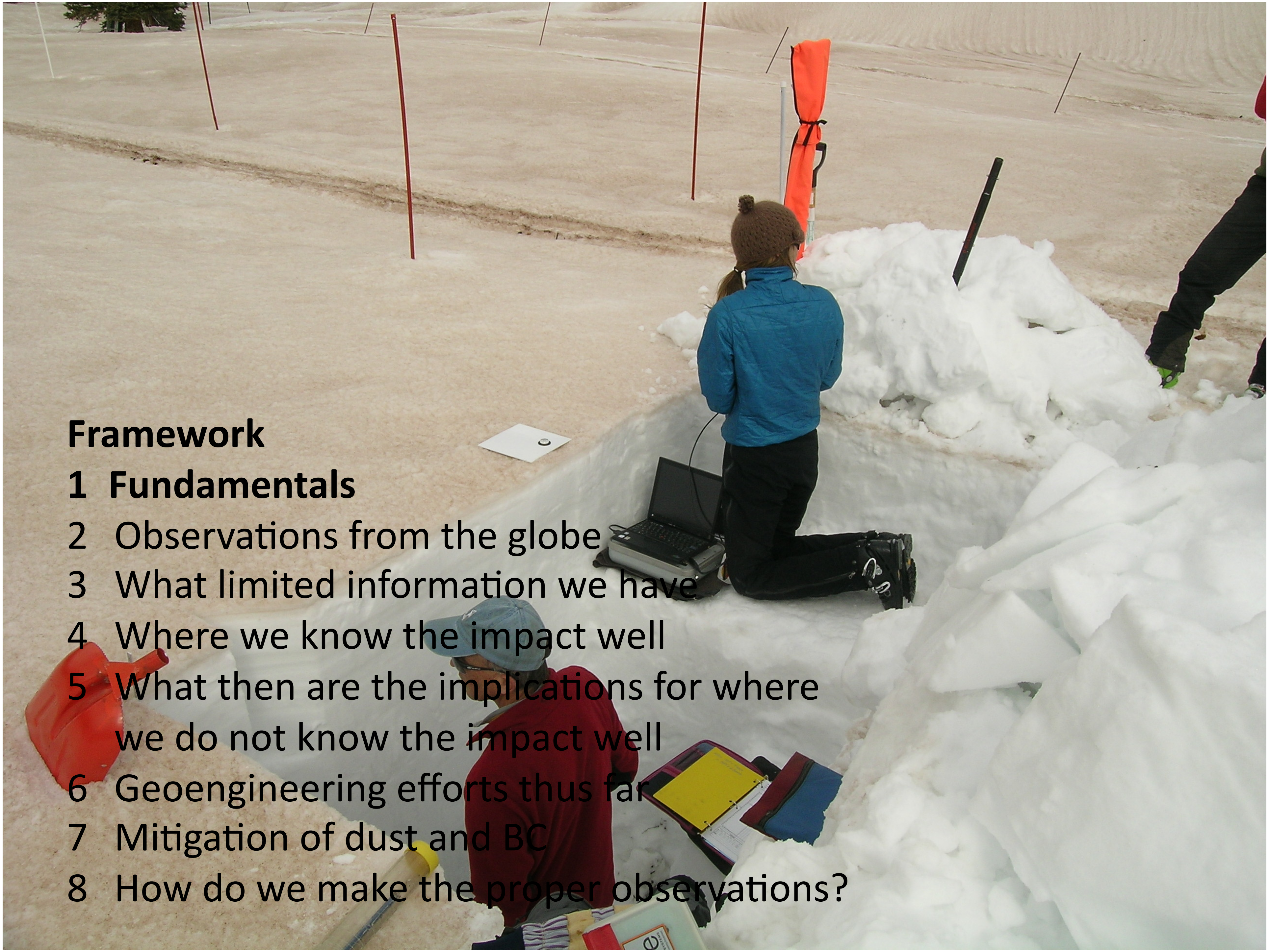
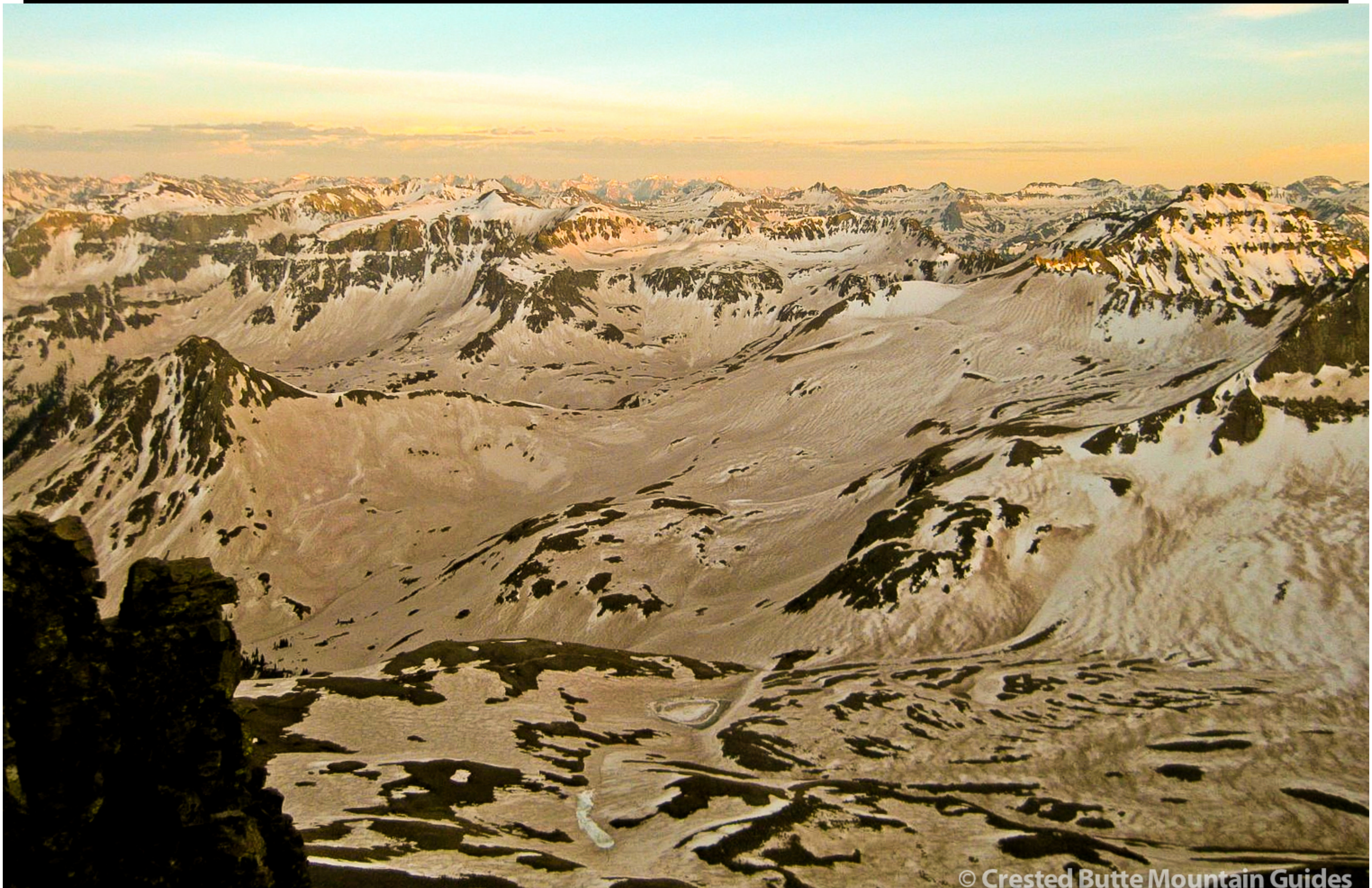
Influences of dust and black carbon on melt of snow and ice: mitigation and geoengineering

Thomas H. Painter, JPL/Caltech

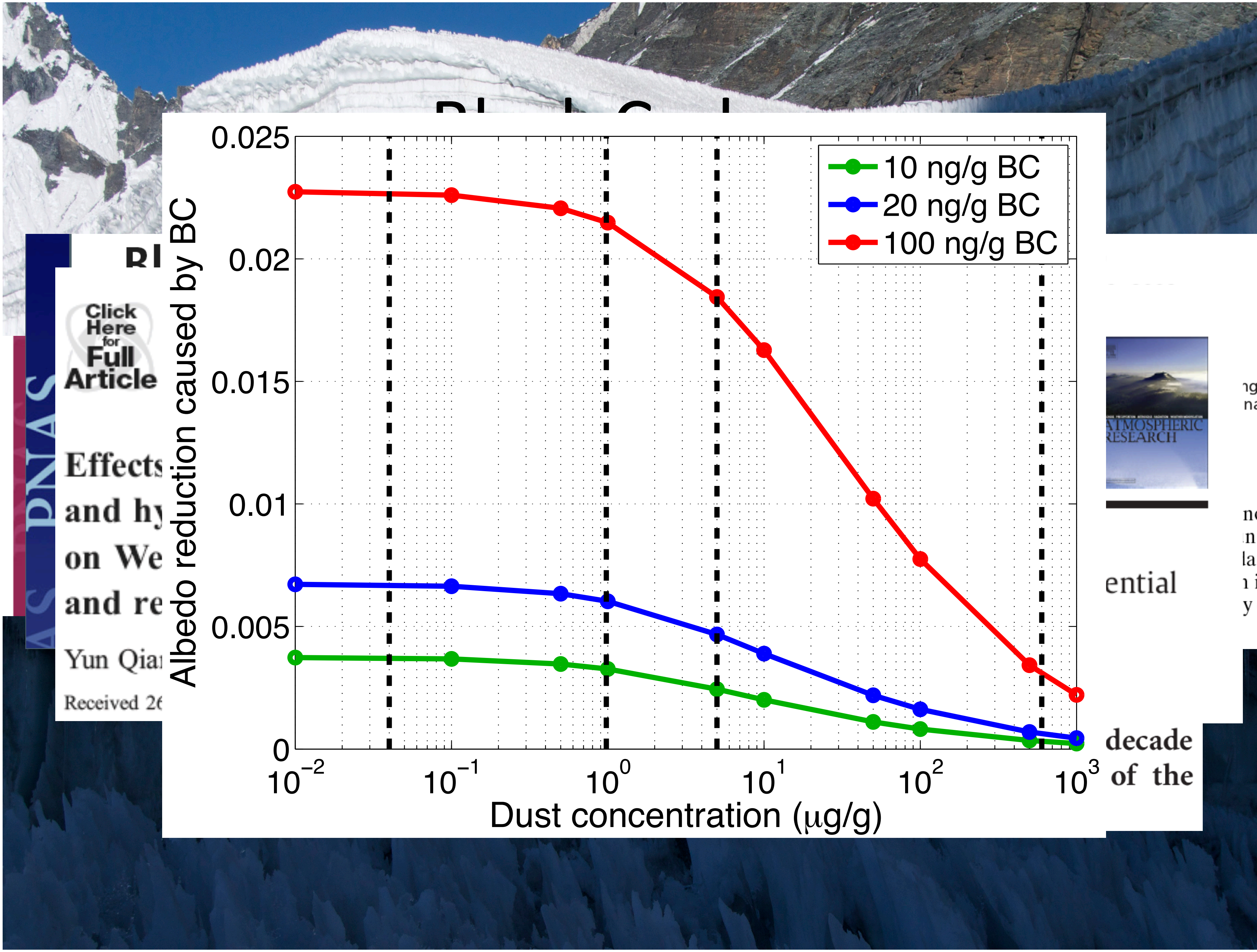
Last week
Lori Garver, NASA Dep Admin
Digging snow and scoping dust


Framework
1 Fundamentals
2 Observations from the globe
3 What limited information we have
4 Where we know the impact well
5 What then are the implications for where we do not know the impact well
6 Geoengineering efforts thus far
7 Mitigation of dust and BC
8 How do we make the proper observations?

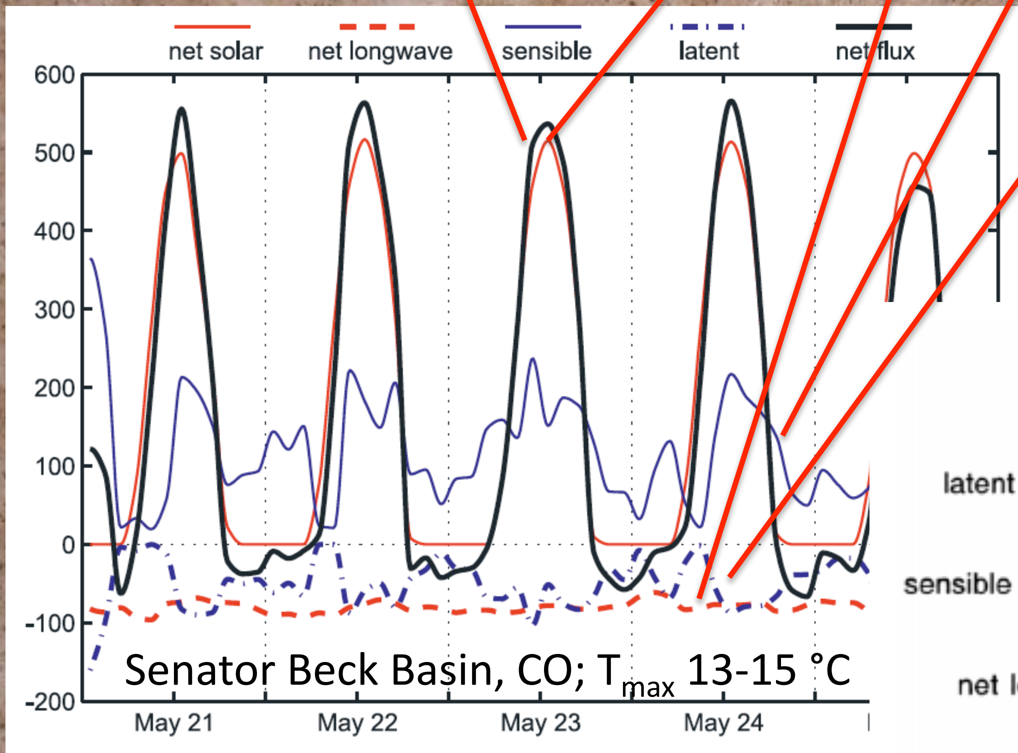
Summit of Mera Peak, Nepal looking south/southwest May 2009 (photo: S. Kaspari).

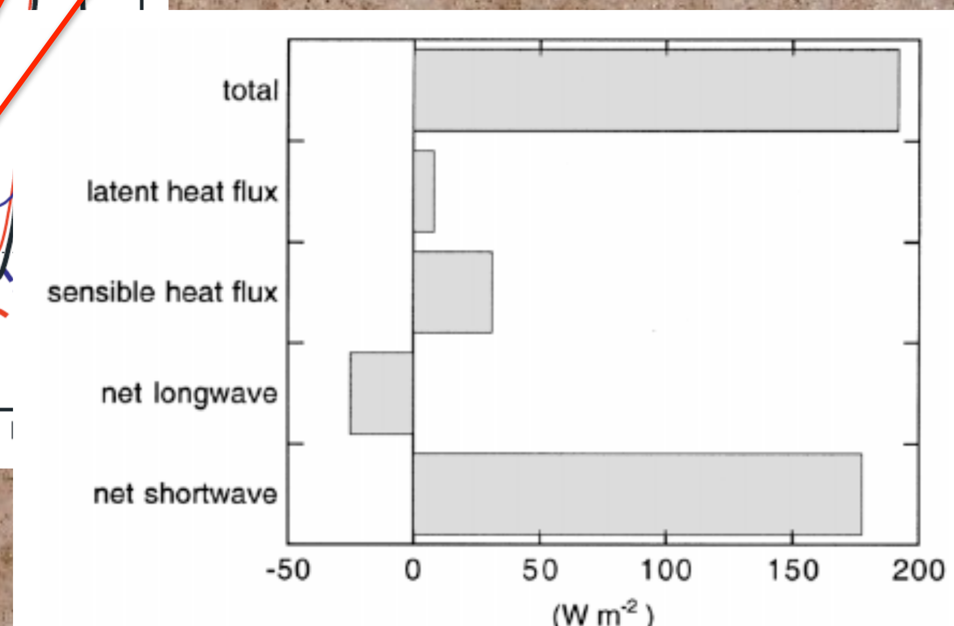


Summit of Mt Sneffels, San Juan Mountains, Colorado May 2009.


