Remote Sensing of Snow

Thomas H. Painter, NASA JPL/Caltech, Pasadena, CA

Outline

- Energy and mass balance
- Fractional snow covered area
- Dust/black carbon radiative forcing in snow
- Airborne Snow Observatory
  - SWE
  - Albedo
- Implementations with CBRFC and BOR

Energy and Mass Balance

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

warming

melting

net SW

net LW

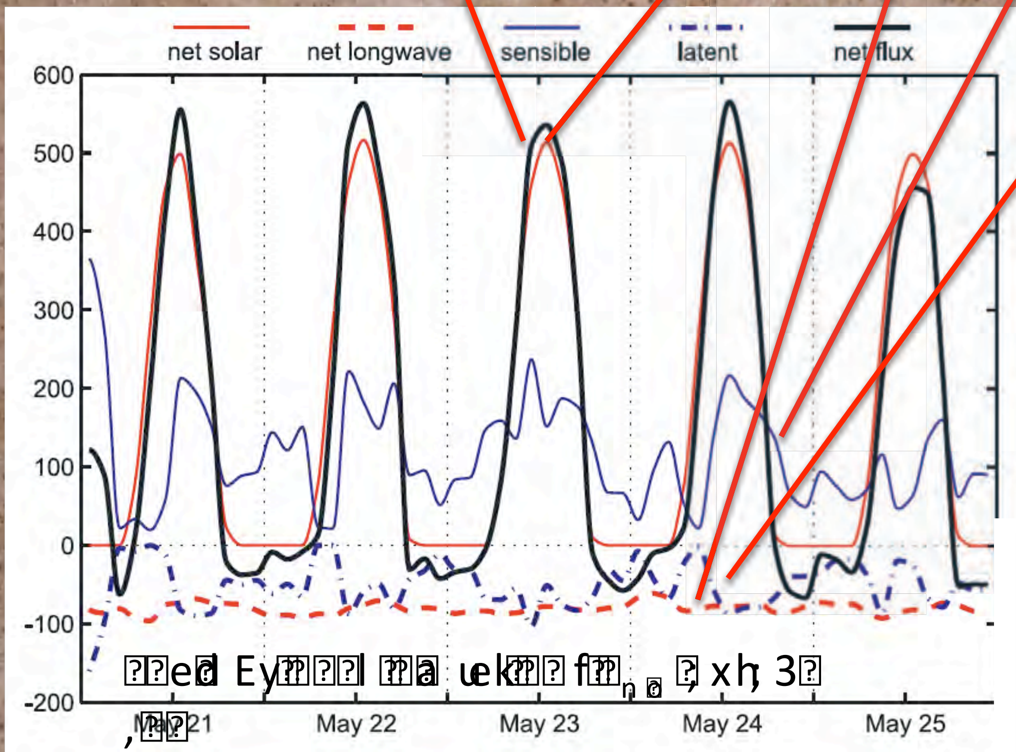
sensible

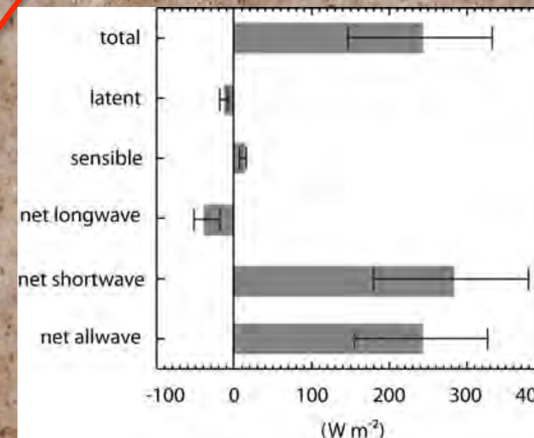
latent

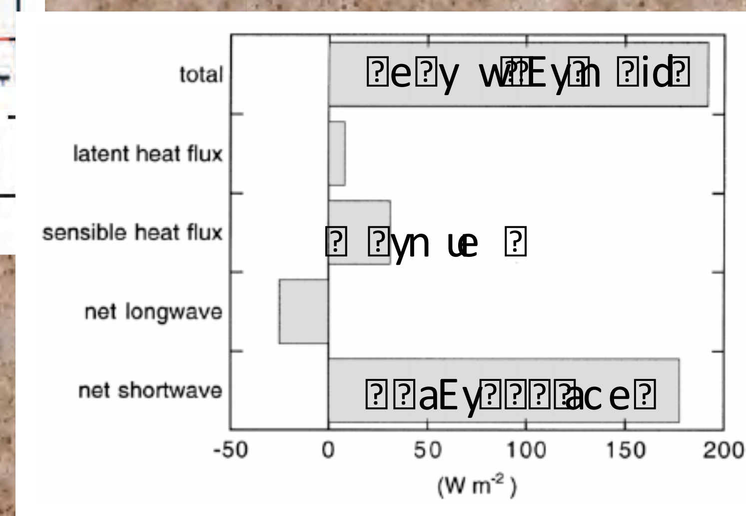
ground

advected

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







[illegible]

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

[illegible]

[illegible]

[illegible]

[illegible]

MODSCAG

MODSCAG

Core: Multiple Endmember Linear Spectral Mixture Analysis (MESMA)

$$R_{S,\lambda} = \sum_{i=1}^{N} F_i R_{\lambda,i} + \varepsilon_\lambda$$

$$\varepsilon_\lambda = R_{S,\lambda} - \sum_{i=1}^{N} F_i R_{\lambda,i}$$

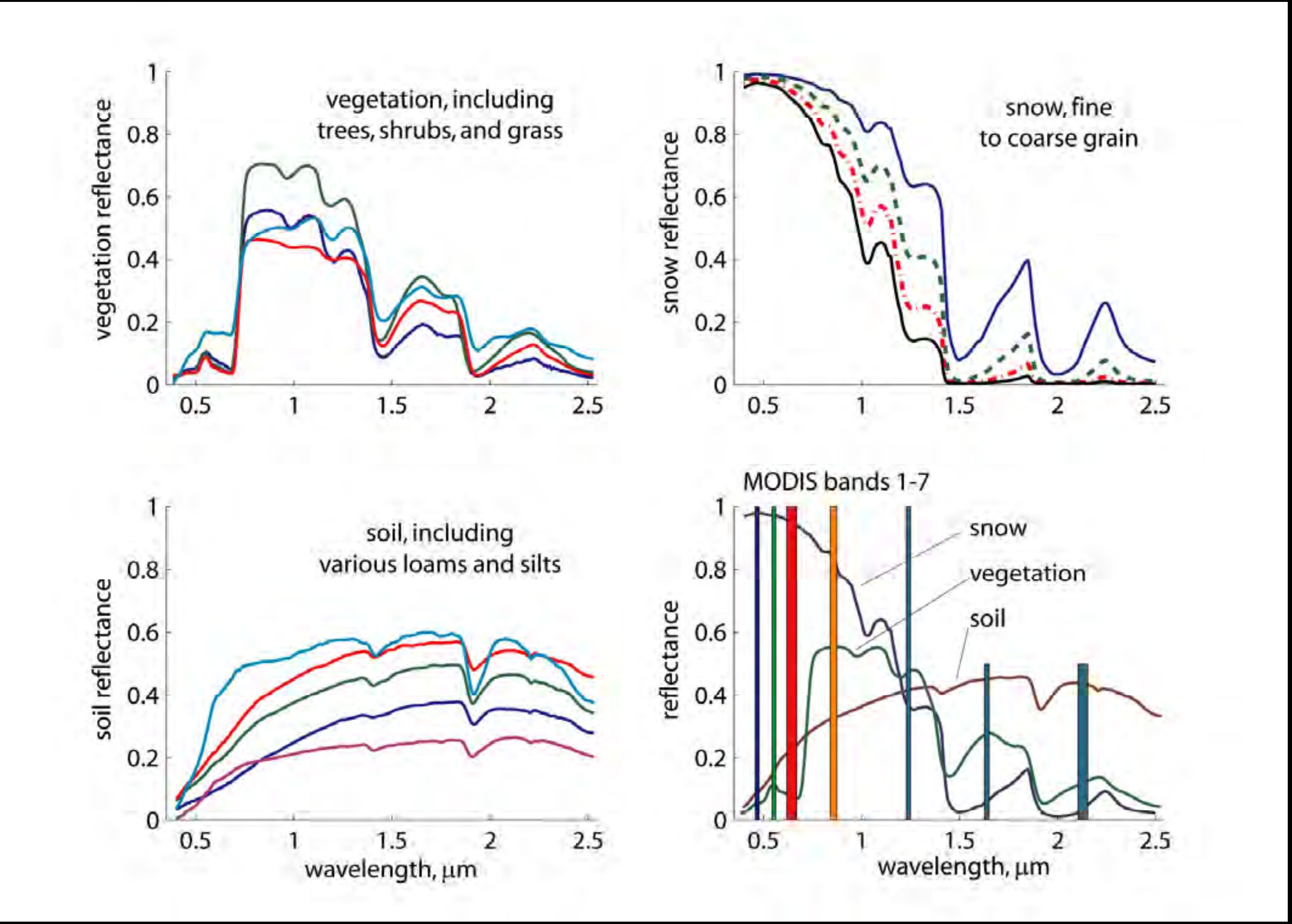
$$RMSE = \left(\frac{1}{M} \sum_{\lambda=1}^{M} \varepsilon_\lambda^2 \right)^{1/2}$$

$R_{s,\lambda}$ is the MOD09 surface reflectance, F_i is the fraction of endmember i, $R_{\lambda,i}$ is the hemispherical-directional reflectance factor of endmember i at wavelength λ, N is the number of spectral endmembers, and ε_λ is the residual error at λ for the fit of the N endmembers. The least-squares fit to F_i can be solved by several standard methods.

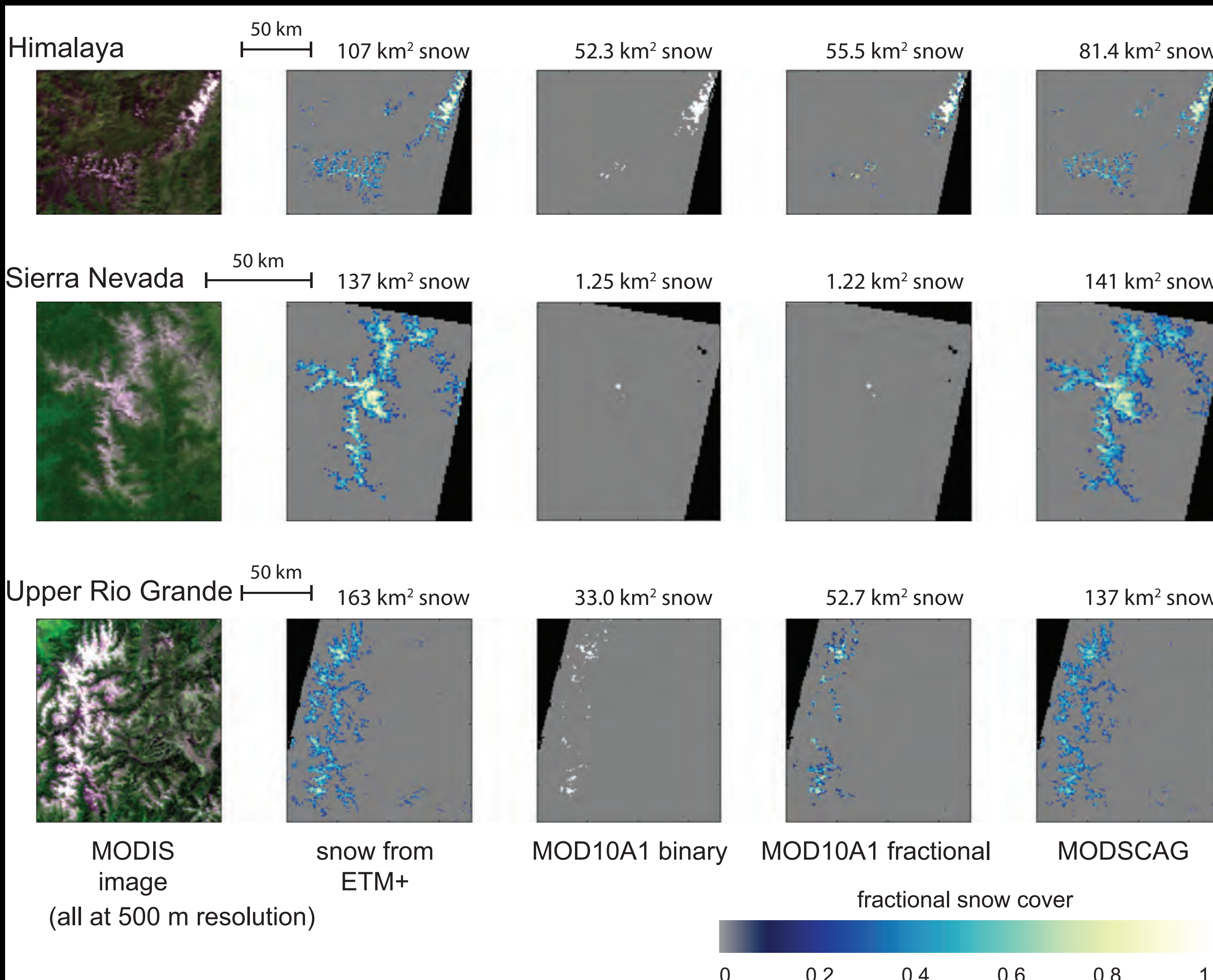
$$f_S = \frac{F_S}{\sum_{p \in S,v,r} F_p} = \frac{F_S}{1 - F_{shade}}$$

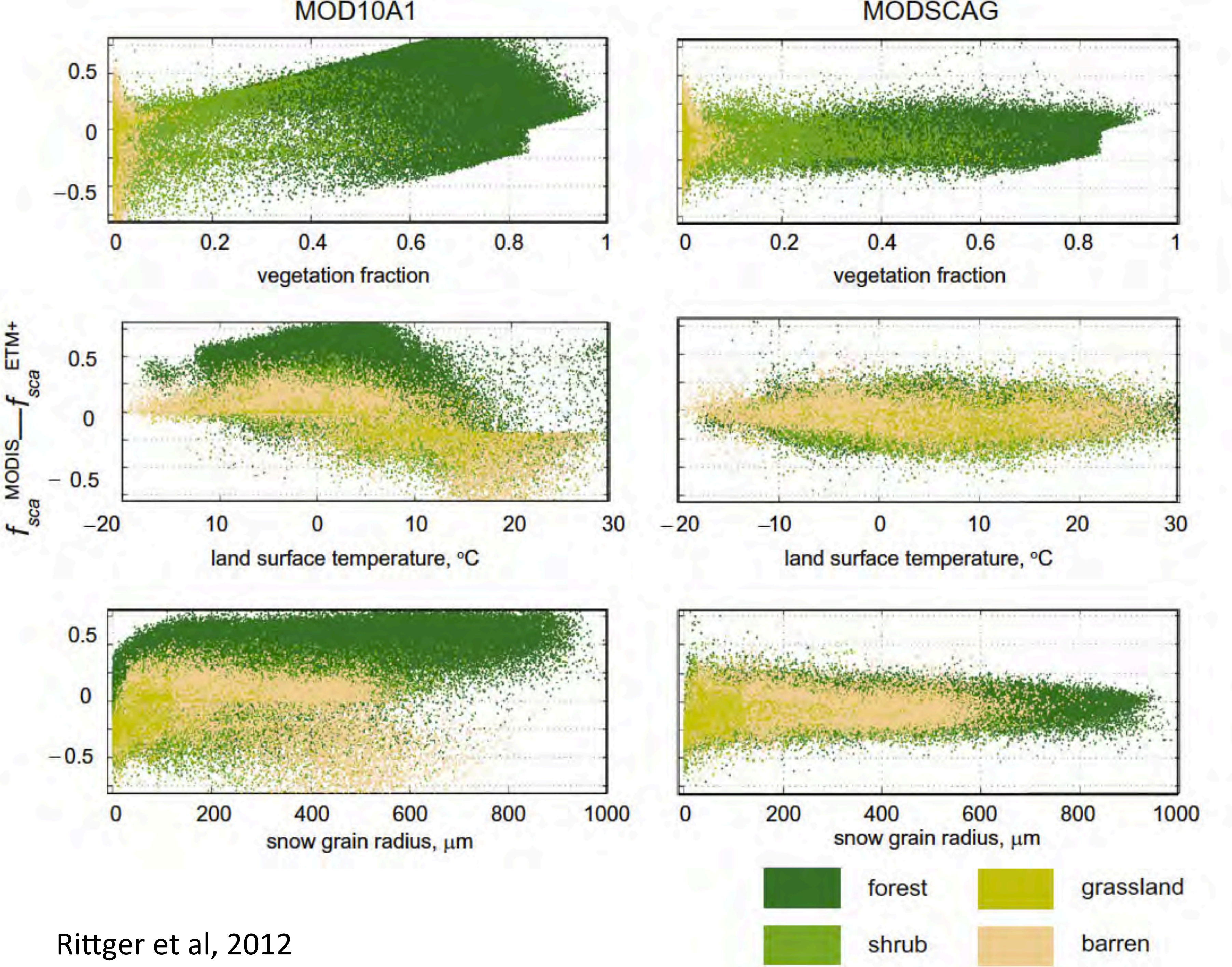
Shade normalization for snow cover and grain size from endmember selection

