Snow:

Getting to Know the Unsung Source of Water Quantity Issues

Sustaining Colorado Watersheds Conference
Avon, Colorado
October 11, 2017

Jeff Derry
Center for Snow and Avalanche Studies
Silverton, CO
snowstudies.org
Colorado Dust-on-Snow Program
codos.org

Liza Mitchell
Roaring Fork Conservancy
Basalt, CO
roaringfork.org

Water Quantity

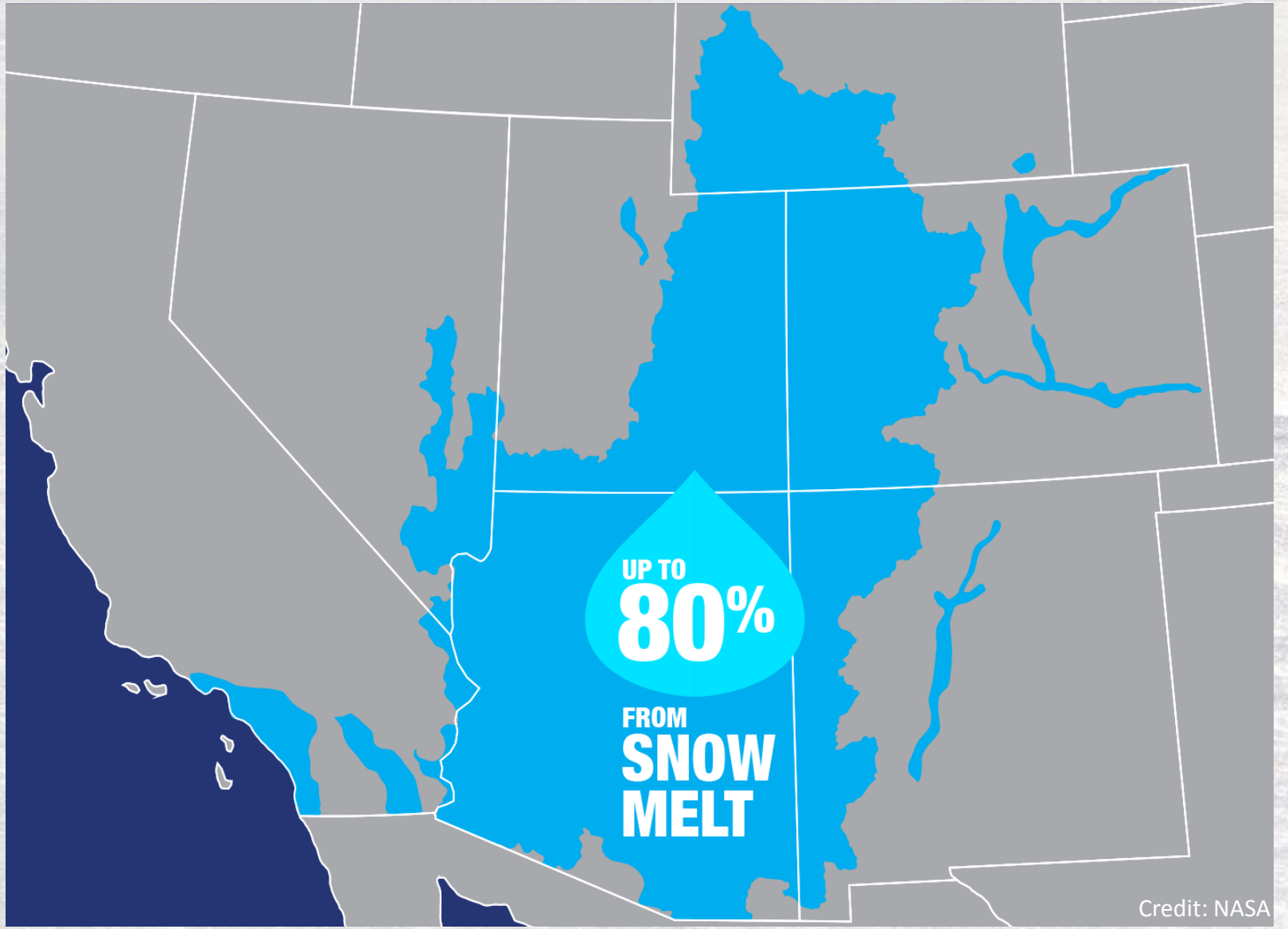
Supply // Demand

COLORADO'S WATER PLAN

SWSI
Statewide Water Supply Initiative

- Improved Efficiencies
- Increased Storage
- **Source water**

Snow = Water



Importance of Snow

- Source and storage system

Snowpack Data

- Data Needs
- Existing Data
- Current Issues and Use in Water Supply Predictions

Moving Forward

- Improving data and predictions
- Improving connection between researchers and application

“You can’t know what is happening in rivers unless you look at snow”

~60 million people in the Western United States depend on snowmelt

(Mankin et al. 2015)

Pacific Standard

MOUNTAINS ARE WARMING TWICE AS FAST AS THE REST OF THE WORLD

To sustain mountain communities, we need more monitoring and better governance.

BOB BERWYN · JUN 19, 2017

AGU PUBLICATIONS

The twenty-first century Colorado River hot drought and implications for the future

Bradley Udall[1,2] and Jonathan Overpeck[2,3]

Jet Propulsion Laboratory
California Institute of Technology

NEWS | JANUARY 27, 2017

Storms Filled 37 Percent of CA Snow-Water Deficit

American West Heating Nearly Twice as Fast as Rest of World, New Analysis Shows

March 27, 2008

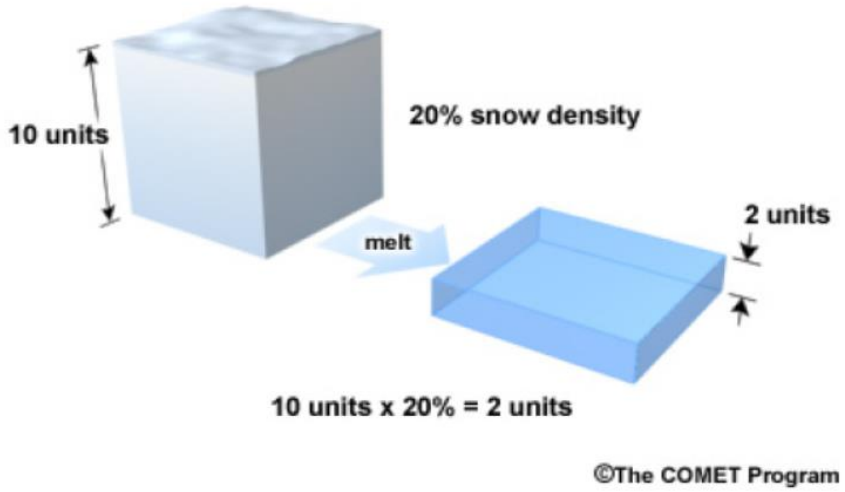
NRDC

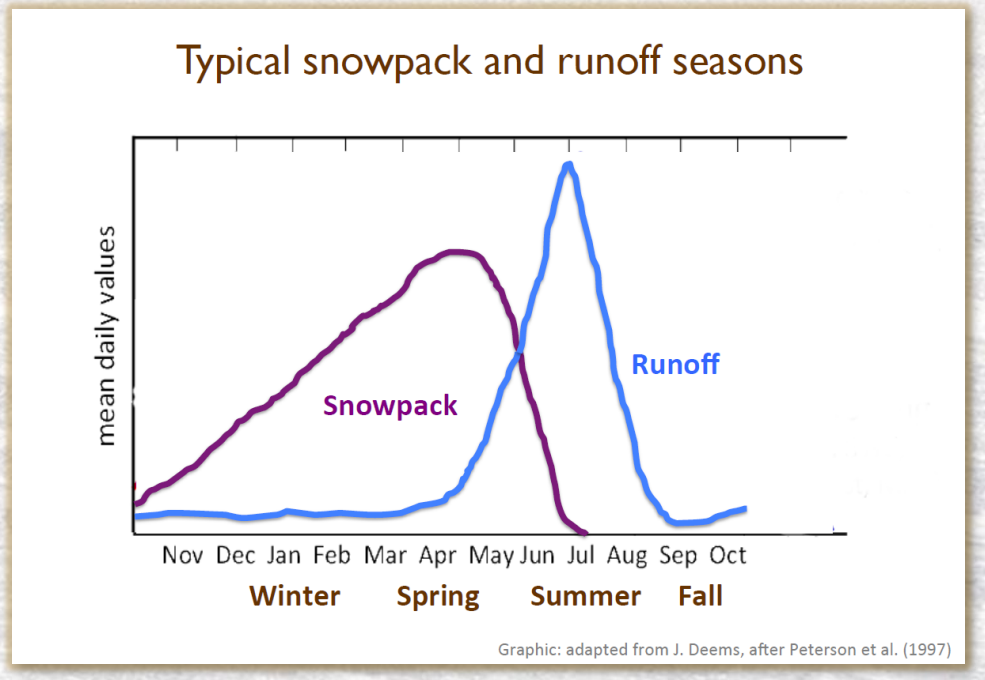
What we need to know about snow

Practical Applications

#1 = Quantity

Snow Water Equivalent (SWE)





Why so critical?