Albedo reduction caused by BC
0.025
0.02
0.015
0.01
0.005
0
10 ng/g BC
20 ng/g BC
100 ng/g BC
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Dust concentration (μg/g)
Click Here for Full Article
PNAS
ATMOSPHERIC RESEARCH

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



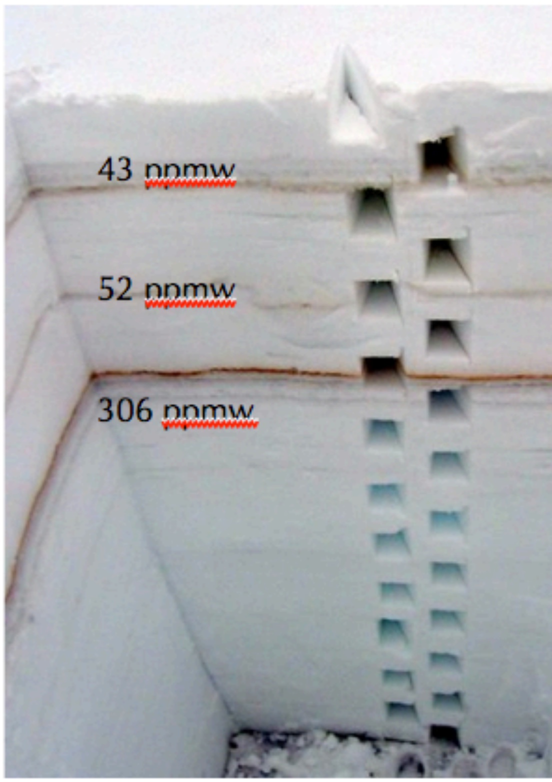


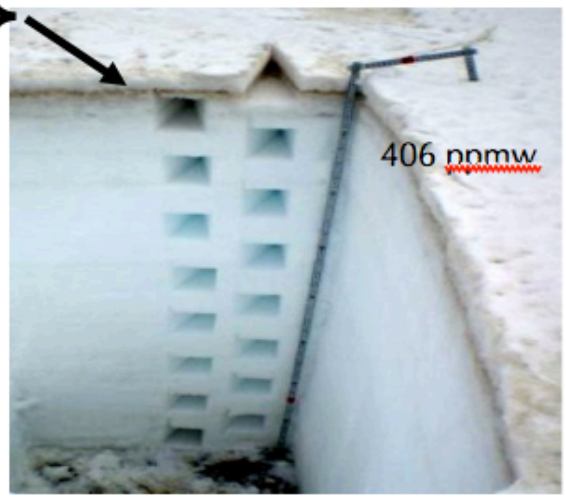
Morteratschgletscher (*Oerlemans, 2000*)

Elk Range, Colorado River Basin, April 2009

The *How* and *How Important* of Radiative Forcing by Dust

Rabbit Ears Pass, Colorado





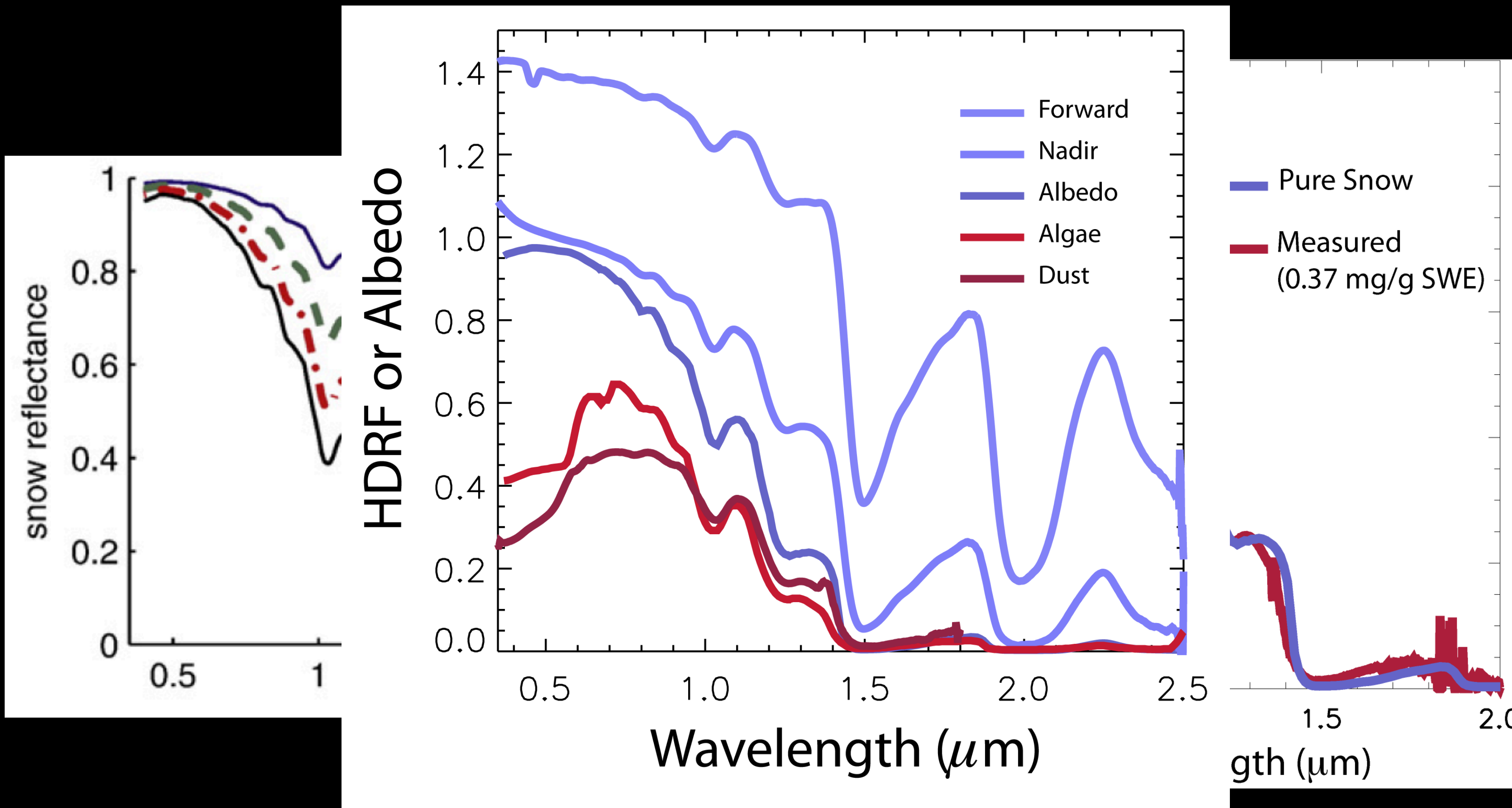
April, 2009

May, 2009

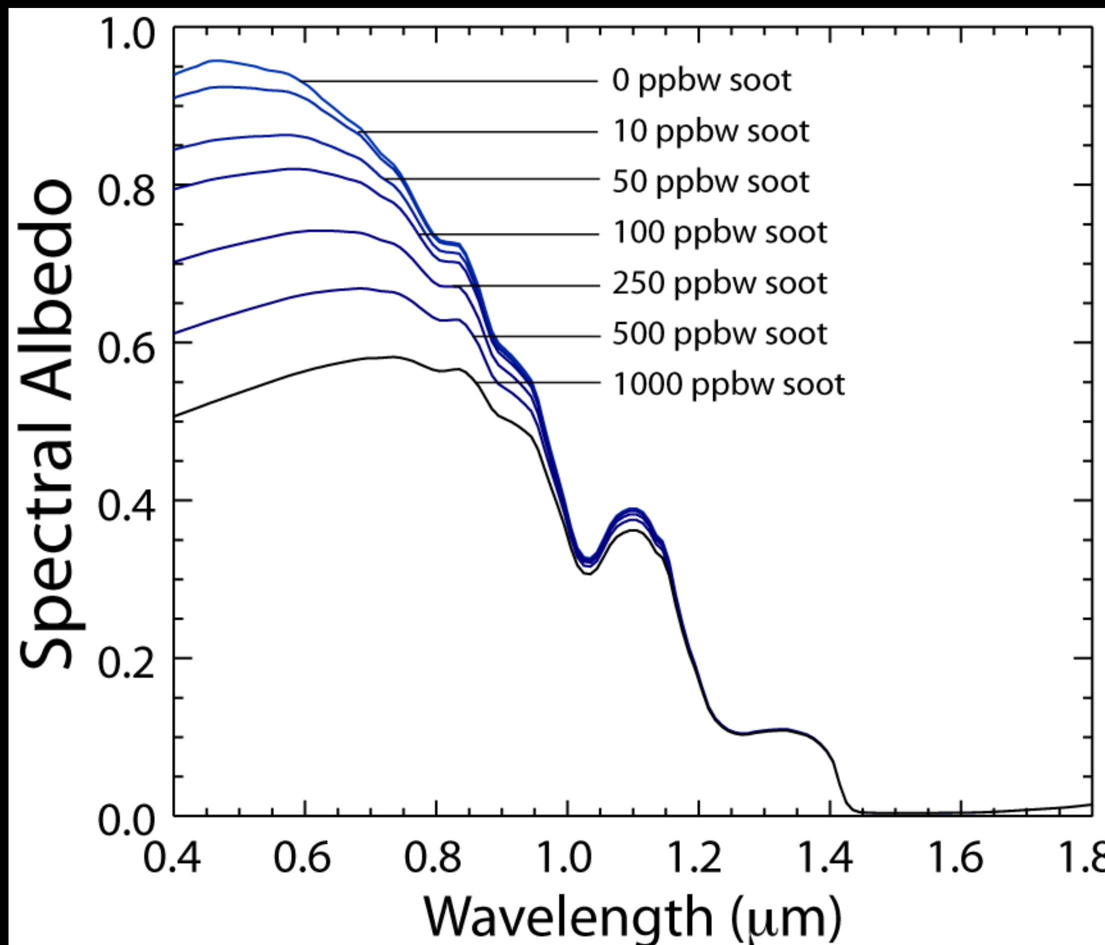
- Dust decreases snow albedo
- Dust deposition comes generally in the spring (*Neff et al*, 2005)
  - solar irradiance is increasing
  - snowpack is warming
- Dust generally accumulates in surface layers and is not entrained in melt - therefore, the surface continues to darken

Elk Range, Colorado River Basin, April 2009

Spectral Albedo



Effect of Increasing Concentration



Radiative Effects of Dust in Snow

As per Hansen and Nazarenko (2004, PNAS)

- Direct effect

  Absorption in visible and near-infrared (for large concentrations)

- First indirect effect

  Enhanced grain growth that further decreases albedo

- Second indirect effect

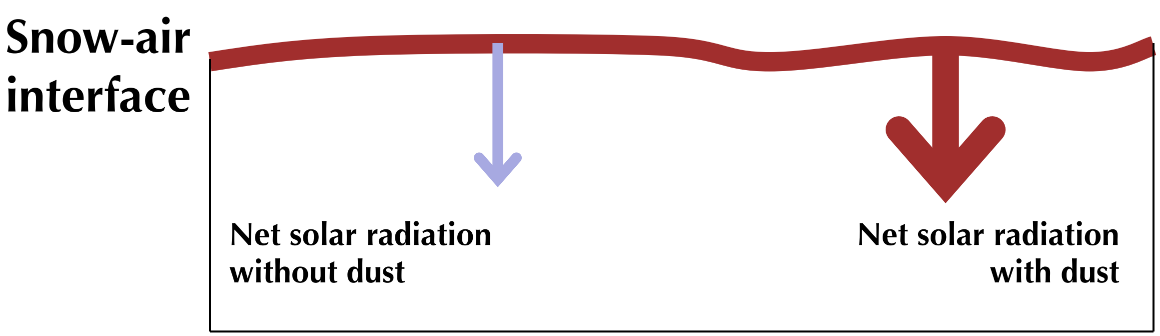
  Earlier exposure of darker substrate (snow-albedo feedback)

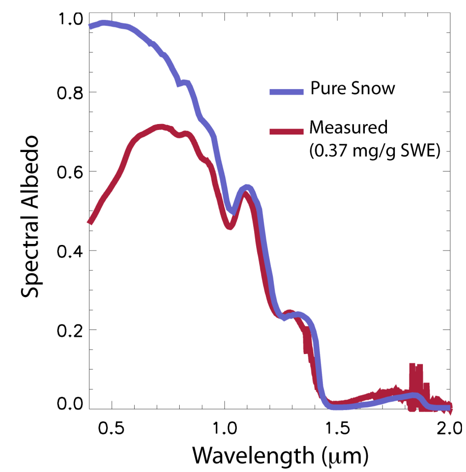
Surface Shortwave Radiative Forcing

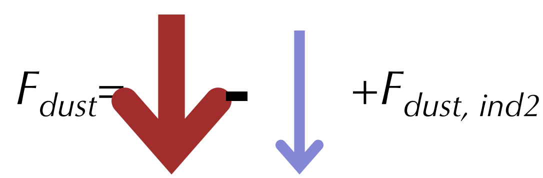
Here, we define *surface shortwave radiative forcing* as:

The perturbation of net shortwave radiation due to the deposition of dust to snow cover (W m^{-2}).

$$F_{dust} = \int_{\lambda=0.28\,\mu m}^{\lambda=3.0\,\mu m} E_{\lambda,tot}\left(\alpha_{\lambda,dustfree} - \alpha_{\lambda,dust}\right) d\lambda + F_{dust,indirect2}$$



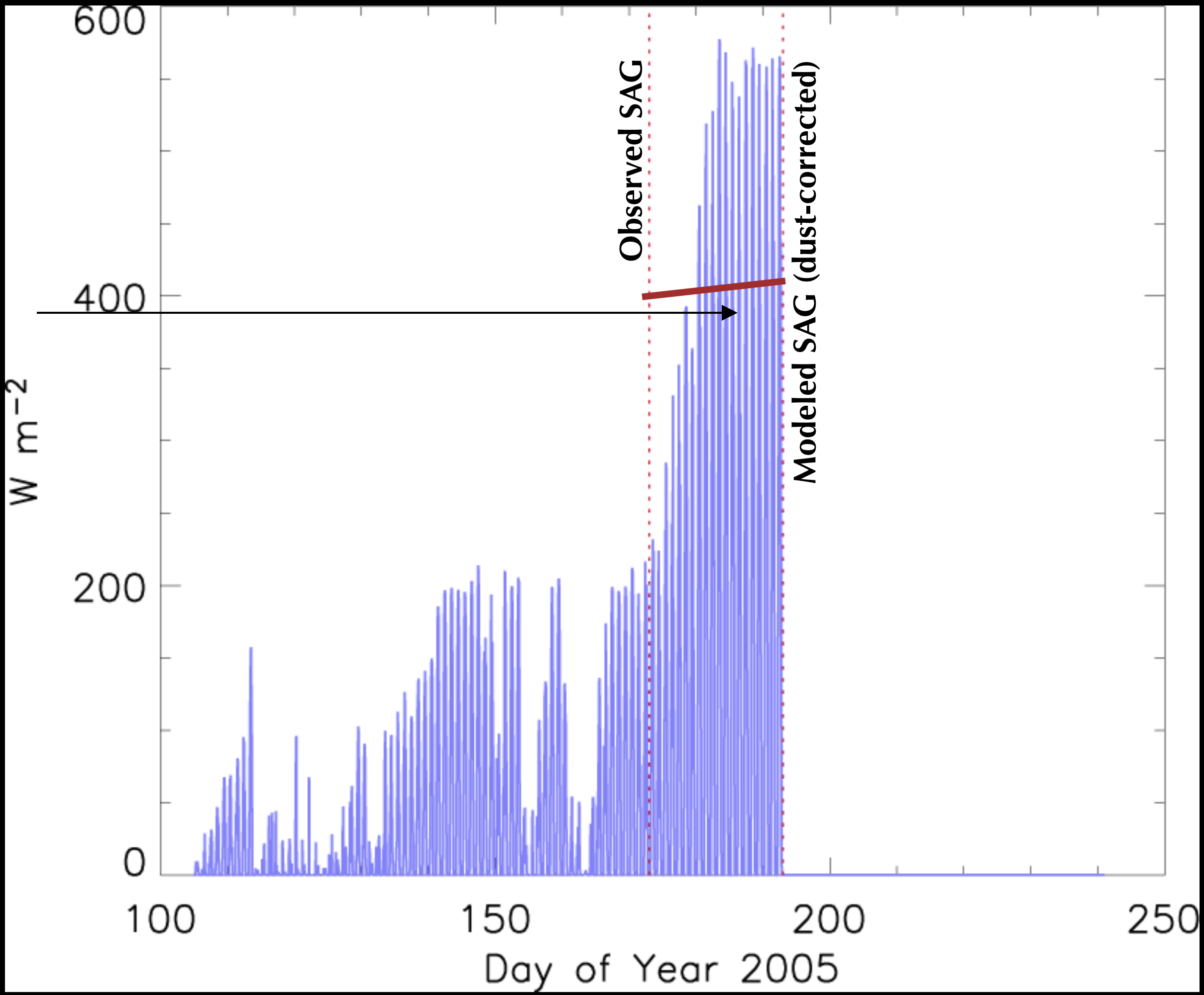




Second Indirect Effect

Mean F_{dust} during period:

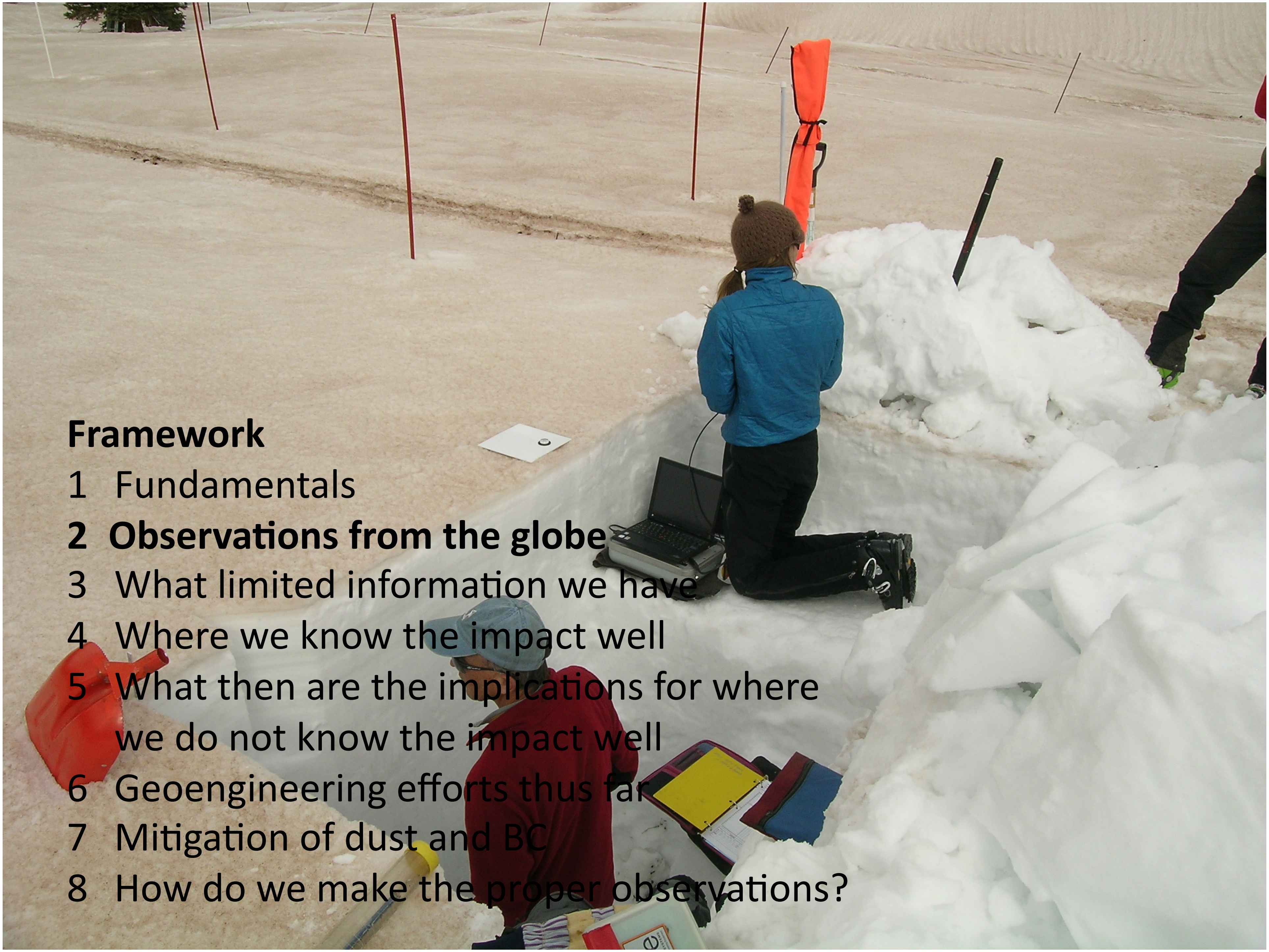
144 W m-2



Based on snowmelt modeling

SNOBAL model

(Marks et al., 1998; Painter et al. 2007)



