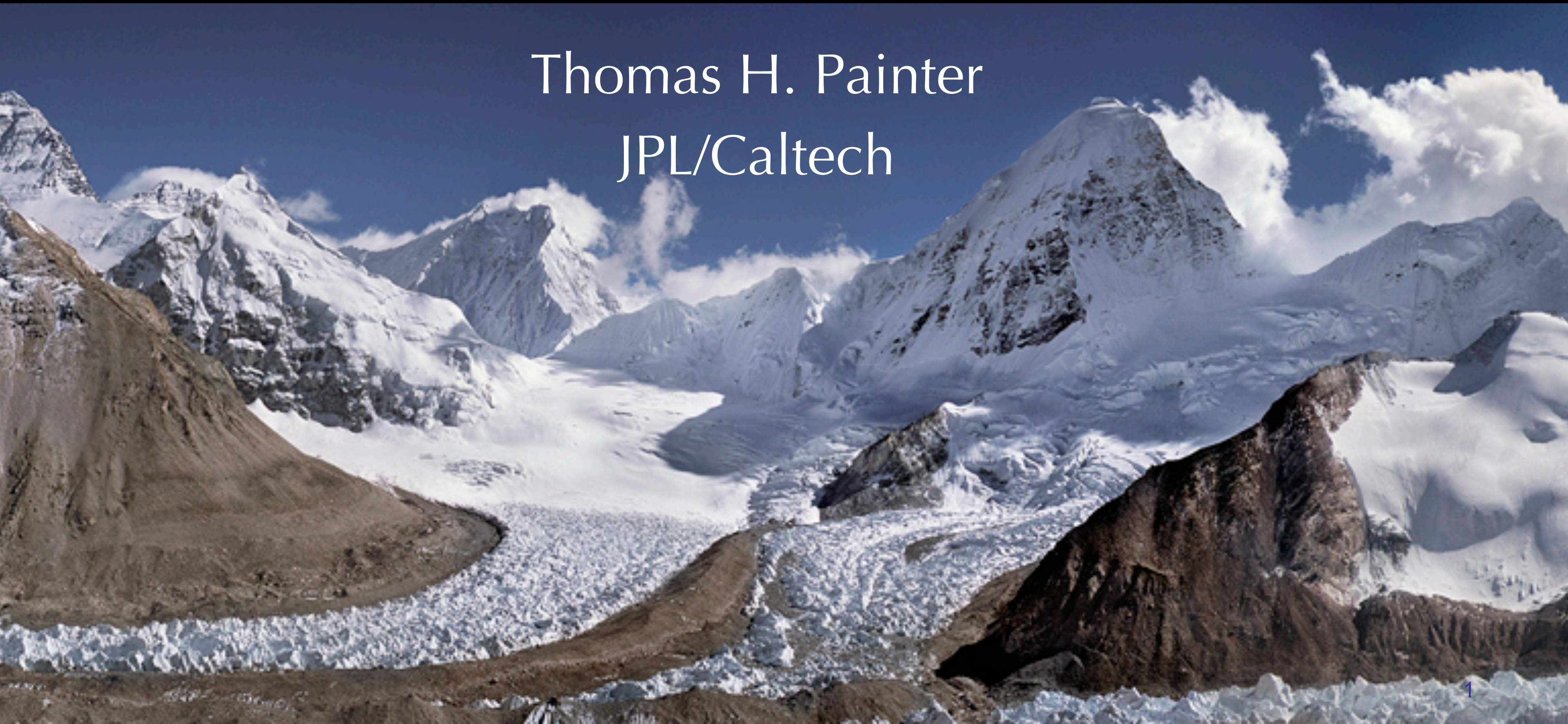
Imaging Spectroscopy of the Global Cryosphere

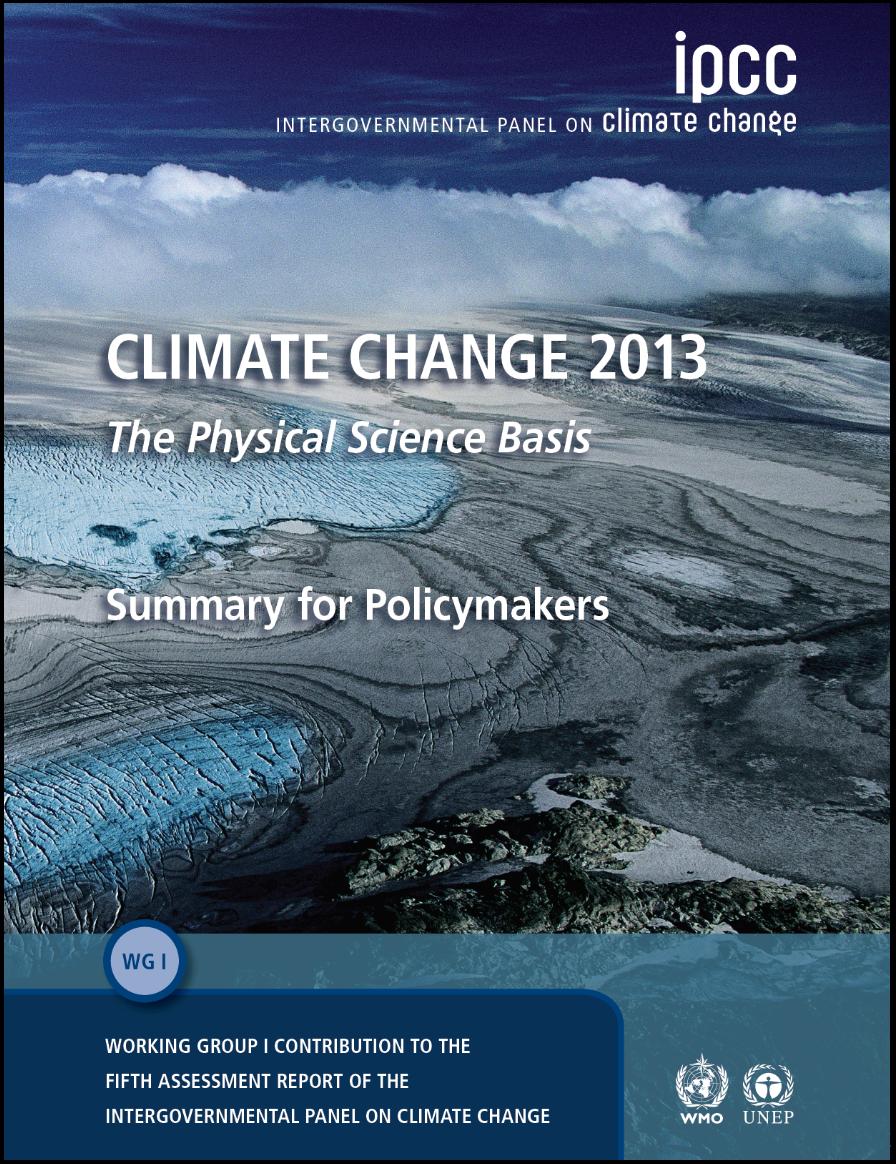
Thomas H. Painter
JPL/Caltech



Science Questions

What are the controls on the global snow-albedo feedback?

What is the response of global snow and ice albedo and melt to temperature increases and dust/BC radiative forcing?



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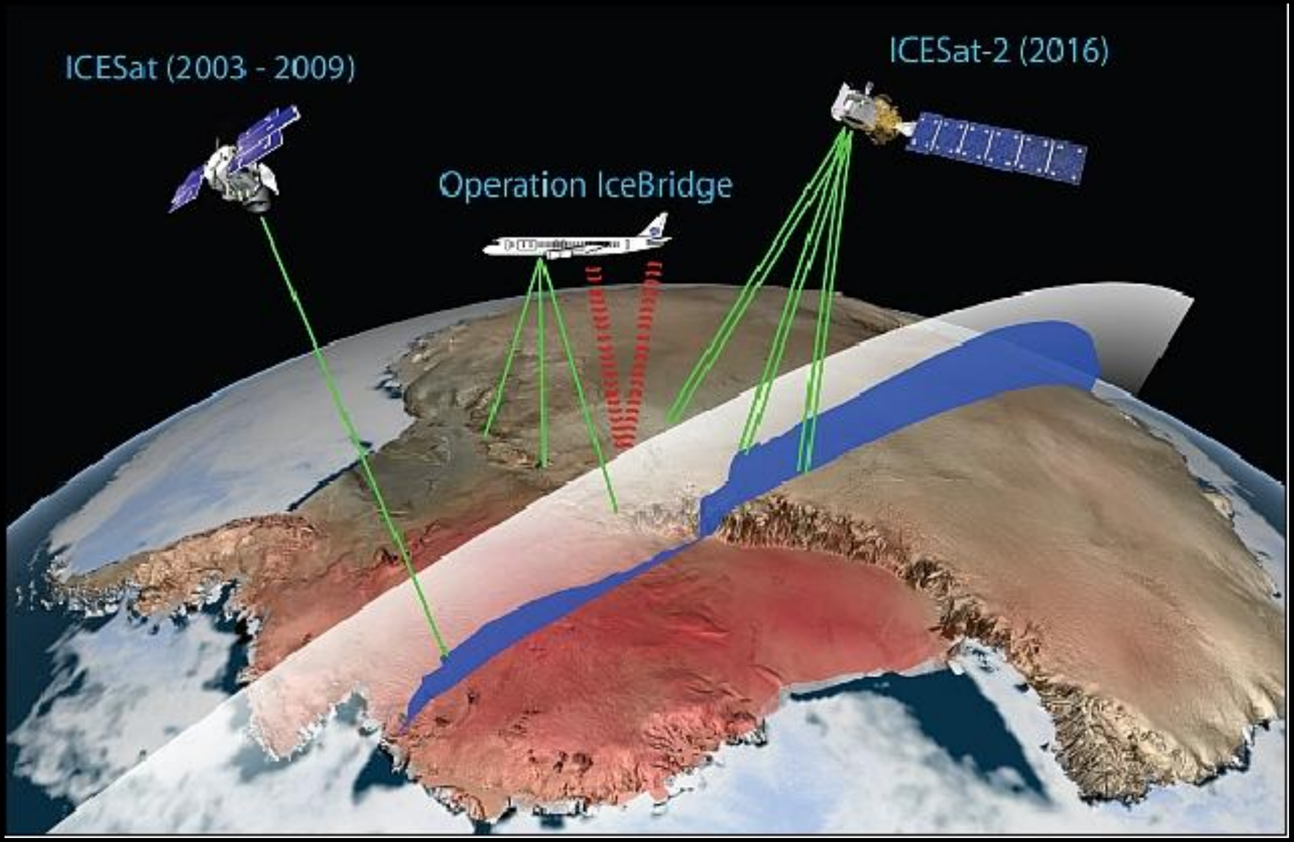


Aren't we already dealing with these with ICESat, ICEBridge, and ICESat-2?!