Spectral libraries



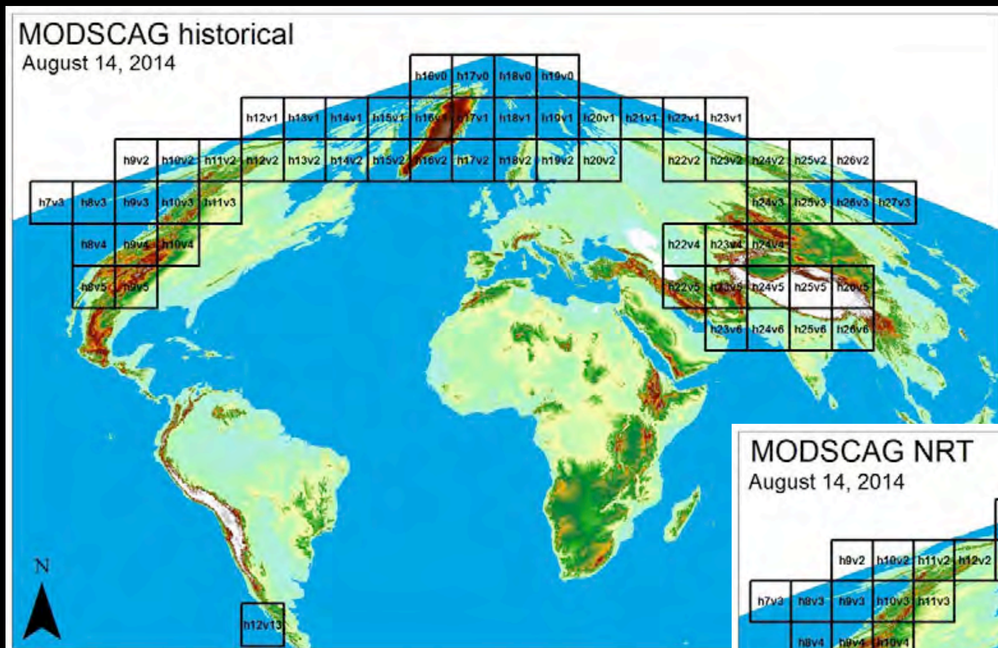
MODSCAG vs MOD10A1

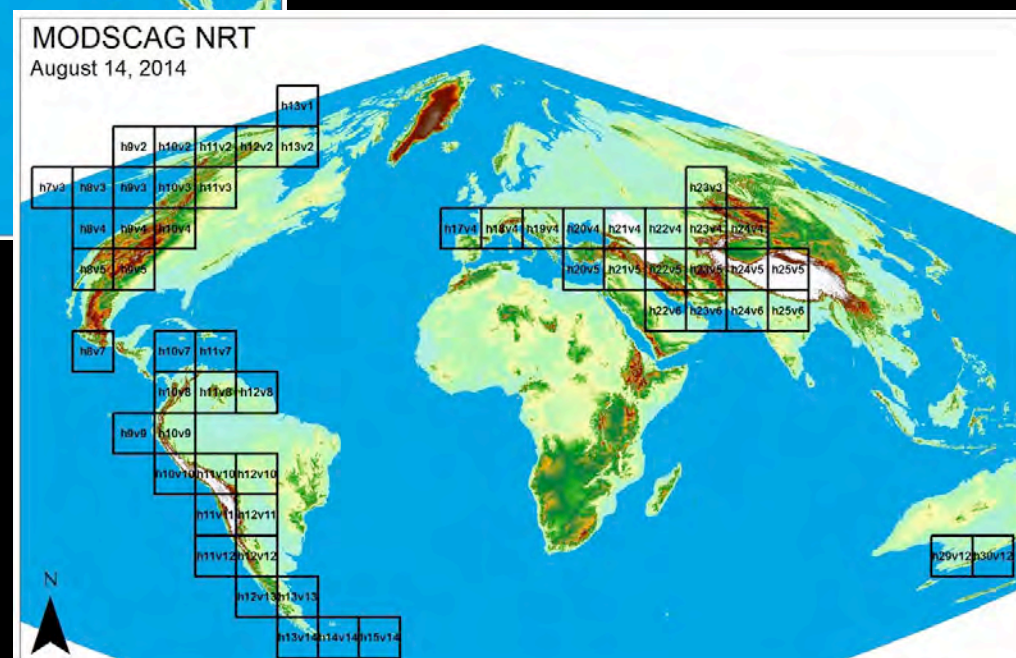




Rittger et al, 2012

MODSCAG

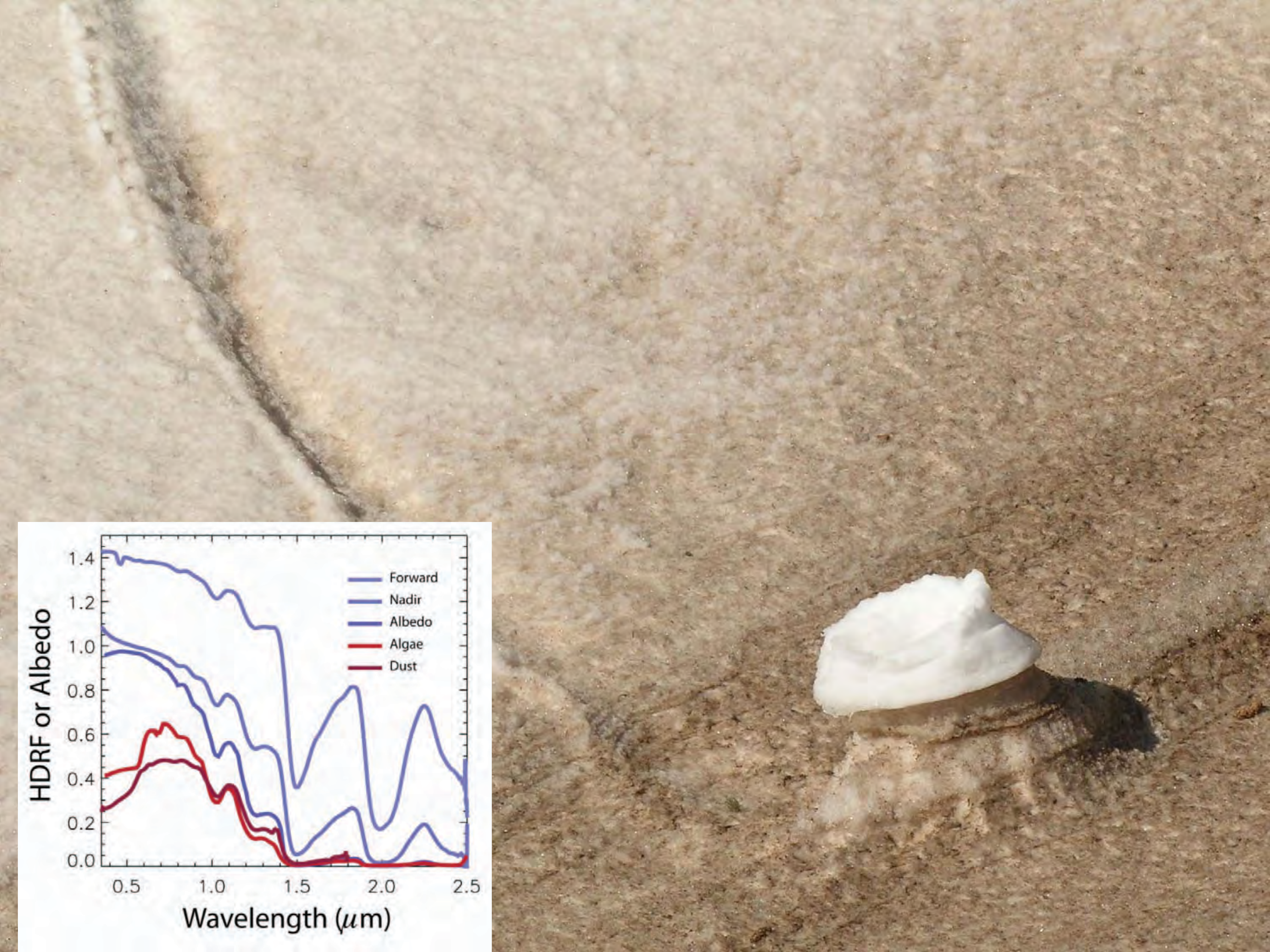

MODSCAG historical
August 14, 2014
h16v0
h17v0
h18v0
h19v0
h12v1
h13v1
h14v1
h15v1
h17v1
h18v1
h19v1
h20v1
h21v1
h22v1
h23v1
h9v2
h10v2
h11v2
h12v2
h13v2
h14v2
h15v2
h16v2
h17v2
h18v2
h19v2
h20v2
h22v2
h23v2
h24v2
h25v2
h26v2
h7v3
h8v3
h9v3
h10v3
h11v3
h24v3
h25v3
h26v3
h27v3
h8v4
h10v4
h22v4
h23v4
h24v4
h24v5
h25v5
h23v6
h24v6
h25v6
h26v6
h12v13
N


MODSCAG NRT
August 14, 2014
h13v1
h9v2
h10v2
h11v2
h12v2
h13v2
h7v3
h8v3
h9v3
h10v3
h11v3
h23v3
h8v4
h9v4
h10v4
h17v4
h19v4
h20v4
h21v4
h22v4
h23v4
h24v4
h20v5
h21v5
h22v5
h24v5
h25v5
h22v6
h23v6
h24v6
h25v6
h8v7
h10v7
h11v7
h10v8
h11v8
h12v8
h9v9
h10v9
h10v10
h11v10
h12v10
h12v11
h11v12
h12v12
h12v13
h13v13
h13v14
h14v14
h15v14
h29v12
h30v12
N

[illegible]

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

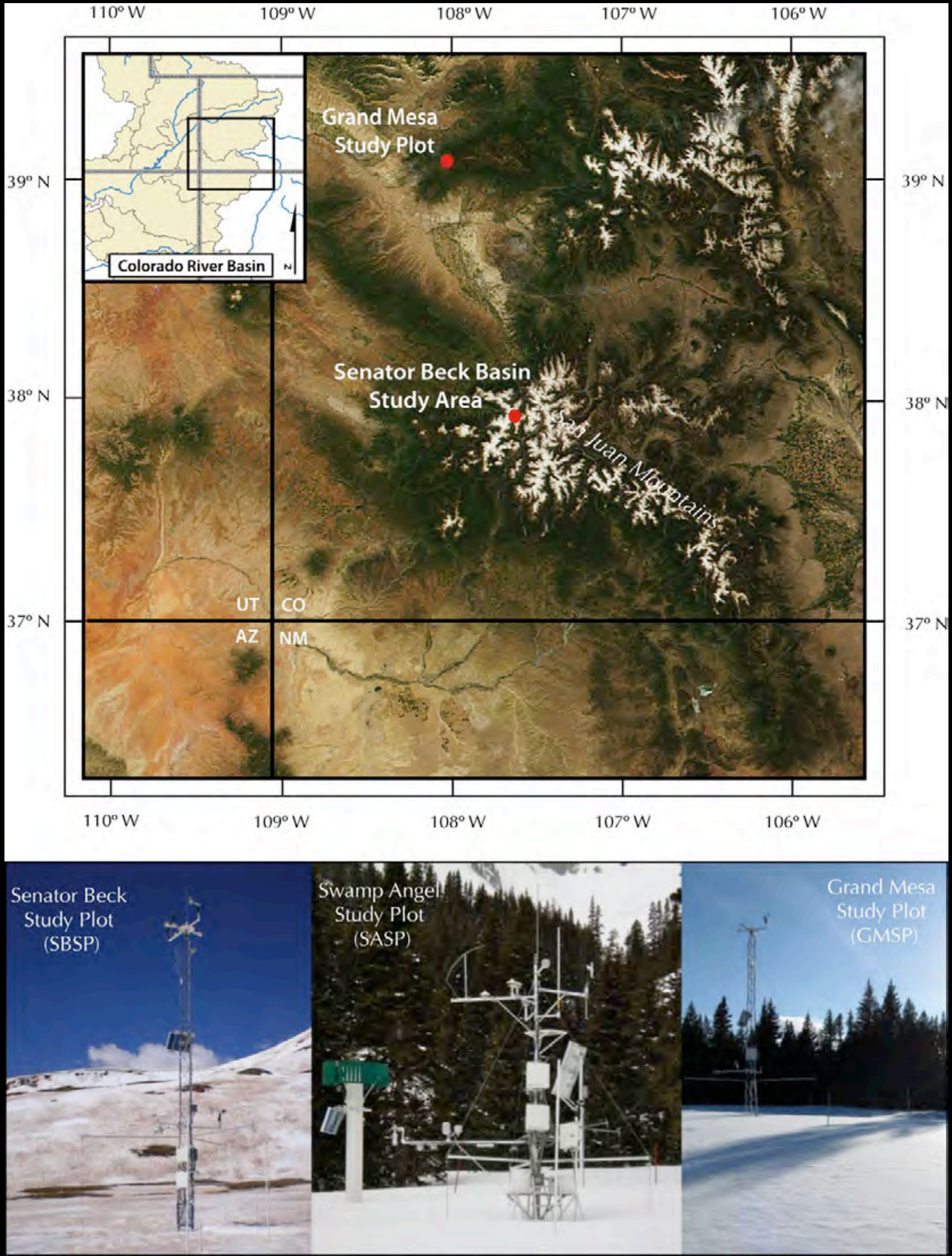
[illegible]



Forward
Nadir
Albedo
Algae
Dust
HDRF or Albedo
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.5
1.0
1.5
2.0
2.5
Wavelength (μm)

Growing EB and Radiation Network

At these, we find that dust radiative forcing accelerates melt by 27-51 days



What's Normal?

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]

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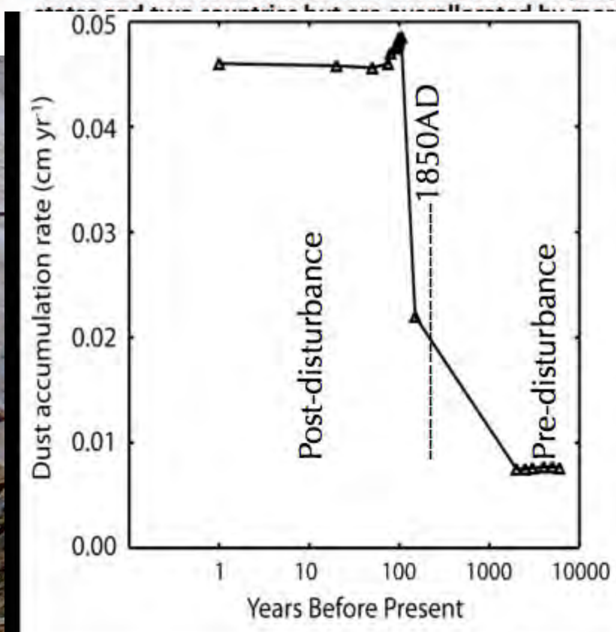
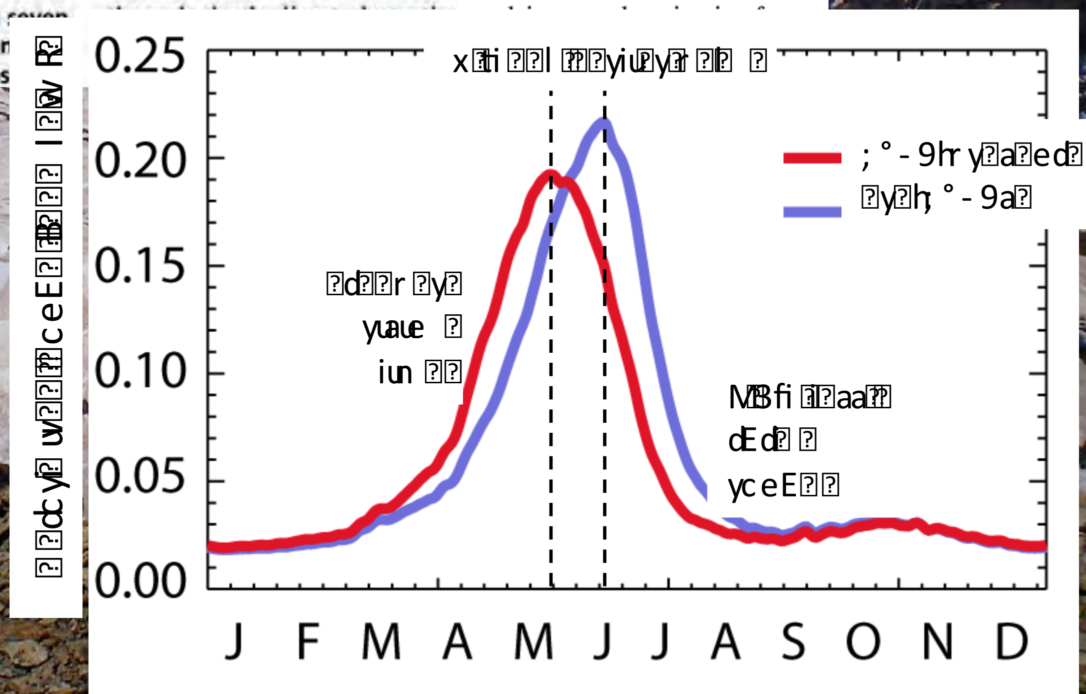
Edited by Peter H. Gleick, Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA, and approved August 3, 2010 (received for review November 12, 2009)

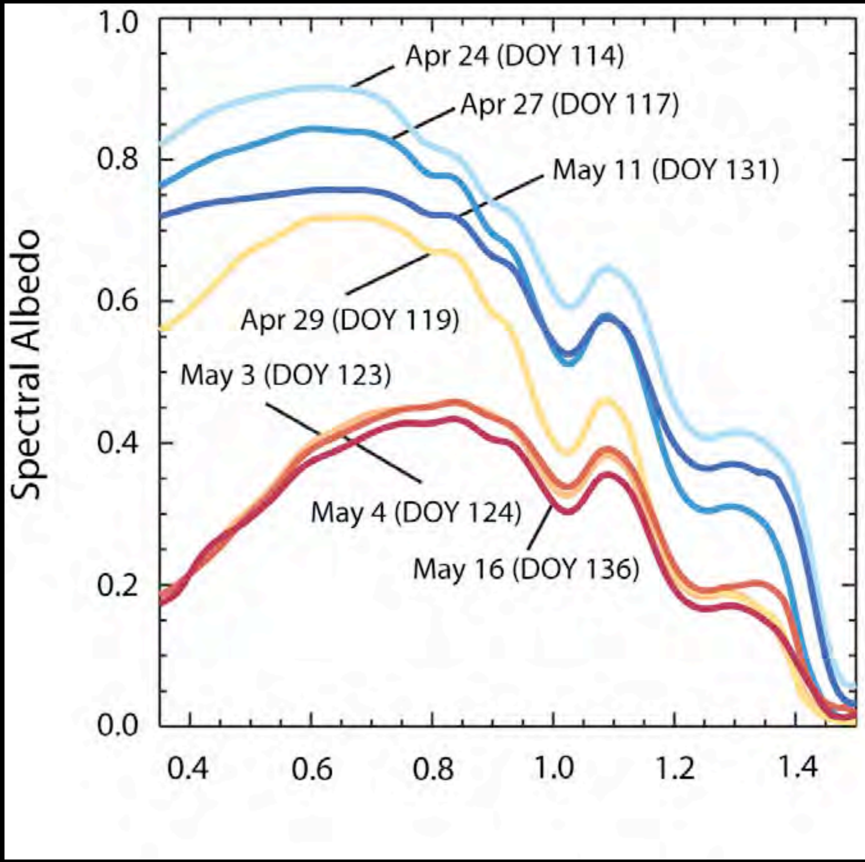
The waters of the Colorado River serve 27 million people in