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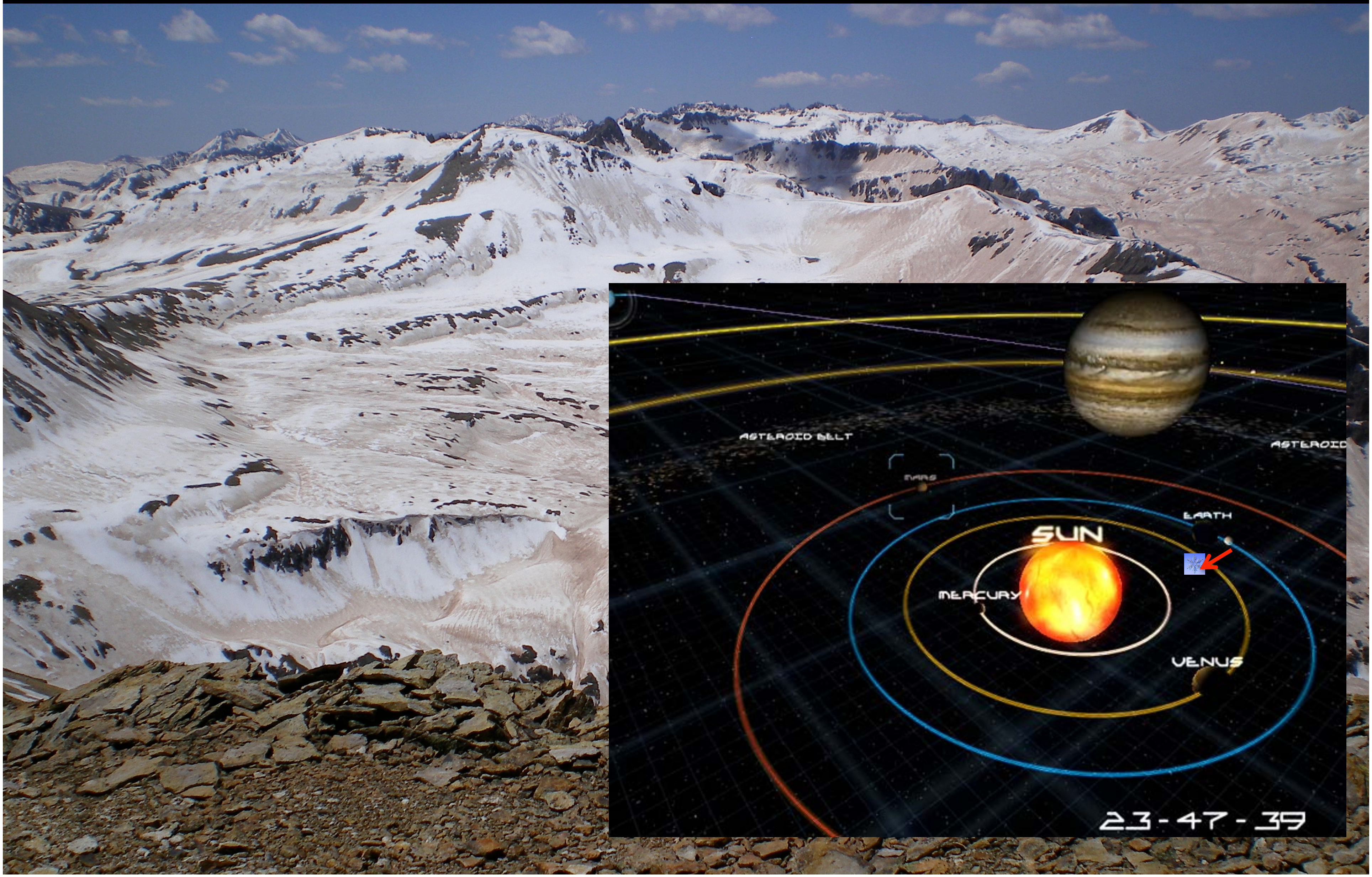
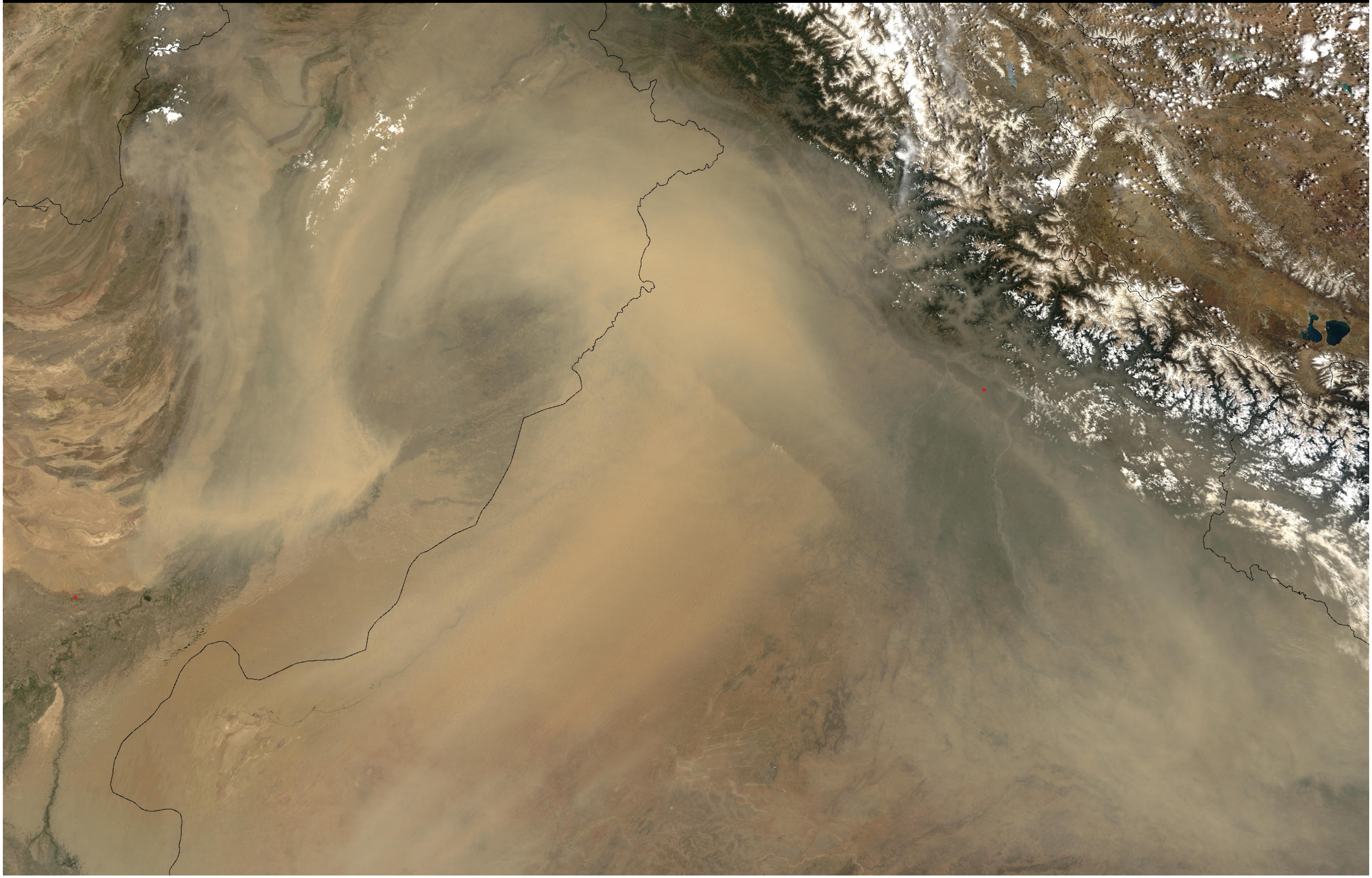
Upper Colorado River Basin



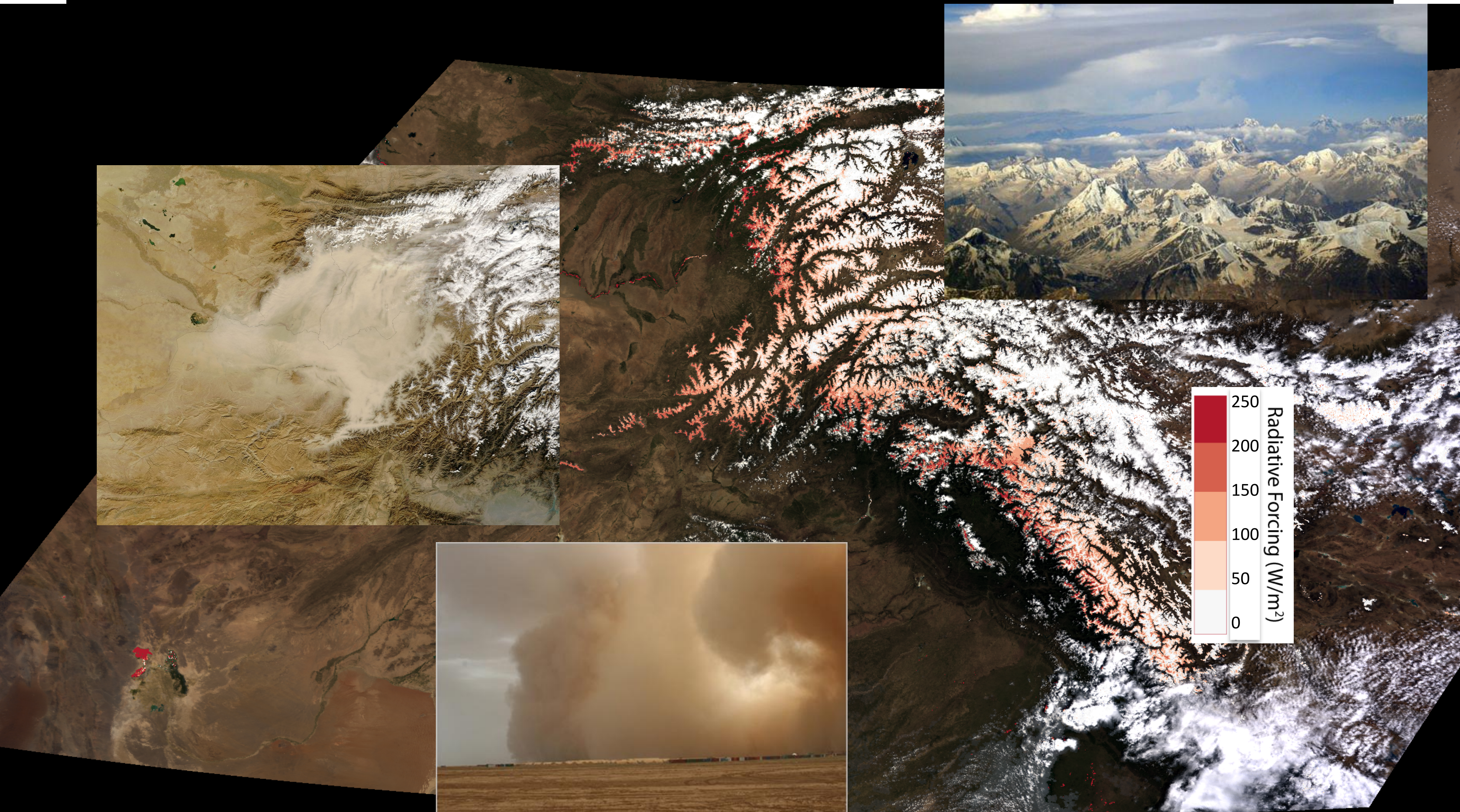
Alaska glaciers

Mt. Kosciuszko, Australia

Indian Himalaya + Tibet



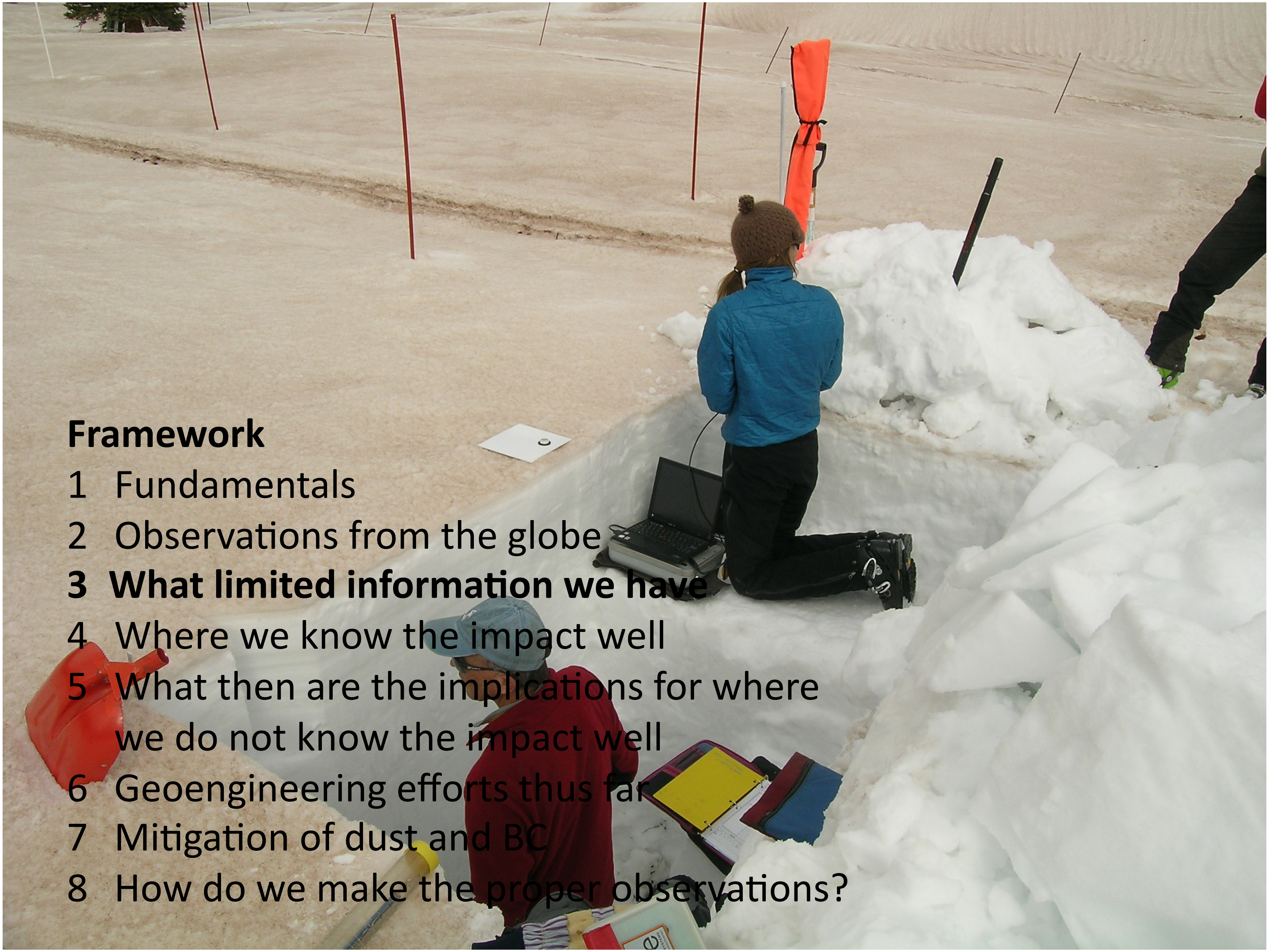
Dust Radiative Forcing, Hindu Kush, Afghanistan



MOD-DRFS model (*Painter and Bryant,* 2011)


Tien Shan, Kazakhstan

Mera Glacier looking south toward Mera summits, May 2009 Source: Susan Kaspari (CWU)