Downstream Compacts

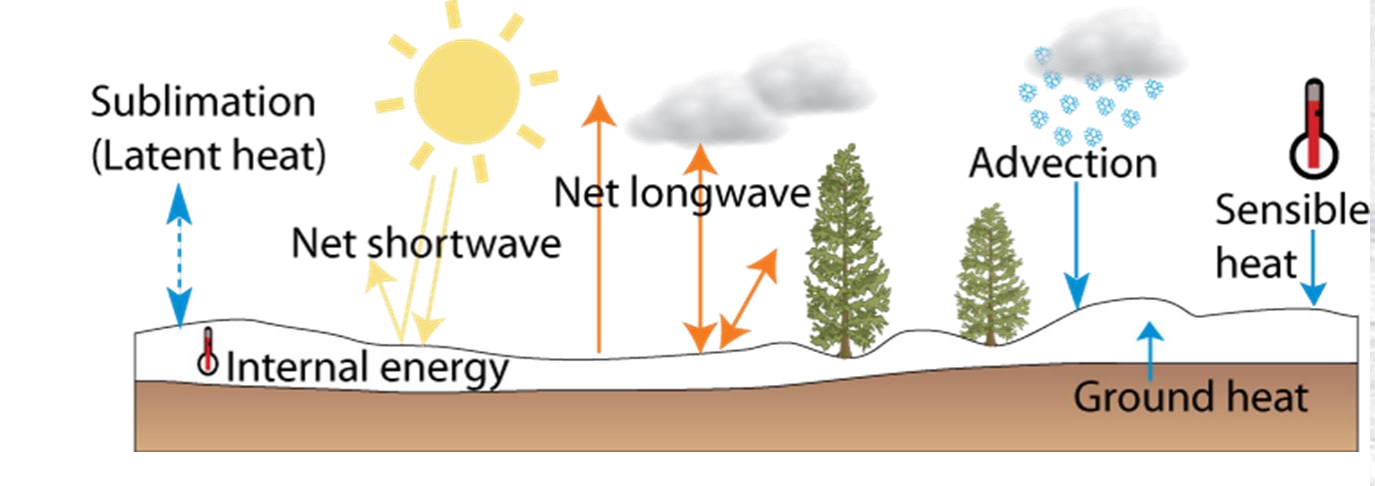
Stakeholders:

- agriculture
- hydropower
- recreation
- municipal
- industry
- environment

What we need to know about snow

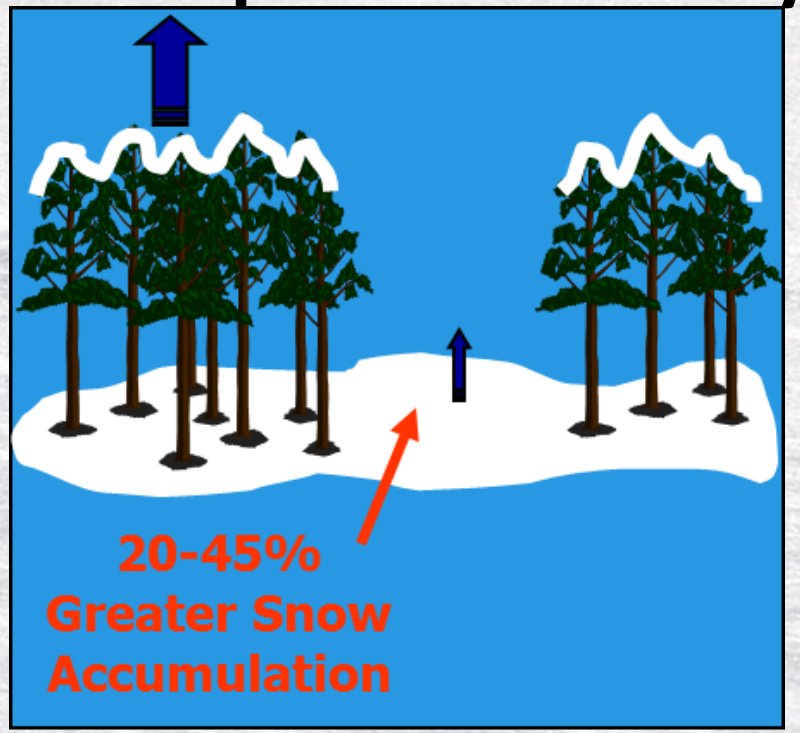
Practical Applications

#2 = External Factors



- Sublimation to Atmosphere
- Antecedent soil moisture conditions
- Incoming Radiation
- Albedo (Energy absorption vs. reflectance)

#3 = Spatial Variability



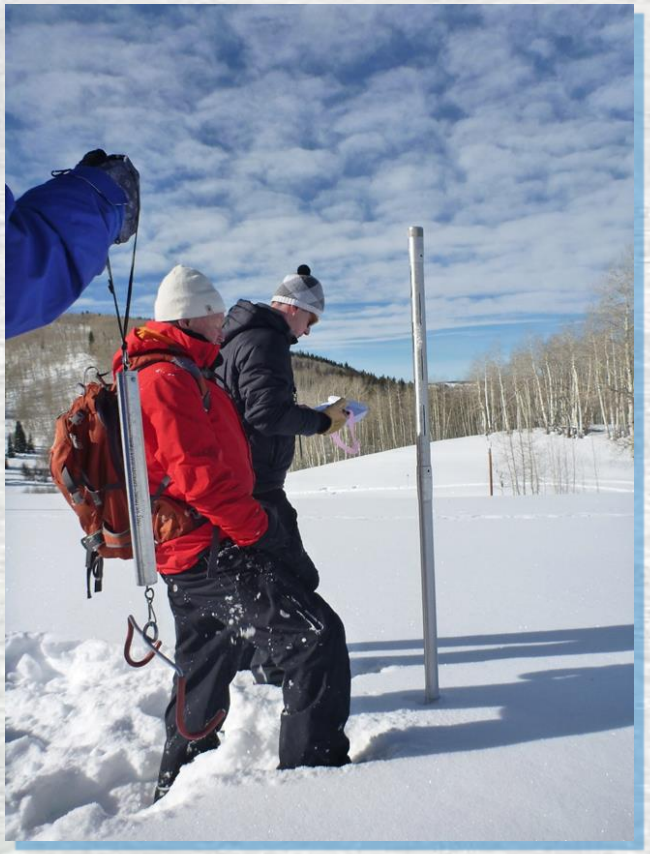
Interception by Trees
Redistribution by Wind

SWE Measurement

Ground Observations (in situ = on site)

a) Snow Courses with Snow Tubes

Transects with snow depth and density



b) Snow Pits

Measure vertical profiles of SWE, and other snow pack variables.