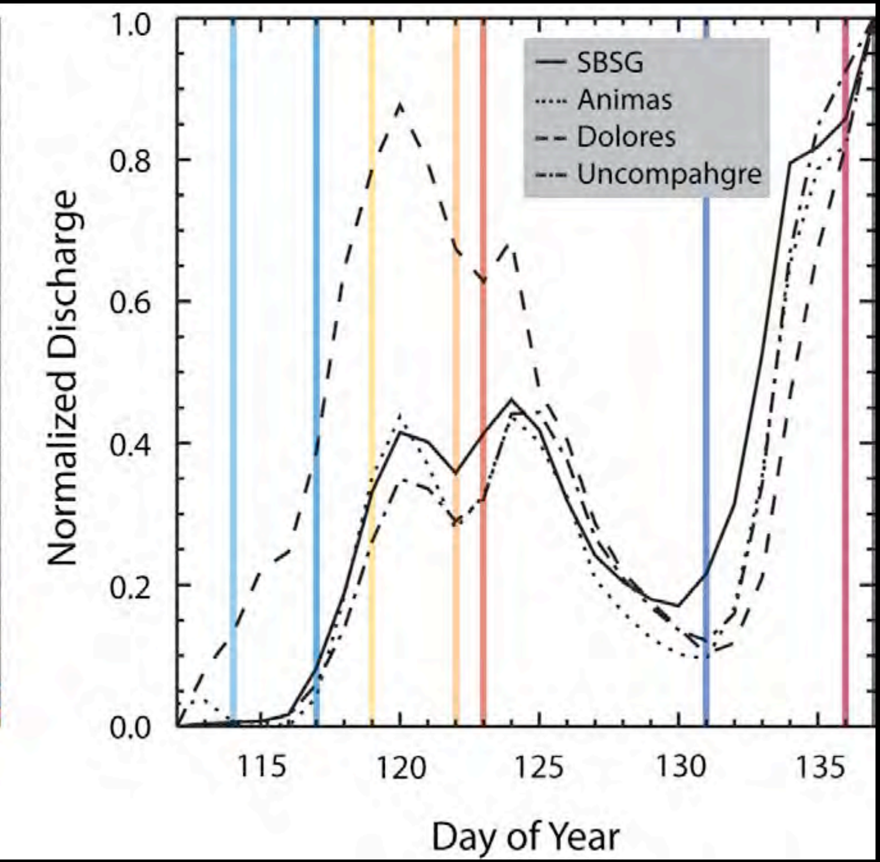


Neff et al 2008 Nature Geosciences

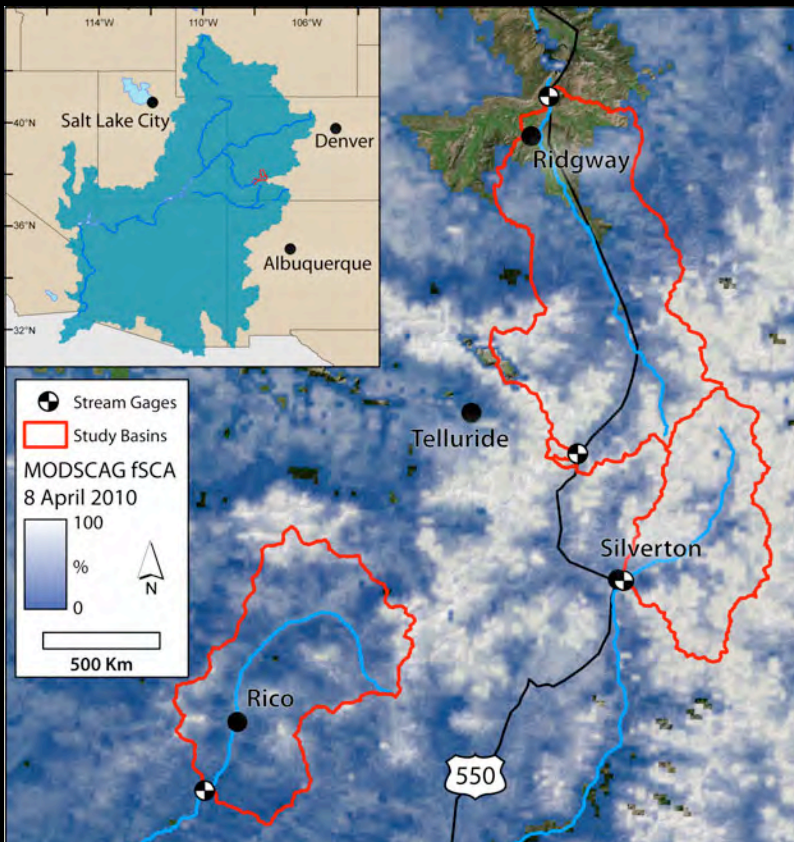


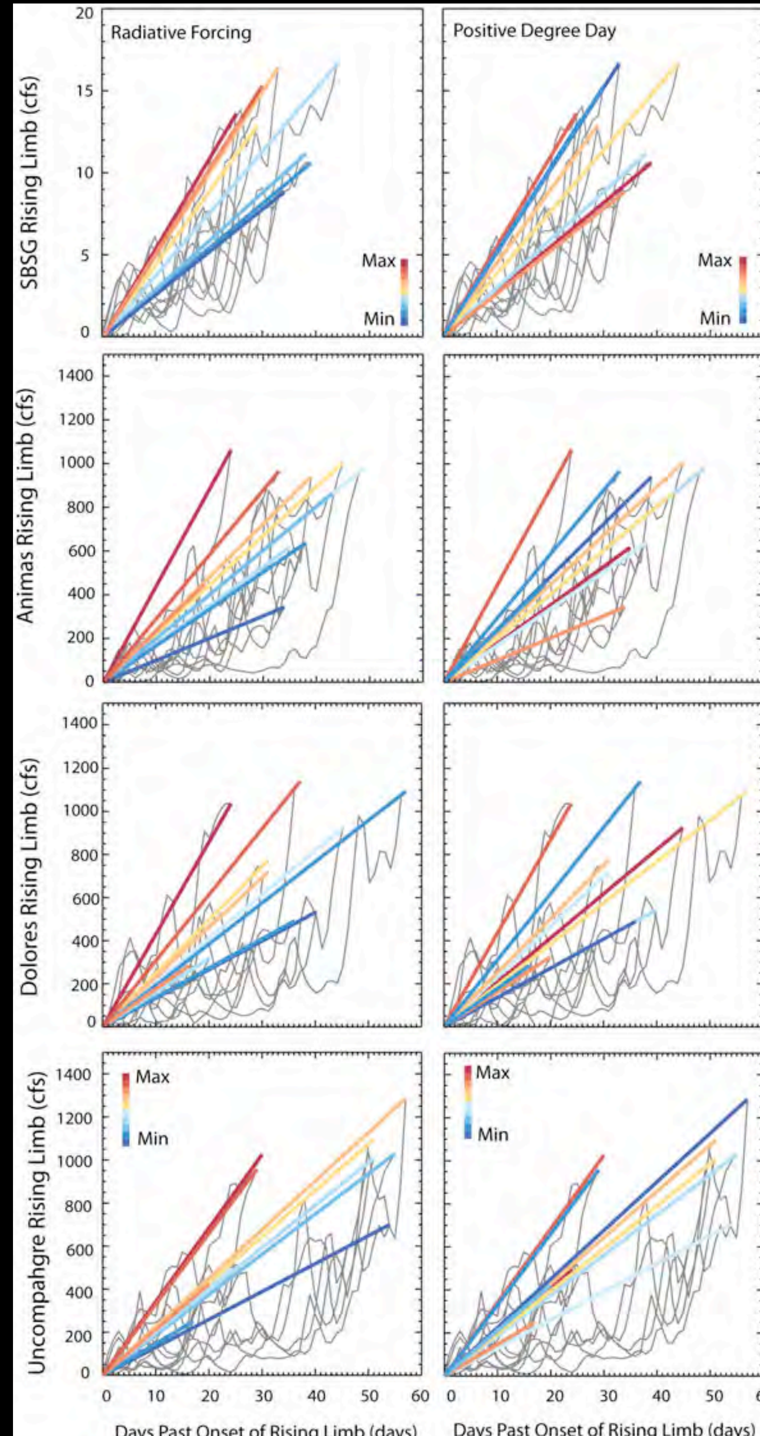
Hydrograph rising limb





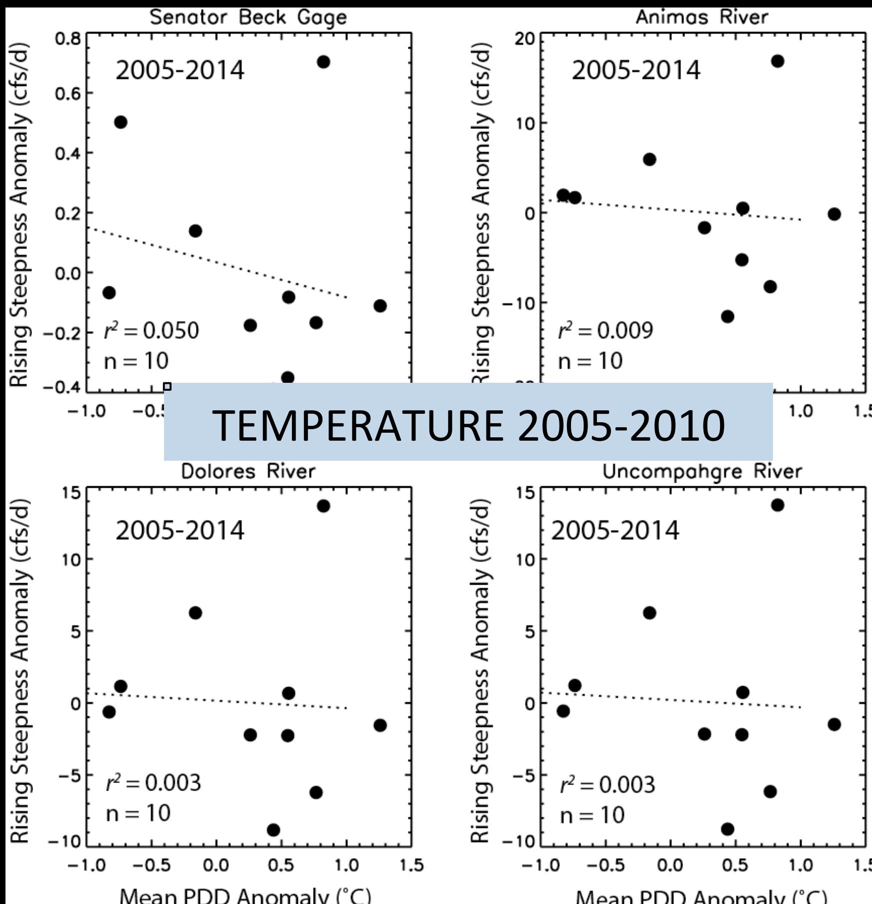
Rising Limb Steepness

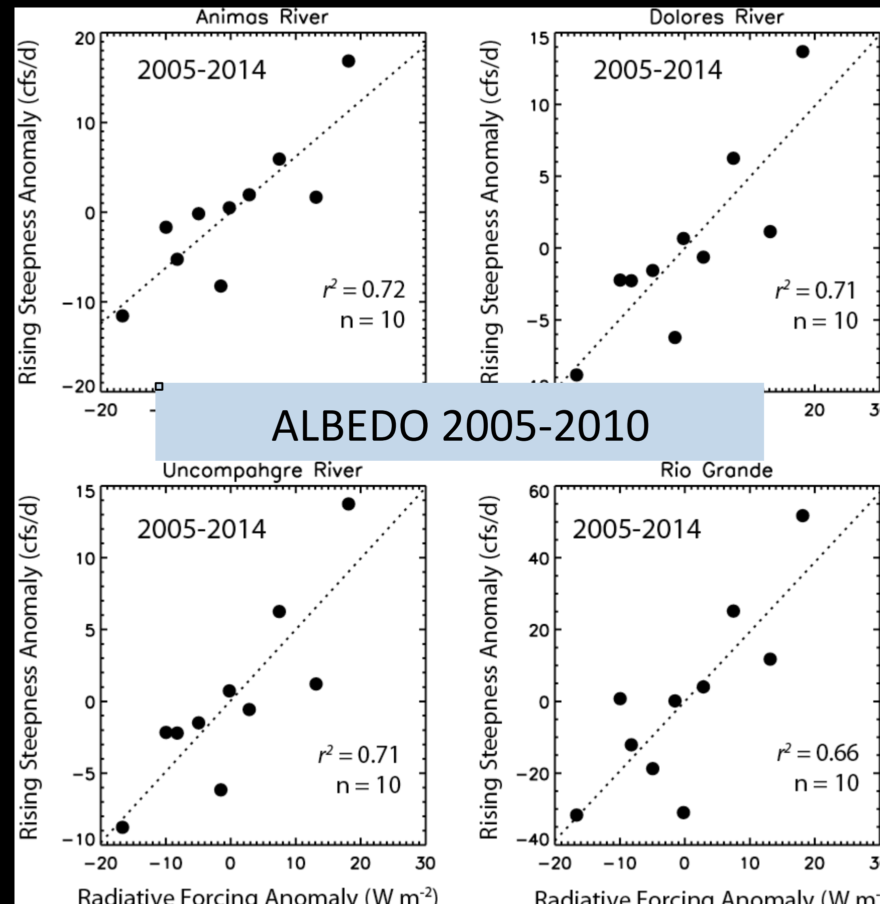




Painter et al in preparation

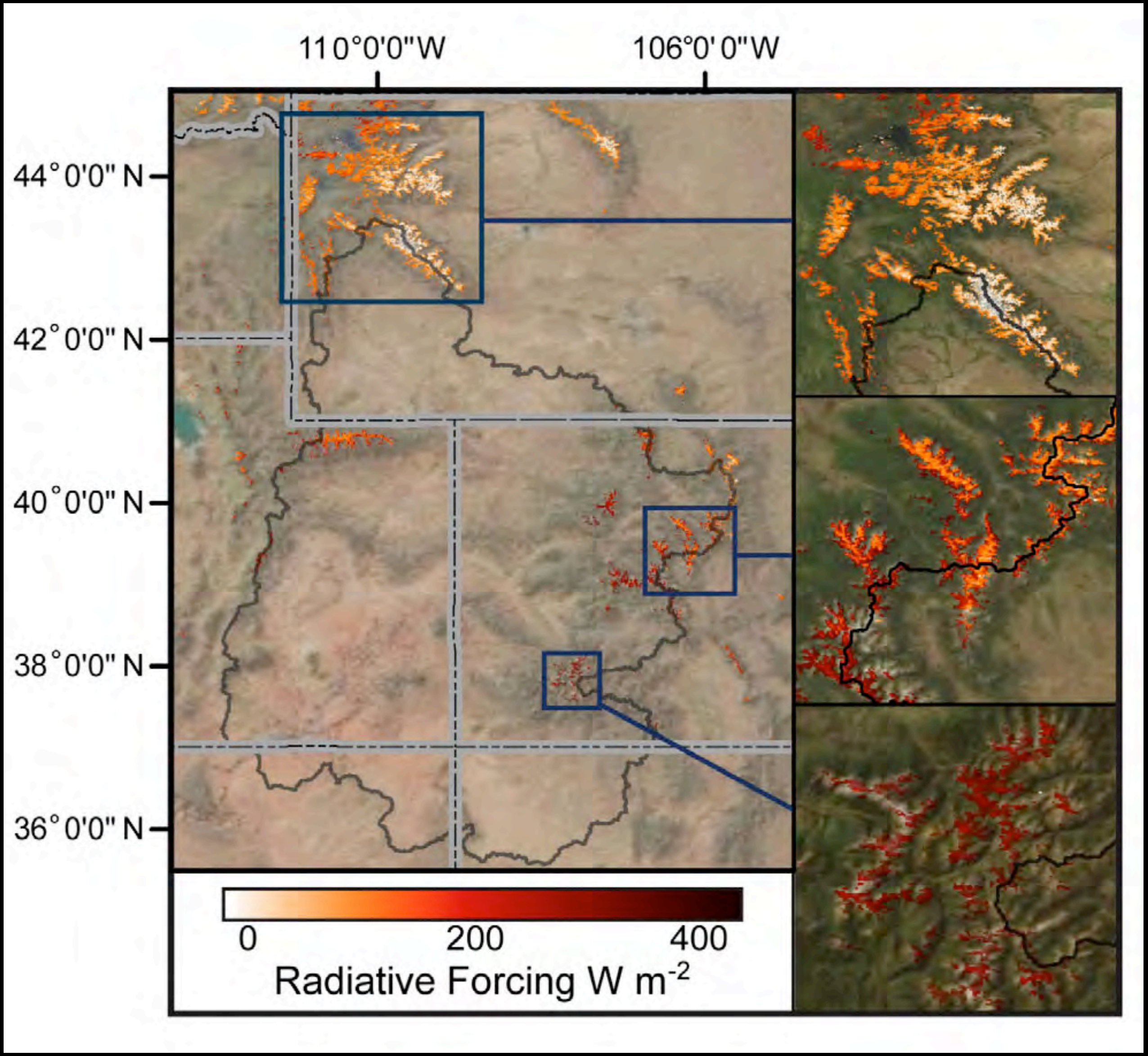
Steepness of rising limb



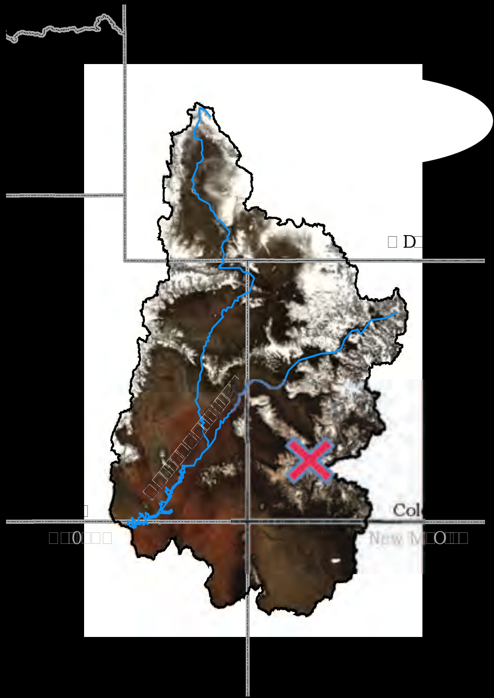


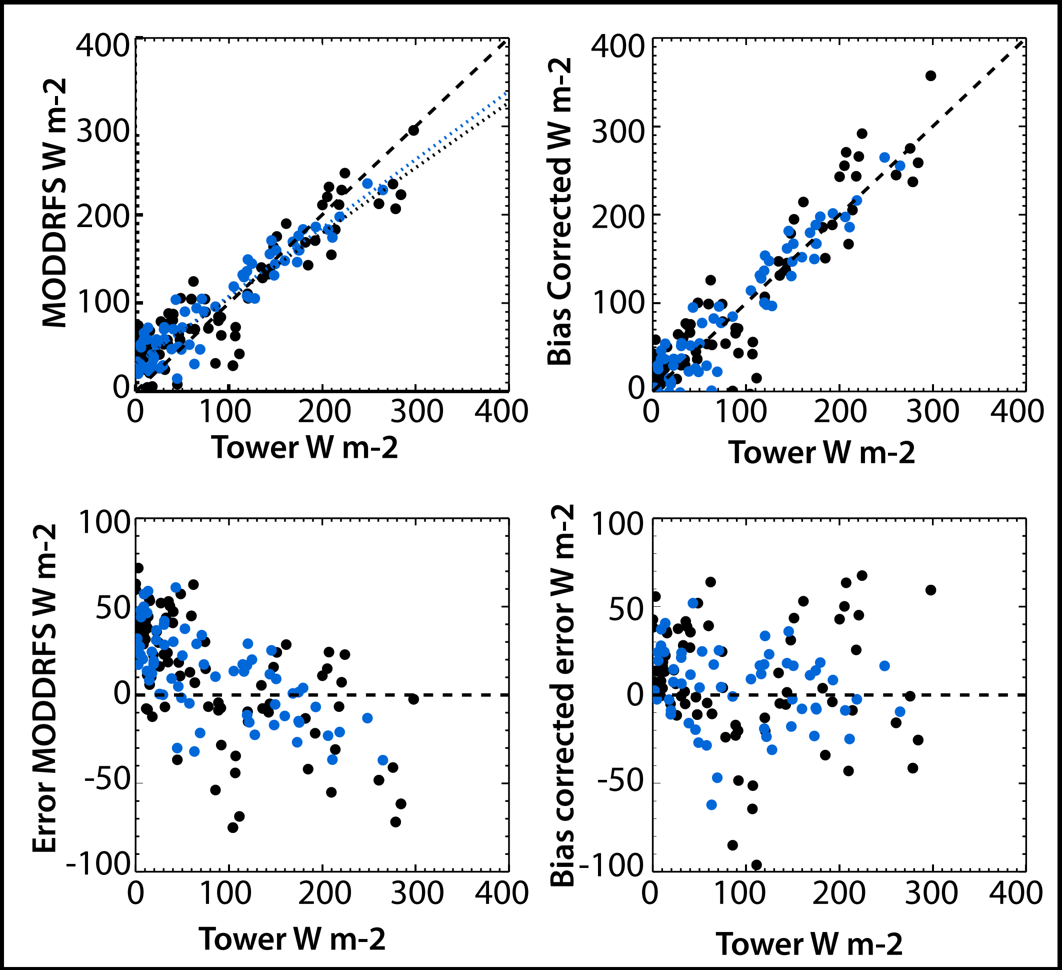
Painter et al (in preparation)