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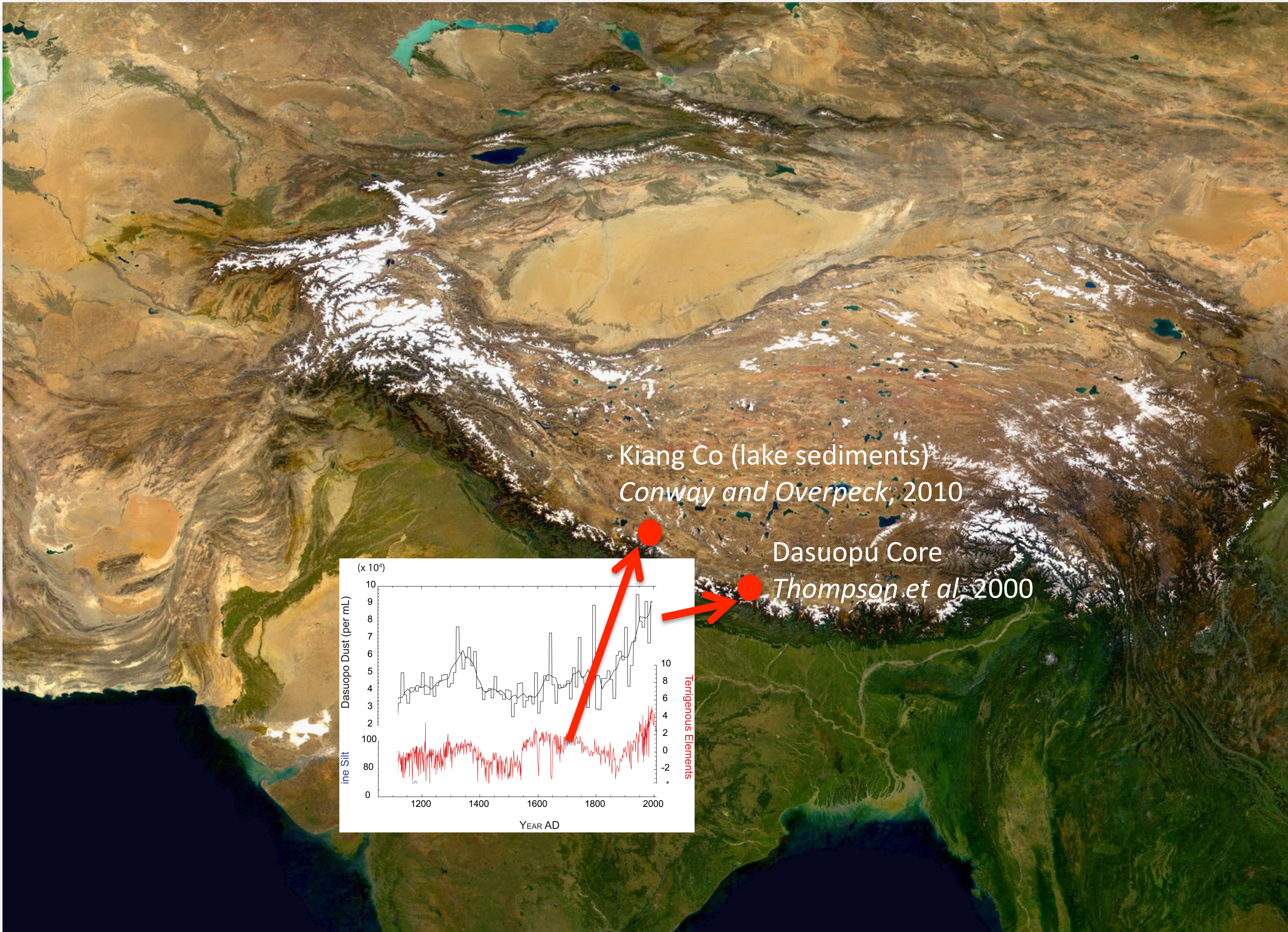
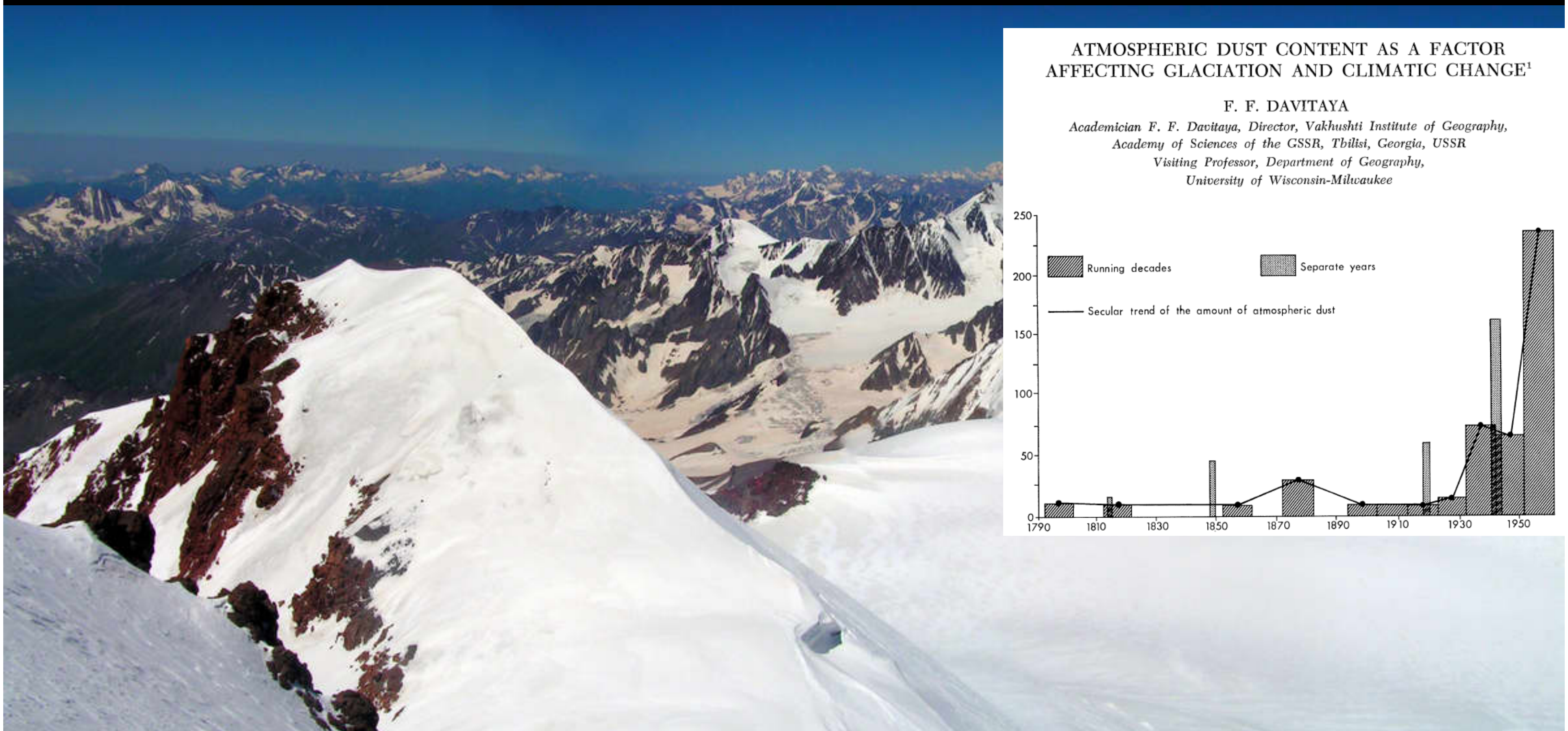

Kiang Co (lake sediments)
Conway and Overpeck, 2010
Dasuopu Core
Thompson et al, 2000
(x 10⁴)
Dasuopo Dust (per mL)
ine Silt
Terrigenous Elements
YEAR AD

Caucasus Mountains



ATMOSPHERIC DUST CONTENT AS A FACTOR AFFECTING GLACIATION AND CLIMATIC CHANGE[1]

F. F. DAVITAYA

Academician F. F. Davitaya, Director, Vakhushti Institute of Geography, Academy of Sciences of the GSSR, Tbilisi, Georgia, USSR
Visiting Professor, Department of Geography, University of Wisconsin-Milwaukee

Antarctic Peninsula

PNAS

20th-Century doubling in dust archived in an Antarctic Peninsula ice core parallels climate change and desertification in South America

Joseph R. McConnell[†‡], Alberto J. Aristarain[§], J. Ryan Banta[†], P. Ross Edwards[†], and Jefferson C. Simões[¶]

[†]Desert Research Institute, Nevada System of Higher Education, Reno, NV 89512; [§]Laboratorio de Estratigrafía Glaciar y Geoquímica del Agua y de la Nieve, Instituto Antártico Argentino, Centro Regional de Investigaciones Científícas y Tecnológicas, 5500 Mendoza, Argentina; and [¶]Núcleo de Pesquisas Antárctica e Climáticas, Universidade Federal do Rio Grande do Sul, CEP 90040-060 Porto Alegre, Brazil

Edited by Inez Y. Fung, University of California, Berkeley, and approved February 9, 2007 (received for review September 1, 2006)

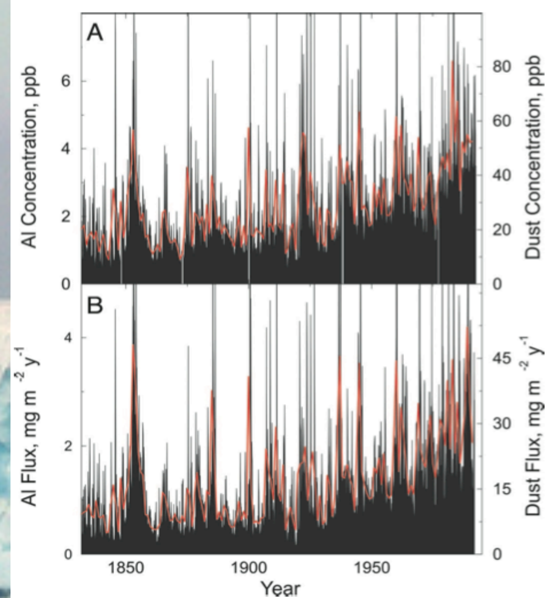
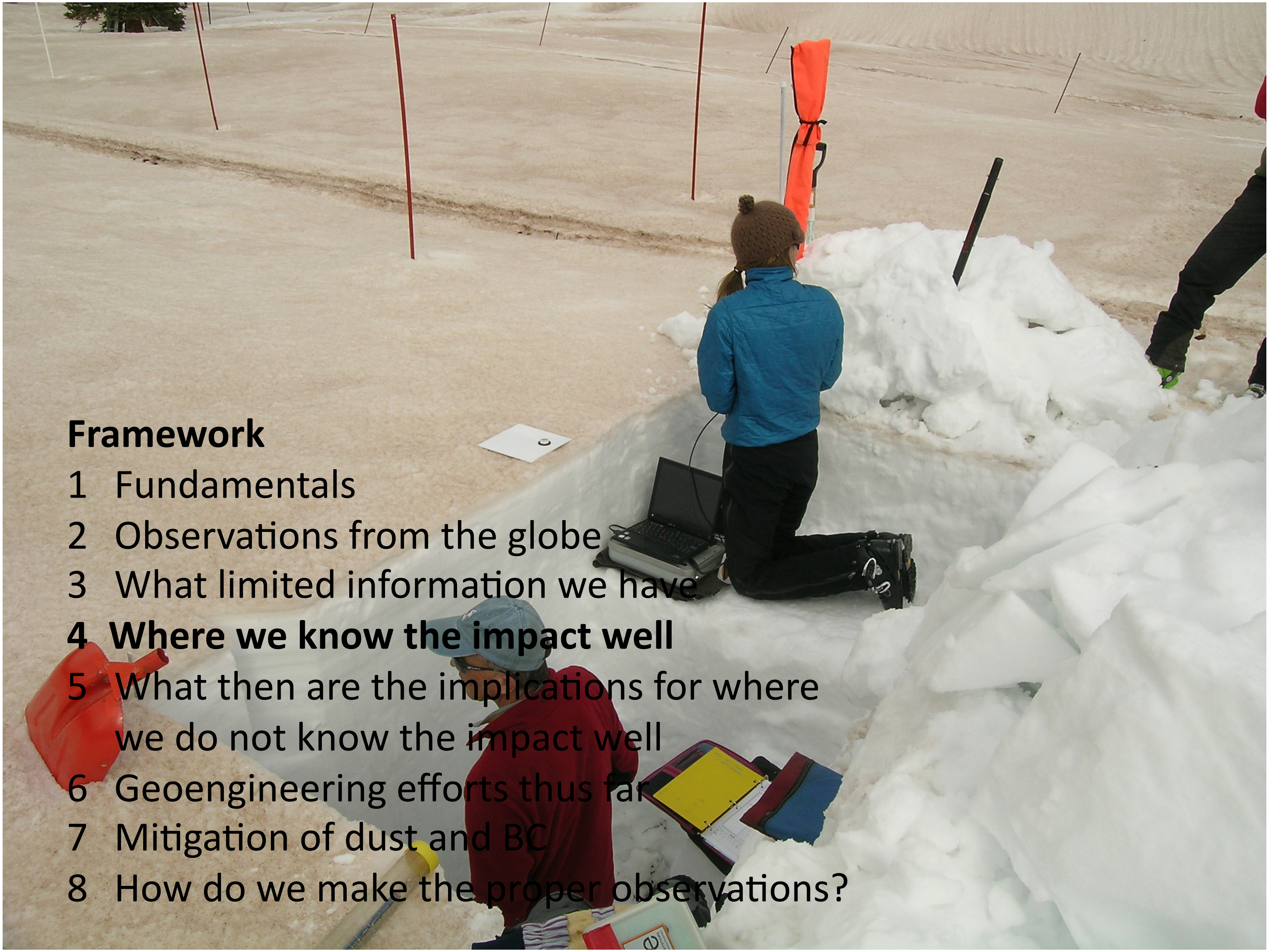


Fig. 2. Monthly averaged aluminum and aluminosilicate dust concentration (*A*) and flux (*B*) from 1832 to 1991 measured in James Ross Island ice cores. The heavy red line shows annual averages. Aluminosilicate dust was computed from the aluminum measurements by using the mean crustal abundance by mass of 8.04%.



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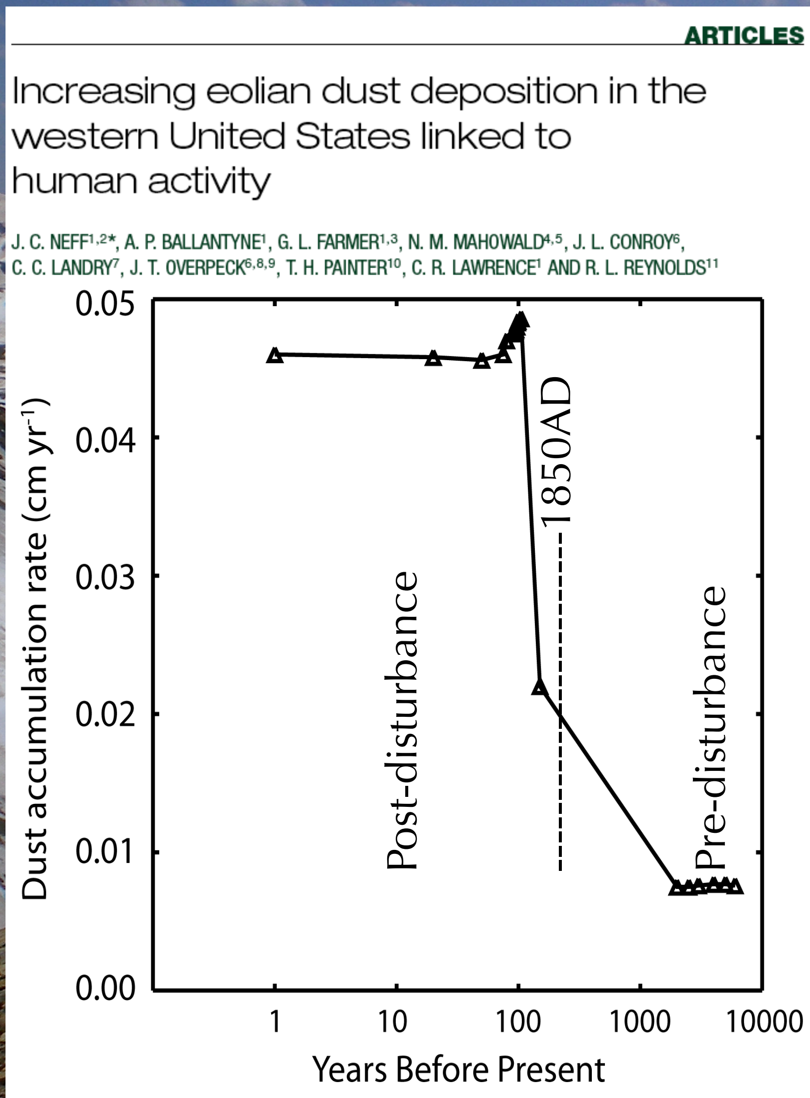
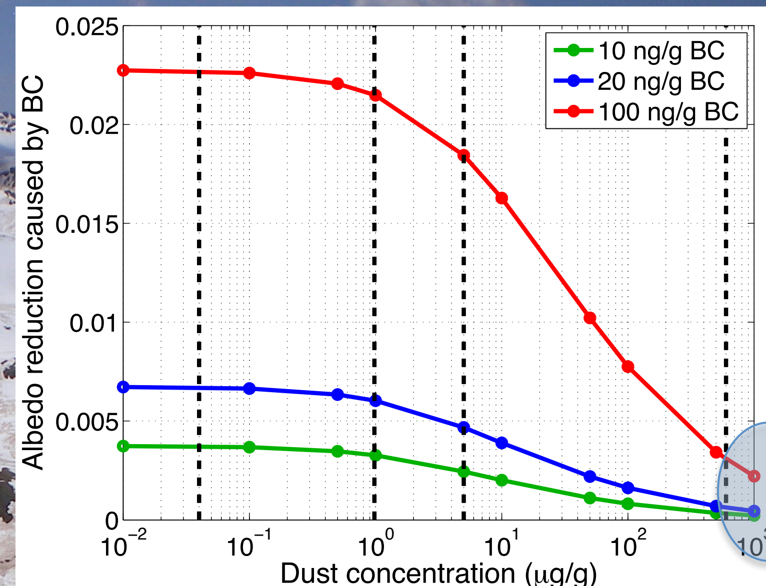
Upper Colorado River Basin



