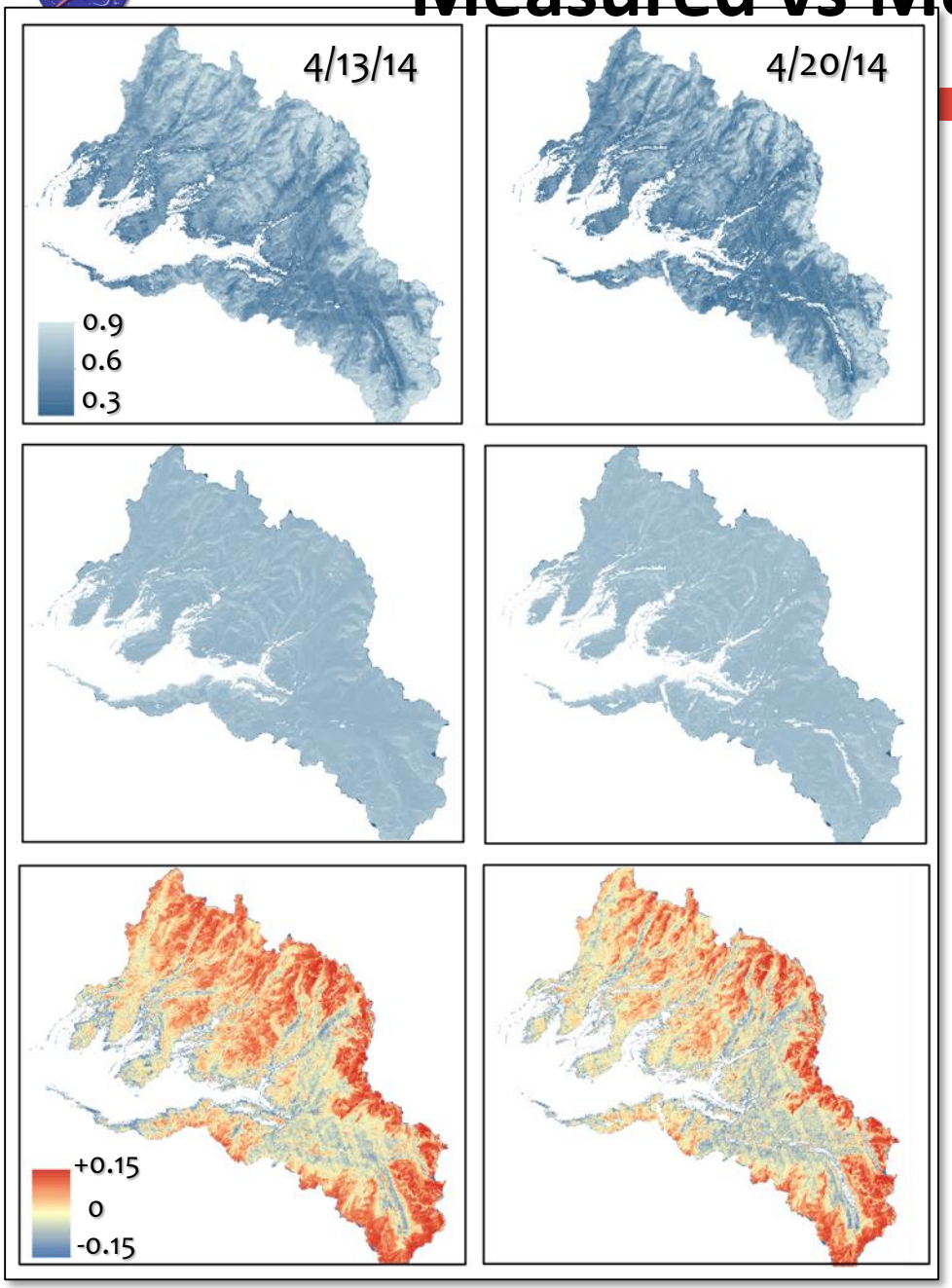
- NCAR team constraining WRF-Hydro mesoscale modeling with ASO time series
- USDA ARS team constraining iSNOBAL snowmelt model with ASO time series
- PNNL team constrain WRF-Chem mesoscale modeling with ASO time series

ASO constraining distributed modeling

- Informs net solar forcing when combined with terrain and cloud corrected incoming solar
- Estimated based on a decay function from time of last storm, and includes an impurity factor
- Calculated in two bands to account for spectral variation
  - Visible (280-700 µm)
  - Near infrared (700-2800 µm)