MODIS Dust Radiative Forcing in SNow



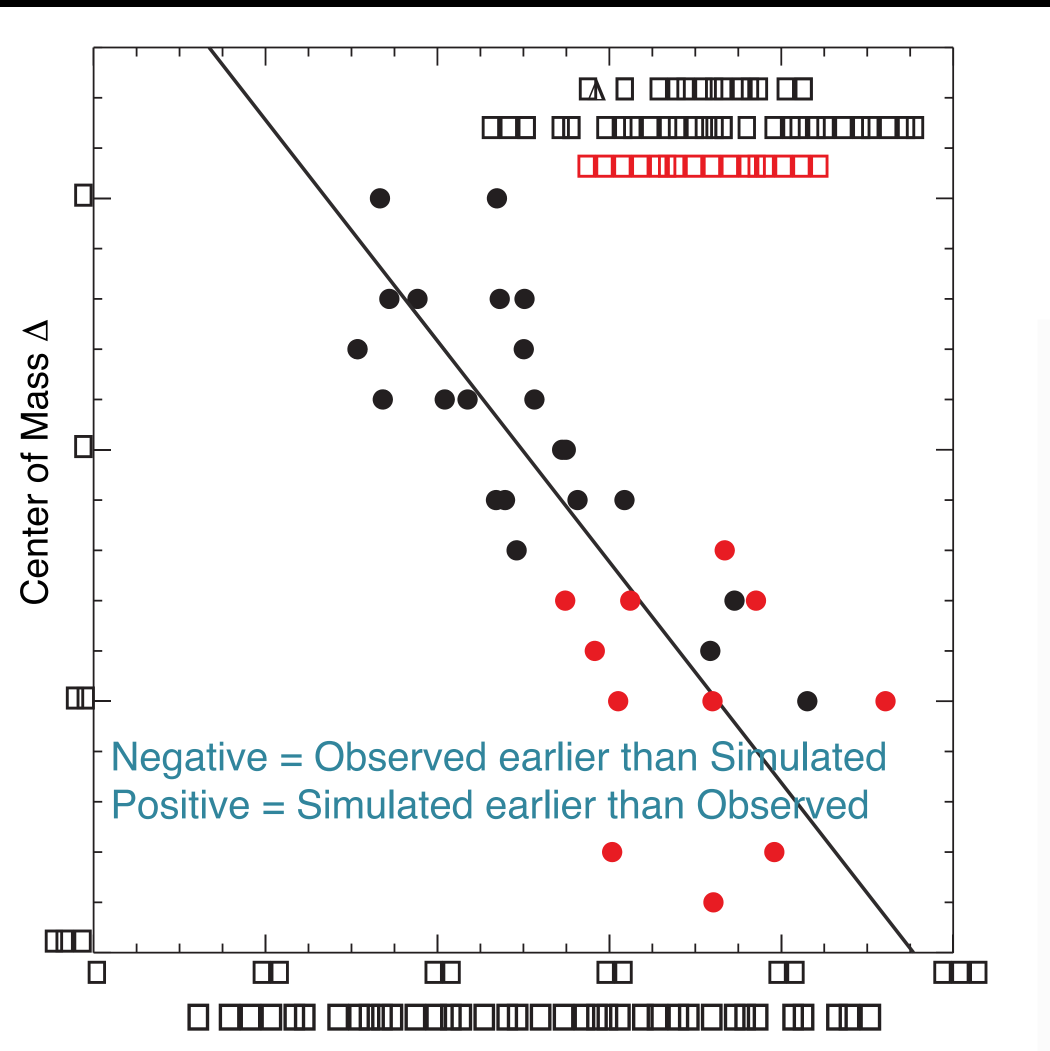
MODDRFS retrievals < 30° sensor zenith vs. energy-balance tower retrievals at time of MODIS overpass.



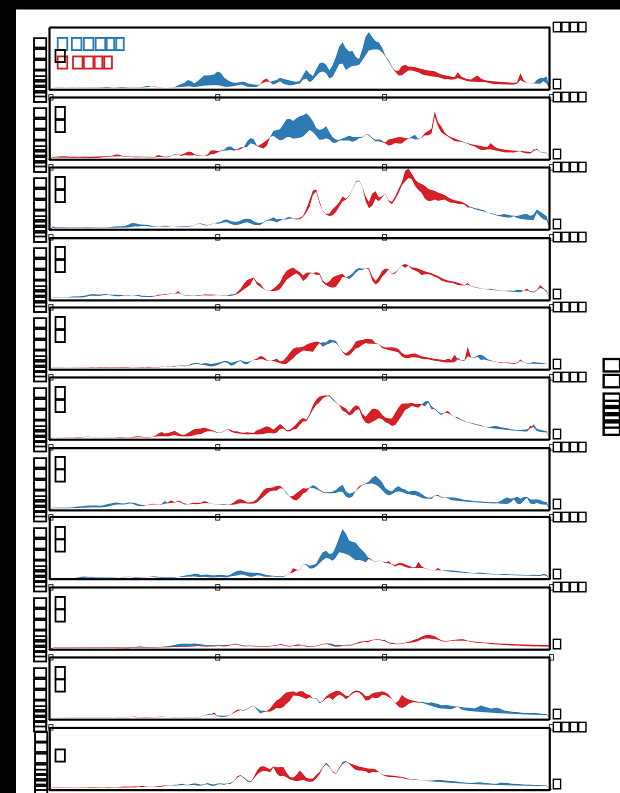


The regression yields coefficients:
$\beta_1 = 0.75 \pm 0.11$ and $\beta_0 = 31.2 \pm 14.4$
MAE = 28 W m-2, RMSE = 33 W m-2

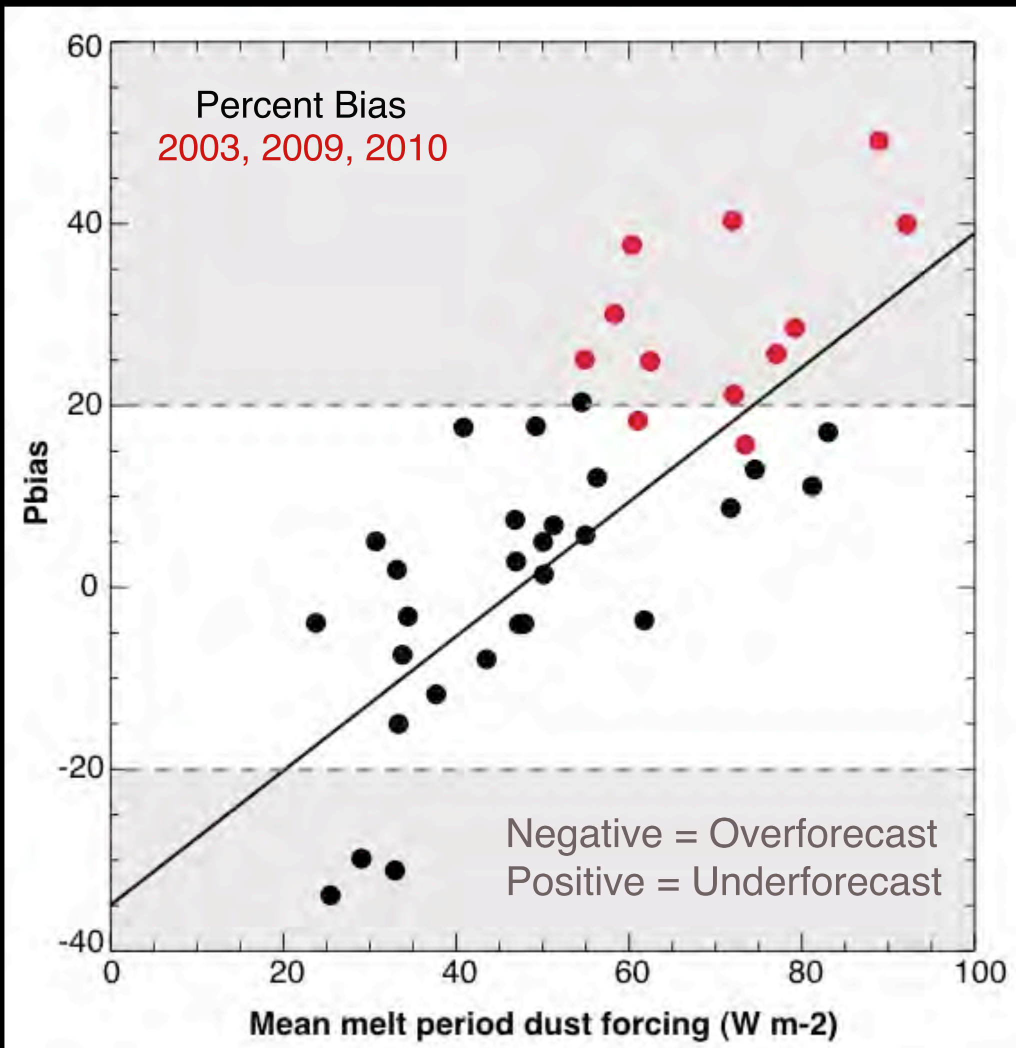
After Bias Correction:
MAE = 25 W m-2, RMSE = 32 W m-2



As dust forcing increases observed streamflow is earlier relative to simulated streamflow.

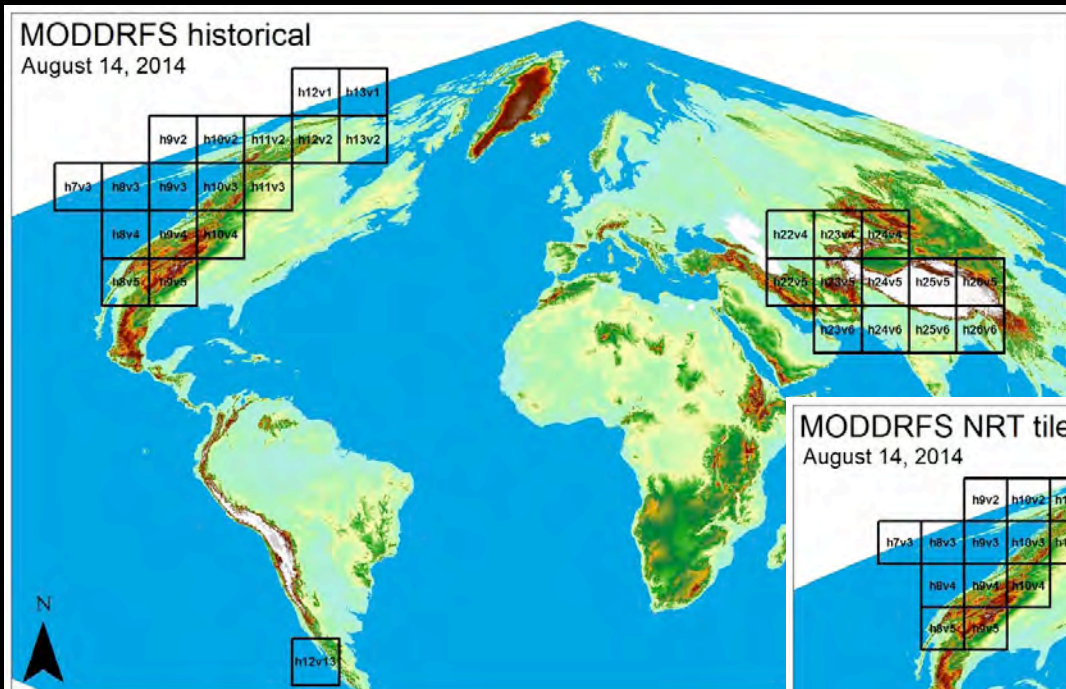


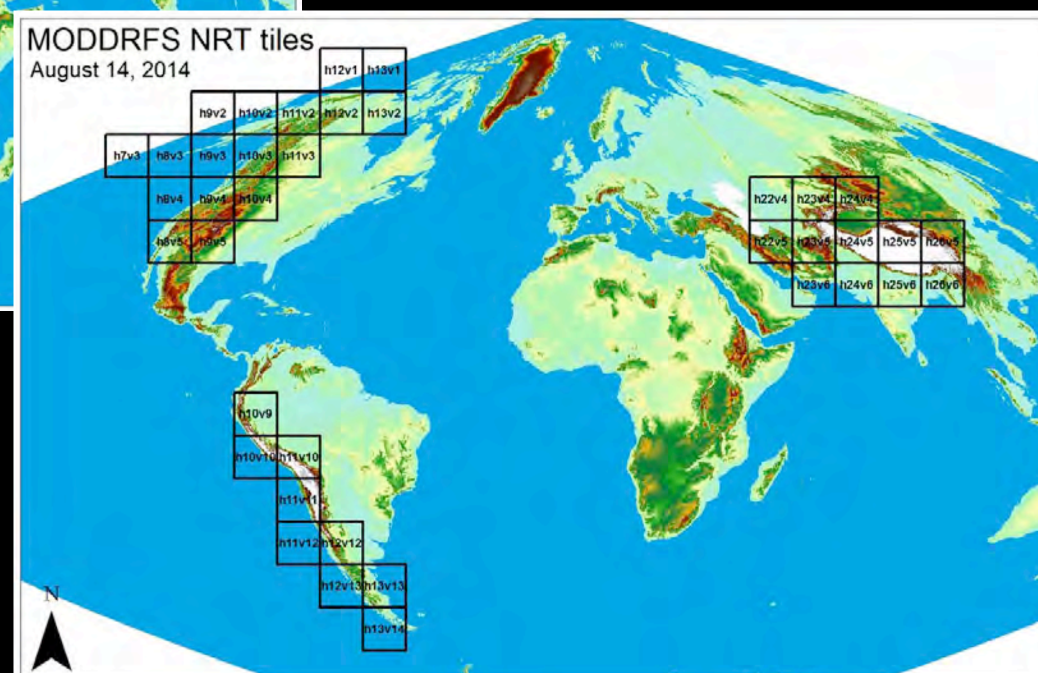
□□□□□□E y□□a d□yyE ya□



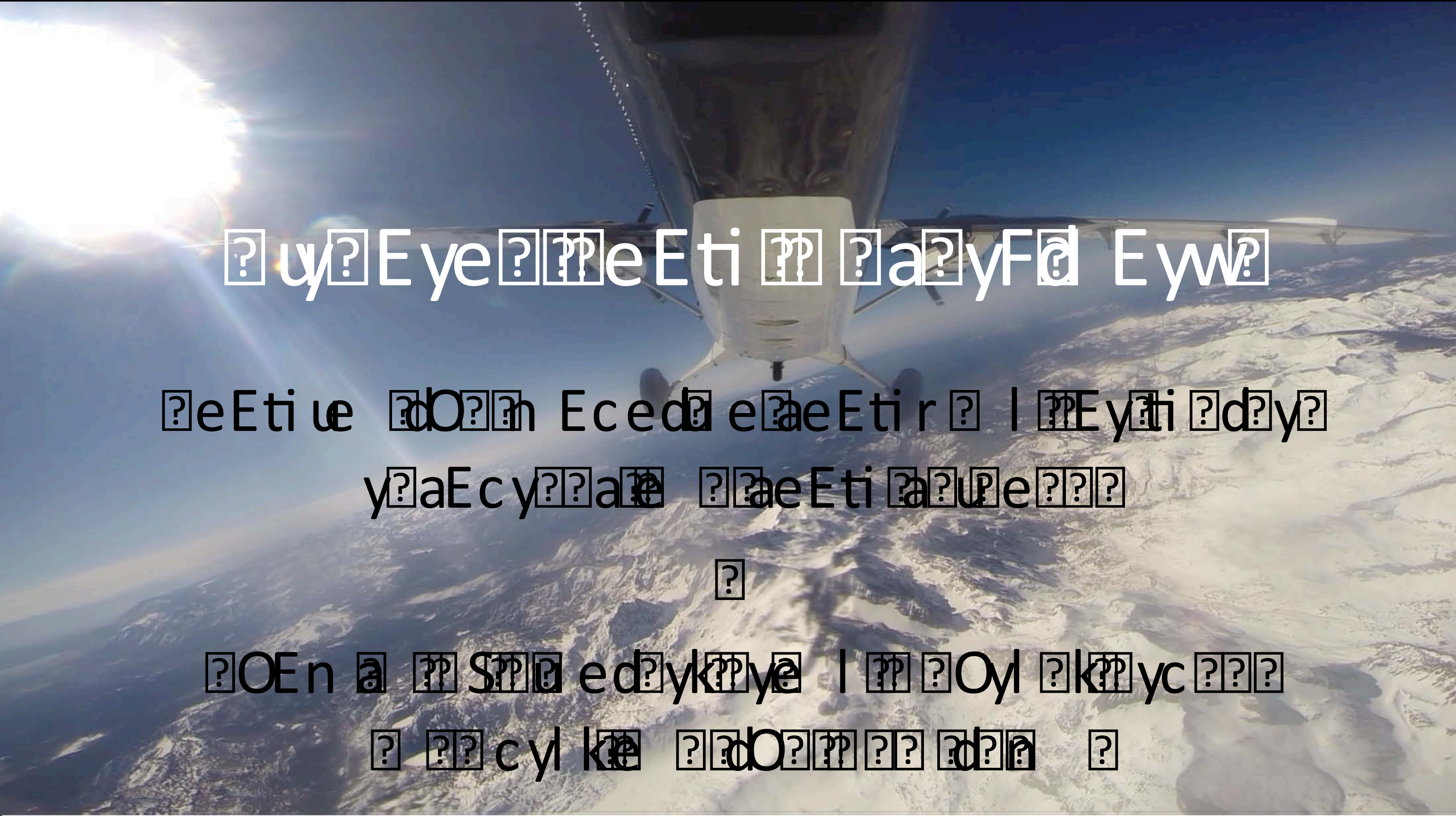
As dust forcing increases, so does the likelihood of underforecast.