c) Snow Pillows, SNOTEL

Snowpack Data Comparison

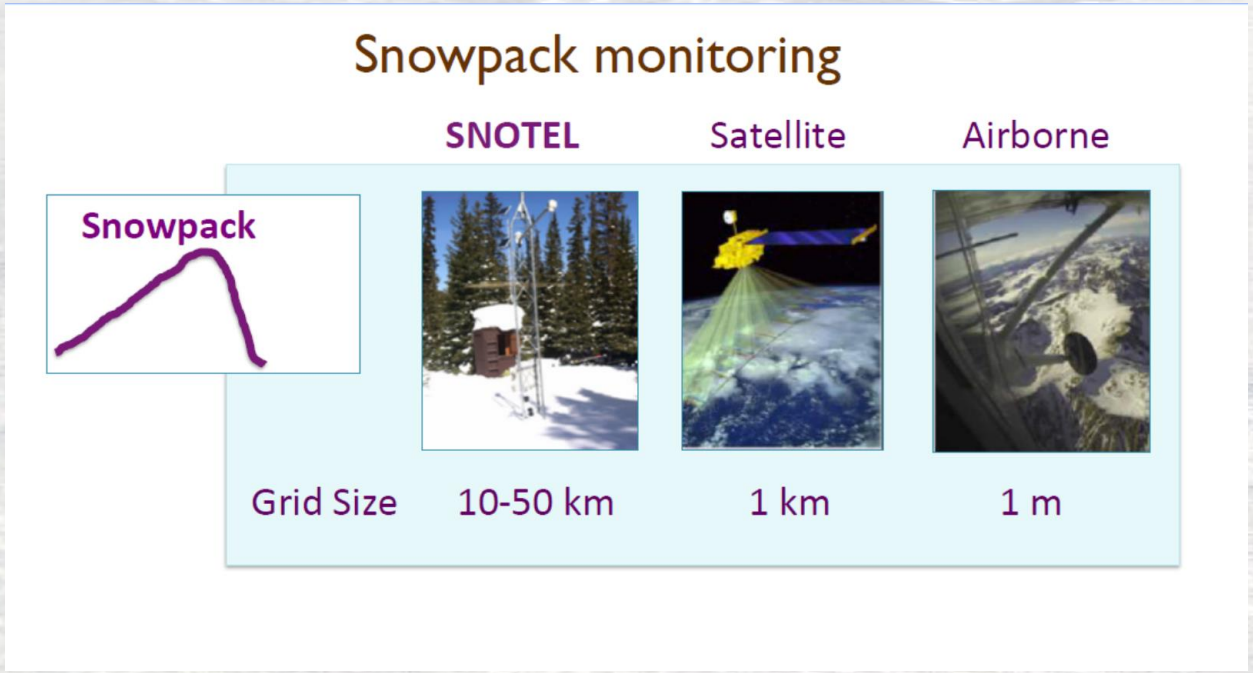
Method	Pro	Con
Snow Course	Higher spatial resolution	Low temporal resolution
SnoTel	Lower spatial resolution	Higher temporal resolution

Additional Considerations

- Relevancy to water professionals
- Public Understanding
- Accessibility
- Interpolation/Statistics
- Costs (financial,
- human resources, instrumentation, maintenance)

SWE Measurement

Remote Sensing Observations



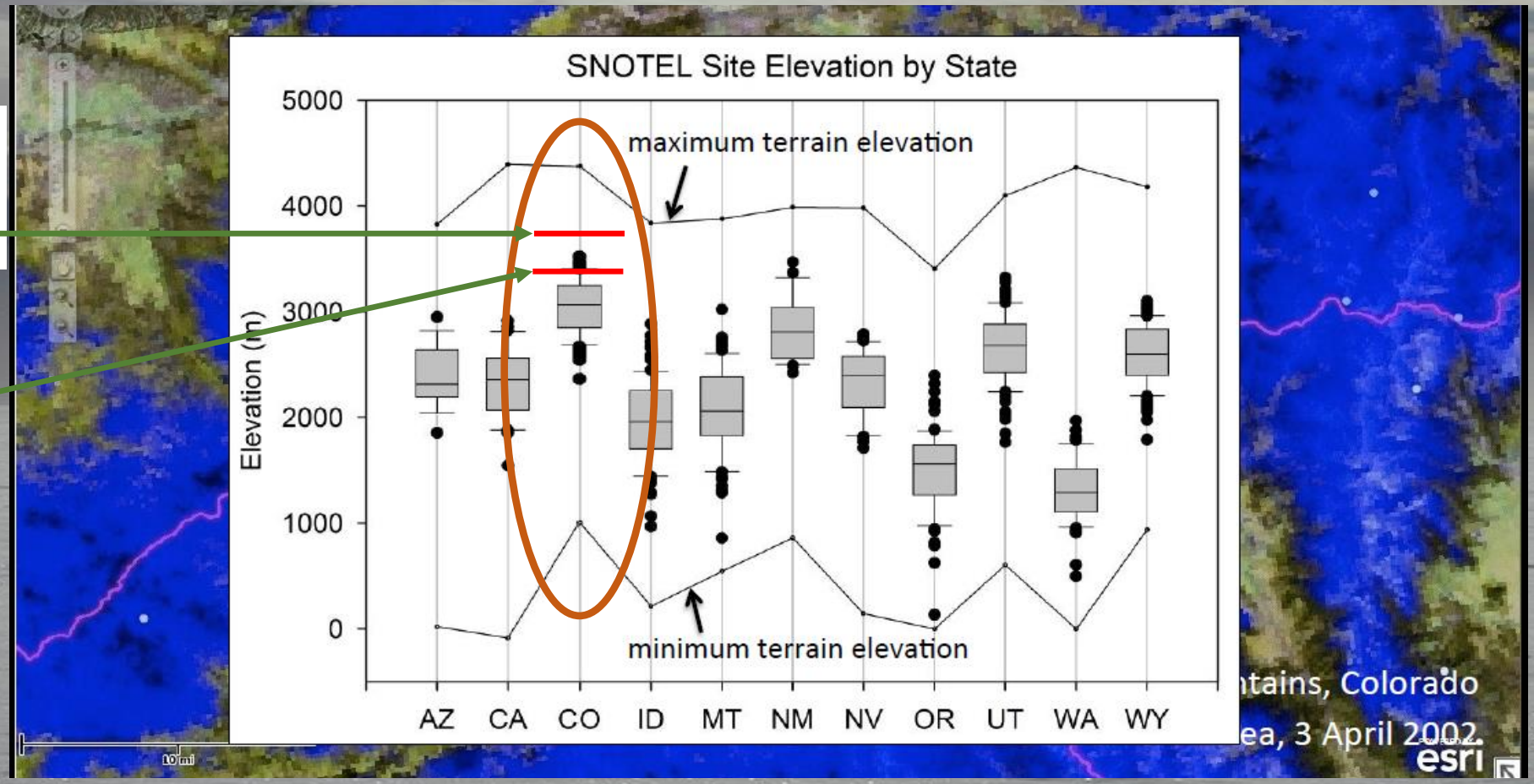
Snowpack Modeling Efforts

-SNODAS, Open Snow, others

Center for Snow and Avalanche Studies:
Helps Fill The Gap of Monitoring at Higher Elevations

Senator Beck Study Plot 12,186’ (3714 m)

Swamp Angel Study Plot 11,060’ (3371 m)



Forecast skill has decreased at many forecast points in the West due to increased climate variability

CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

P. C. D. Milly,[1]* Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains; annual global invest-

An uncertain future challenges water planners.

that has emerged from climate models (see figure, p. 574).