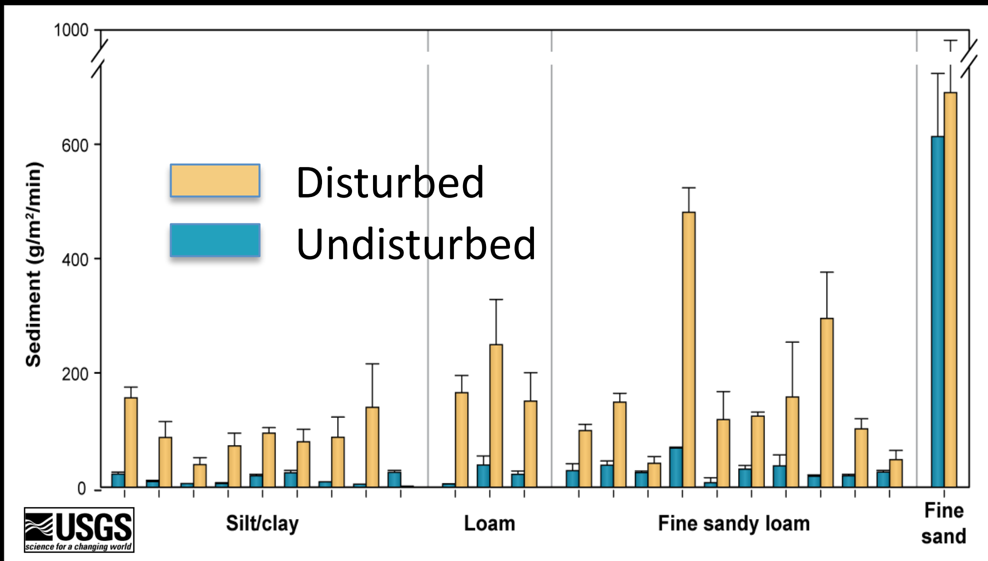
ARTICLES

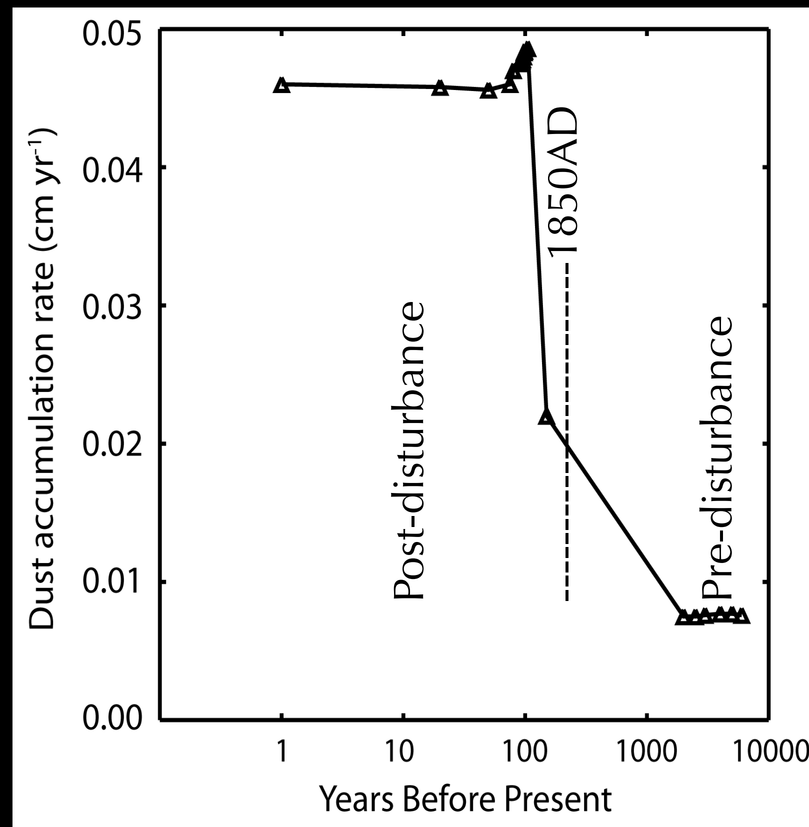
Increasing eolian dust deposition in the western United States linked to human activity

J. C. NEFF[1,2]*, A. P. BALLANTYNE[1], G. L. FARMER[1,3], N. M. MAHOWALD[4,5], J. L. CONROY[6], C. C. LANDRY[7], J. T. OVERPECK[6,8,9], T. H. PAINTER[10], C. R. LAWRENCE[1] AND R. L. REYNOLDS[11]



Crust disturbance is the key



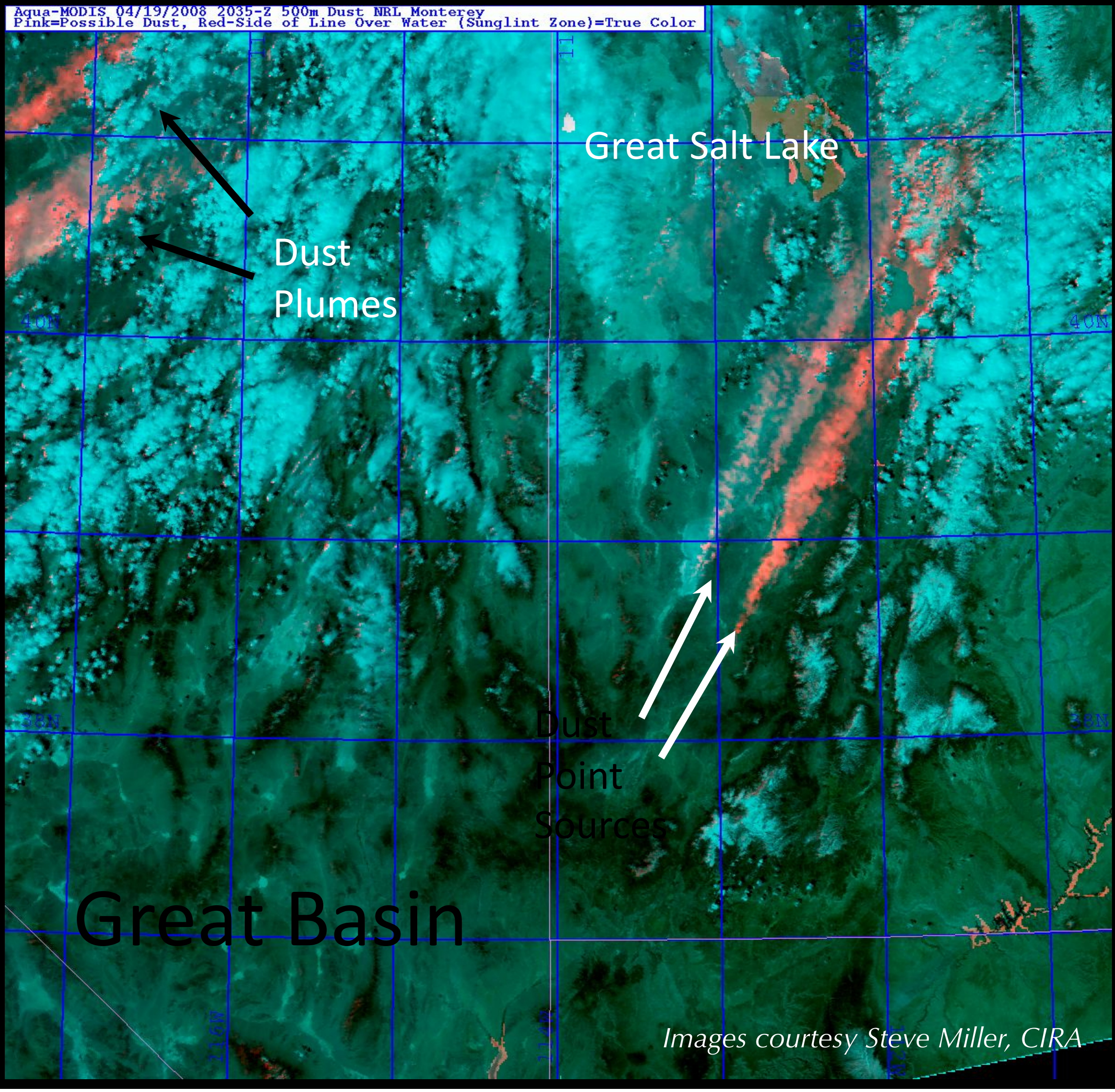


- Desert surfaces are commonly armored by crusts
- Most surfaces have very low dust emissions until crusts are disturbed
- When disturbed, sediment production increases by up to 550 times

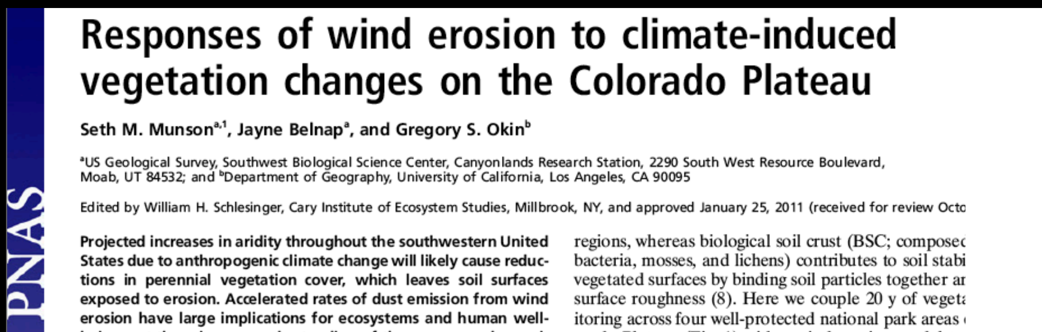
(courtesy Jayne Belnap, USGS)

Dust Sources Are Regional

Dust Sources Are Regional



What do we face in the future?



Responses of wind erosion to climate-induced vegetation changes on the Colorado Plateau

Seth M. Munson[a,1], Jayne Belnap[a], and Gregory S. Okin[b]

[a]US Geological Survey, Southwest Biological Science Center, Canyonlands Research Station, 2290 South West Resource Boulevard, Moab, UT 84532; and [b]Department of Geography, University of California, Los Angeles, CA 90095

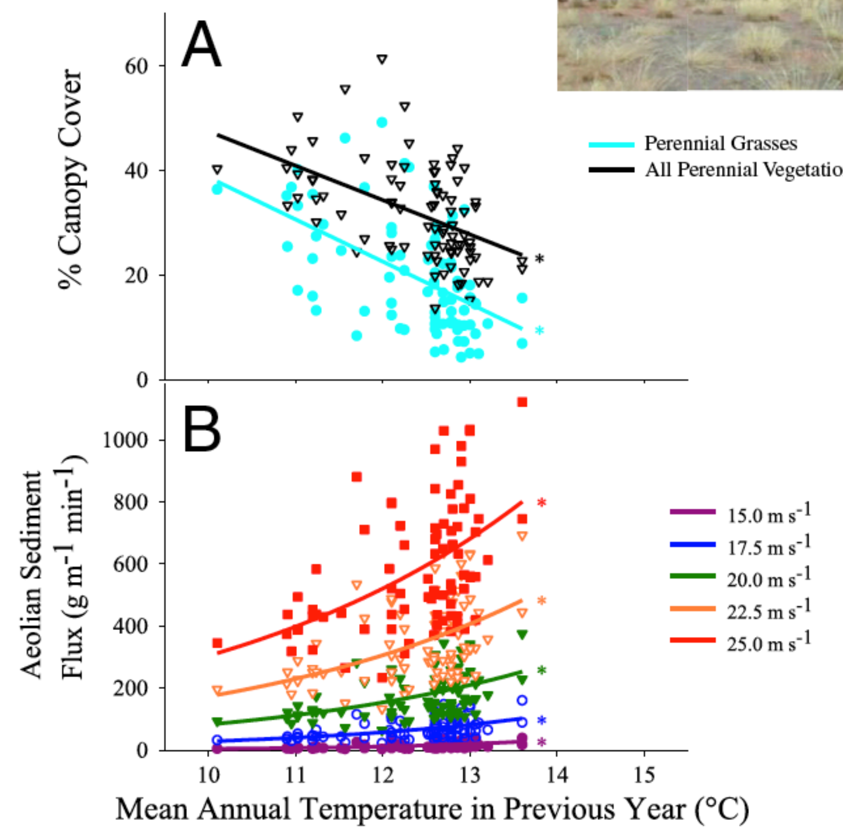
Edited by William H. Schlesinger, Cary Institute of Ecosystem Studies, Millbrook, NY, and approved January 25, 2011 (received for review Octo

Projected increases in aridity throughout the southwestern United States due to anthropogenic climate change will likely cause reductions in perennial vegetation cover, which leaves soil surfaces exposed to erosion. Accelerated rates of dust emission from wind erosion have large implications for ecosystems and human well-

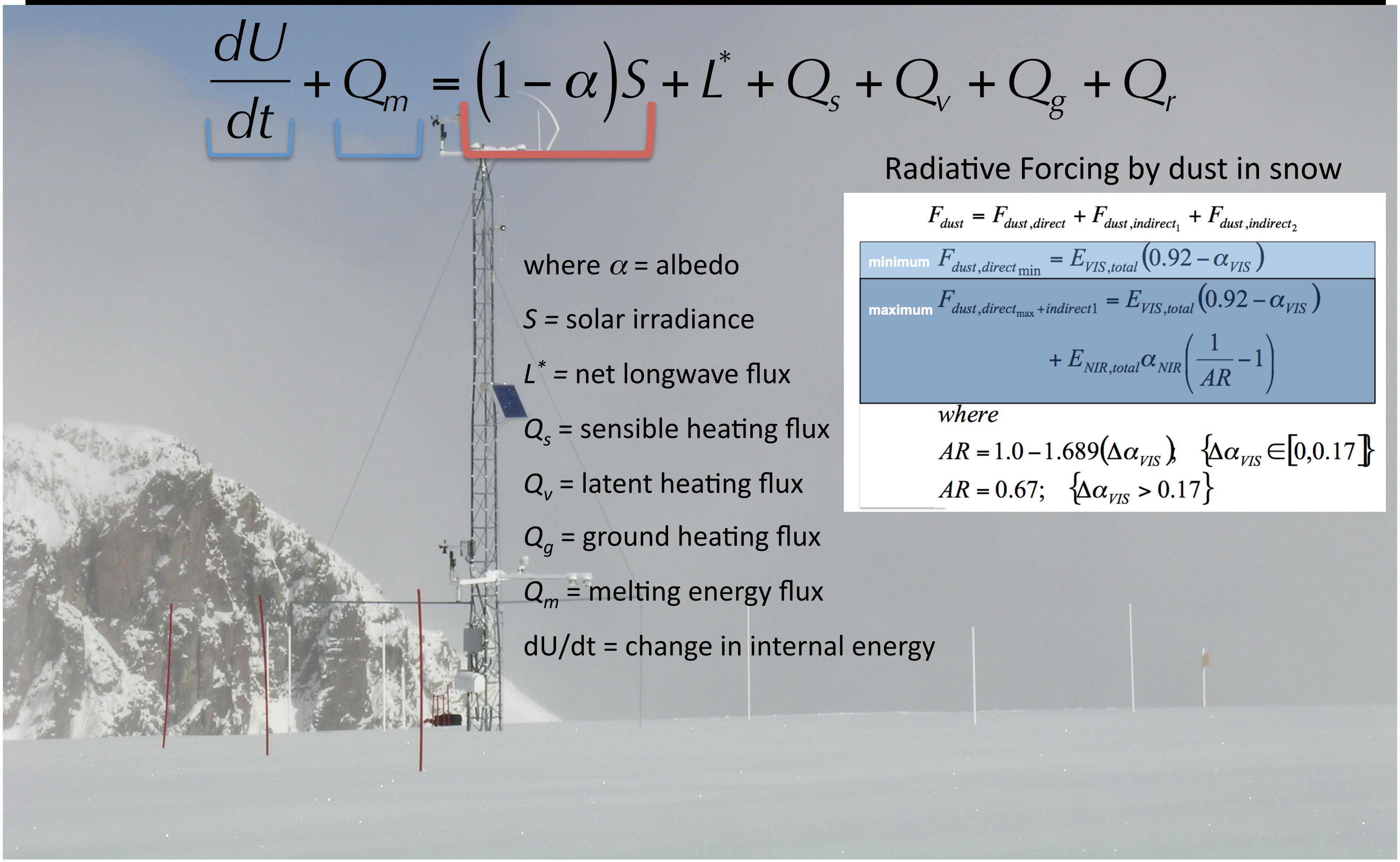
regions, whereas biological soil crust (BSC; compose bacteria, mosses, and lichens) contributes to soil stabi vegetated surfaces by binding soil particles together ar surface roughness (8). Here we couple 20 y of veget itoring across four well-protected national park areas

PNAS

Increased aridity from climate change in American Southwest should then lead to exponential increases in dust emission.