MODDRFS





snow.jpl.nasa.gov



Jet Propulsion Laboratory
California Institute of Technology

Snow Surveys

Western Water Assessment

McGurk Hydrologic

NSIDC
National Snow and Ice Data Center

[illegible]

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

[illegible]

[illegible]


Knowing the magnitude and timing
of snowmelt runoff requires
knowing
SNOW WATER EQUIVALENT and
SNOW ALBEDO

The way we've measured snow in the West since 1910

The way we want to see it

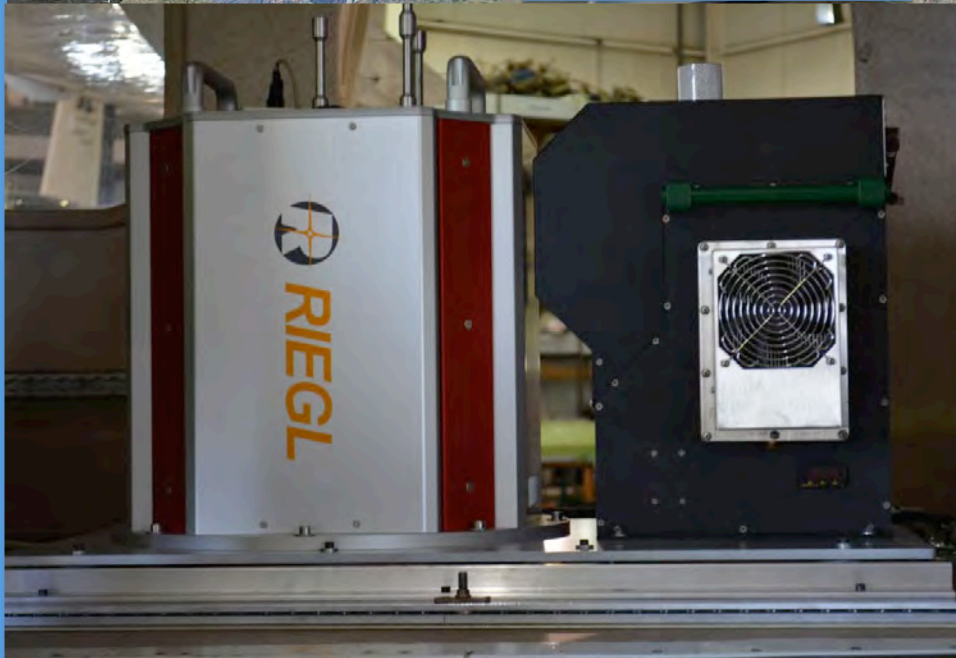
Albedo

CASI-1500 Imaging Spectrometer
0.35-1.05 □m
2 m spatial resolution from 4000 AGL

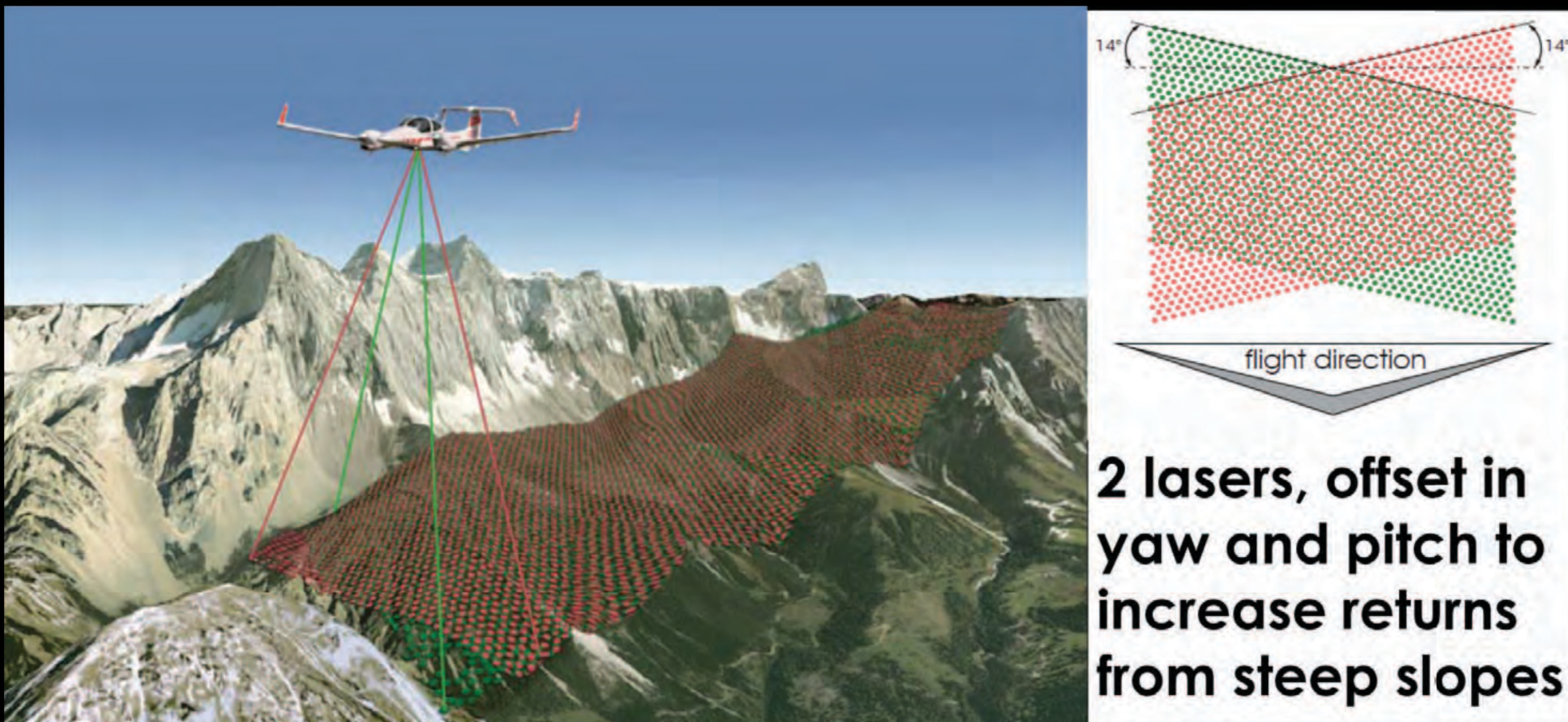
Snow Water Equivalent

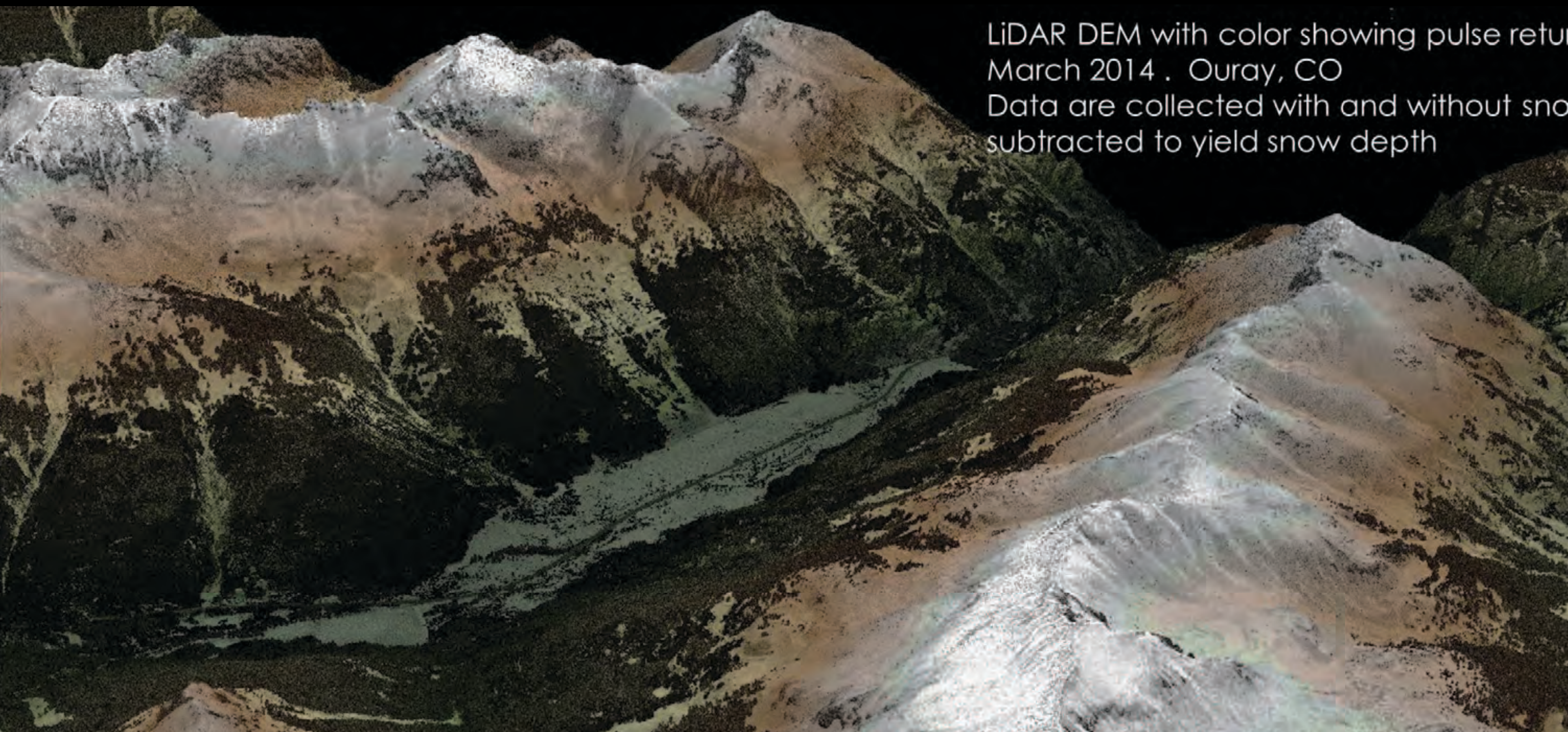
Riegl Q1560 3D Scanning lidar
1064 nm, canopy penetration
1 m spatial resolution

- Retrieve topography snow-free and snow-on
- Difference gives snow depth
- SWE comes from assimilation of modeled density field constrained by observations
- SWE variation primarily from depth



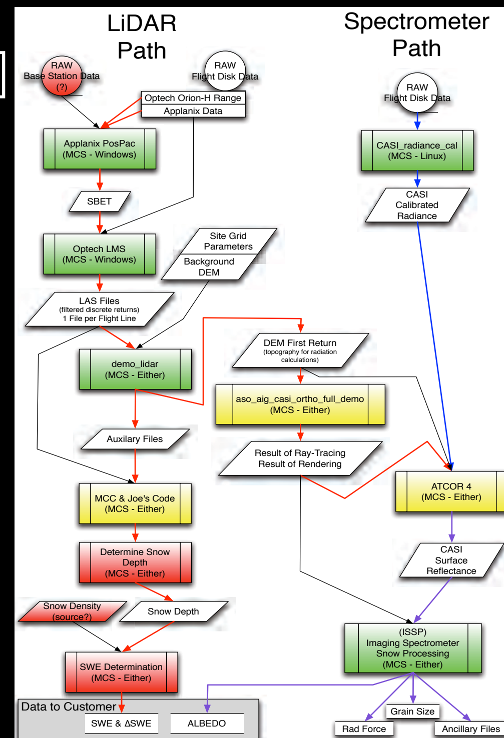

ASO
NASA AIRBORNE SNOW OBSERVATORY
Measuring Spatial Distribution of Snow Water Equivalent and Snow Albedo


14°
14°
flight direction
2 lasers, offset in yaw and pitch to increase returns from steep slopes

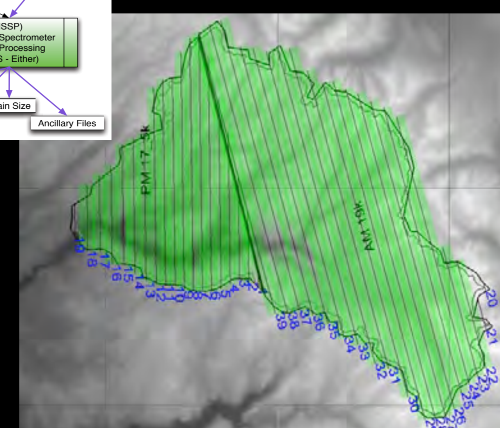

LiDAR DEM with color showing pulse retu
March 2014 . Ouray, CO
Data are collected with and without sno
subtracted to yield snow depth

[illegible]

- [illegible]
- [illegible]
- [illegible]



LiDAR Path
Spectrometer Path
RAW Base Station Data (?)
RAW Flight Disk Data
Optech Orion-H Range
Applanix Data
Applanix PosPac (MCS - Windows)
SBET
Optech LMS (MCS - Windows)
Site Grid Parameters
Background DEM
LAS Files (filtered discrete returns) 1 File per Flight Line
demo_lidar (MCS - Either)
Auxilary Files
MCC & Joe's Code (MCS - Either)
Determine Snow Depth (MCS - Either)
Snow Density (source?)
Snow Depth
SWE Determination (MCS - Either)
Data to Customer
SWE & ΔSWE
ALBEDO
RAW Flight Disk Data
CASI_radiance_cal (MCS - Linux)
CASI Calibrated Radiance
DEM First Return (topography for radiation calculations)
aso_aig_casi_ortho_full_demo (MCS - Either)
Result of Ray-Tracing Result of Rendering
ATCOR 4 (MCS - Either)
CASI Surface Reflectance
(ISSP) Imaging Spectrometer Snow Processing (MCS - Either)
Grain Size
Rad Force
Ancillary Files

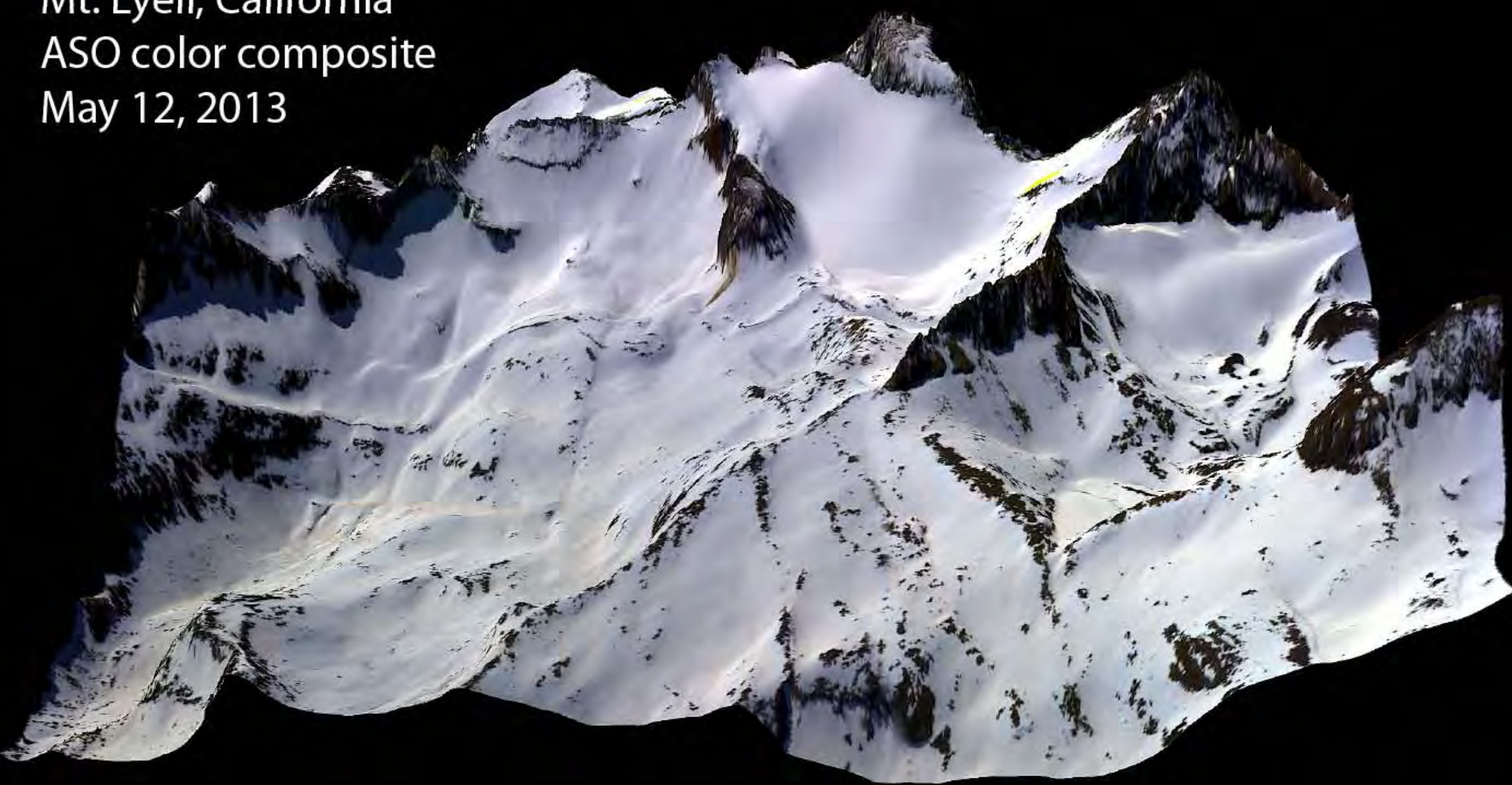


PM 17.5k
AM 19k

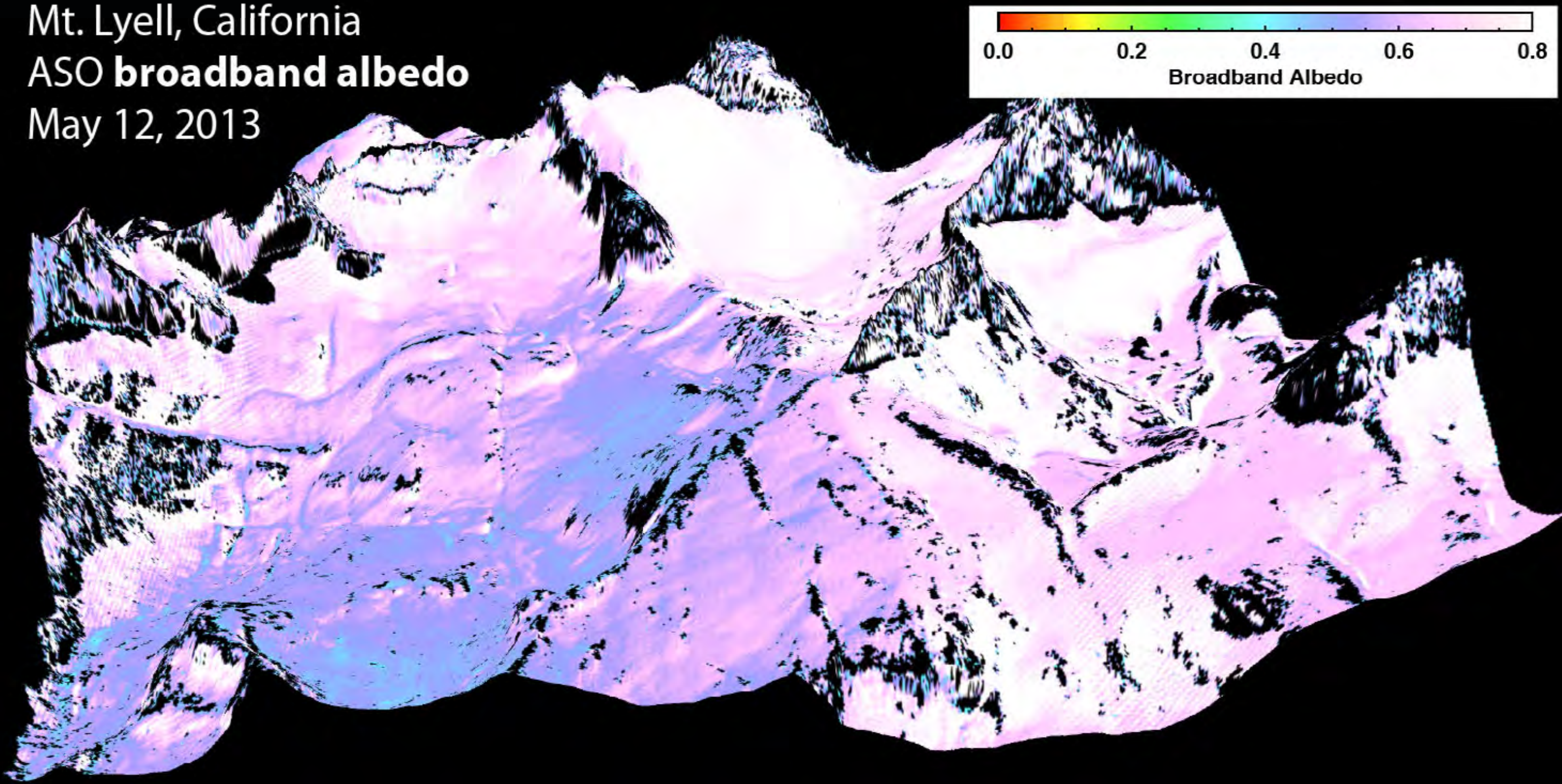
[illegible]