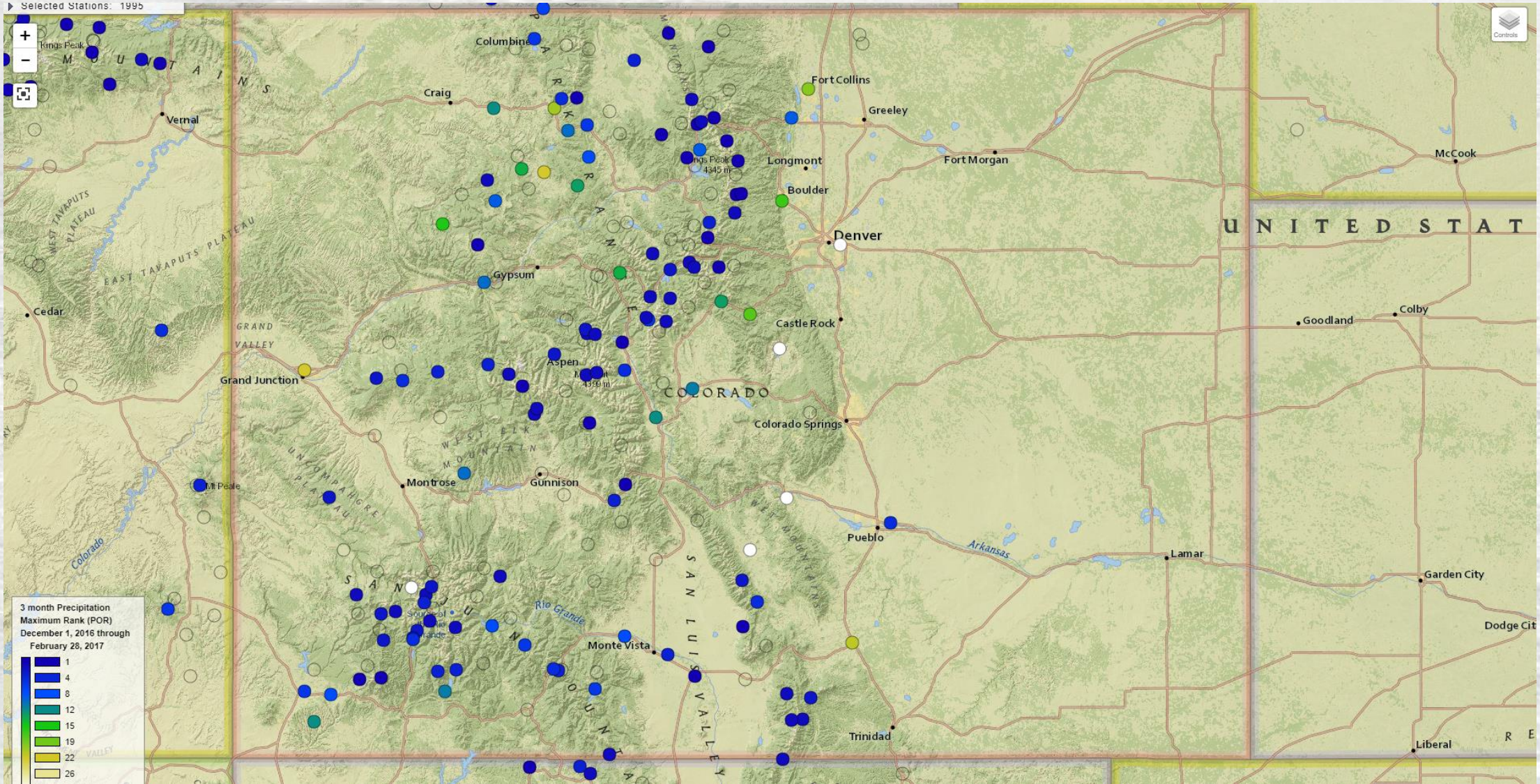
Why now? That anthropogenic climate change affects the water cycle (*9*) and water supply (*10*) is not a new finding. Nevertheless, sensible objections to discarding stationarity have been raised. For a time, hydroclimate had not demonstrably exited the envelope of natural variability and/or the effective range of optimally operated infrastructure (*11*, *12*). Accounting for the substantial uncertainties of climatic parameters estimated from short records (*13*) effectively hedged against small climate changes. Additionally, climate projections were not considered credible (*12*, *14*).

Recent developments have led us to the opinion that the time has come to move beyond the wait-and-see approach. Projections of runoff changes are bolstered by the recently demonstrated retrodictive skill of cli-

How did stationarity die? Stationarity is dead because substantial anthropogenic change of Earth's climate is altering the means and extremes of precipitation, evapotranspiration, and rates of discharge of rivers (*4*, *5*) (see figure, above). Warming aug-