Energy Balance Towers - Upper Colorado River Basin



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

where α = albedo

S = solar irradiance

L^* = net longwave flux

Q_s = sensible heating flux

Q_v = latent heating flux

Q_g = ground heating flux

Q_m = melting energy flux

dU/dt = change in internal energy

Radiative Forcing by dust in snow

$$F_{dust} = F_{dust,direct} + F_{dust,indirect_1} + F_{dust,indirect_2}$$

minimum $F_{dust,direct\,\min} = E_{VIS,total}(0.92 - \alpha_{VIS})$

maximum $F_{dust,direct_{\max}+indirect1} = E_{VIS,total}(0.92 - \alpha_{VIS}) + E_{NIR,total}\alpha_{NIR}\left(\frac{1}{AR} - 1\right)$

where

$AR = 1.0 - 1.689(\Delta\alpha_{VIS}); \quad \{\Delta\alpha_{VIS} \in [0, 0.17]\}$

$AR = 0.67; \quad \{\Delta\alpha_{VIS} > 0.17\}$

Snow Melt

2005 - 2009

Springtime dust radiative forcing
25-110 W/m^2

Dust Forcing
26-50 Days

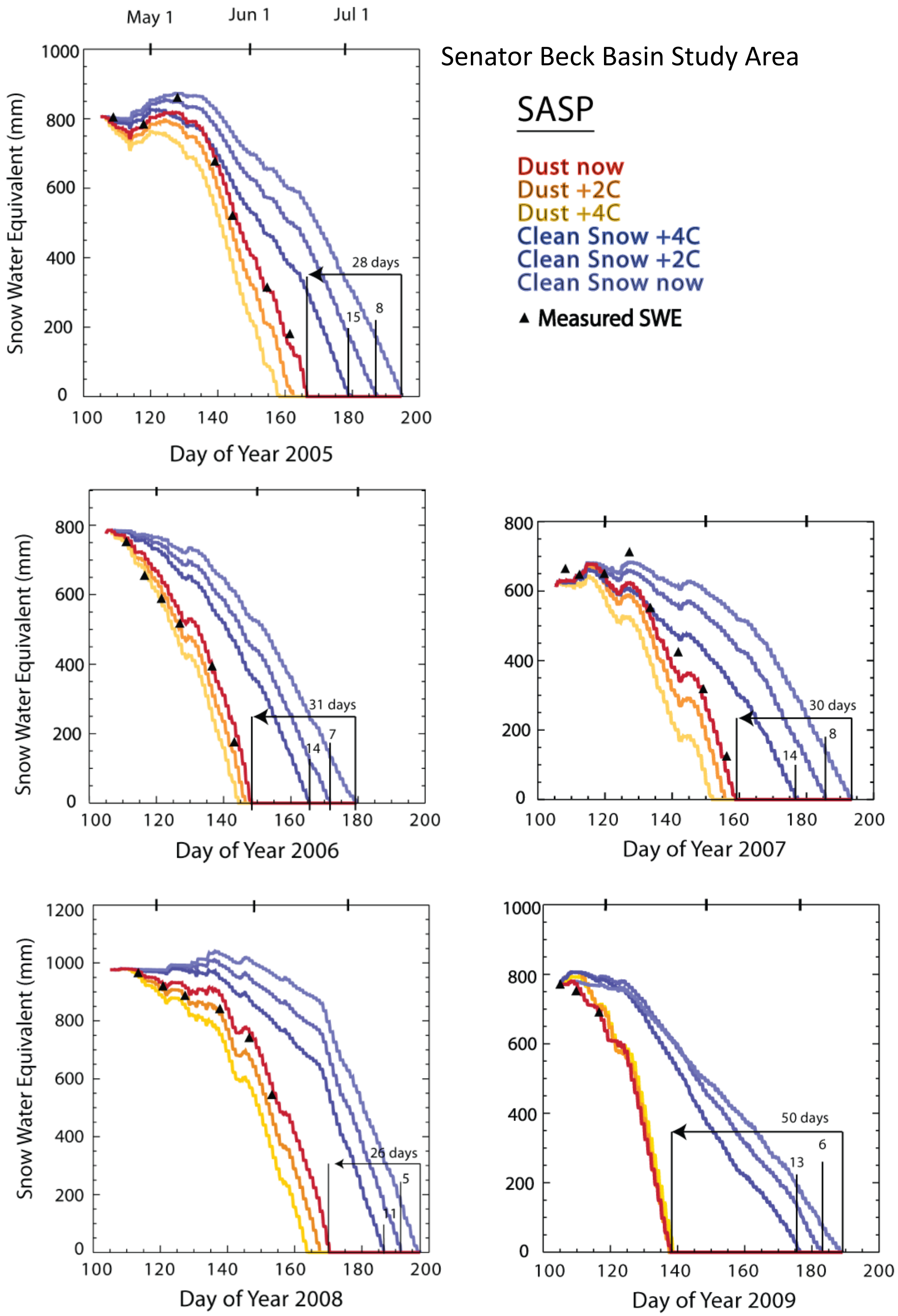
Dust Plus 2^o
28-50 Days

Clean Plus 2^o
5-8 Days

Dust Plus 4^o
32-50 Days

Clean Plus 4^o
11-15 Days

from *Painter et* al 2007; Skiles *et al,* in preparation



PNAS

Response of Colorado River runoff to dust radiative forcing in snow

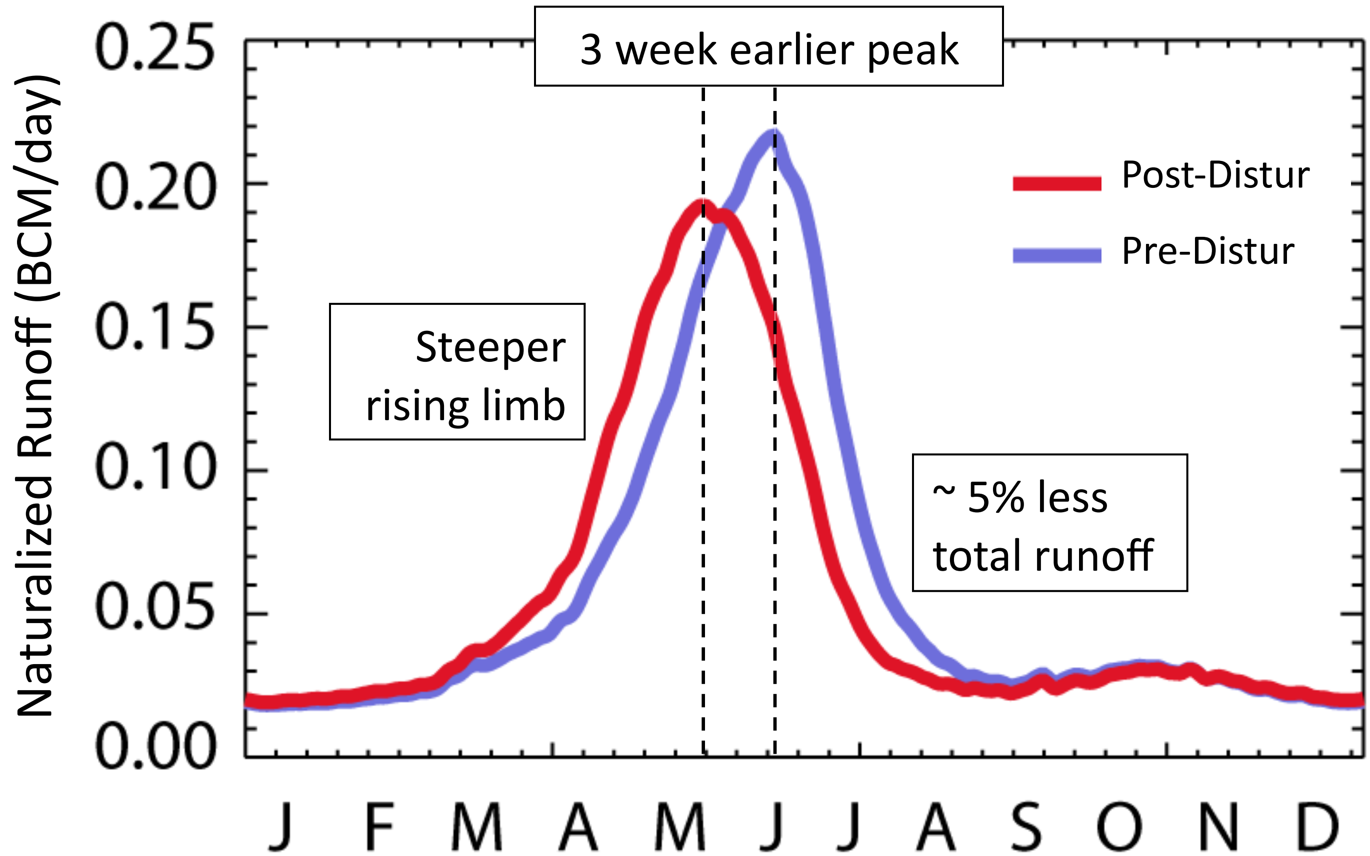
Thomas H. Painter[a,b,1], Jeffrey S. Deems[c,d], Jayne Belnap[e], Alan F. Hamlet[f], Christopher C. Landry[g], and Bradley Udall[d]

[a]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; [b]Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles, CA 90095; [c]National Snow and Ice Data Center, Boulder, CO 80309; [d]National Oceanic and Atmospheric Administration Western Water Assessment, Boulder, CO 80309; [e]United States Geological Survey, Southwest Biological Center, Moab, UT 84532; [f]University of Washington, Department of Civil and Environmental Engineering, Seattle, WA 98195; and [g]Center for Snow and Avalanche Studies, Silverton, CO 81433

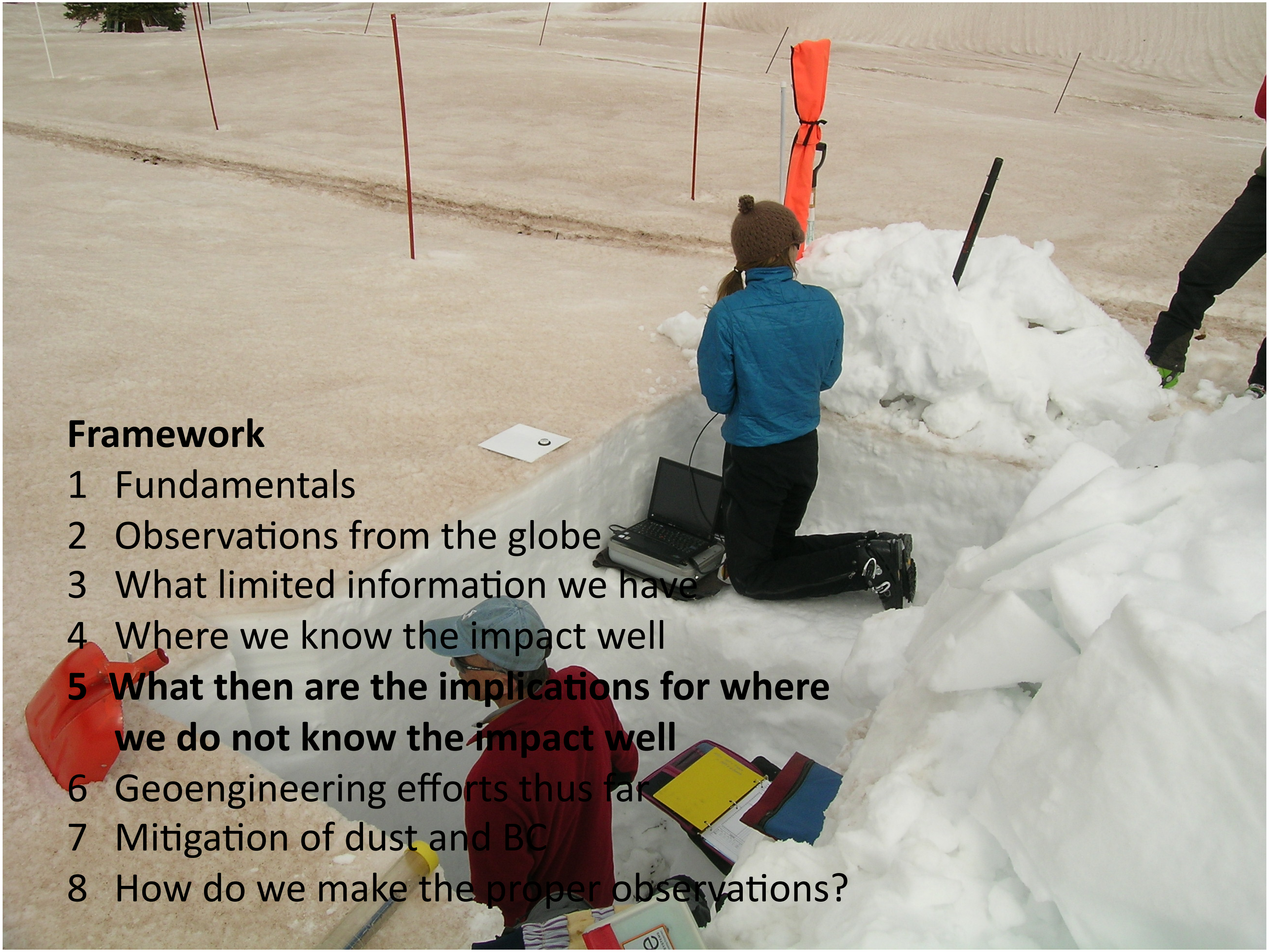
Edited by Peter H. Gleick, Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA, and approved August 3, 2010 (received for review November 12, 2009)

The waters of the Colorado River serve 27 million people in seven states and two countries but are overallocated by more than 10% of the river's historical mean. Climate models project runoff losses of through dust's direct absorption and increased grain size from accelerated snow metamorphism. Present day dust concentrations cause an average March/April/May radiative forcing in

Runoff
Lee's Ferry, AZ



Daily averages, 1915-2003



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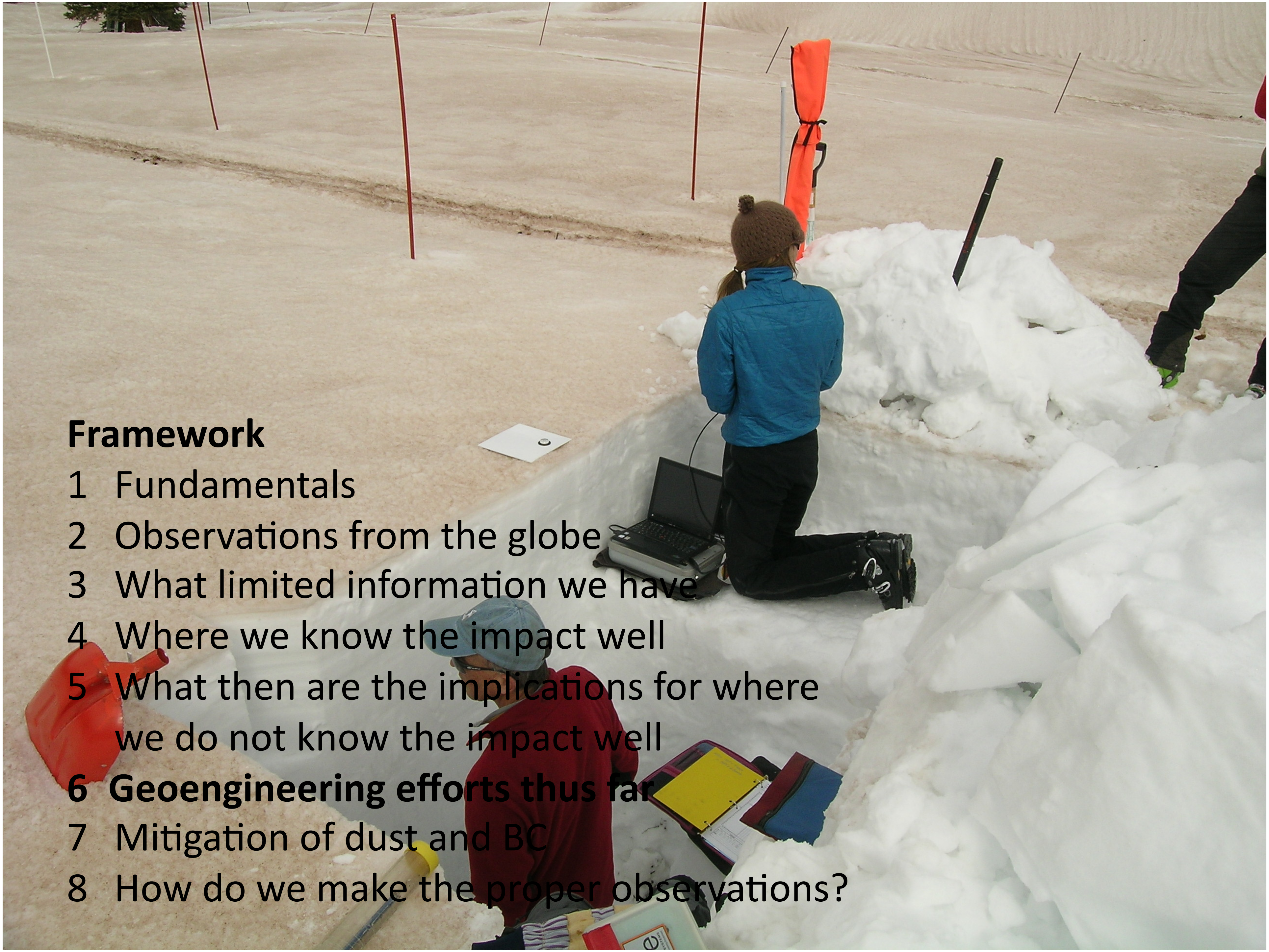
Implications for Mountain Glaciers

- Warming of snow surface increases sublimation rates
- Accelerated snowmelt and retreat of snow cover markedly can increase energy fluxes to glacier ice
- Dust loading in most systems appears to be greatest in lower elevations, most heavily impacting and expanding ablation zones
- Dust's impact is **absolutely** sensitive to temporal dynamics of snow cover, hypsometry, cloud cover
- The N-fold increases in dust loading that we are discovering since the mid-1800s poses a complication