ASO

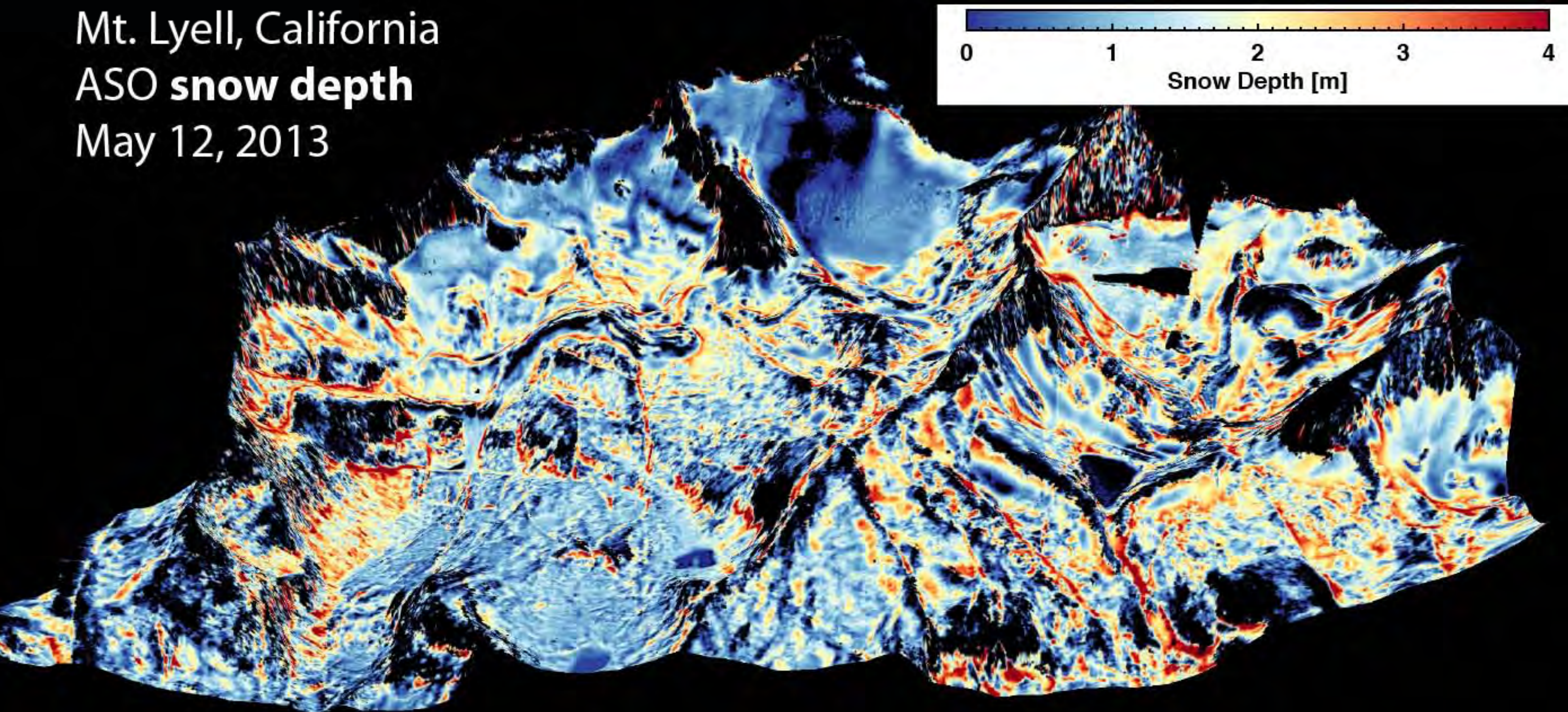
Mt. Lyell, California
ASO color composite
May 12, 2013



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



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



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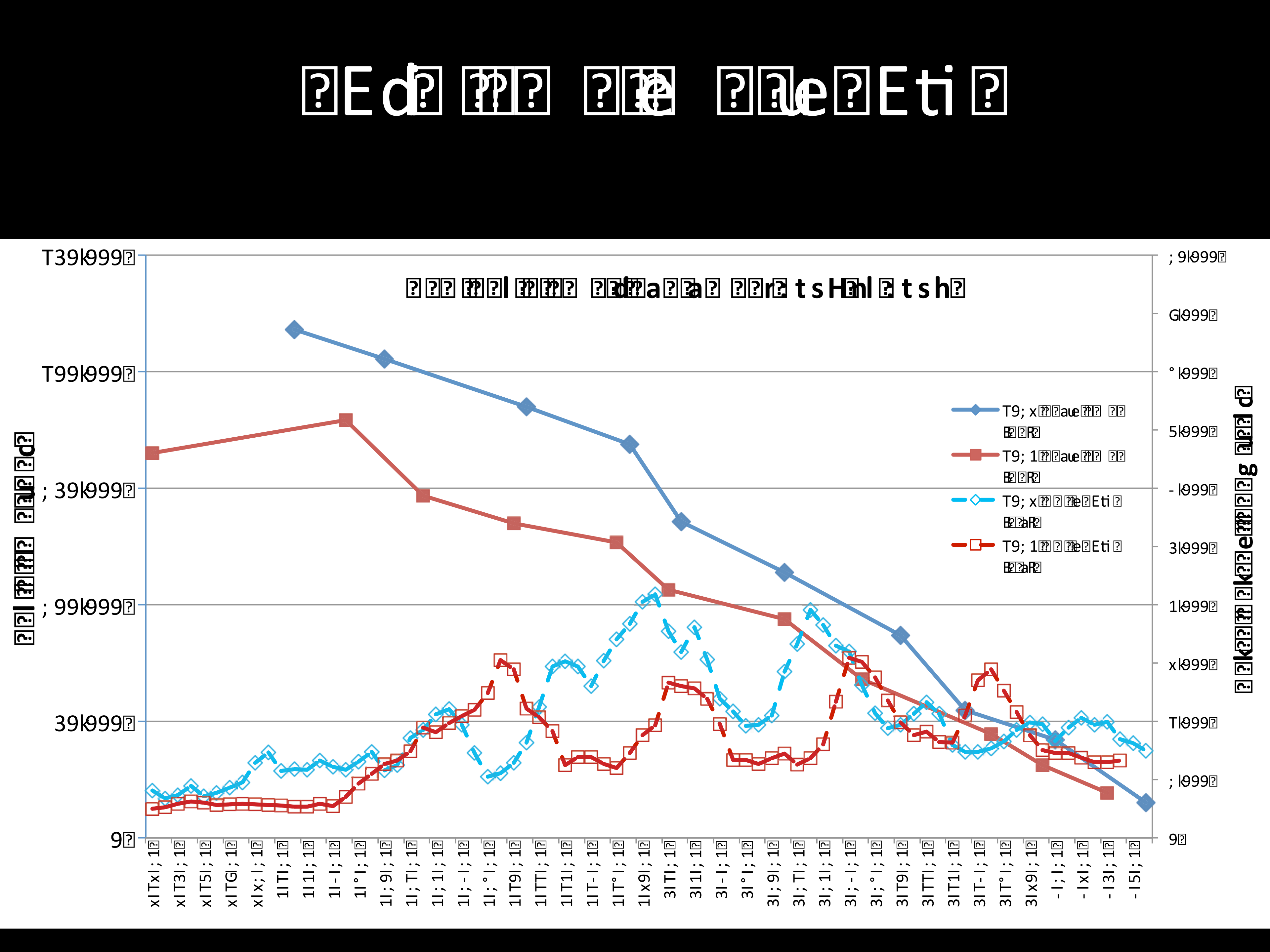
c E ic n e u F y a ue

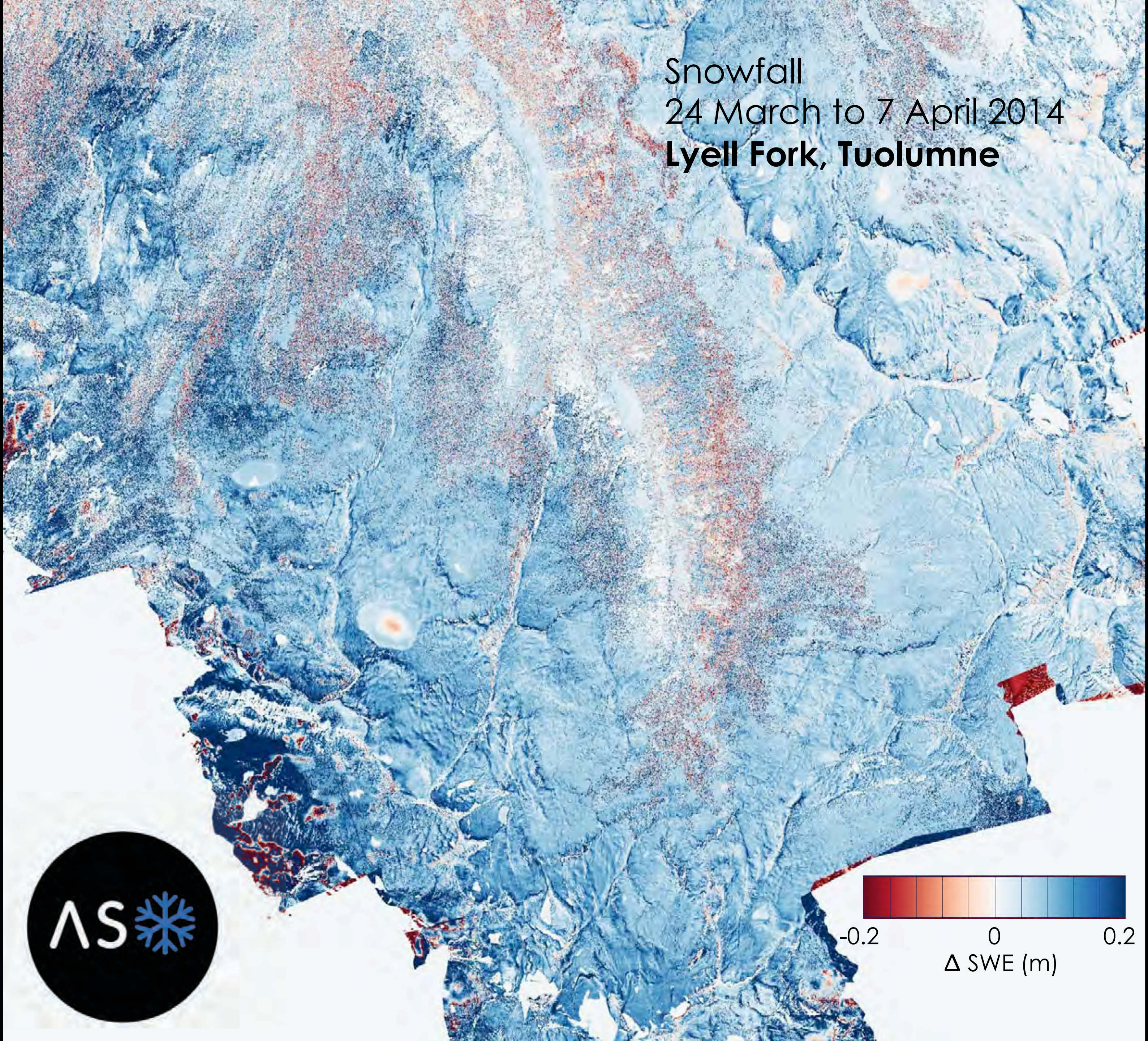
AIRBORNE SNOW OBSERVATORY

Snow Water Equivalent
2014

AIRBORNE SNOW OBSERVATORY

Snow Albedo
2014




Snowfall
24 March to 7 April 2014
Lyell Fork, Tuolumne
-0.2
0
0.2
Δ SWE (m)
ΛS

In California, Reading the Snow to Tell the Future for the Water Supply

NO!

Ground measurements are critical.

Max Whittaker / ew York Times

Frank Gehrke, cen has led snowpack surveys in California for a quarter-centu . The state's multib llar agricultural industry p close attention.

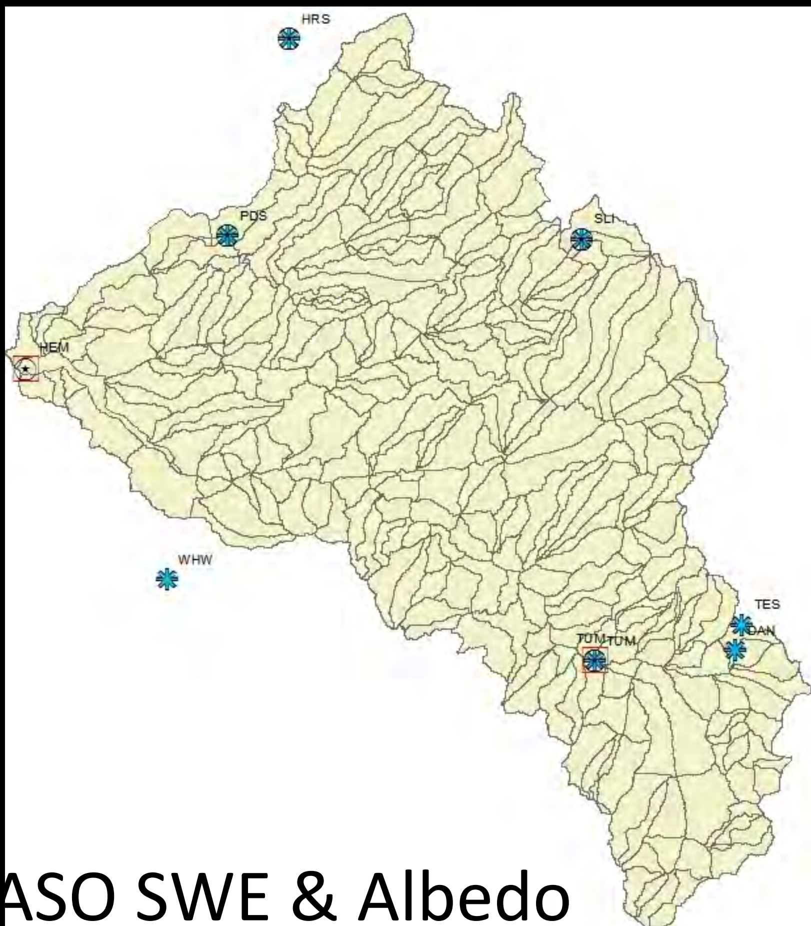
By NORIMITSU ONISHI
Published: February 7, 2013

PHILLIPS, Calif. — Along Highway 50 in the Sierra Nevada,

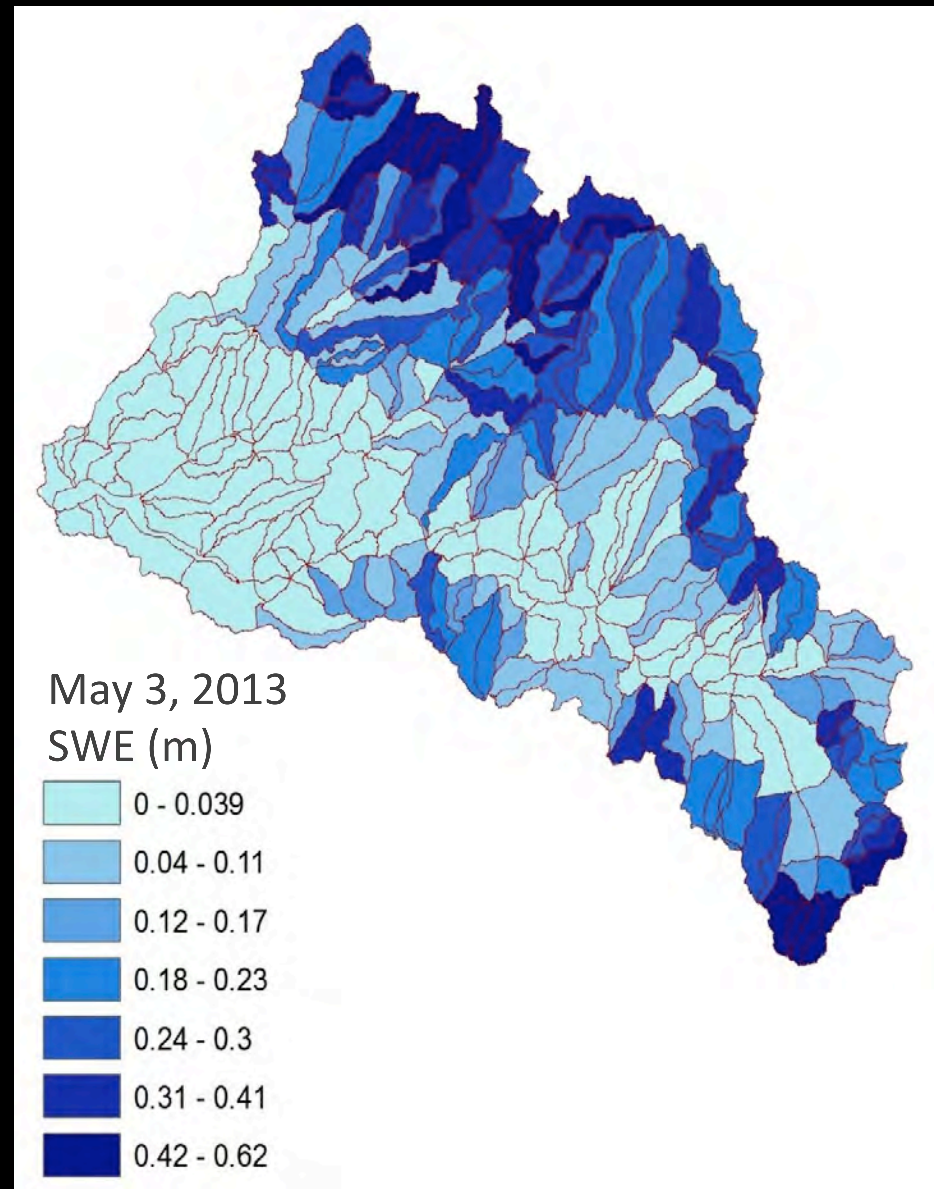
FACEBOOK

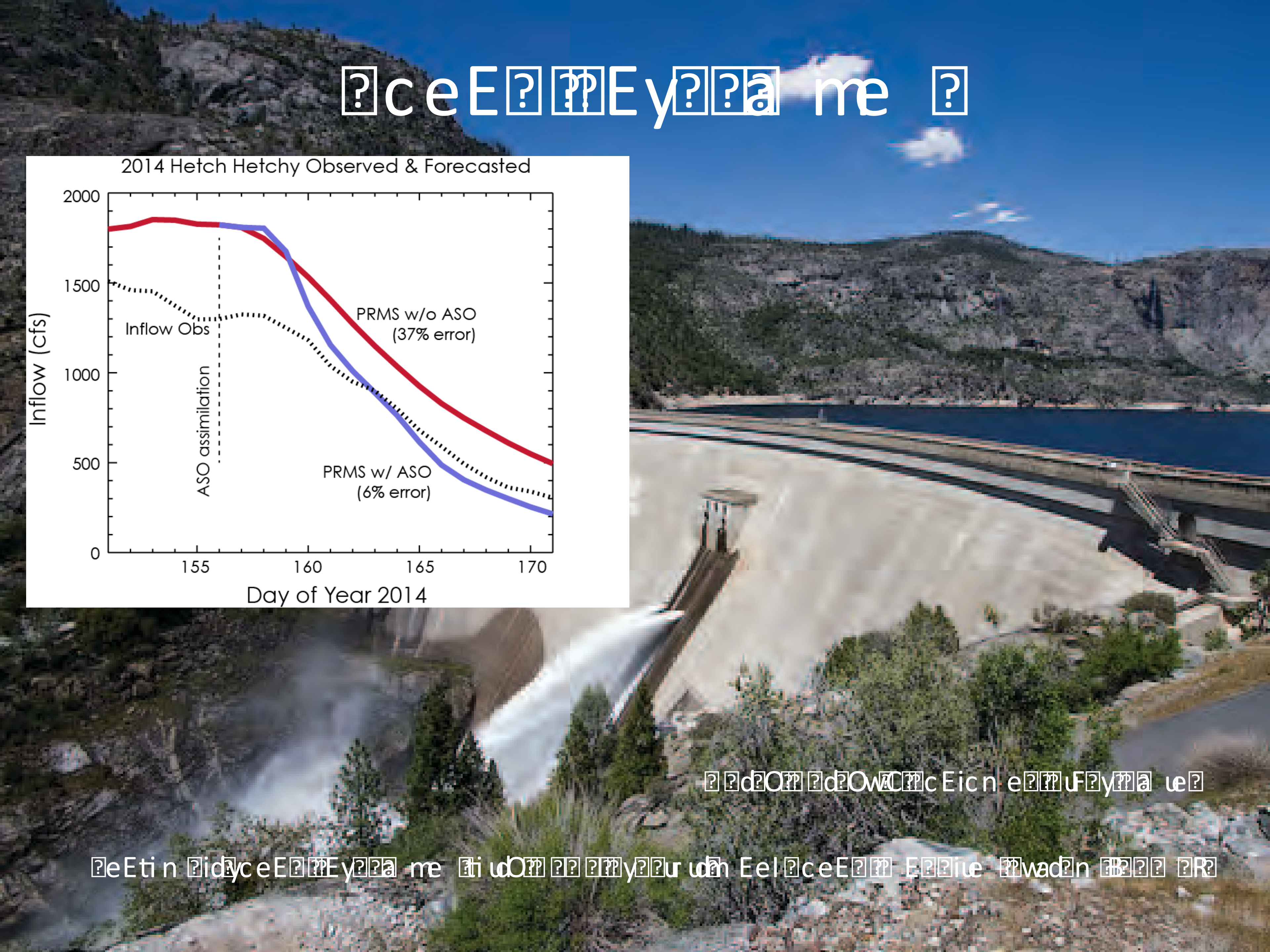
Tuolumne Basin above Hetch Hetchy Reservoir