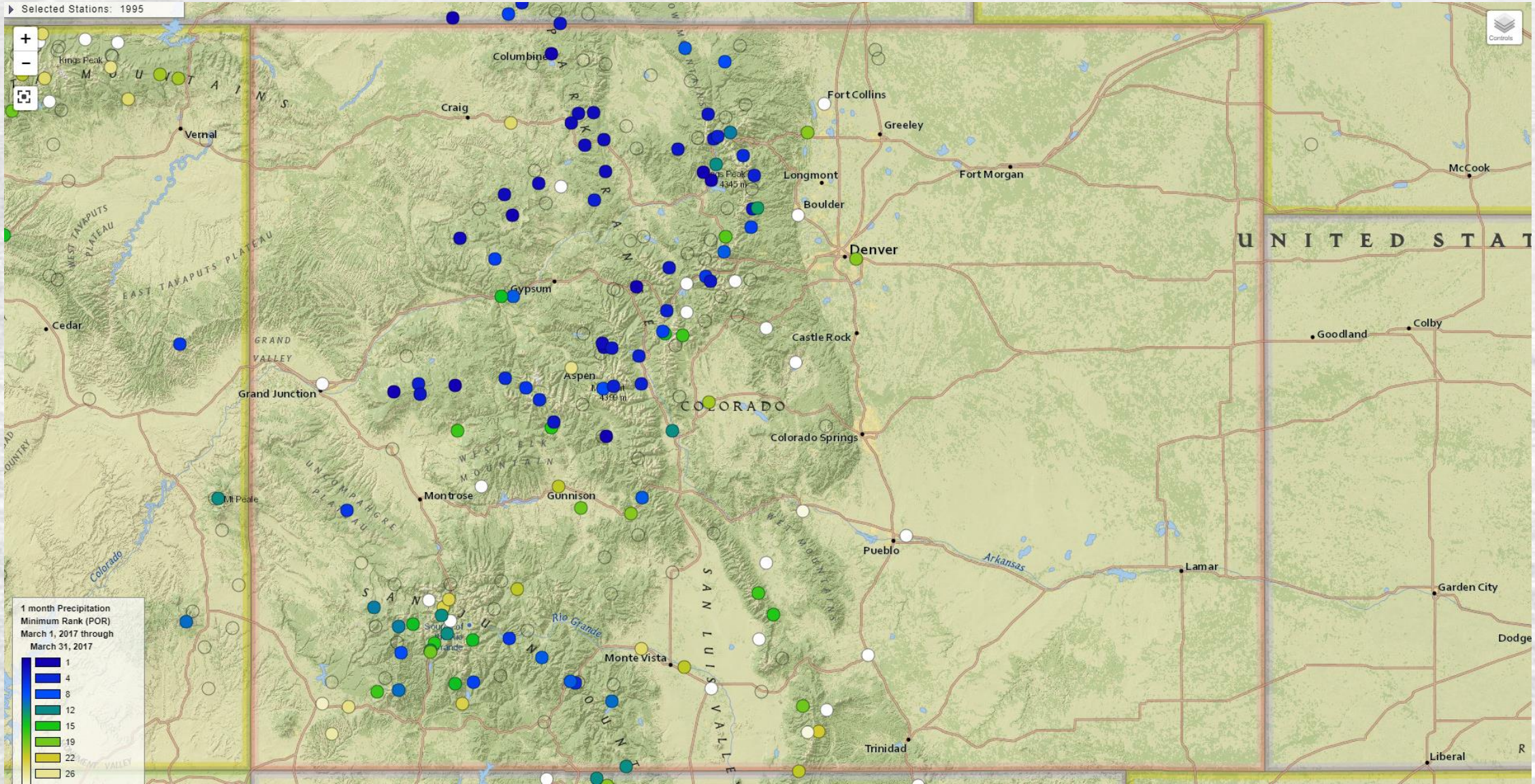
December-February Precipitation

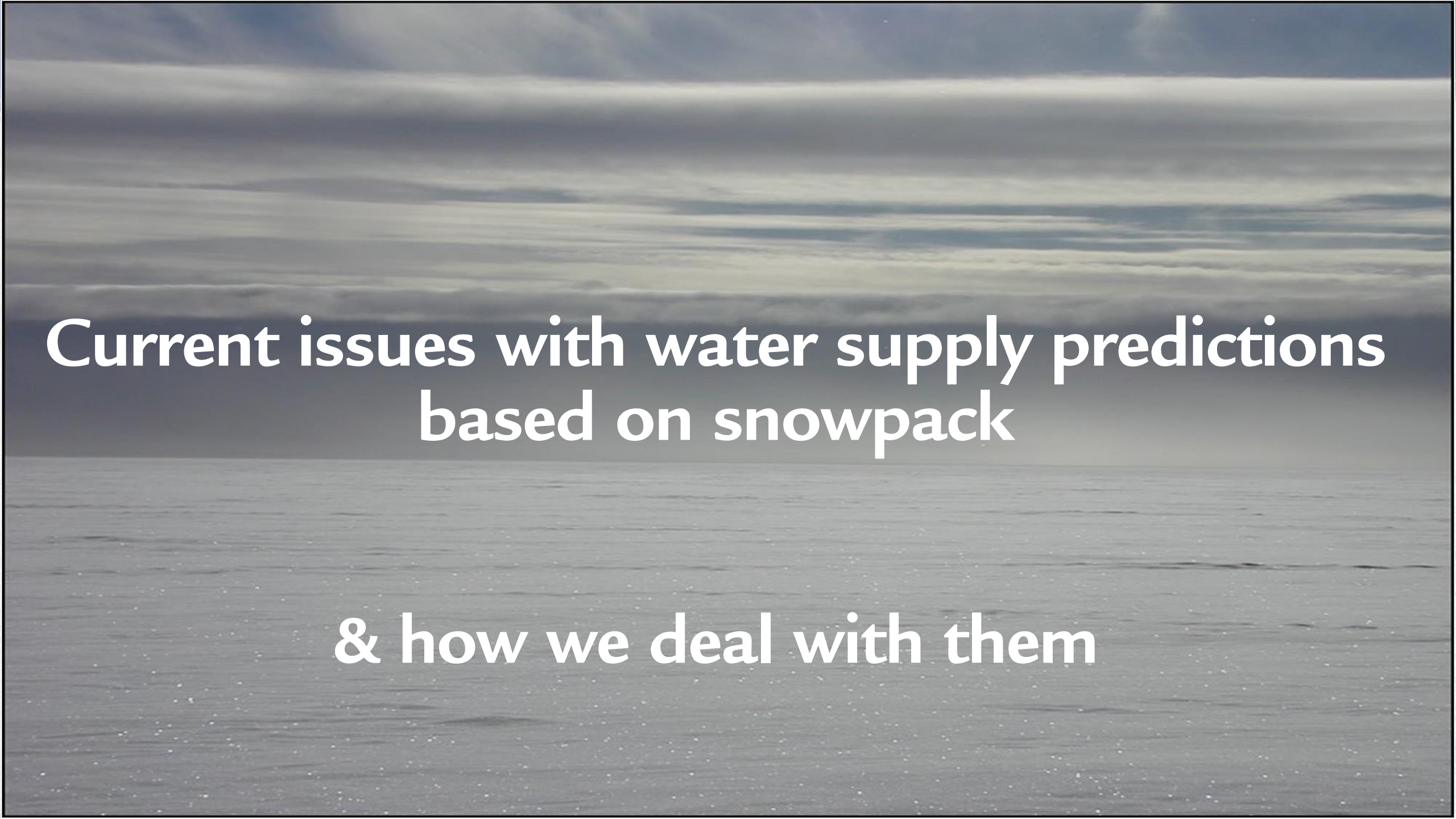
Maximum Precipitation Ranking at SNOTEL Sites



Warmest March on Record (Period: 1895-2017)

Minimum Precipitation Ranking at SNOTEL Sites




Current issues with water supply predictions based on snowpack
& how we deal with them

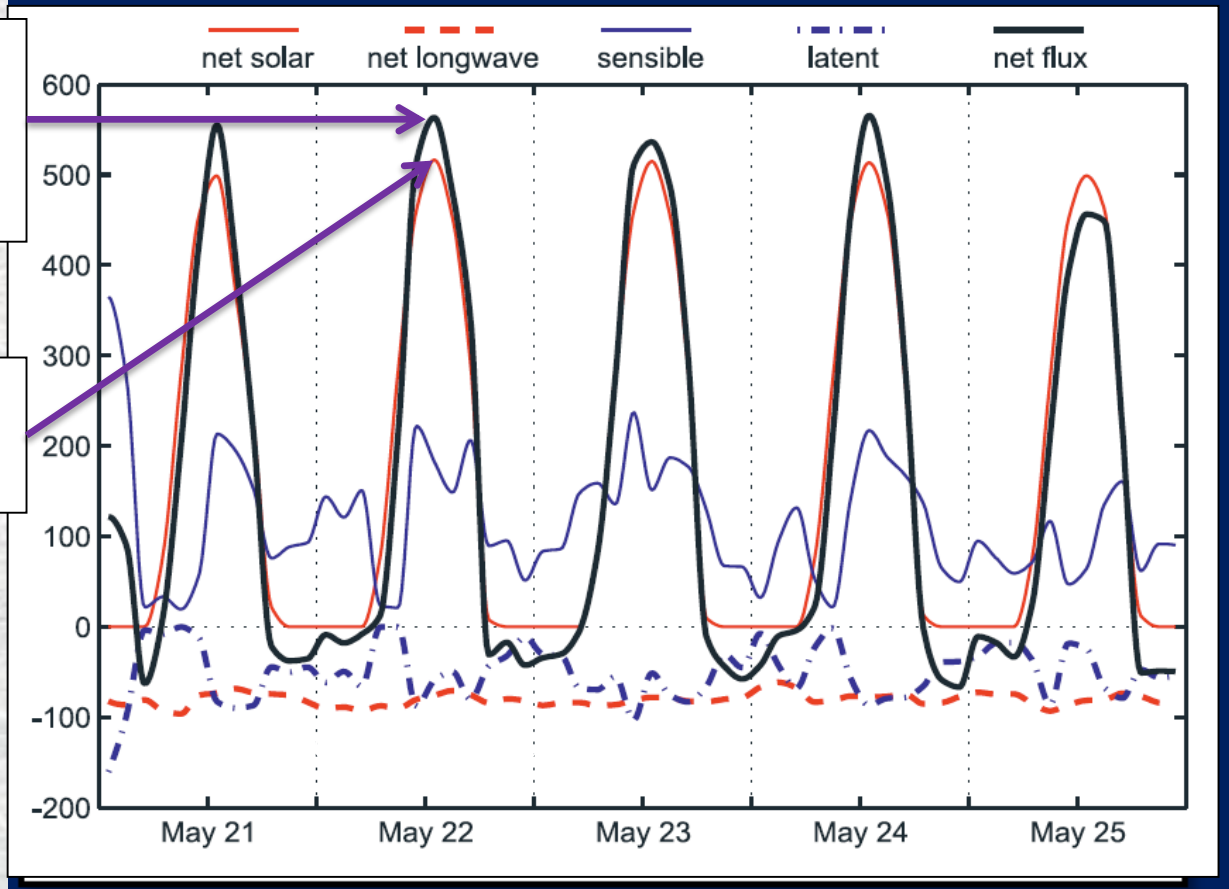
Net Flux | Net Solar | Net Longwave | Sensible Heat | Latent Heat

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

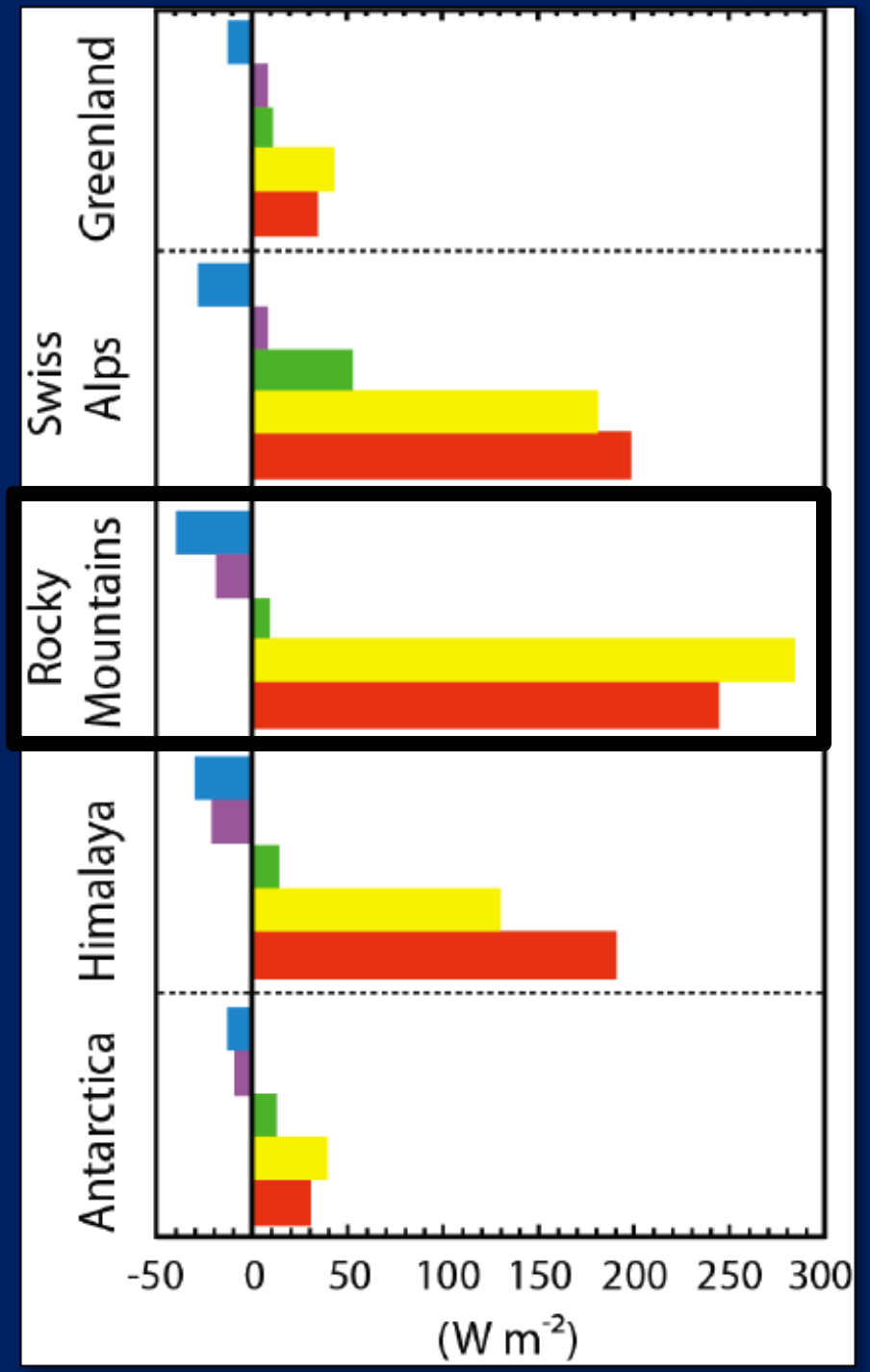
Albedo

Sum of energy balance terms (melt energy)