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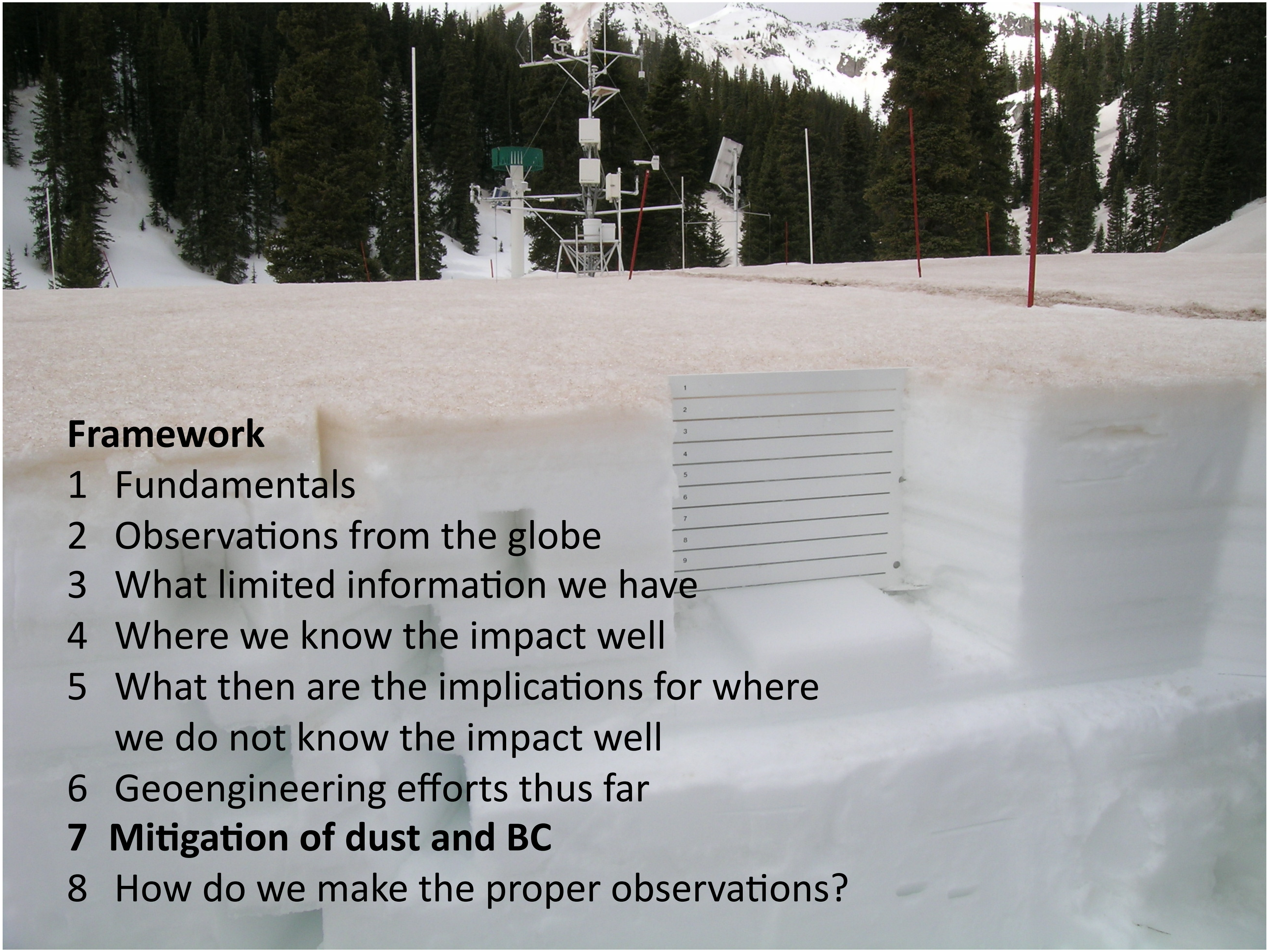
Niwot Ridge, Colorado

10 days, 35 cm differential melt

30 days, 1.05 m differential melt

Geoengineering



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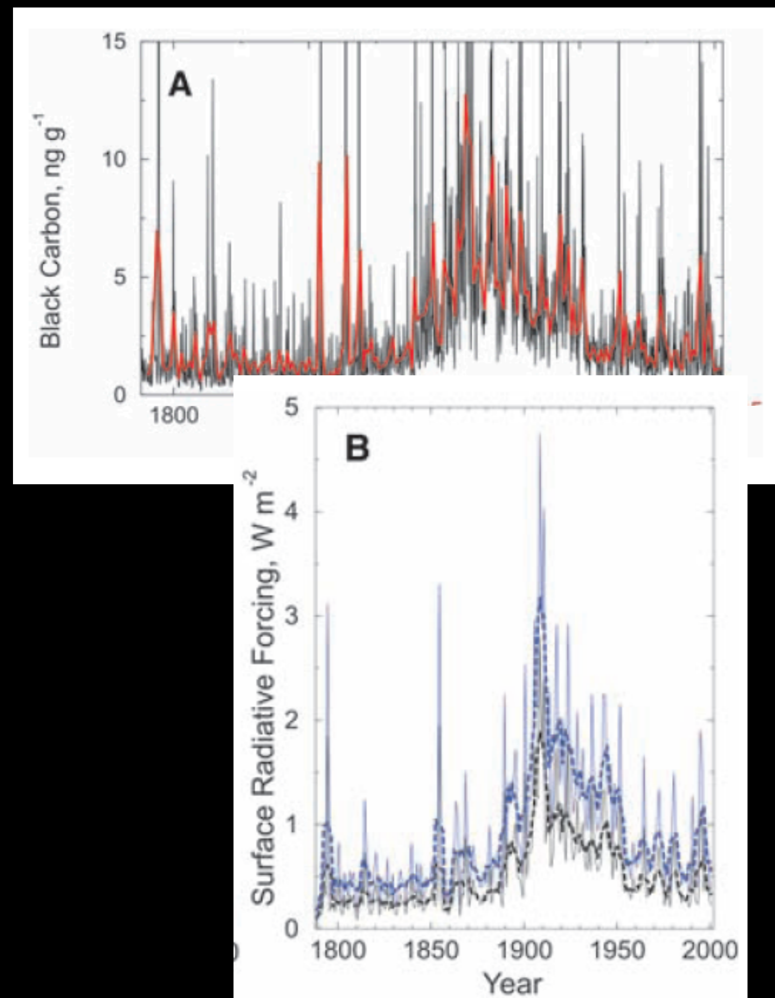
Greenland BC

Science AAAS

20th-Century Industrial Black Carbon Emissions Altered Arctic Climate Forcing
Joseph R. McConnell, *et al.*
Science **317**, 1381 (2007);
DOI: 10.1126/science.1144856

20th-Century Industrial Black Carbon Emissions Altered Arctic Climate Forcing

Joseph R. McConnell,[1]* Ross Edwards,[1] Gregory L. Kok,[2] Mark G. Flanner,[3] Charles S. Zender,[3] Eric S. Saltzman,[3] J. Ryan Banta,[1] Daniel R. Pasteris,[1] Megan M. Carter,[4] Jonathan D. W. Kahl[4]



Mitigation

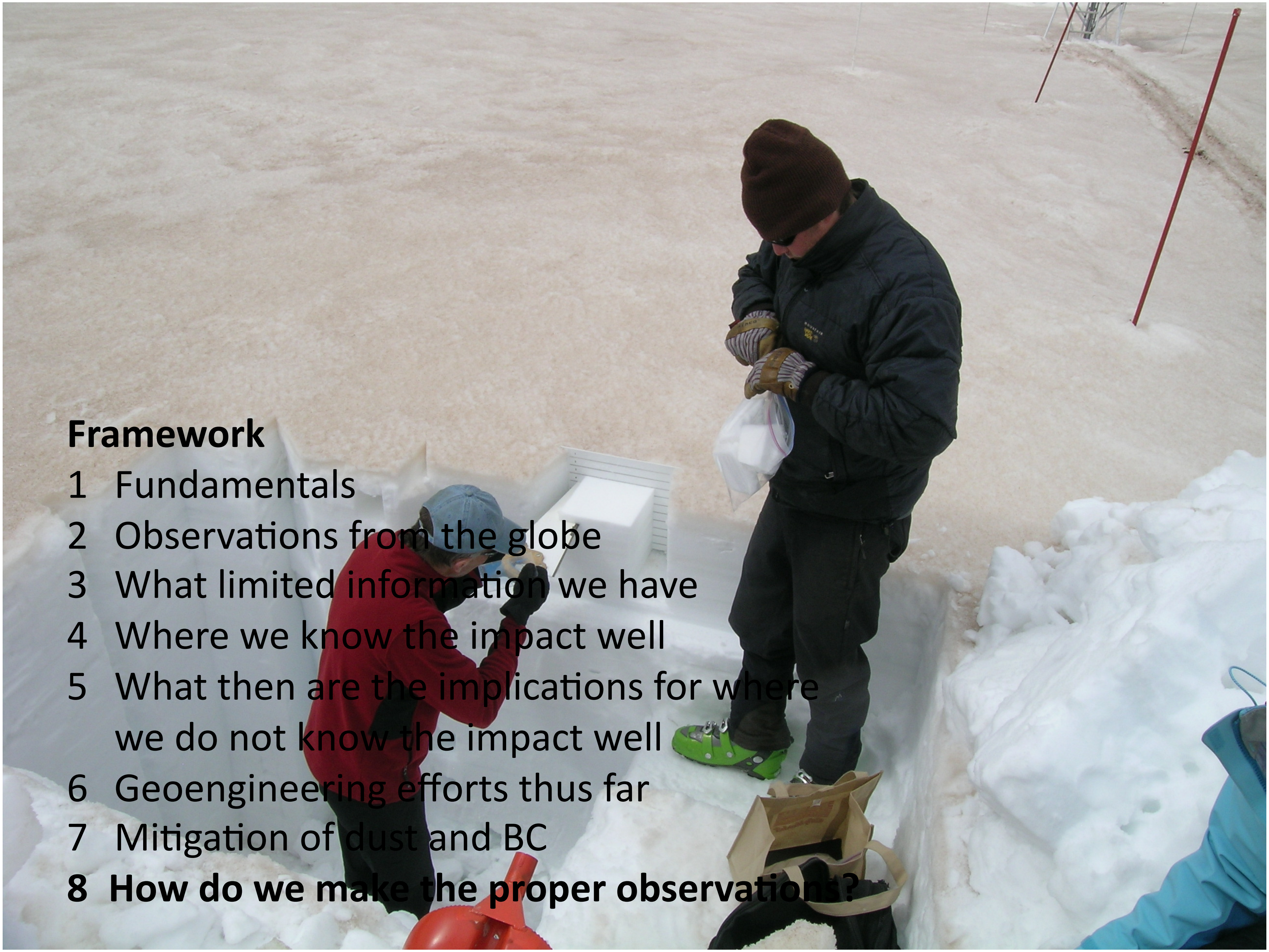
- Dept of Interior, BLM, BOR now pushing for dust mitigation in the Upper Colorado River Basin
- Efforts underway with Navajo Nation to reduce dust emissions
- Inoculation of disturbed soils for reestablishment of cryptobiotic crusts
- Ramanathan and others pushing for the mitigation of black carbon emissions

Fate of Mountain Glaciers

Glacier Measurements Need to Be Expanded and Improved

The remoteness and dangerous nature of work above 6000 m is one reason why we have few detailed measurements, other than of glacier length and size, in high mountain systems like the Himalayas and Andes. Current remote sensing technologies can detect changes in glacier and snow extent, but do not quantify relative forcings or provide important snow and ice properties, such as grain size, local impurities, and surface liquid water content. However, airborne and space-borne imaging spectrometers will soon allow us to make spatially comprehensive measurements of these surface properties. Put in context by more extensive observations from large-scale field campaigns, and in situ energy balance and mass balance measurements, imaging spectrometers will be used to construct and validate the next generation of high resolution glacier mass balance models. Quantitative observations are the key.

PONTIFICIA ACADEMIA SCIENTIARVM



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Recent Debate

Atmos. Chem. Phys., 11, 1929–1948, 2011
www.atmos-chem-phys.net/11/1929/2011/
doi:10.5194/acp-11-1929-2011

Atmospheric Chemistry and Physics

Sensitivity studies on the impacts of Tibetan Plateau snowpack pollution on the Asian hydrological cycle and monsoon climate

Y. Qian[1], M. G. Flanner[2], L. R. Leung[1], and W. Wang[3]

[1]Pacific Northwest National Laboratory, Richland, WA, USA
[2]University of Michigan, Ann Arbor, MI, USA
[3]NOAA National Centers for Environmental Prediction, Camp Springs, MD, USA

Received: 27 August 2010 – Published in Atmos. Chem. Phys. Discuss.: 5 October 2010
Revised: 21 January 2011 – Accepted: 16 February 2011 – Published: 2 March 2011

But they both are missing the most important dataset – the observations of radiative forcing and associated measurements of energy and mass balance

NEWS

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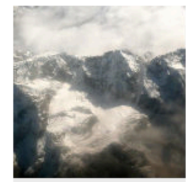
Sooty Himalayan snow 'warms climate, alters monsoons'

Archita Bhatta
23 March 2011 | EN

[NEW DELHI] Black carbon landing on snow may be accelerating the melting of Himalayan glaciers more than atmospheric soot or even greenhouse gases such as carbon dioxide (CO_2), according to a study.



Himalayan snow cover: going up or down?
Flickr/Girl in the Rain

The effects of this carbon, a key component of soot, could change the timing and intensity of the monsoons; increase the chances of downstream floods and reduce farmers' access to irrigation when they most need it, researchers say.

The Cryosphere Discuss., 5, 755–777, 2011
www.the-cryosphere-discuss.net/5/755/2011/
doi:10.5194/tcd-5-755-2011

The Cryosphere Discussions

Changes in seasonal snow cover in Hindu Kush-Himalayan region

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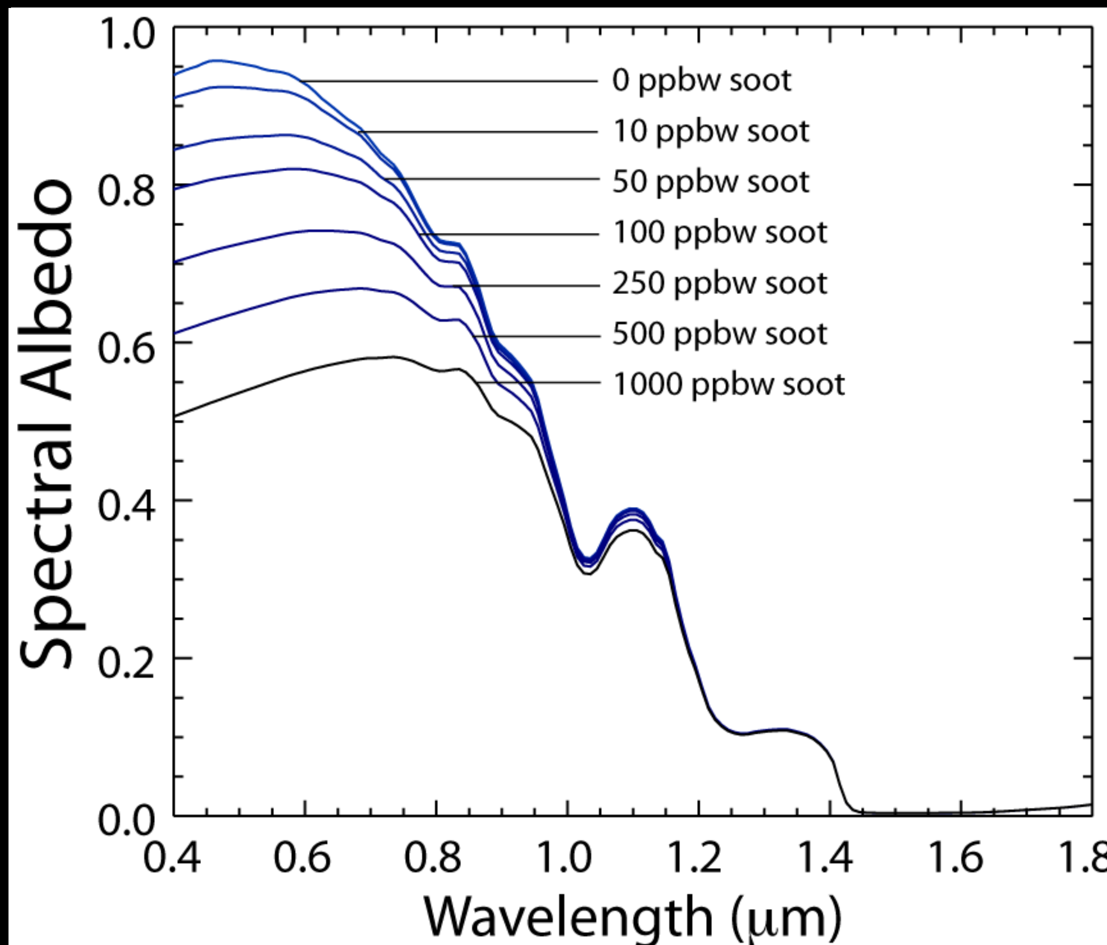
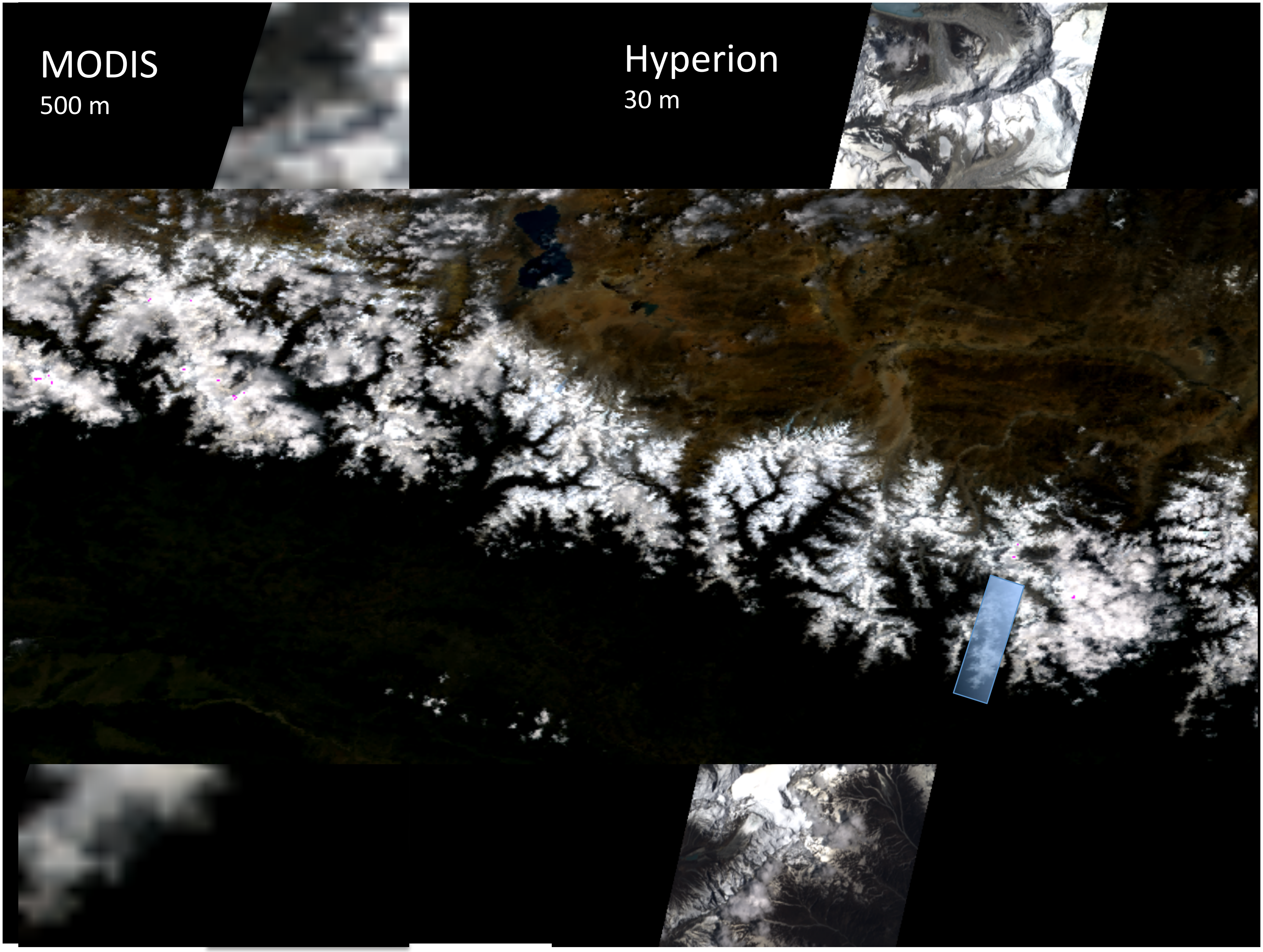
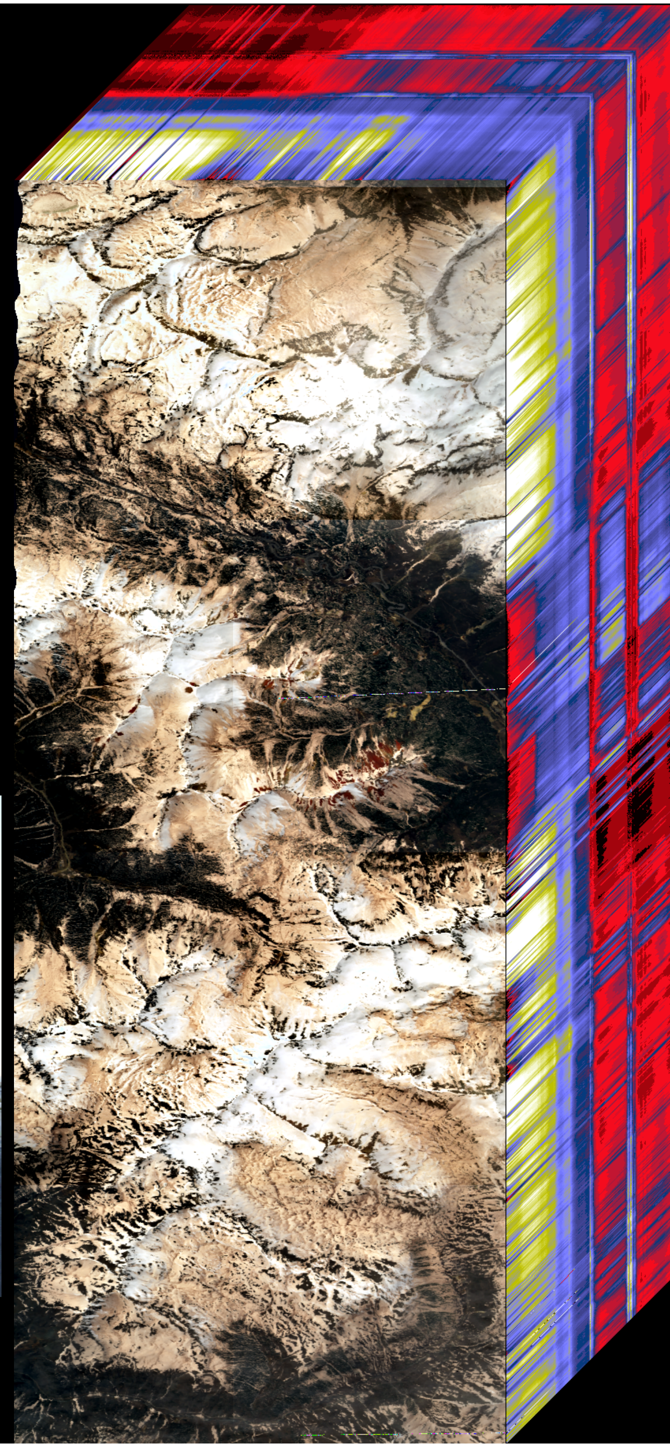
What does MODIS give us?