SWE/Met Stations & PRMS Model Units



ASO SWE & Albedo

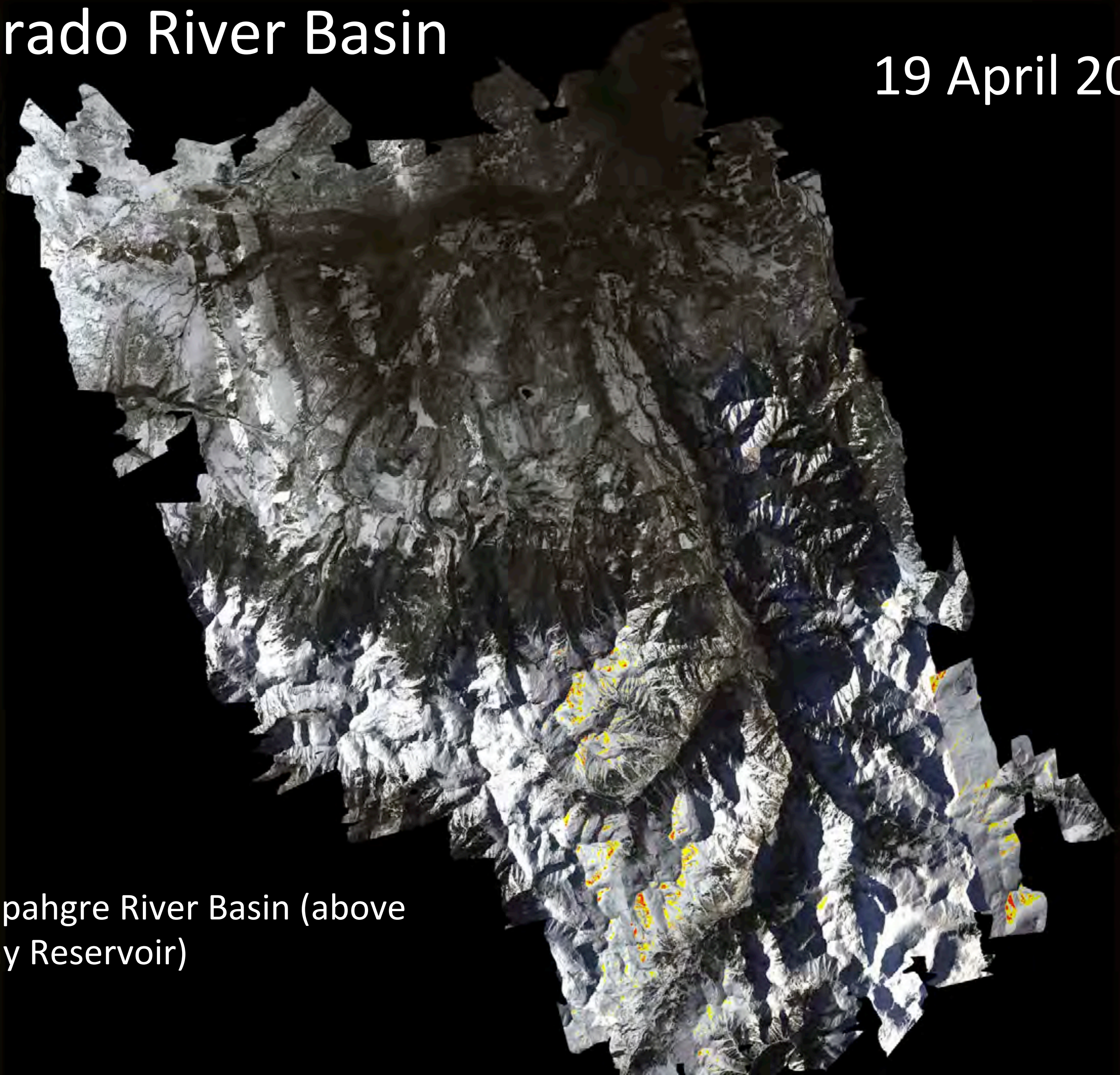




2014 Hetch Hetchy Observed & Forecasted
Inflow (cfs)
Day of Year 2014
2000
1500
1000
500
0
155
160
165
170
Inflow Obs
ASO assimilation
PRMS w/o ASO
(37% error)
PRMS w/ ASO
(6% error)

Colorado River Basin

19 April 2013



Uncompahgre River Basin (above Ridgway Reservoir)

Colorado River Basin

17 May 2013

Uncompahgre River Basin (above Ridgway Reservoir)

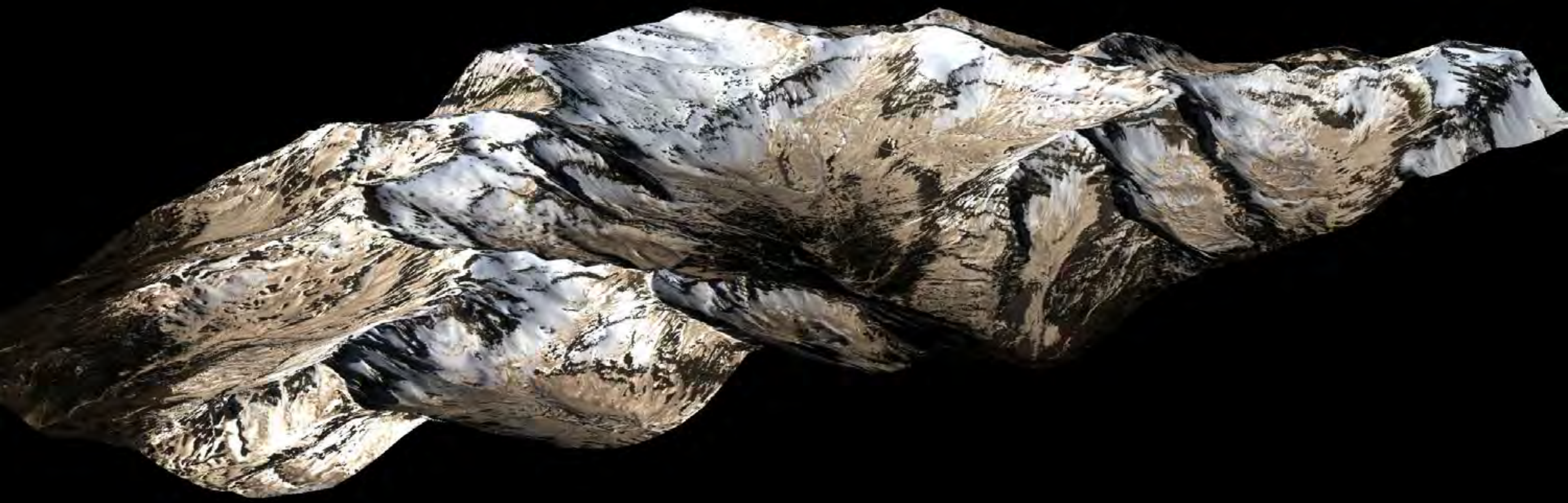
Colorado River Basin

17 May 2013

Uncompahgre River Basin (above Ridgway Reservoir)

Colorado River Basin

17 May 2013



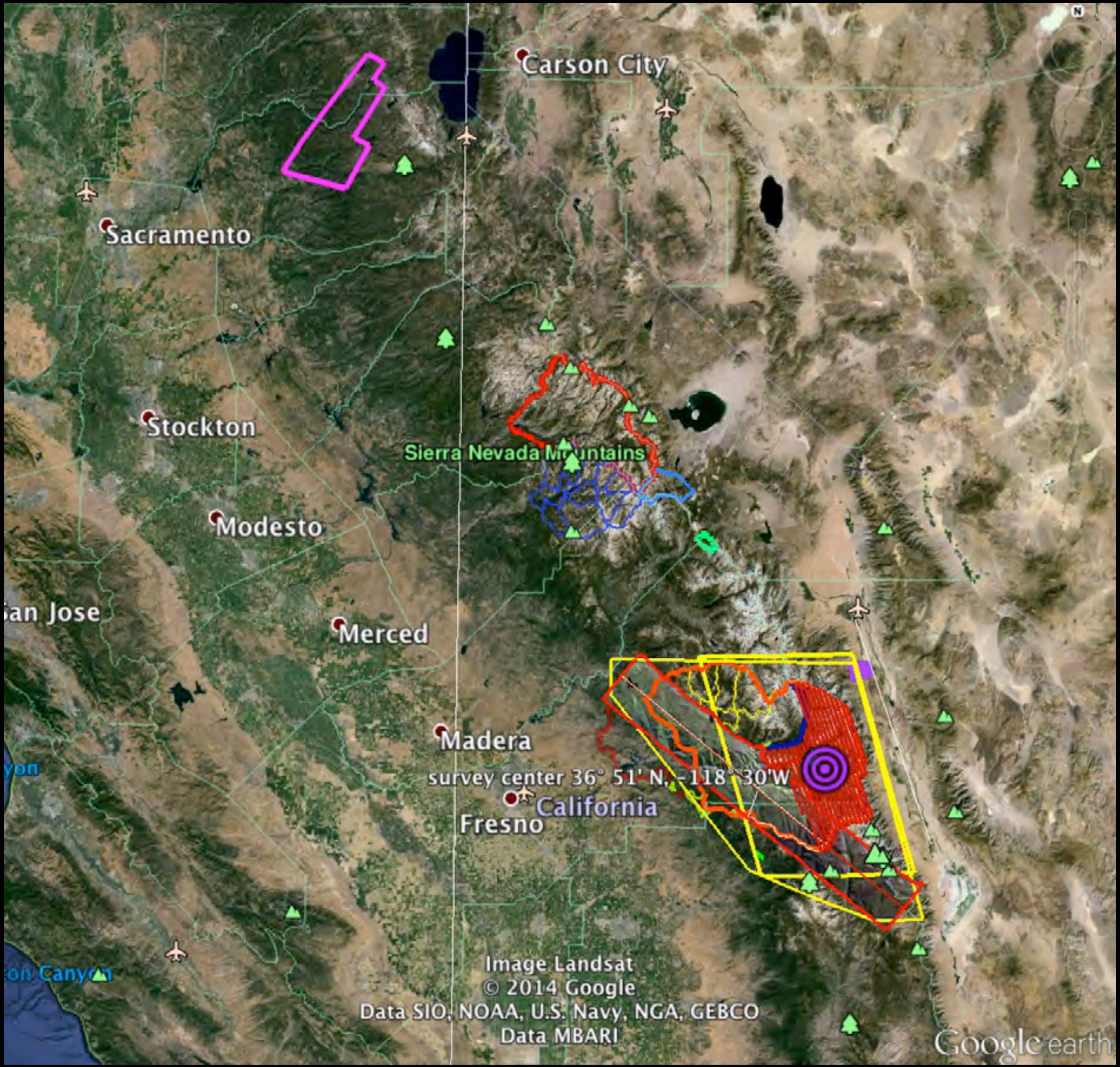
Uncompahgre River Basin (above Ridgway Reservoir)

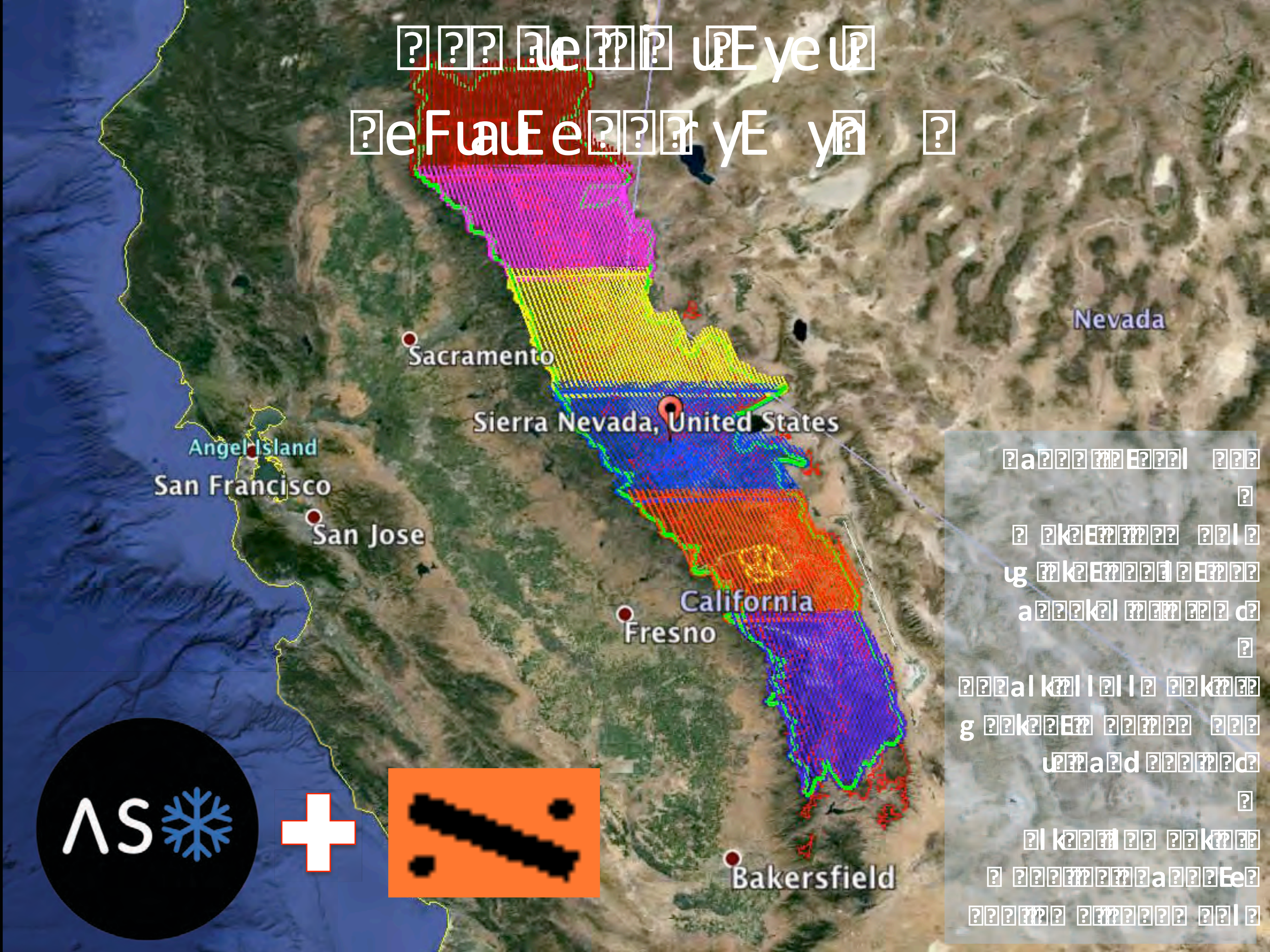
Colorado River Basin

17 May 2013

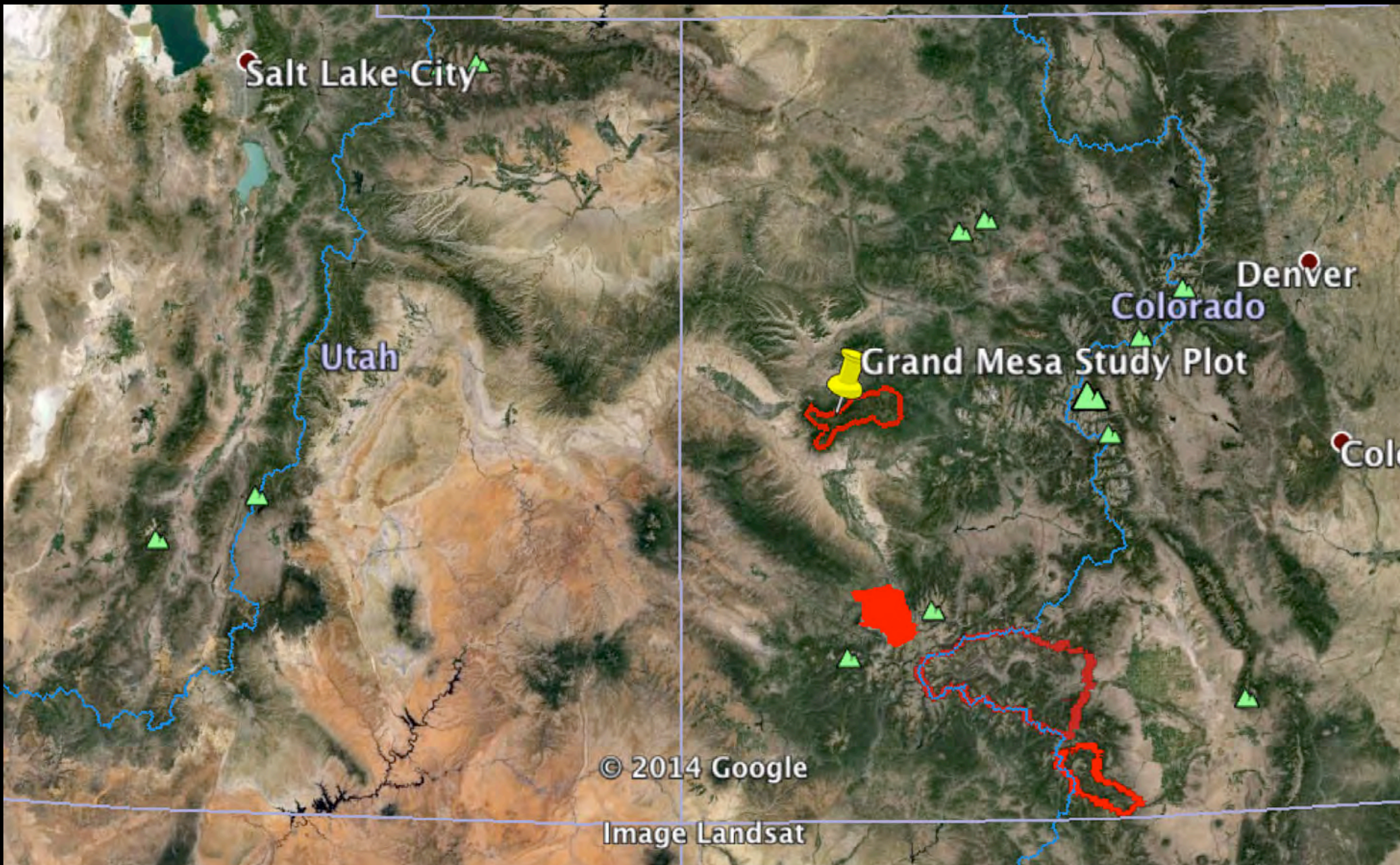
Uncompahgre River Basin (above
Ridgway Reservoir)