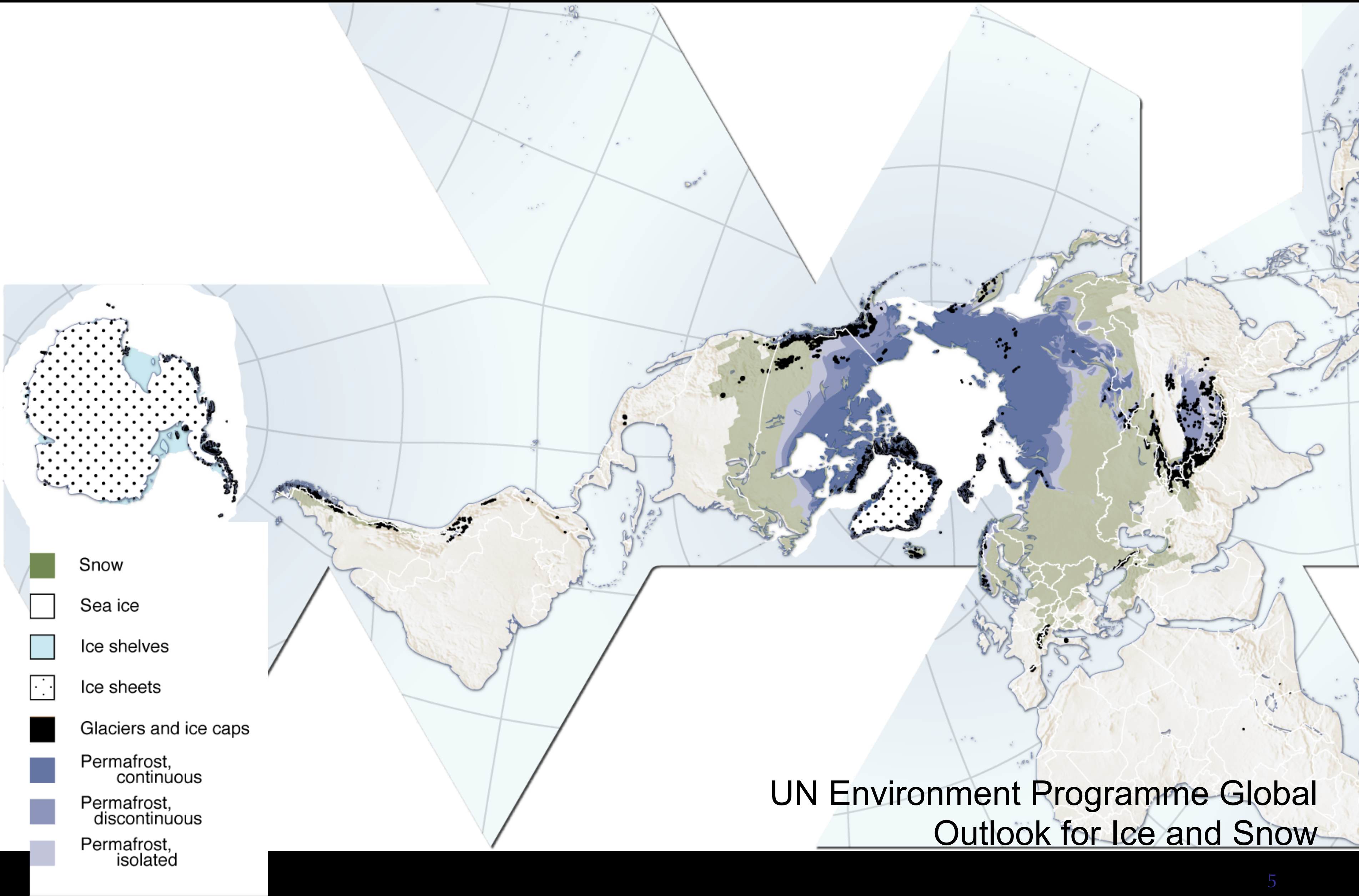
Nope – those are just the changes in mass – no attribution to forcing of changes in mass.

Background

- The snow albedo feedback amplifies changes in global radiative forcing, particularly in high latitude regions which are highly sensitive to changes in climate
- Snow/ice albedo and melt are highly sensitive to trace amounts of light absorbing impurities (e.g. black carbon)
- Roughly one-fifth of Earth's population uses melted snow or glacial ice in some capacity for water resources
- Glacier and ice sheet runoff accounts for a large fraction of sea level rise
- The timing and magnitude of snowmelt runoff modulate regional climate and hydroclimate, dominates ecosystem function in vast regions, and contribute to most major flooding events

Uncertainties in our understanding of the processes that control snow albedo feedbacks result in large uncertainties in projected changes in climate and sea level

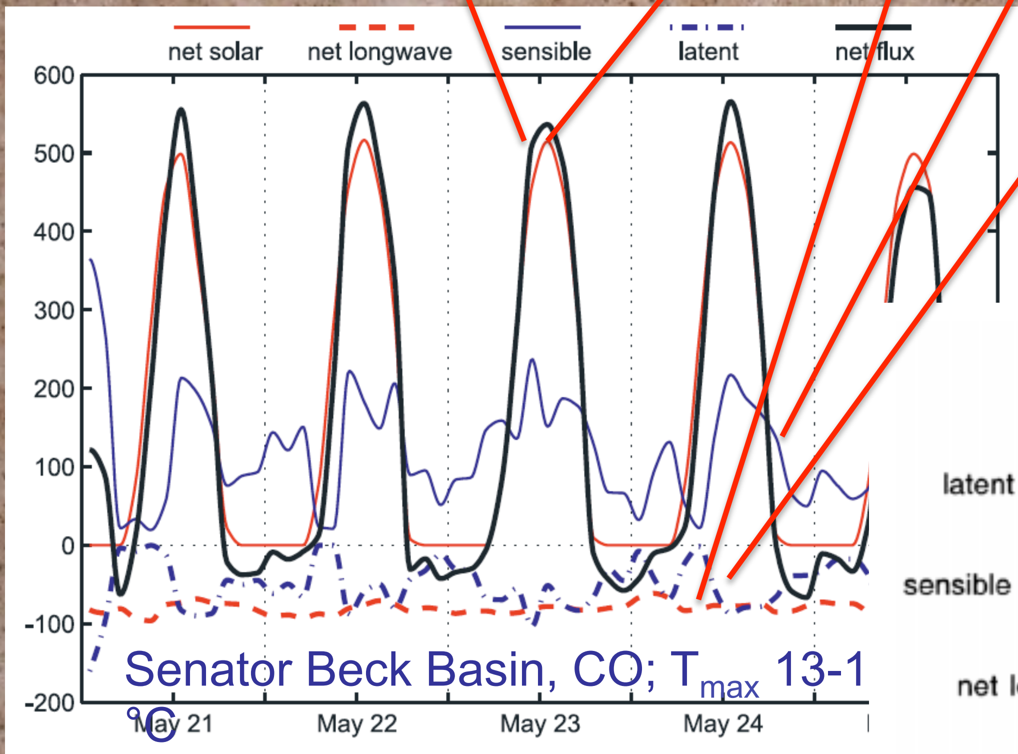
Global Cryosphere



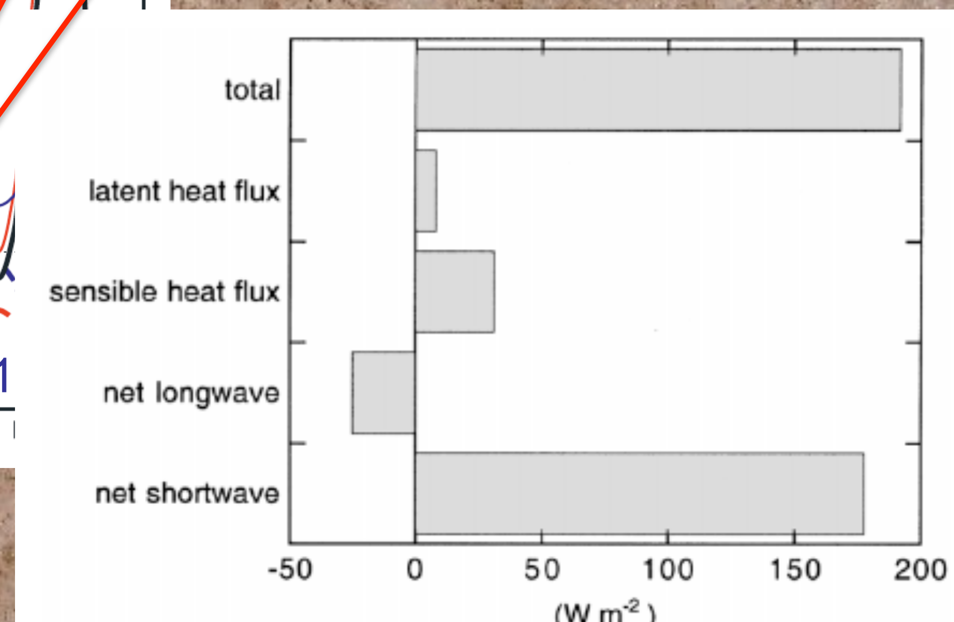
UN Environment Programme Global Outlook for Ice and Snow

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

What controls snowmelt?