MODIS
500 m
Hyperion
30 m

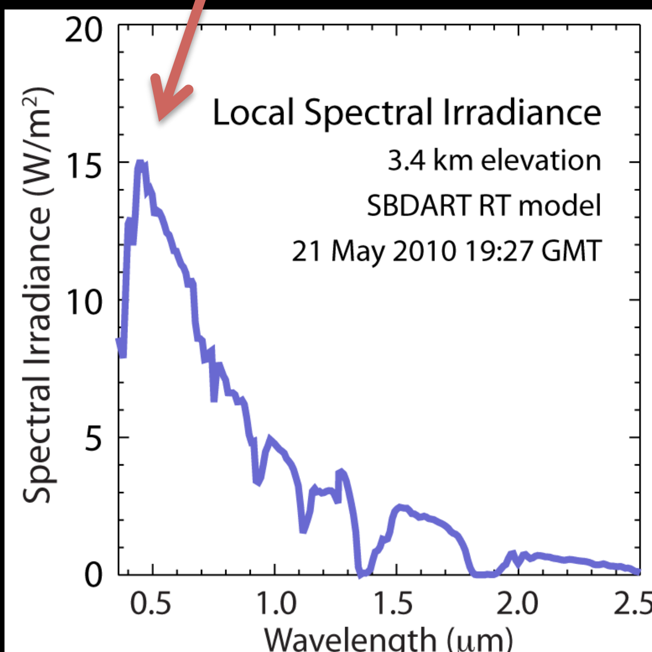
NASA Airborne Visible/ Infrared Imaging Spectrometer (AVIRIS)

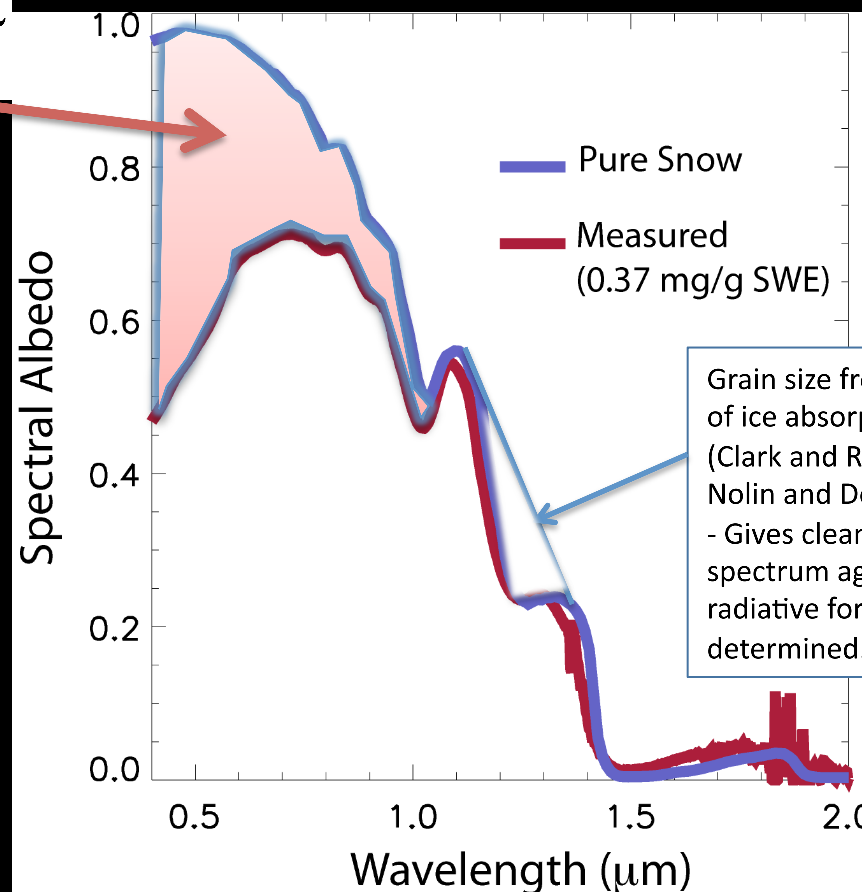
Spectral range:	350 to 2500 nm
Spectral resolution:	10 nm
Spatial resolution:	20 m (from 20km)



AVIRIS Light Absorbing Impurities in Snow and Ice (AVI-LAISI)

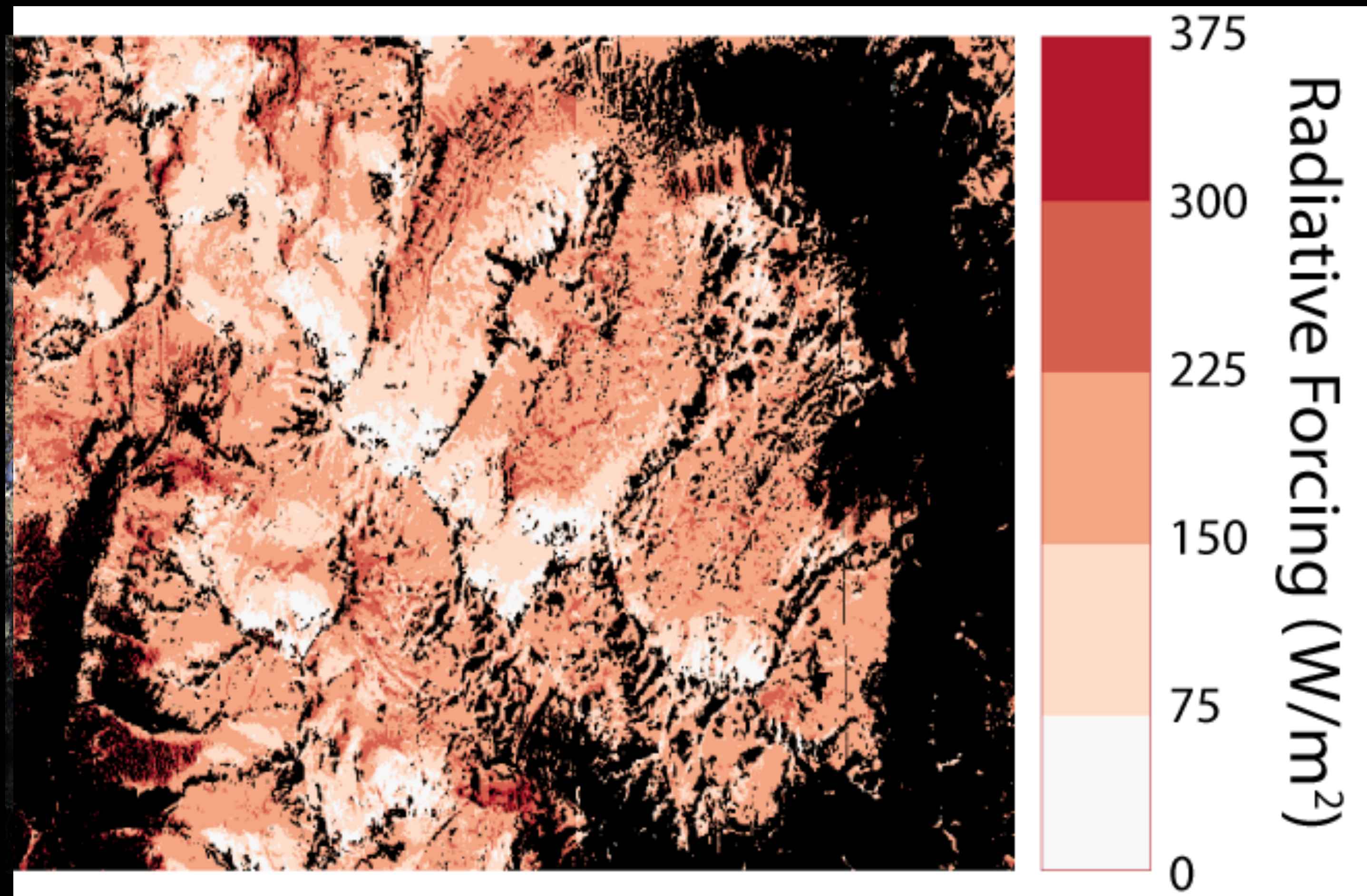
$$RF = \sum_{0.35\,\mu m}^{1.15\,\mu m} E_\lambda \left(R_{\lambda,clean} - R_{\lambda,dust} \right) d\lambda$$





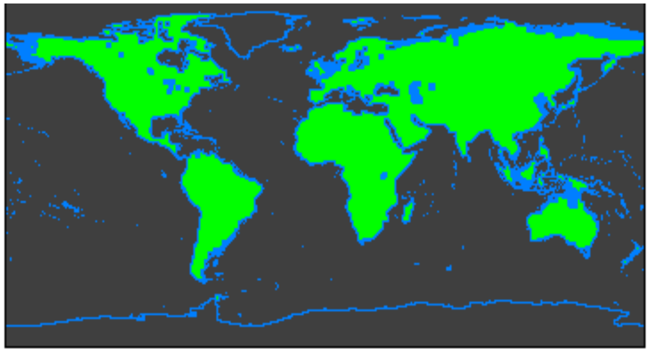
Grain size from integral of ice absorption feature (Clark and Roush 1984; Nolin and Dozier 2000)
- Gives clean snow spectrum against which radiative forcing is determined.

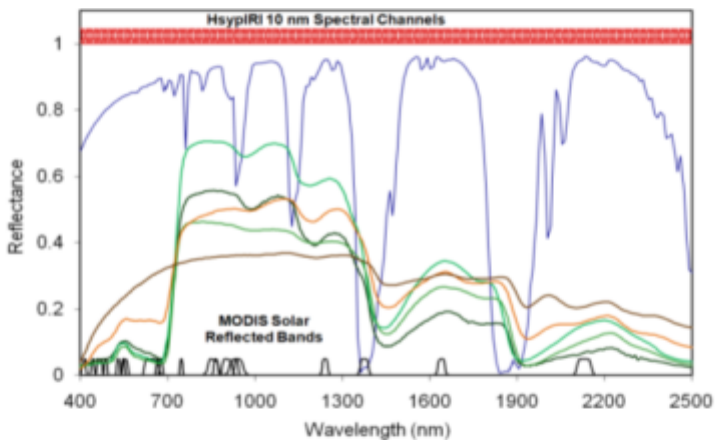
Colorado River Basin

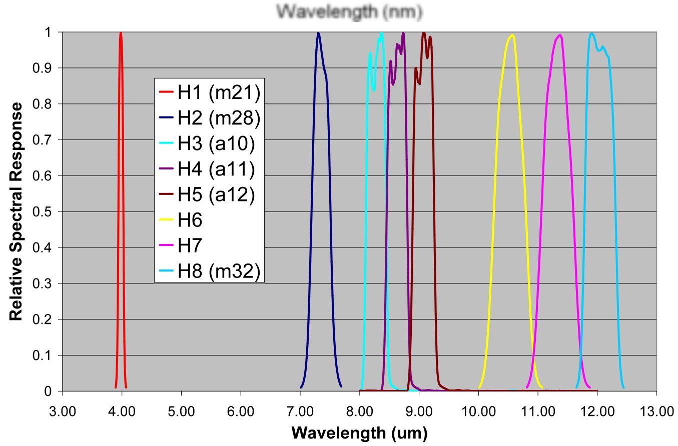


AVI-LAISI *Painter* 2010 in preparation
21 May 2010, Senator Beck Basin, Colorado

HyspIRI Science Measurements



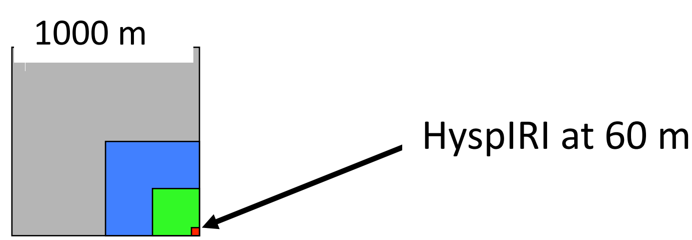




HyspIRI is a global mission, measuring land and shallow aquatic habitats at 60 meters and deep oceans at 1km every 5 days (TIR) and every 19 days (VSWIR)

HyspIRI's VSWIR imaging spectrometer directly measures the full solar reflected spectrum of the Earth from 380 – 2500nm at 10 nm.

HyspIRI's TIR directly samples the Earth's emitted thermal energy in 7 bands between 7.5-12 µm, & 1 band between 3-5 µm



Both the VSWIR and TIR instrument concepts are high heritage with no new technology

Conclusions

- In the Colorado Rocky Mountains, springtime dust radiative forcing ranges from 25-110 W/m^2.
- Shortening of snow duration ranges from 25-50 days.
- Dust loading in CRB has increased 5-7 times since the mid 1800s.
- There are clear indications of increasing dust loads in many of the glacier covered mountain systems of the globe. With increased aridity, we likely face increased dust emission unless surfaces can be restabilized.

Conclusions

- We lack the measurements in other systems and in particular in the HKH, in situ instrumentation is difficult to situate.
- Remote sensing must be used to address these needs, MODIS helpful in qualitative measures
- Imaging spectroscopy in particular is necessary to quantify the radiative forcings


Naulik Glacier, Nepal
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