ASO in California
Present + Near Future



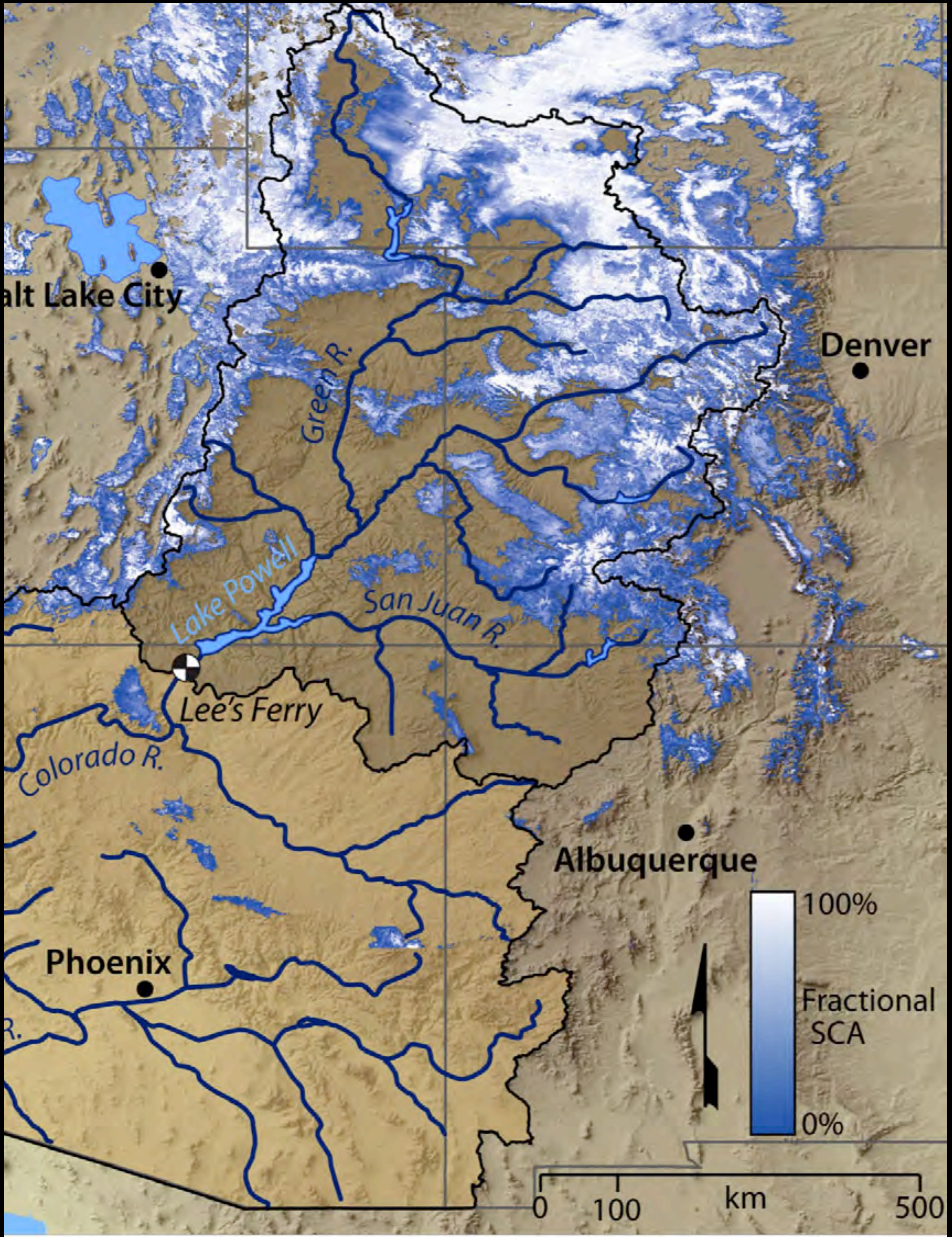

Nevada
Sacramento
Sierra Nevada, United States
Angel Island
San Francisco
San Jose
California
Fresno
Bakersfield

ASO in Colorado River Basin
Present + Near Future



ASO in Colorado River Basin
Present + Near Future

ASO in Colorado: Envisioned program



Integration of precision NASA snow products with the operations of the Colorado Basin River Forecast Center to improve decision making under drought conditions

PI Painter (JPL), Bender (CBRFC), Andreadis (JPL), Oaida (UCLA), Deems (CU)

Highlight: During 2013-2014, CBRFC and JPL built upon initial progress made during the first two years of the project by:

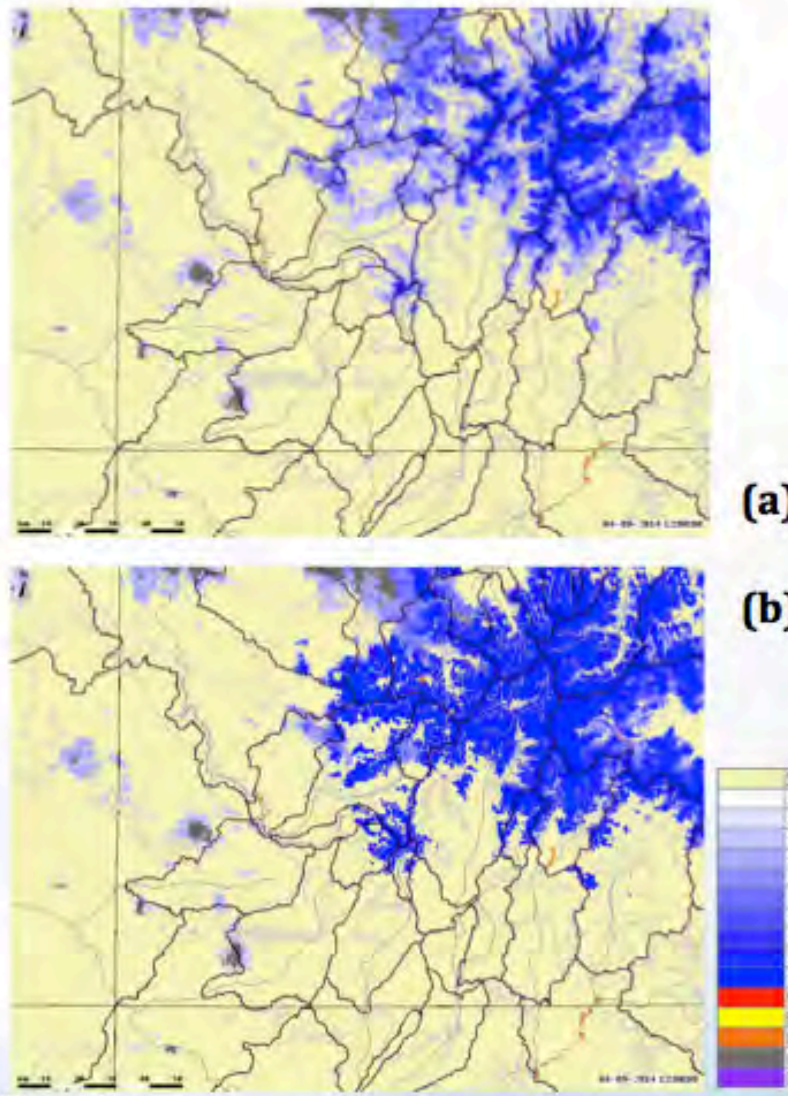
- introducing a second fSCA dataset to CBRFC
- building remote sensing knowledge at CBRFC
- expanding the use of dust-on-snow information (more details on next slide)

Relevance:

"canopy-adjusted" MODSCAG fSCA

- vegetation (particularly conifers) impacts MODIS fSCA retrievals
- many CBRFC streamflow forecast points = outlets of forested watersheds
- "viewable" fSCA = more accurate in remote sensing sense but vegetation can obscure snowpack and artificially reduce fSCA values (Fig. 1a)
- JPL provided CBRFC with "canopy-adjusted" MODSCAG fSCA (Fig. 1b) after discussion between the groups of vegetation impacts on the fSCA retrieval

CBRFC forecasters gain snow cover extent information in which the vegetation influence has been reduced.



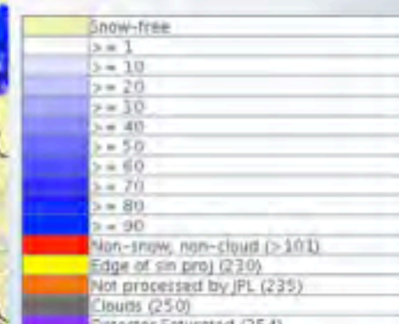
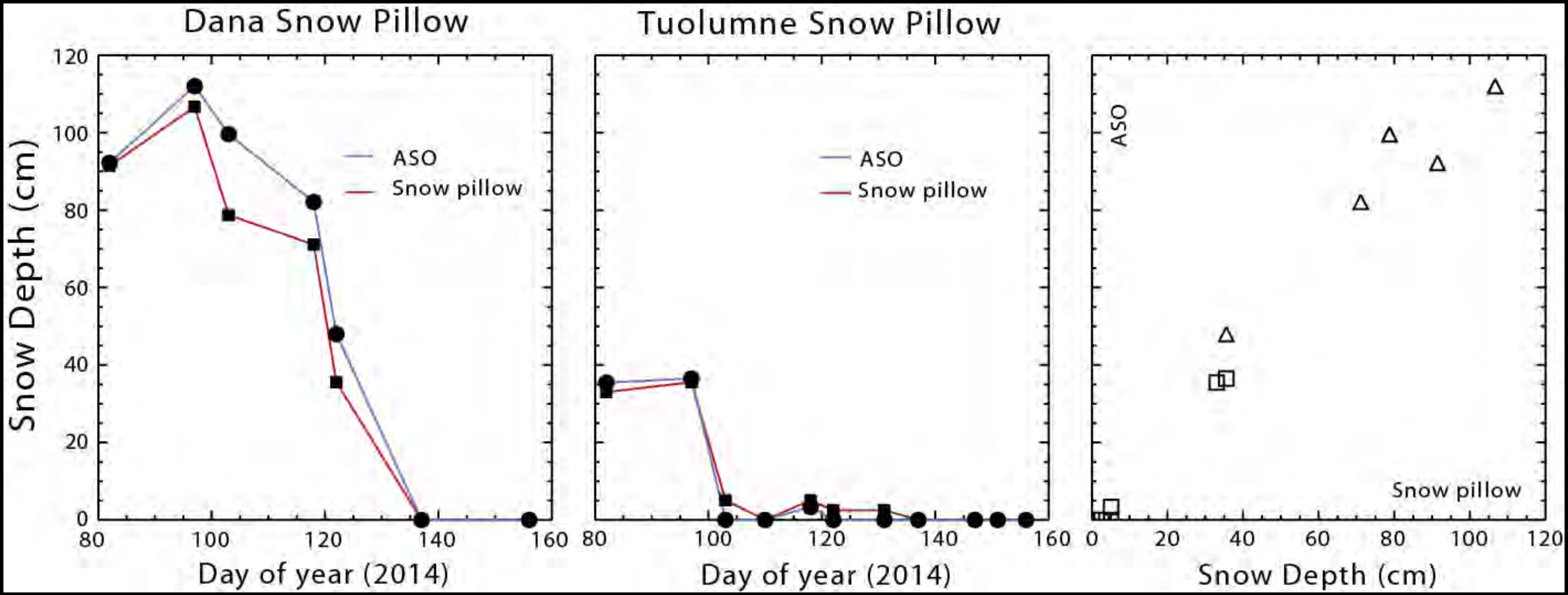
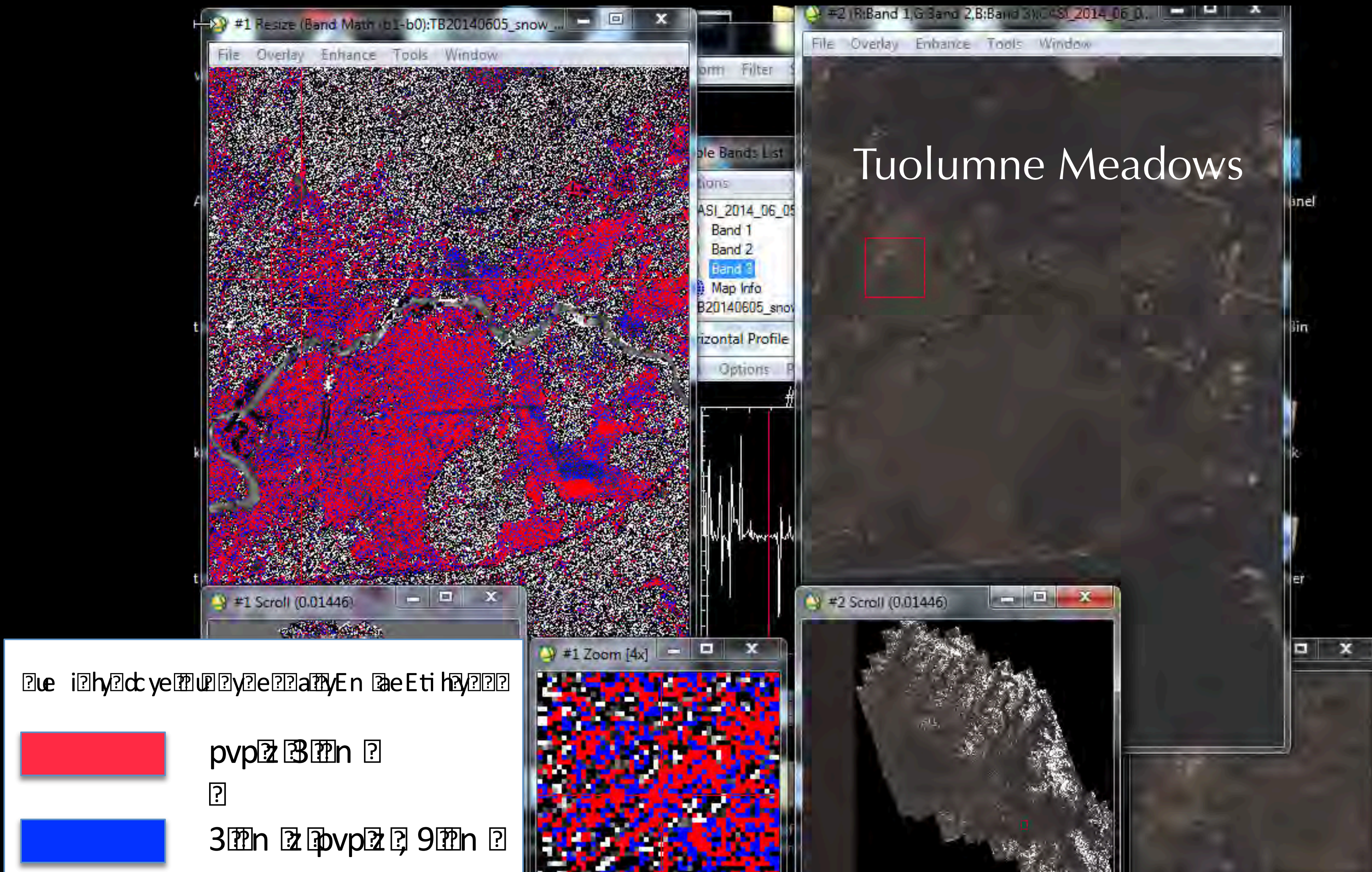


Figure 1:
Graphical display of MODSCAG (a) "viewable" and (b) "canopy-adjusted" gridded fSCA over southwestern Colorado, April 9, 2014, as viewed by CBRFC forecasters within CHPS.

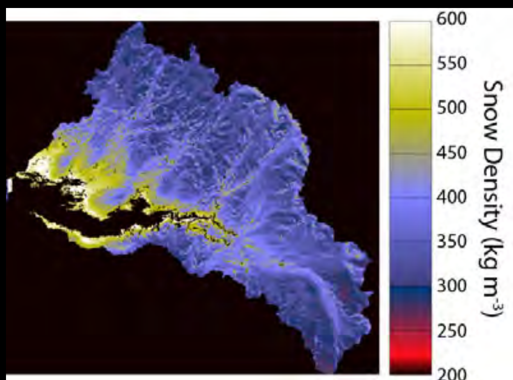
Validation

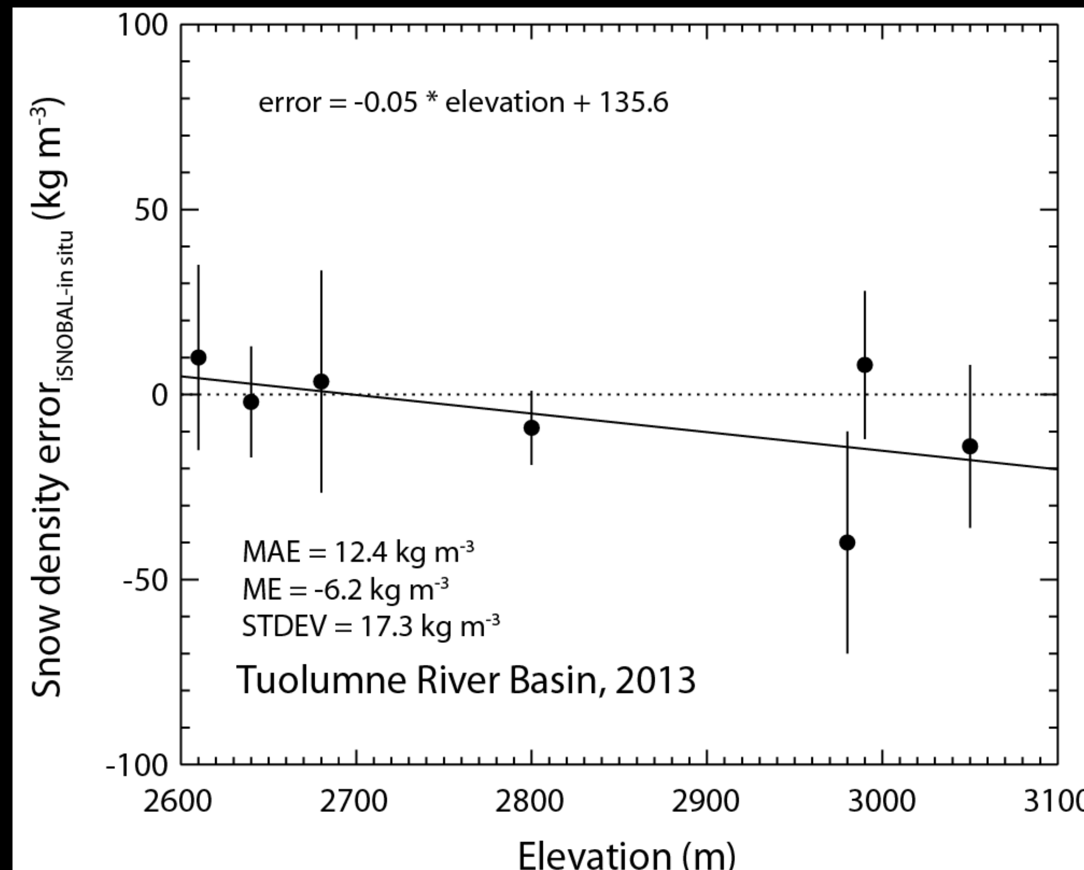


Dana Snow Pillow
Tuolumne Snow Pillow
Snow Depth (cm)
ASO
Snow pillow
ASO
Snow pillow
ASO
Snow pillow
Day of year (2014)
Day of year (2014)
Snow Depth (cm)



#1 Resize (Band Math (b1-b0):TB20140605_snow_...
File Overlay Enhance Tools Window
#2 (R:Band 1,G:Band 2,B:Band 3):C4SI_2014_06_0...
Tuolumne Meadows
Band 1
Band 2
Band 3
Map Info
#1 Scroll (0.01446)
#2 Scroll (0.01446)
#1 Zoom [4x]


600
550
500
450
400
350
300
250
200
Snow Density (kg m-3)


error = -0.05 * elevation + 135.6
MAE = 12.4 kg m-3
ME = -6.2 kg m-3
STDEV = 17.3 kg m-3
Tuolumne River Basin, 2013
Snow density error iSNOBAL-in situ (kg m-3)
Elevation (m)
100
50
0
-50
-100
2600
2700
2800
2900
3000
3100

MODSCAG

- There has been frequent comments that MODSCAG is tuned only to the Sierra Nevada
- Given that MODSCAG is physically-based and not empirical, this is not a valid statement
- Spectral libraries are dense for vegetation and rock/soils