Senator Beck Basin, CO; T_{max} 13-1 °C



Morteratschgletscher (*Oerlemans, 2000*)

Elk Range, Colorado River Basin, April 2009

Greenland Melt

The Cryosphere, 6, 821–839, 2012
www.the-cryosphere.net/6/821/2012/
doi:10.5194/tc-6-821-2012
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The Cryosphere

Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers

ve[4,5], M. Tedesco[6], D. K. Hall[7], and K. Steffen[5]

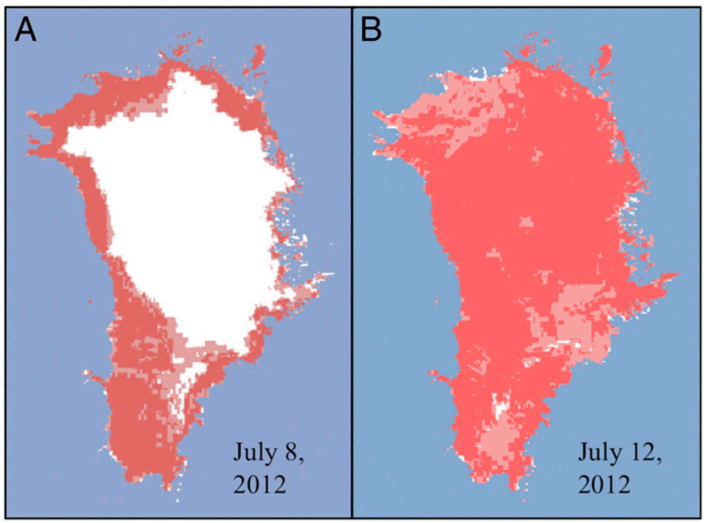


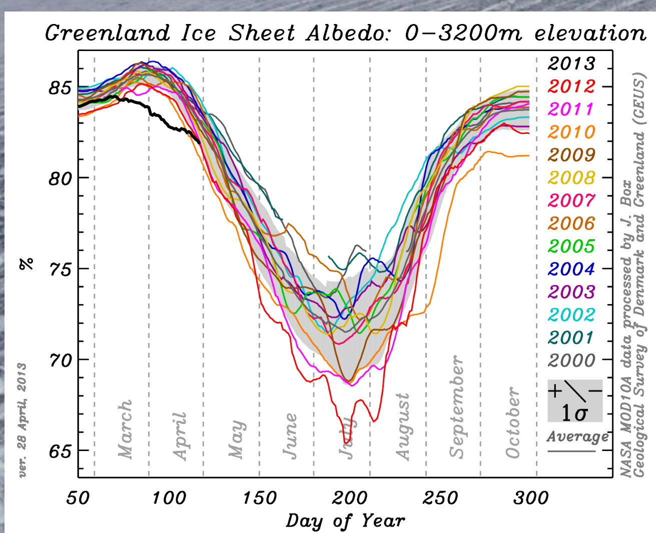
Fig. 1. Melt extent over the GIS determined from Oceansat-2 satellite scatterometer, Special Sensor Microwave Imager/Sounder, and Moderate-resolution Imaging Spectroradiometer satellite data for (*A*) July 8, 2012, and (*B*) July 12, 2012. Red areas indicate melt detected by the satellites, white areas indicate no melt, and blue represents ocean. The surface of almost the entire ice sheet, including the dry snow region, experienced melt on July 12, 2012. Figure courtesy of Dorothy Hall, NASA Goddard Space Flight Center.

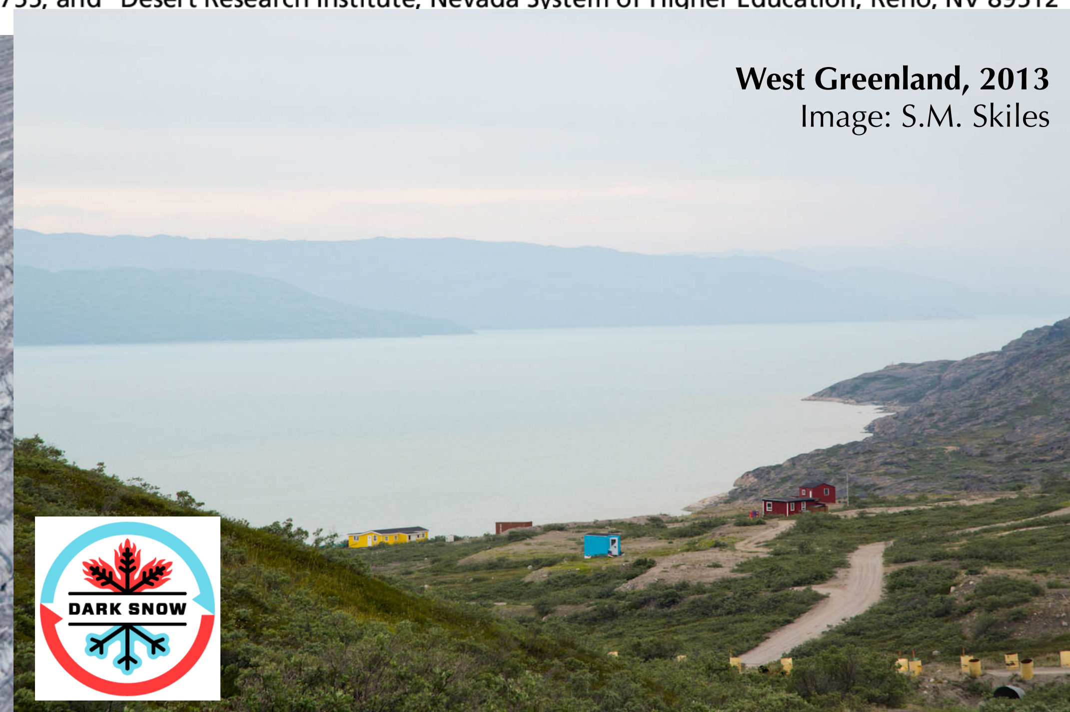
Greenland Albedo

Climate change and forest fires synergistically drive widespread melt events of the Greenland Ice Sheet

Kaitlin M. Keegan[a,1], Mary R. Albert[a], Joseph R. McConnell[b], and Ian Baker[a]

[a]Thayer School of Engineering, Dartmouth College, Hanover, NH 03755; and [b]Desert Research Institute, Nevada System of Higher Education, Reno, NV 89512





West Greenland, 2013
Image: S.M. Skiles

BC in Arctic

Environ. Res. Lett. **9** (2014) 064001 Y Qian *et al*

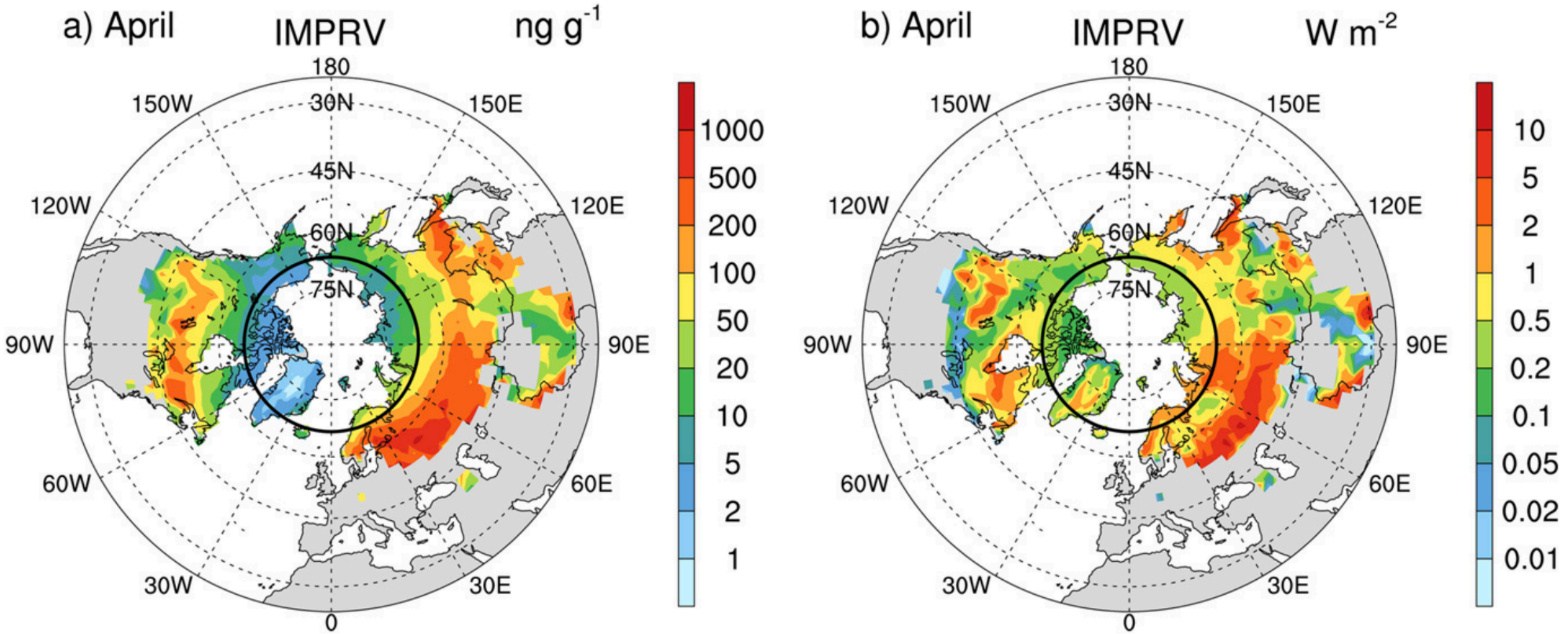
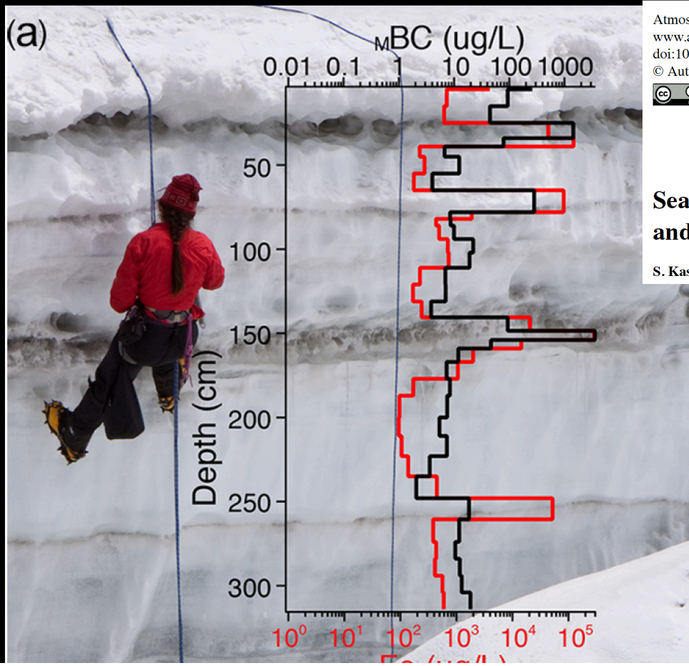


Figure 2. Spatial distribution of CAM5 (IMPRV) simulated ten-year monthly mean (April) (a) BC concentration in top snow layer (in ng g^{-1}) and (b) forcing induced by BC in snow column (W m^{-2}), averaged when snow is present over land.