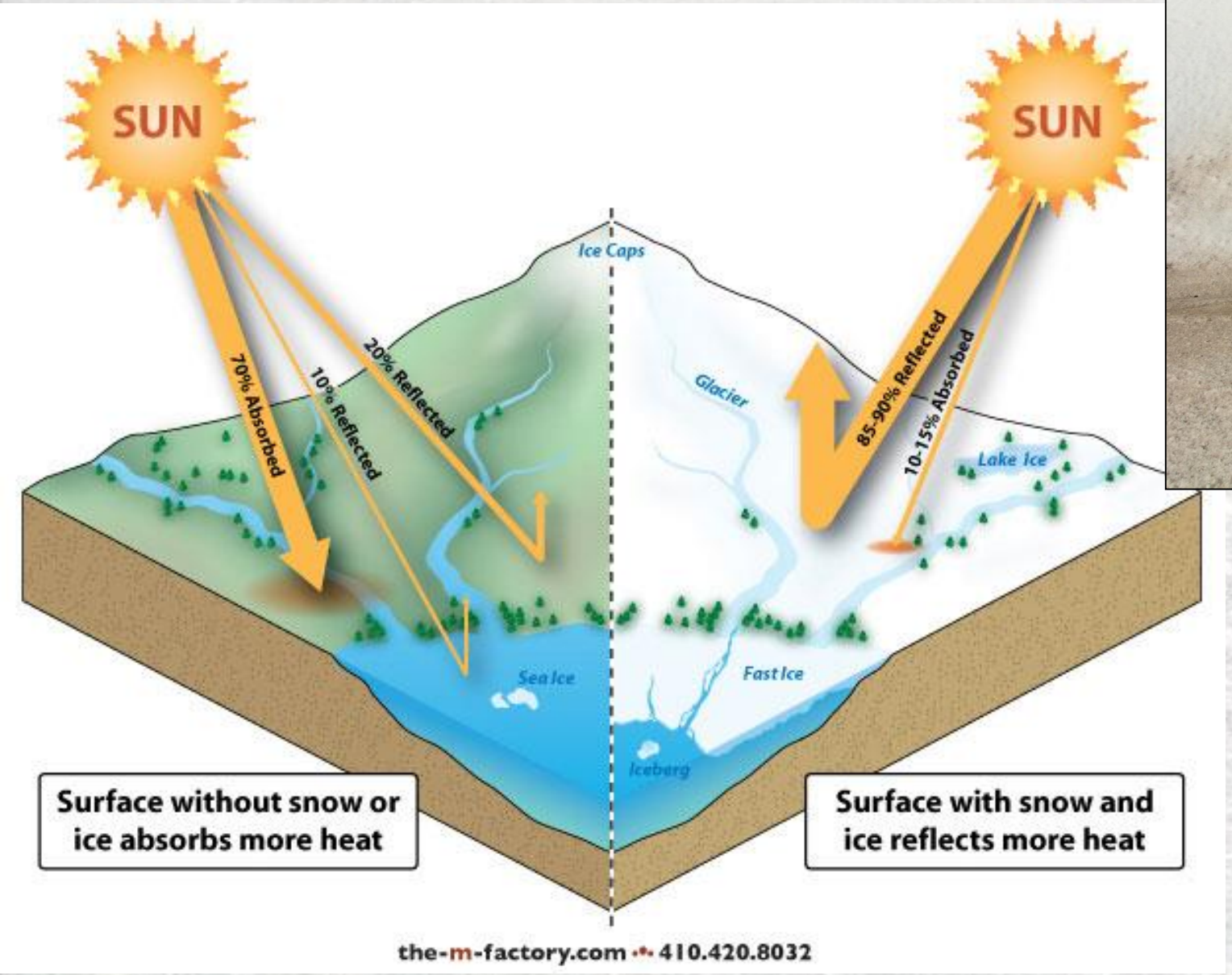
Net Solar radiation



San Juan Mountains, 2005



Solar radiation drives snowmelt



Dust from the southern Colorado Plateau—the biggest dust source today in the U.S.