Measured vs Modeled Albedo

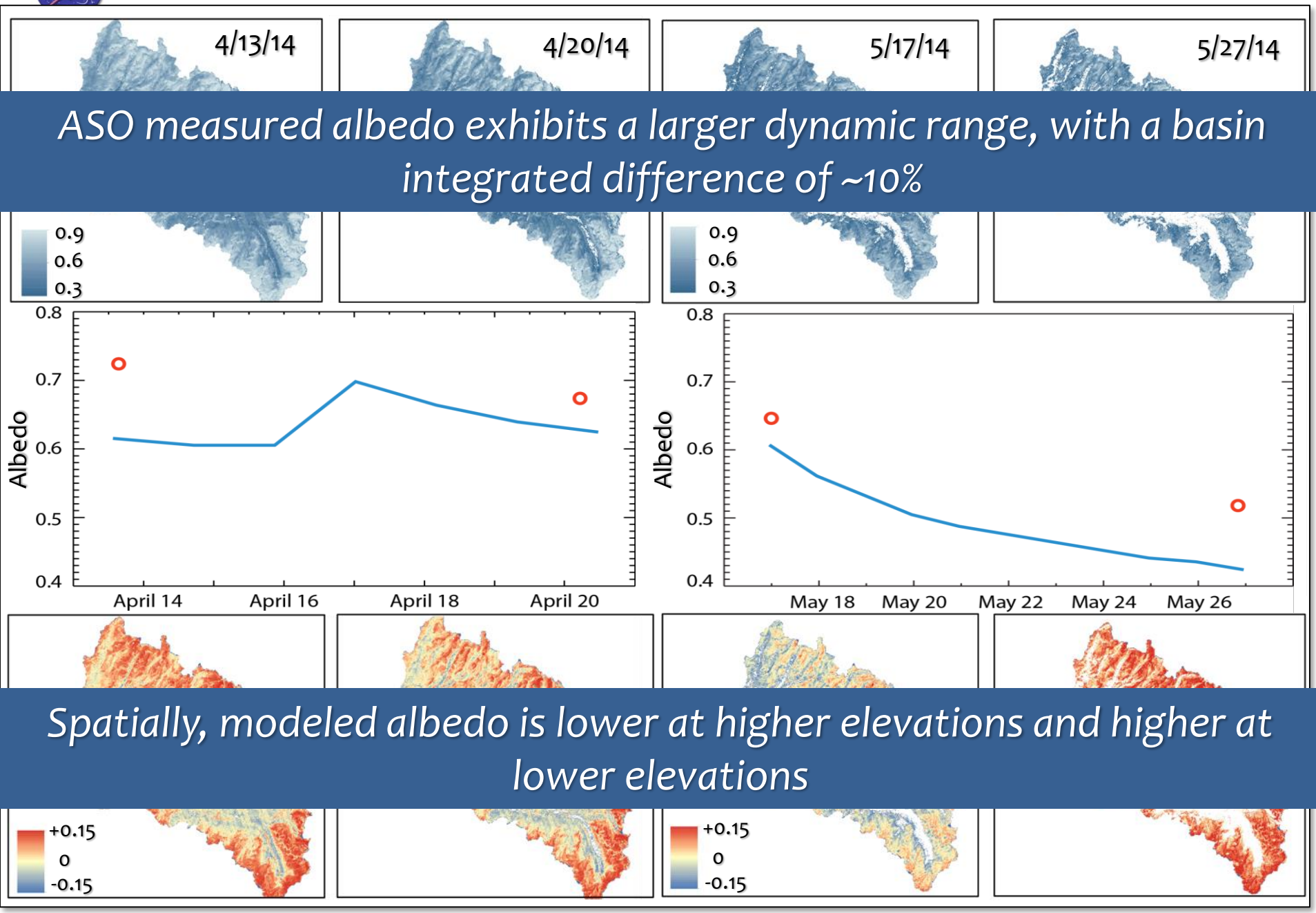


ASO broadband albedo

iSNOBAL broadband albedo

ASO/iSNOBAL difference map

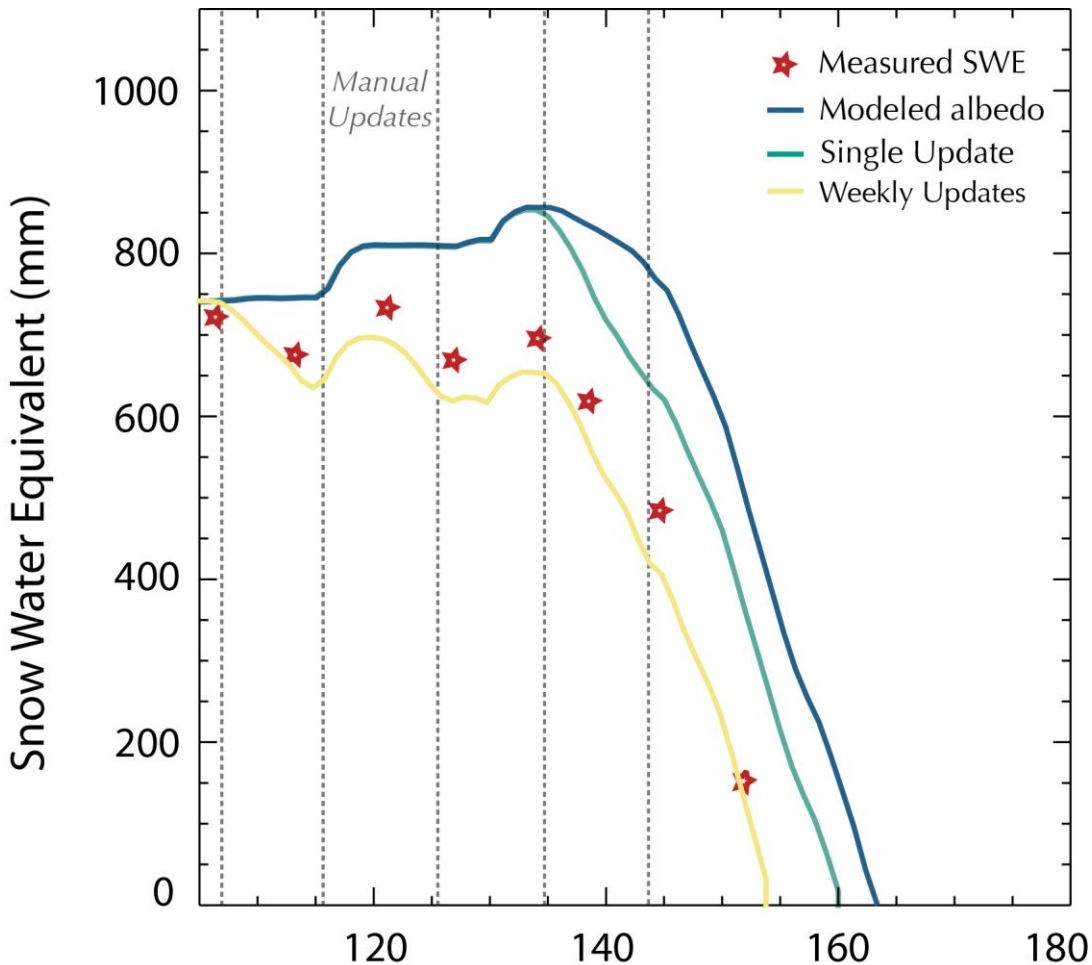
Measured vs Modeled Albedo



ASO measured albedo exhibits a larger dynamic range, with a basin integrated difference of ~10%

Spatially, modeled albedo is lower at higher elevations and higher at lower elevations

Updating iSNOBAL albedo



Running left across the STM

NASA or ESA or ISSI or TOPC or … Science Goals	DS Science Objectives	Scientific Measurement Requirements: Physical Parameters	Scientific Measurement Requirements: Observable	Mission Requirements: Parameter	Mission Requirements: Performance	Mission Requirements: Requirement	Mission Requirements: Performance
	• What is the contribution of regional warming (including its influence on snow grain size growth) and radiative forcing by dust and black carbon to present day snow and ice melt? • How will climate-driven and population-driven increase in desertification and fire [illegible] lead to accelerated [illegible] and perturbation [illegible] global water cycle and regional water supplies? • How will perturbations of snow and ice albedo impact mountain and ice sheet glacier mass balance? • For how long would reduction of radiative forcing by dust and BC mitigate against increased melt and sea level rise from climate warming?	Snow and ice spectral albedo in 400-2200 nm spectral range with 30 nm spectral resolution by 0.03 Spectrally-integrated snow albedo in the range 0.3–0.9 unitless, by 0.015 Snow grain radius: 50-2000 µm, by 20 µm Solar at-surface radiative forcing by dust/BC/organics by 3 W m^{-2}	**Visible shortwave infrared (VSWIR) radiance spectra, 400-2200 nm:** 40 nm precision at 400-900 nm for radiative forcing due to dust and BC 30 nm precision at 980–1070 nm for snow grain size 10 nm precision at 740–780 nm for oxygen A-band atmospheric correction 10 nm precision at 860–1020 nm and 1050–1250 nm for water vapor corrections	Spectral range	**350-2500nm**	**TBD**	**LEO** **11:00 LT; nodal drift over mission < 30 min**
				Spectral resolution	**< 9 nm**	**TBD**	
					> 200 (NIR)	**TBD**	
				Radiometric range	**1.9× Lambertian**	**TBD**	**Etc.**
				Spatial resolution		**TBD**	
				Swath	**3[illegible] km, nadir @ 500 km min altitude**	**TBD**	
				Calibration:		**TBD**	

OK, let's do it

Acknowledgements

- Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.
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