Hindu Kush-Himalaya



Atmos. Chem. Phys., 14, 8089–8103, 2014
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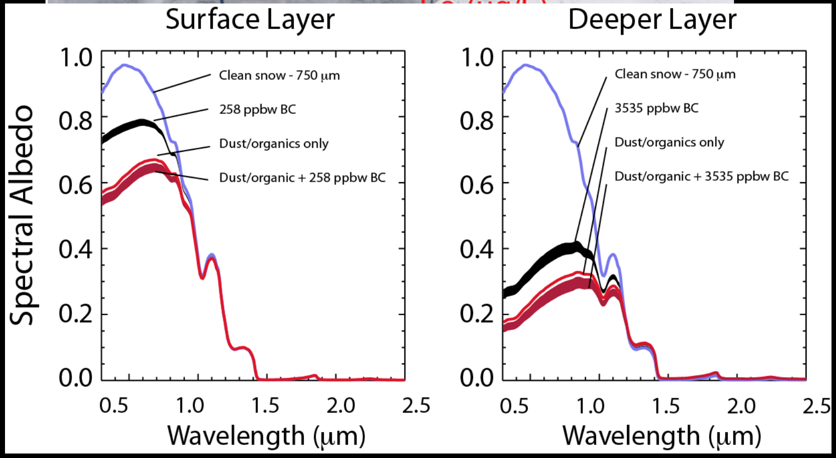
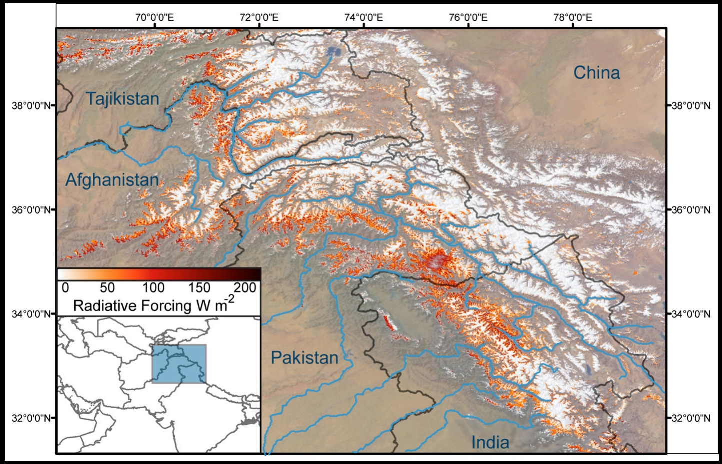
Atmospheric Chemistry and Physics
Open Access

Seasonal and elevational variations of black carbon and dust in snow and ice in the Solu-Khumbu, Nepal and estimated radiative forcings

S. Kaspari[1], T. H. Painter[2], M. Gysel[3], S. M. Skiles[4,5], and M. Schwikowski[6]





MODIS Dust Radiative Forcing in Snow
Painter et al 2012

BC ends LIA in Alps

PNAS PNAS PNAS

End of the Little Ice Age in the Alps forced by industrial black carbon

Thomas H. Painter[a,1], Mark G. Flanner[b], Georg Kaser[c], Ben Marzeion[c], Richard A. VanCuren[d], and Waleed Abdalati[e]

[a]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; [b]Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, Ann Arbor, MI 48109; [c]Institute of Meteorology and Geophysics, University of Innsbruck, 6020 Innsbruck, Austria; [d]Air Quality Research Center, University of California, Davis, CA 95616; and [e]Earth Science and Observation Center, Cooperative Institute for Research in Environmental Sciences, Boulder, CO 80309

Edited by Susan Solomon, Massachusetts Institute of Technology, Cambridge, MA, and approved July 19, 2013 (received for review February 19, 2013)

Glaciers in the European Alps began to retreat abruptly from their mid-19th century maximum, marking what appeared to be the end of the Little Ice Age. Alpine temperature and precipitation records suggest that glaciers should instead have continued to grow until circa 1910. Radiative forcing by increasing deposition of industrial black carbon to snow may represent the driver of the abrupt glacier retreats in the Alps that began in the mid-19th century. Ice cores indicate that black carbon concentrations increased abruptly in the mid-19th century and largely continued to increase into the 20th century, consistent with known increases in black carbon emissions from the industrialization of Western Europe. Inferred annual surface radiative forcings increased stepwise to 13–17 $W \cdot m^{-2}$ between 1850 and 1880, and to 9–22 $W \cdot m^{-2}$ in the early 1900s, with snowmelt season (April/May/June) forcings reaching greater than 35 $W \cdot m^{-2}$ by the early 1900s. These snowmelt season radiative forcings would have resulted in additional annual snow melting of as much as 0.9 m water equivalent across the melt season. Simulations of glacier mass balances with radiative forcing-equivalent changes in atmospheric temperatures result in conservative estimates of accumulating negative mass balances of magnitude −15 m water equivalent by 1900 and −30 m water equivalent by 1930, magnitudes and timing consistent with the observed retreat. These results suggest a possible physical explanation for the abrupt retreat of glaciers in the Alps in the mid-19th century that is consistent with existing temperature and precipitation records and reconstructions.

Simulations of glacier-length variations using glacier flow and mass balance models forced with instrumental and proxy temperature and precipitation fail to match the timing and magnitude of the observed late 19th century retreat (8–12). Matches between simulations and observations have only been achieved when additional glacier mass loss is imposed after 1865, or when
preci… re-
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sumr… ht,
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not f… u-
latior… ve
mass … *to*
point … ure
not captured well in the ambient climatic records" [italics added for emphasis] (10). In other words, Huybrechts et al. (10) suggest that some forcing beyond changes in temperature and precipitation was driving a large part of the negative mass balance.

Glacier mass balance is controlled by accumulation at higher elevations and ablation at lower elevations. In each year, glacier

Significance

The end of the Little Ice Age in the European Alps has long been a paradox to glaciology and climatology. Glaciers in the Alps began to retreat abruptly in the mid-19th century, but reconstructions of temperature and precipitation indicate that glaciers should have instead advanced into the 20th century. We observe that industrial black carbon in snow began to increase markedly in the mid-19th century and show with simulations that the associated increases in absorbed sunlight by black carbon in snow and snowmelt were of sufficient magnitude to cause this scale of glacier retreat. This hypothesis offers a physically based explanation for the glacier retreat that maintains consistency with the temperature and precipitation reconstructions.

ENVIRONMENTAL SCIENCES

SUSTAINABILITY SCIENCE

Dust RF in Colorado River Basin

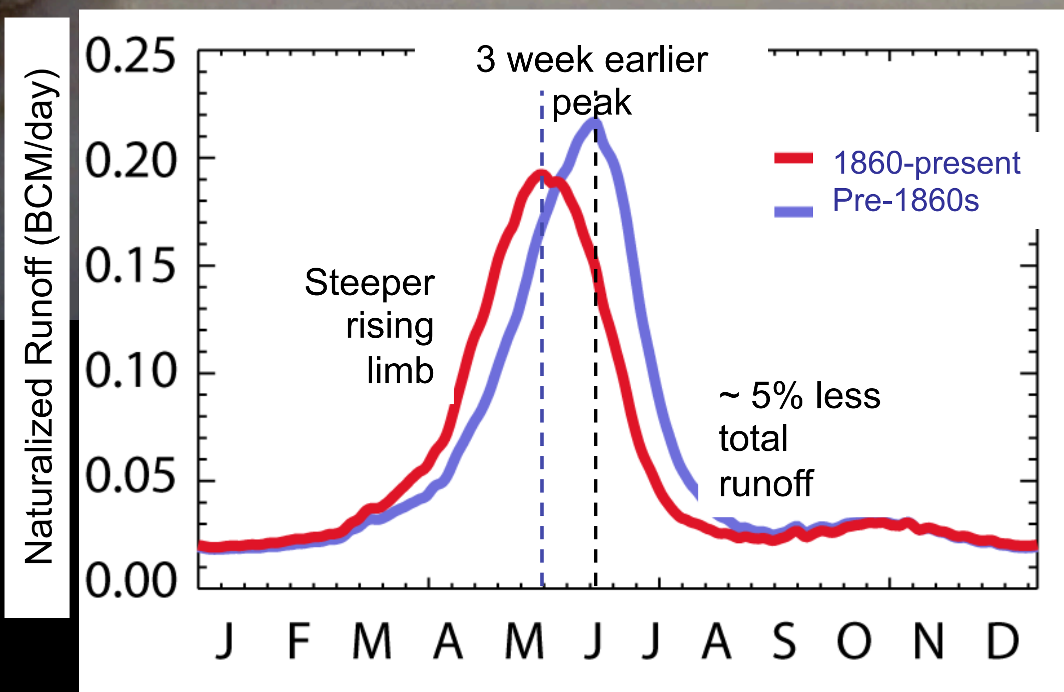
WATER RESOURCES RESEARCH, VOL. 48, W07522, doi:10.1029/2012WR011986, 2012