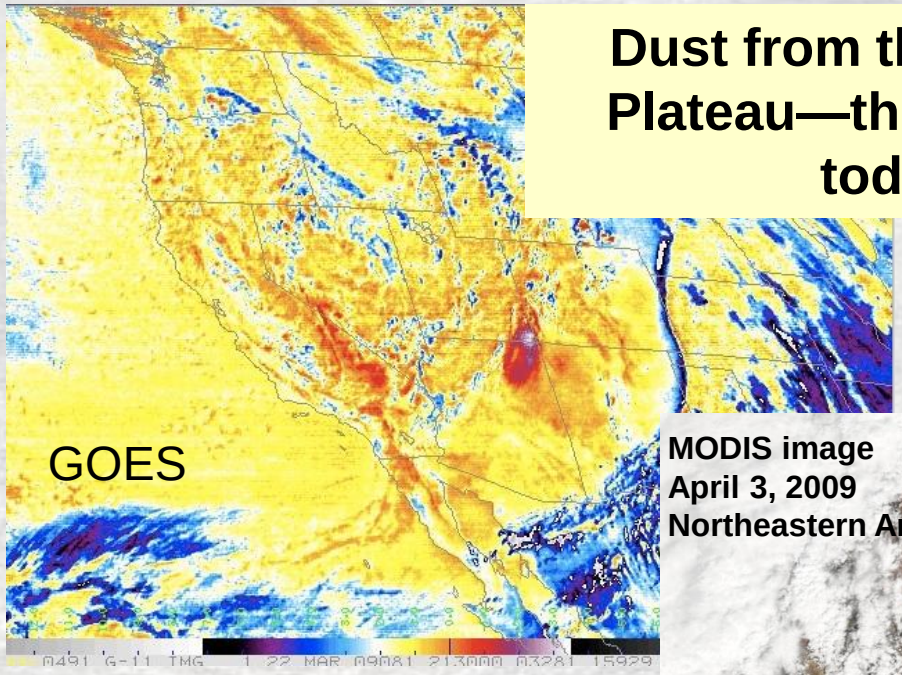
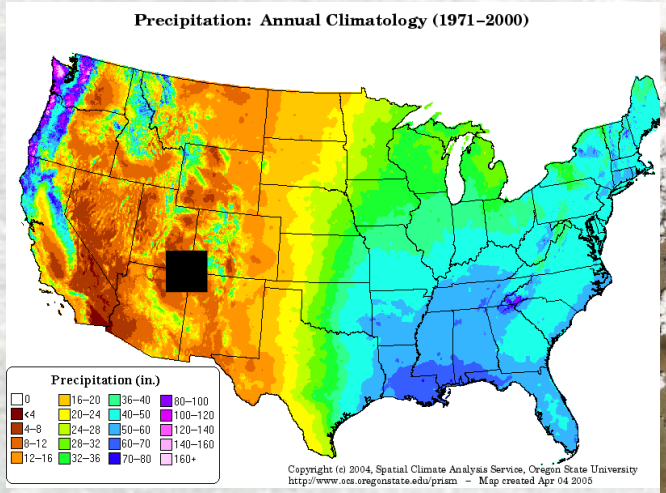
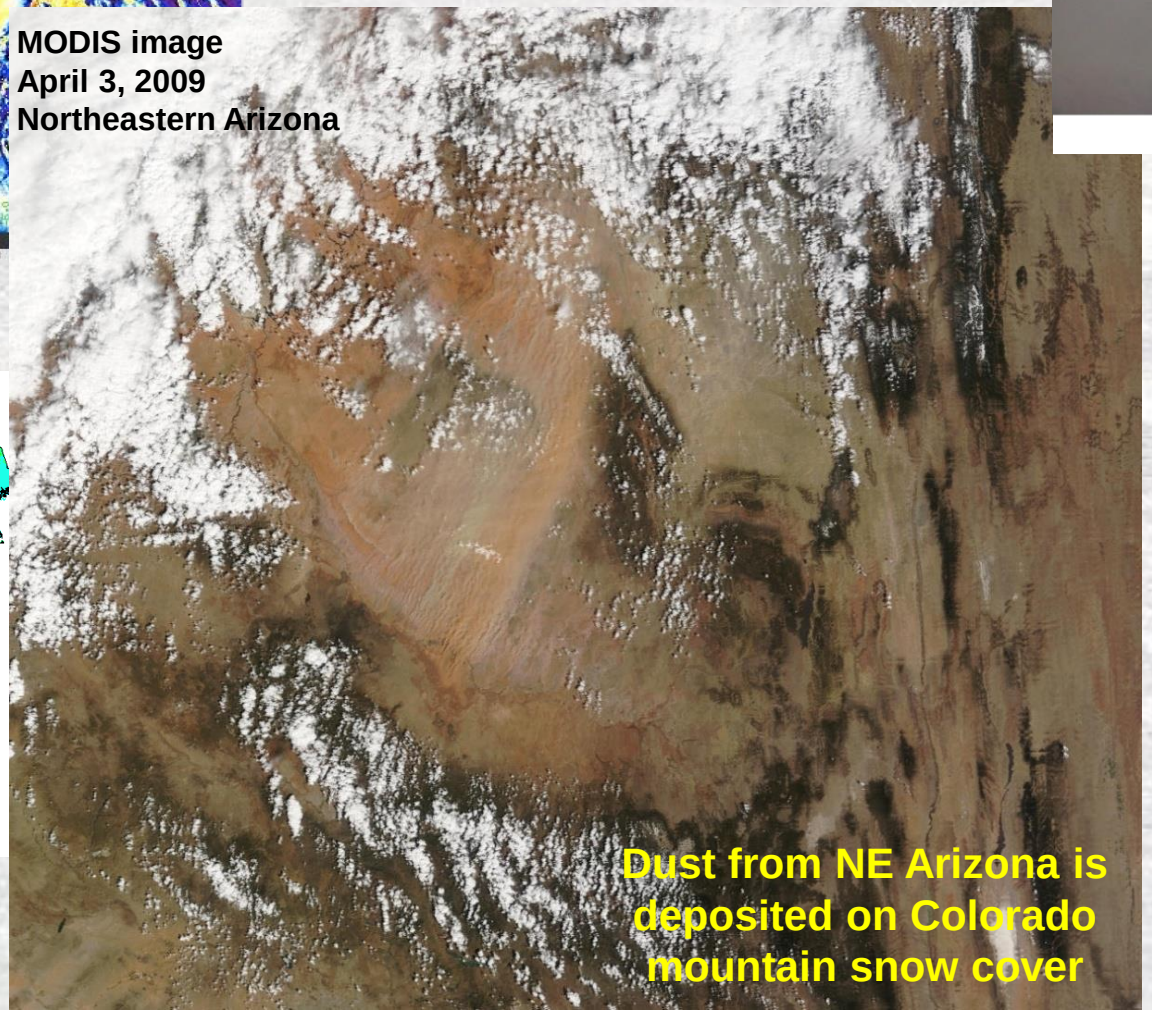


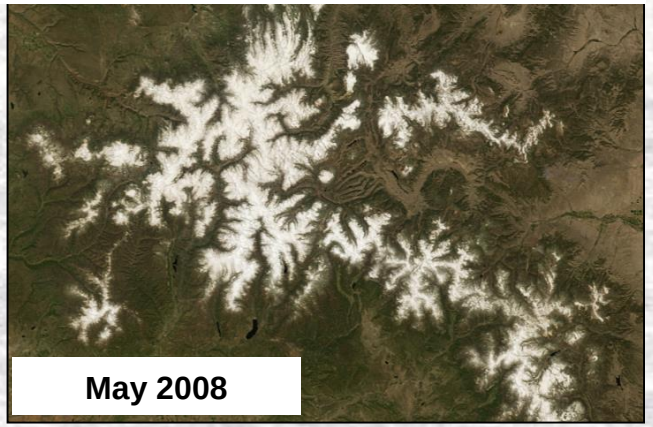
Photo by Doug Barnum USGS Apr. 28, 2010

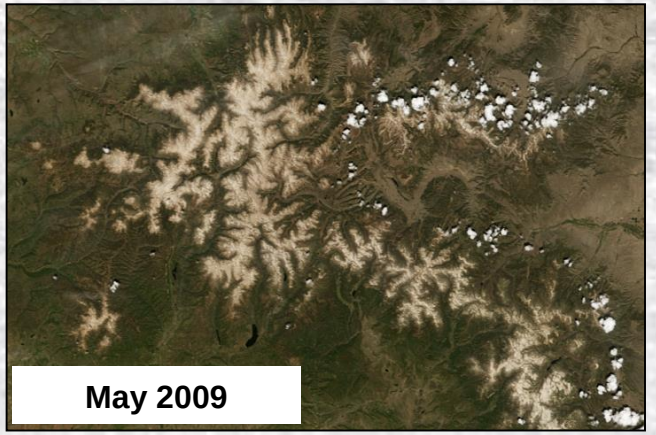
MODIS image
April 3, 2009
Northeastern Arizona