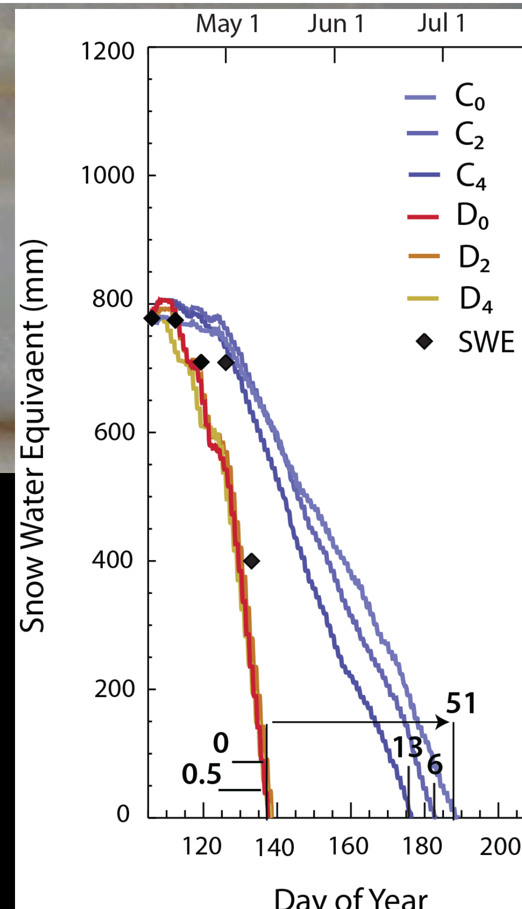
Dust radiative forcing in snow of the Upper Colorado River Basin: 2. Interannual variability in radiative forcing and snowmelt rates

S. McKenzie Skiles,[1,2] Thomas H. Painter,[1,2,3] Jeffrey S. Deems,[4,5] Ann C. Bryant,[6] and Christopher C. Landry[7]

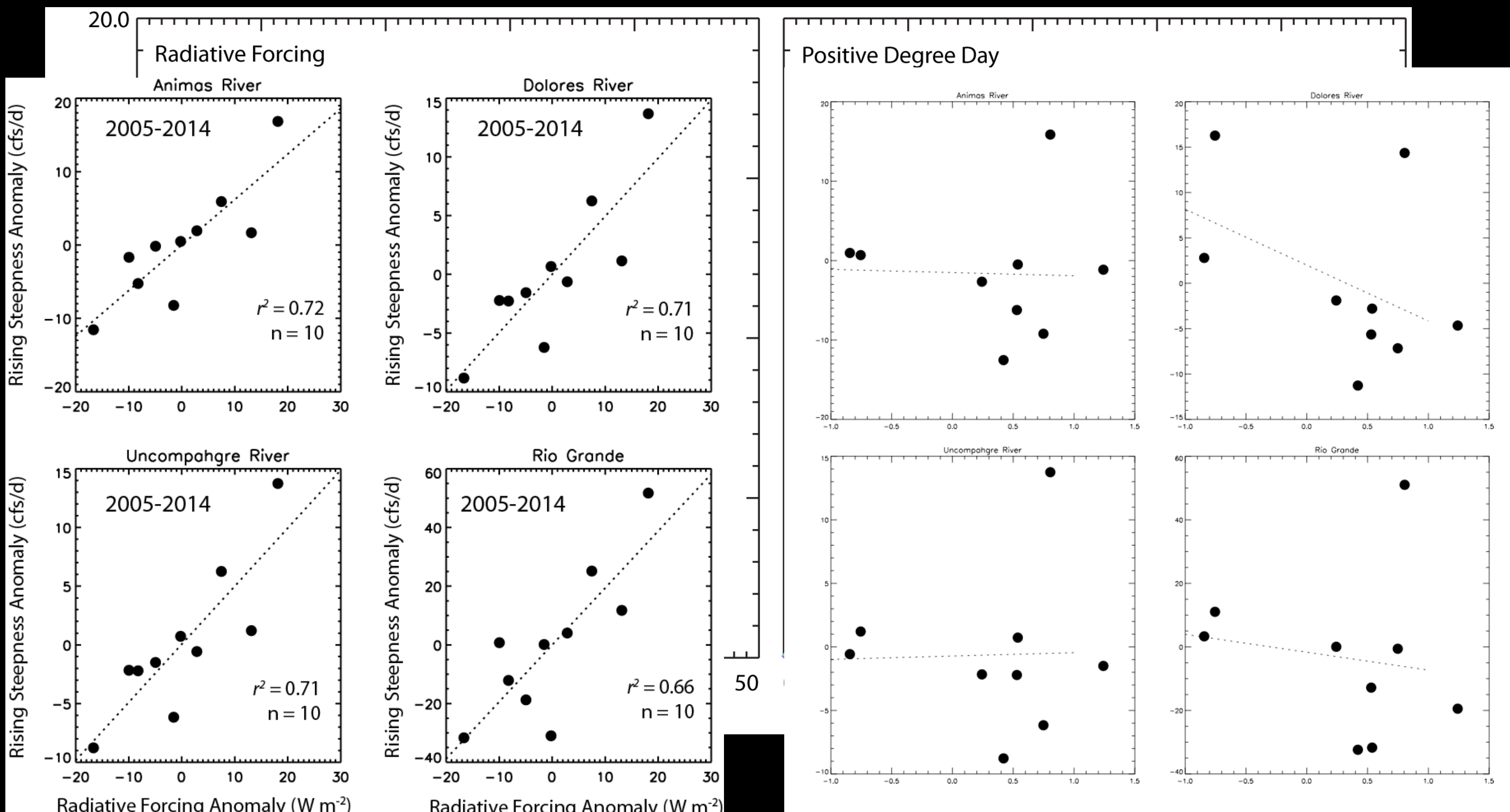
Response of Colorado River runoff to dust radiative forcing in snow

Thomas H. Painter[a,b,1], Jeffrey S. Deems[c,d], Jayne Belnap[e], Alan F. Hamlet[f], Christopher C. Landry[g], and Bradley Udall[d]

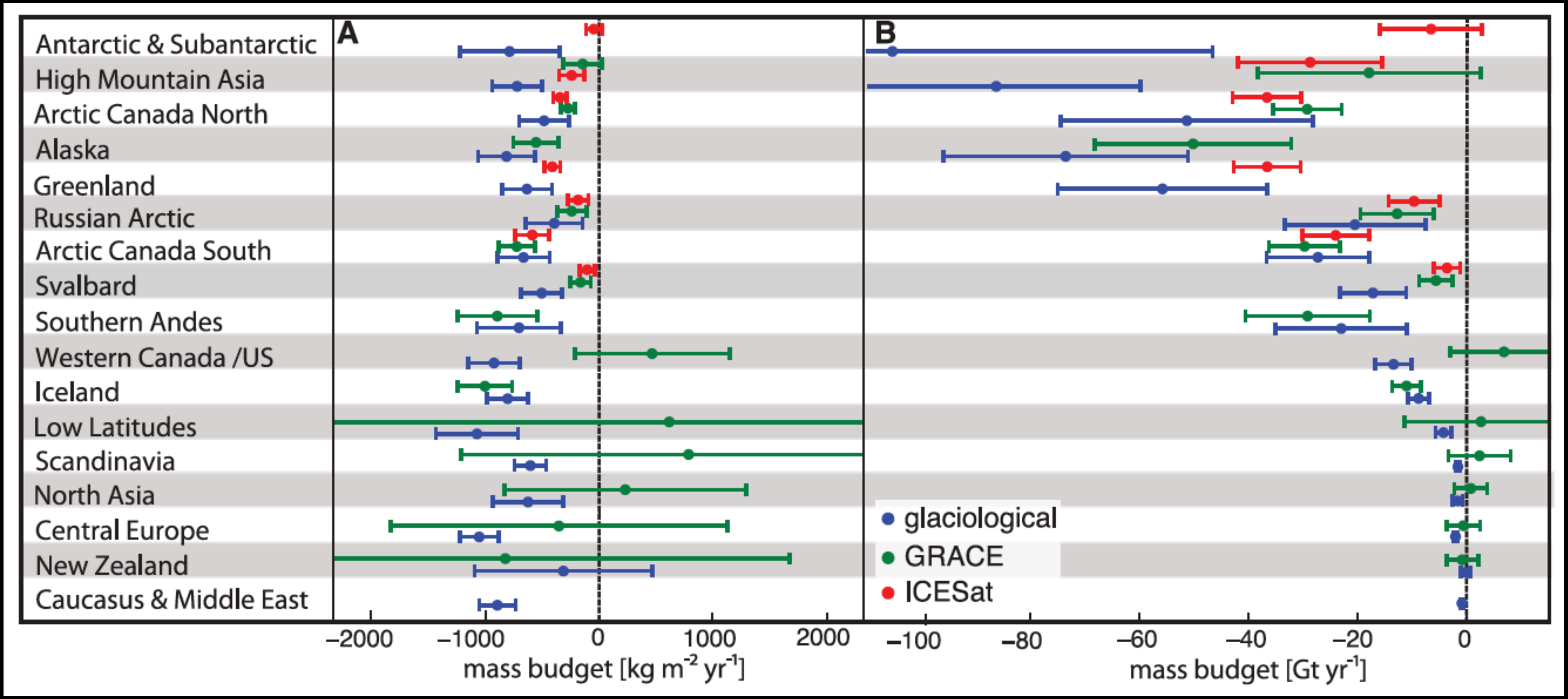




How fast rivers come up

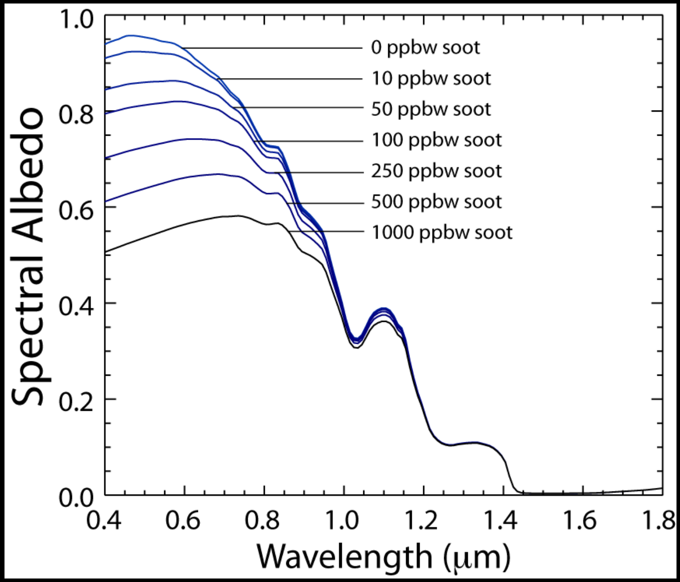


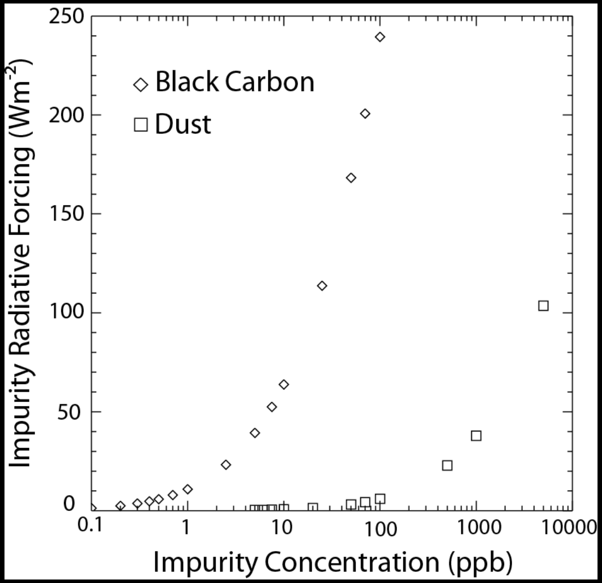
Uncertainties in Glacier Mass Balance contributions to SLR



Gardner et al 2013

Why a spectrometer?





Robust retrievals that come from imaging spectrometer and provide critical understanding of cryosphere forcings

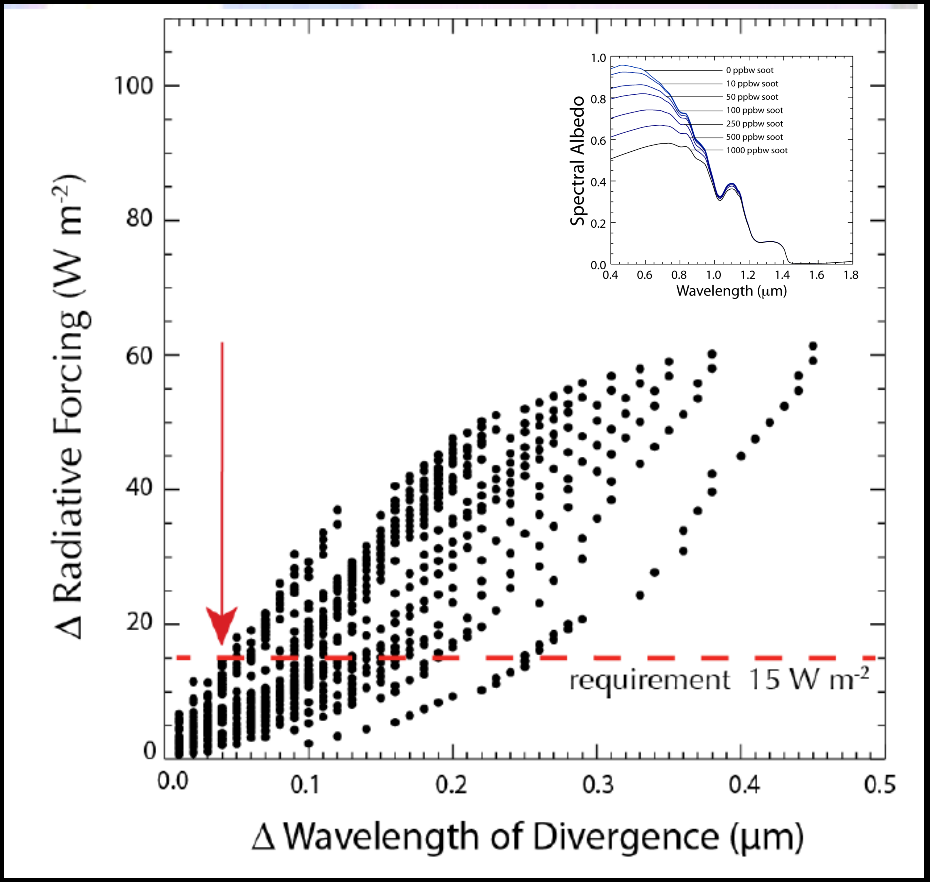
- Spectral albedo
- Snow grain size
- Dust/BC radiative forcing in snow and ice
- Snow surface liquid water content

All retrievals are demonstrated with AVIRIS or ASO

Spectral resolution drivers

- To understand changes in snow depth/ice height to within 0.25 m
- With enthalpy of fusion, a 0.25 m snowpack with density 80 kg/m^3 is equivalent to 6 W/m^2 or instantaneous *15 W/m^2*

➔ < 40 nm spectral resolution



Again, the Science Questions

What are the controls on the global snow-albedo feedback?

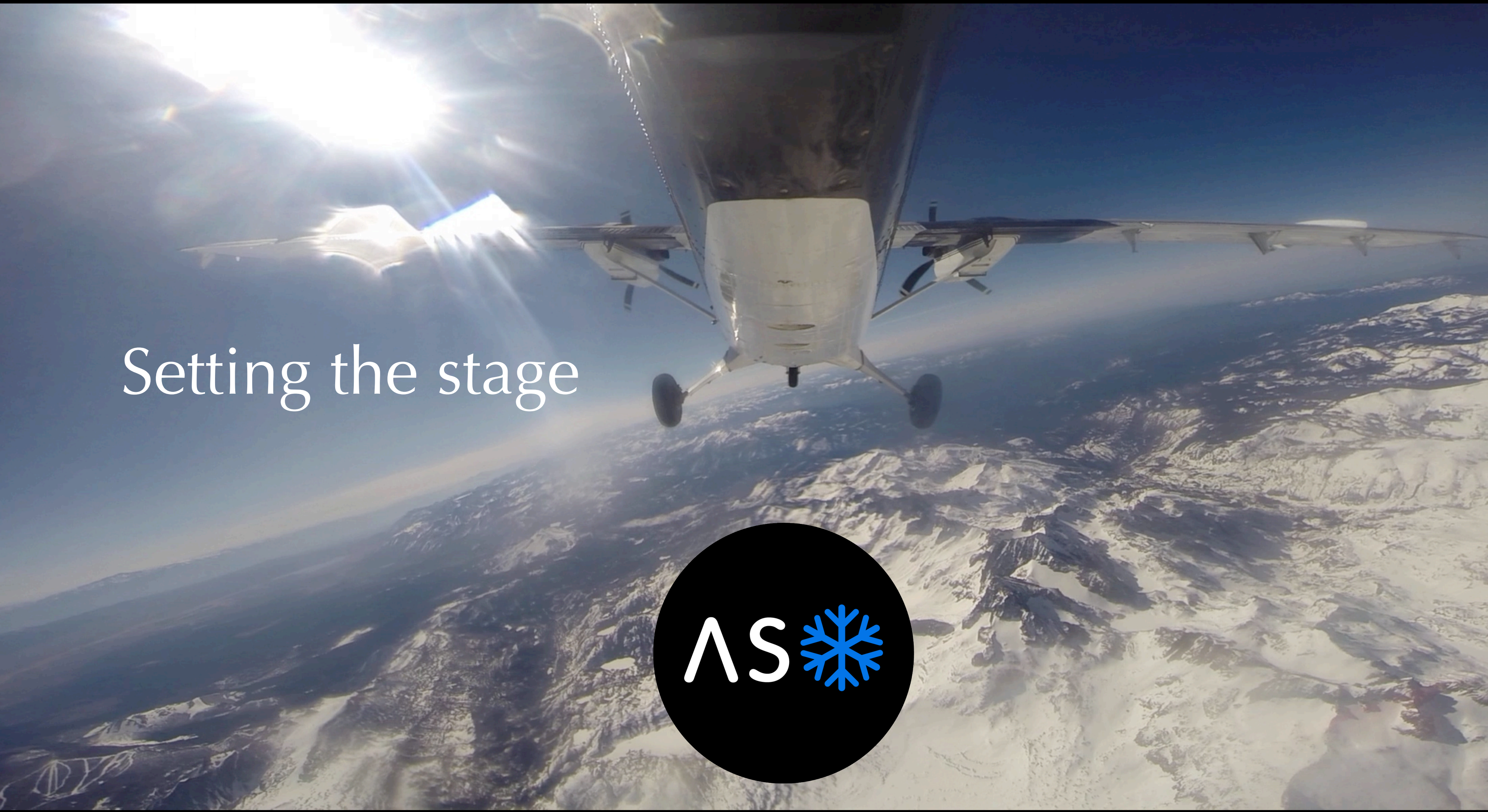
What is the response of global snow and ice albedo and melt to temperature increases and dust/BC radiative forcing?

We need a spaceborne imaging spectrometer to answer these critical questions.

The rest of the water cycle has or will soon have missions.

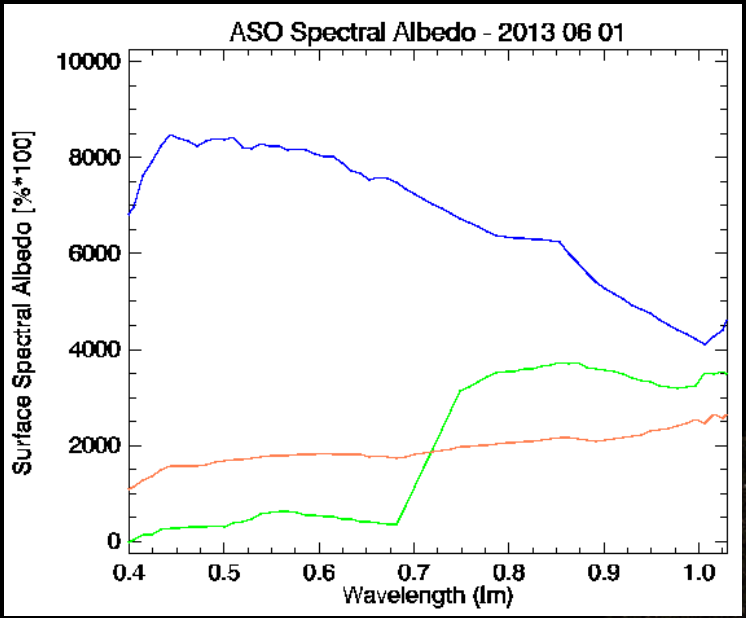
Such a mission directly addresses the fundamental questions in Climate Change and Variability, Water and Energy Cycle, Carbon Cycles and Ecosystems through understanding the cryosphere

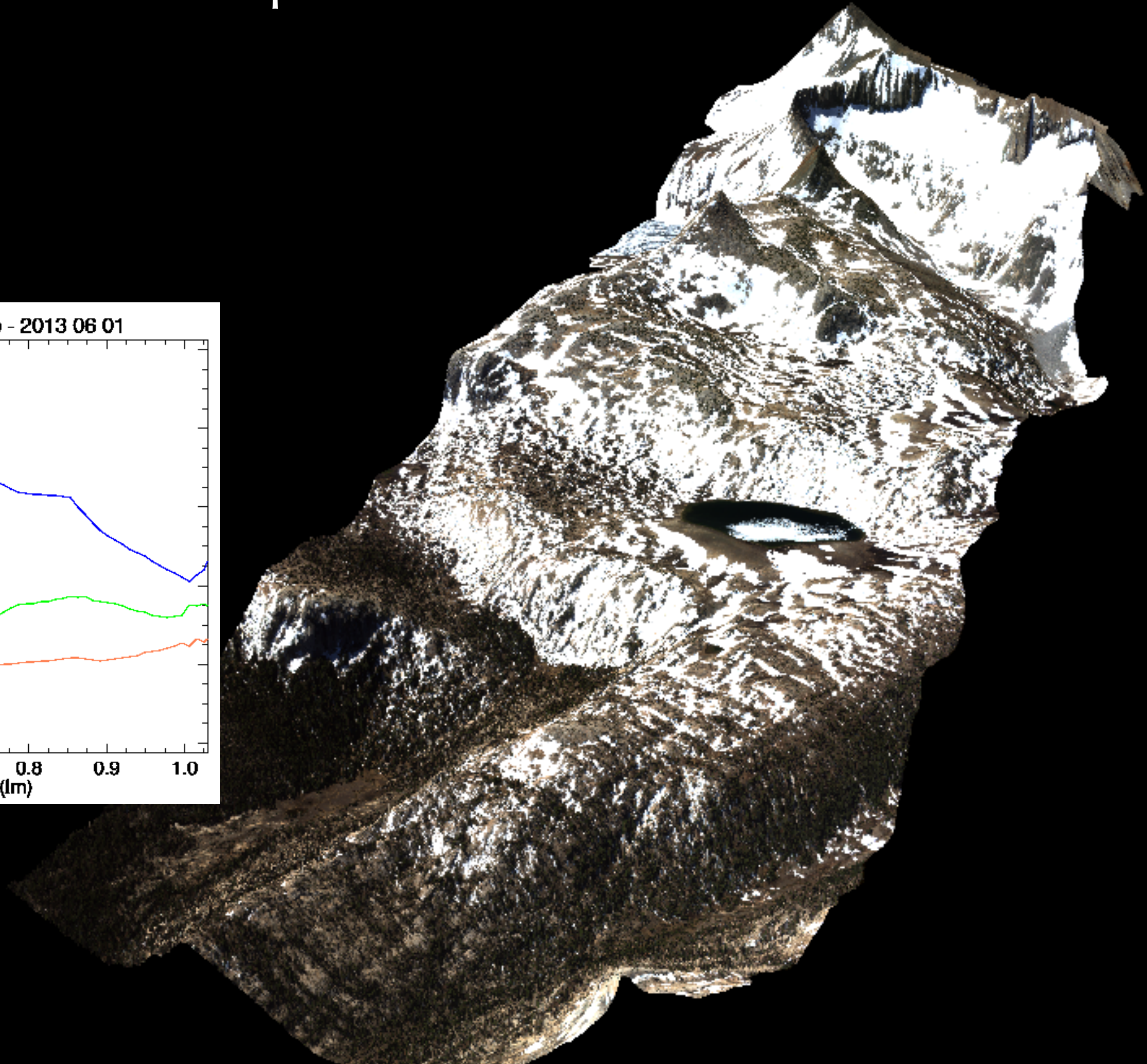
Airborne Snow Observatory




Albedo
Imaging Spectrometer
0.35-1.05 μm
2 m spatial resolution from 4000 AGL
3D Scanning LiDAR
1064 nm
1 m spatial resolution
Snow Water Equivalent
RIEGL

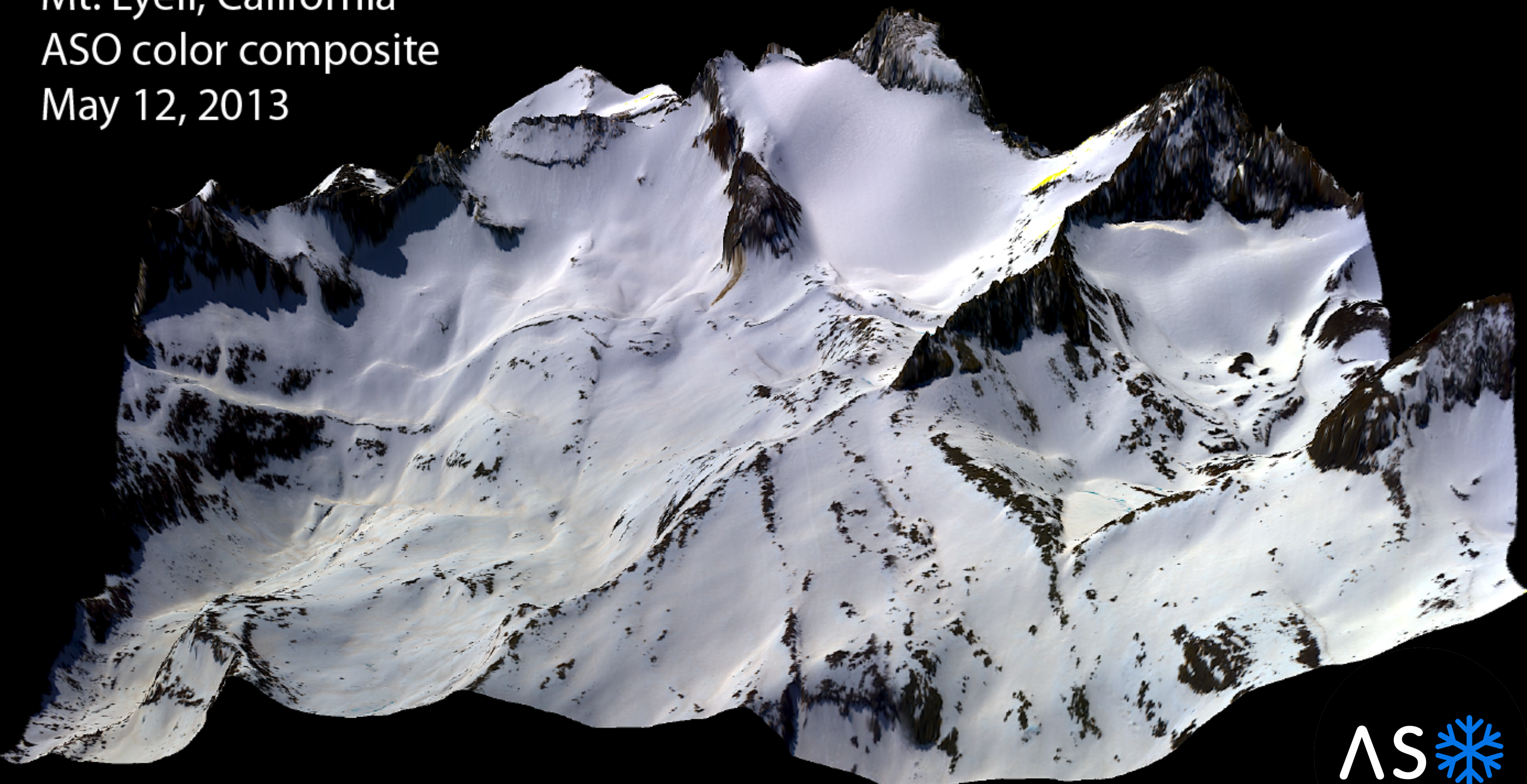
ASO Spectral Albedo





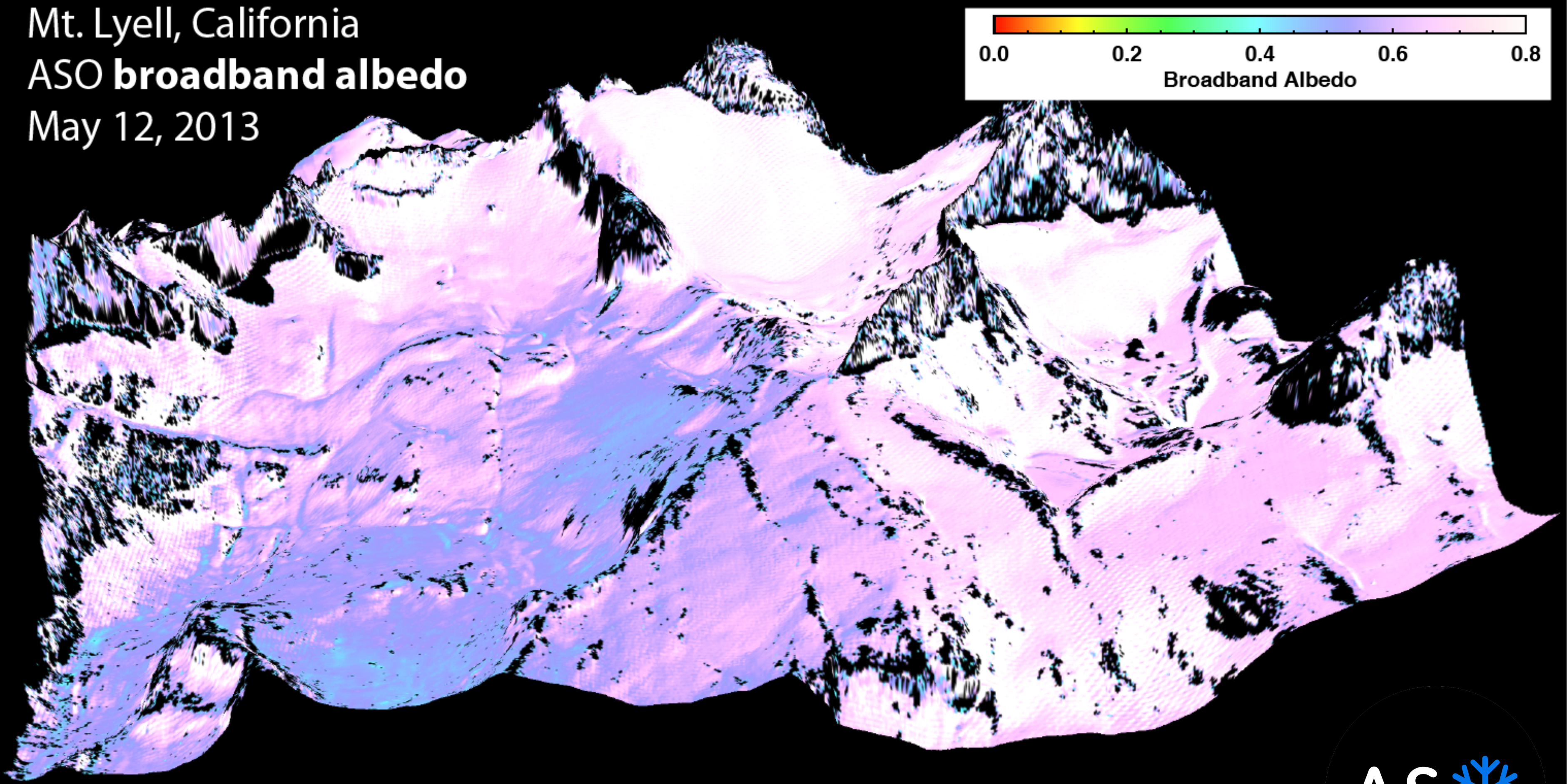
ASO-DM1 Results

Mt. Lyell, California
ASO color composite
May 12, 2013



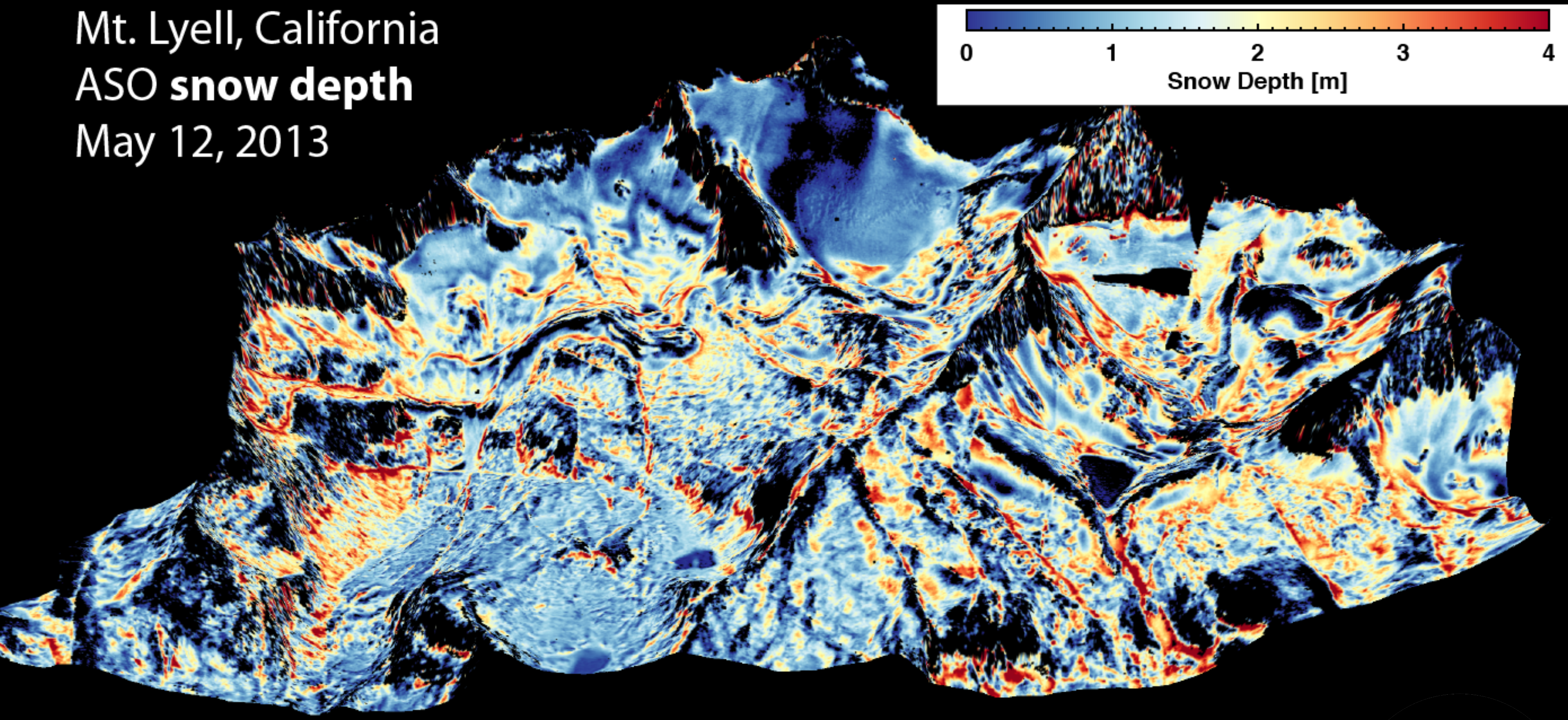
ASO-DM1 Results

Mt. Lyell, California
ASO **broadband albedo**
May 12, 2013



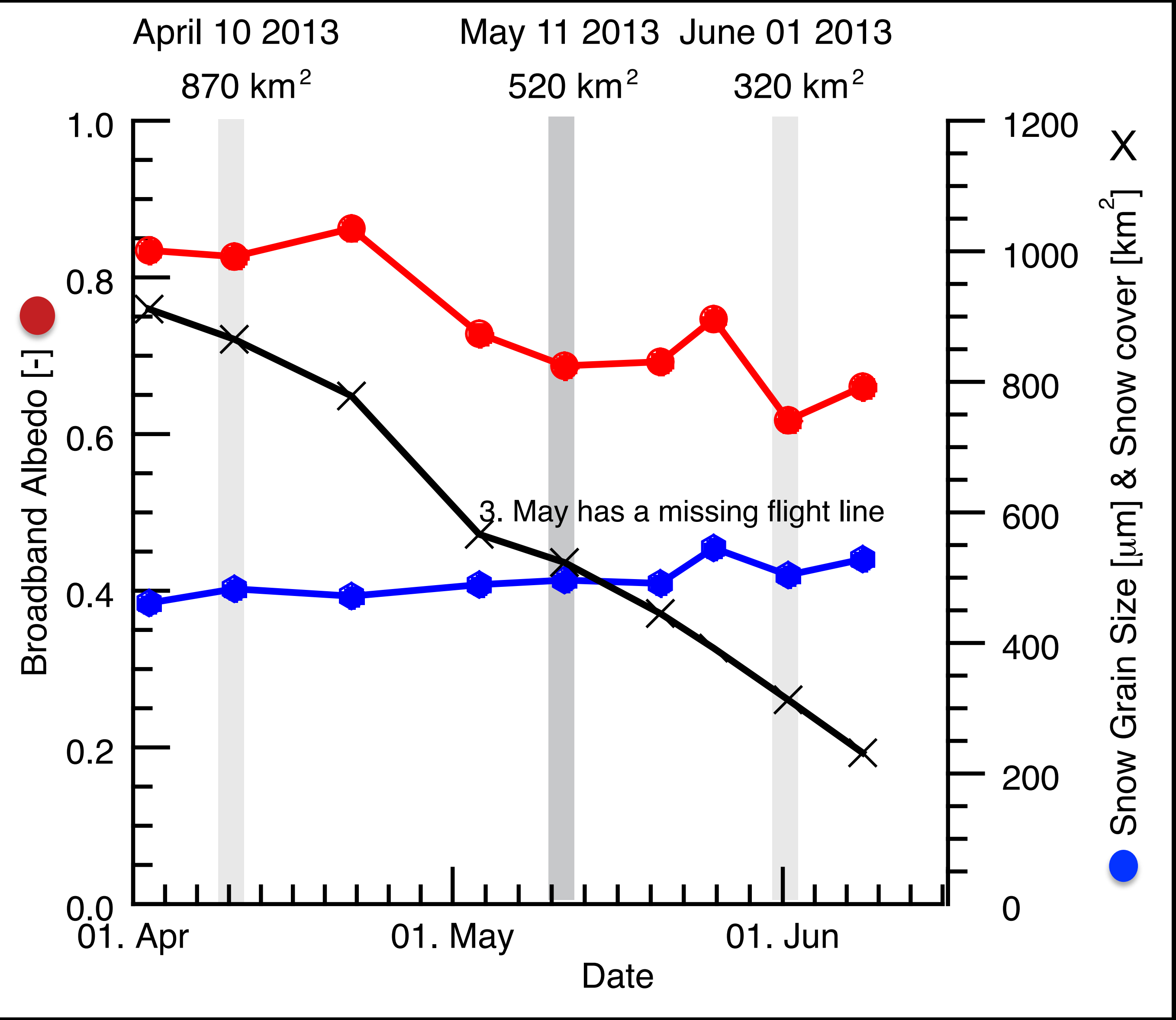
ASO-DM1 Results

Mt. Lyell, California
ASO **snow depth**
May 12, 2013



ASO SWE and albedo 2014

ASO Tuolumne snowmelt 2013



Why is it urgent

- Relative contributions by forcings of mass loss from glaciers and ice sheets remain unknown due insufficient measurements and constraints on regional climate and hydroclimate modeling
- Mountain glaciers and ice sheets have ongoing retreat and downwasting
- A strong mitigation opportunity against warming impacts on the cryosphere may rest in reducing particulate loading – unlike reducing CO_2 a "regional solution to a regional problem"
- The World Bank is calling for these mitigation efforts already, but measurements are needed now to be able to understand efficacy of mitigation effort.