Dust from NE Arizona is deposited on Colorado mountain snow cover



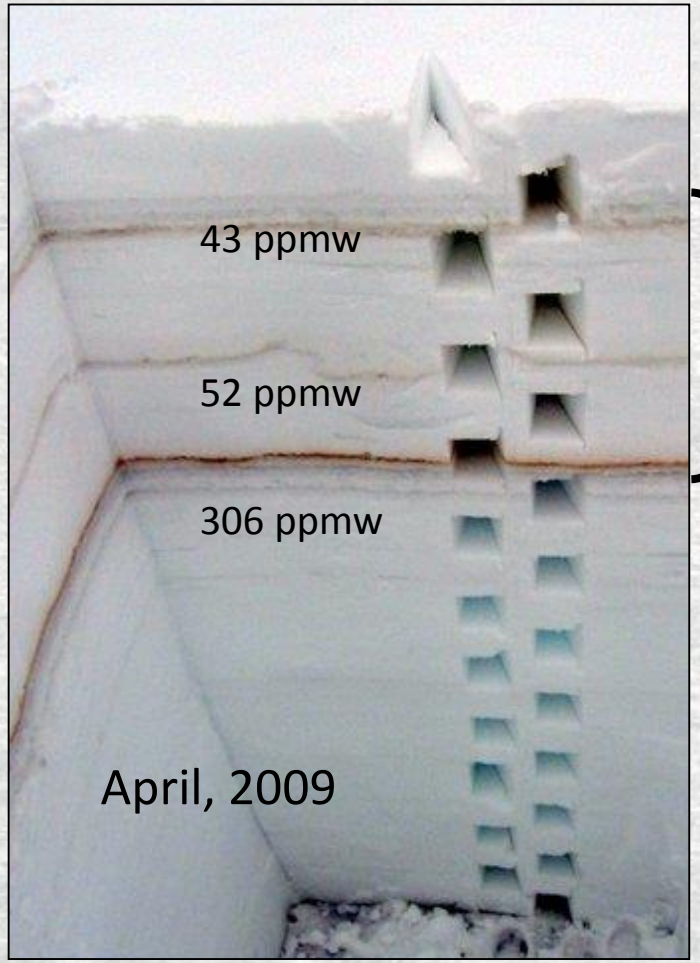


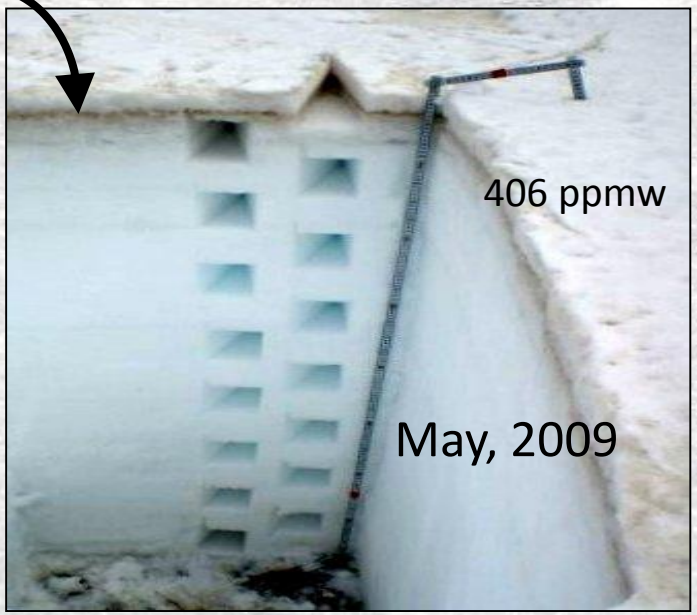
USGS

Snowmelt and River Forecasting

Dust accumulates on surface

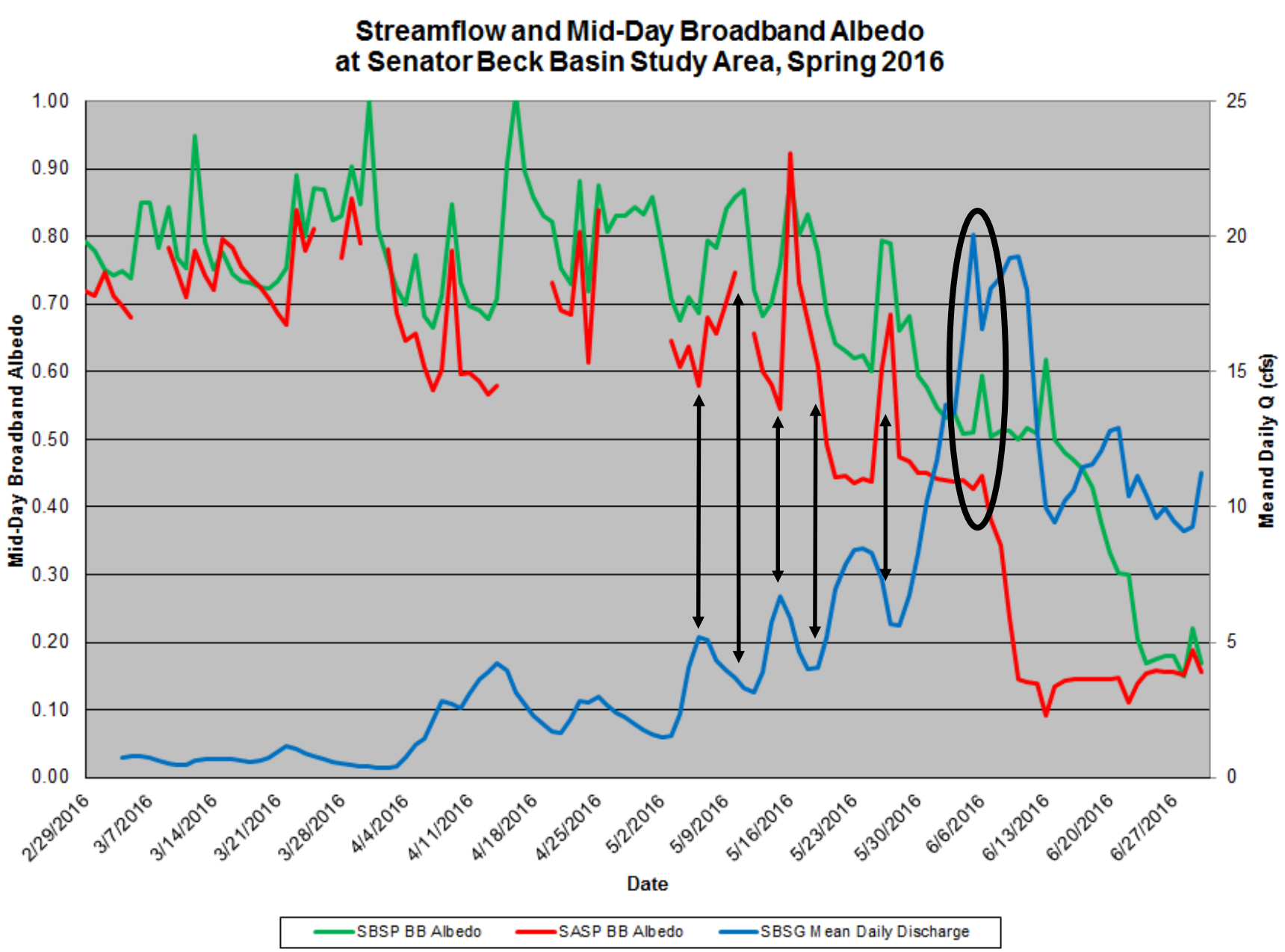
Rabbit Ears Pass, Colorado





<u>Dust-on-Snow Affects</u>

- Timing of snow melt
- Rate of snow melt
- Reduce total runoff yields



Year	# dust events	# spring dust events	# days melt advanced
2005	4	4	28
2006	8	6	31
2007	8	6	30
2008	9	9	26
2009	12	9	50

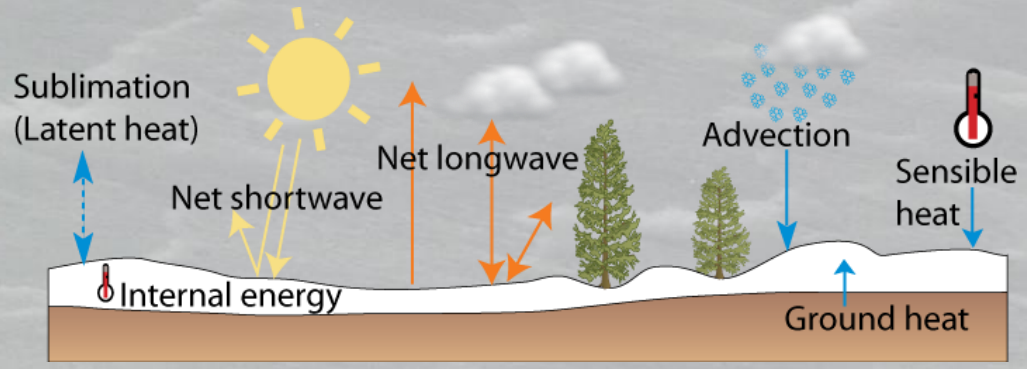
Skiles, S. M., T. H. Painter, J. S. Deems, A. C. Bryant, and C. Landry (2012), Dust radiative forcing in snow of the Upper Colorado River Basin: Part II. Interannual variability in radiative forcing and snowmelt rates, *Water Resour. Res.*, doi:10.1029/2012WR011986.

Controls on Snowmelt

Knowing the magnitude and timing of snowmelt runoff requires knowing

SNOW WATER EQUIVALENT & SNOW ALBEDO

Snowmelt & runoff simulation & forecasting



Temperature index runoff model

- e.g. CBRFC; SAC/SNOW-17
- *Q = f(SWE, T_{air}*melt factor)*
- Calibrated relationship between air temperature and snowmelt
- Calibrated to observations

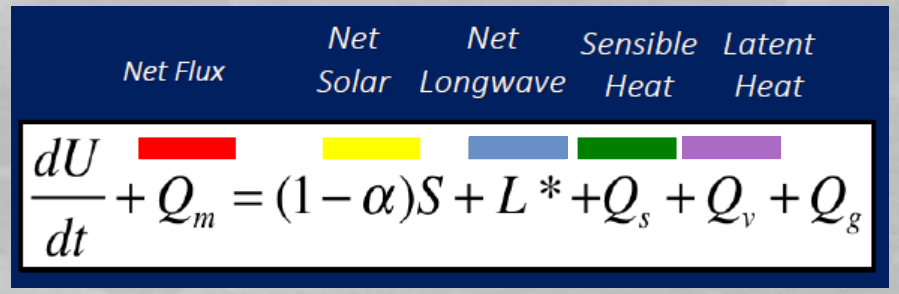
Statistical water supply forecast

- e.g. NRCS
- *Q = f(SWE)*
- Regression based
- Relates winter/spring SWE obs to spring/summer streamflow
- Calibrated to years in period of record

Both methods assume calibrations apply to current conditions

Physically-based hydrology model

- e.g. PRMS



- Common research

Colorado Basin River Forecast Center (CBRFC)
Snowmelt Forecast Errors and Dust

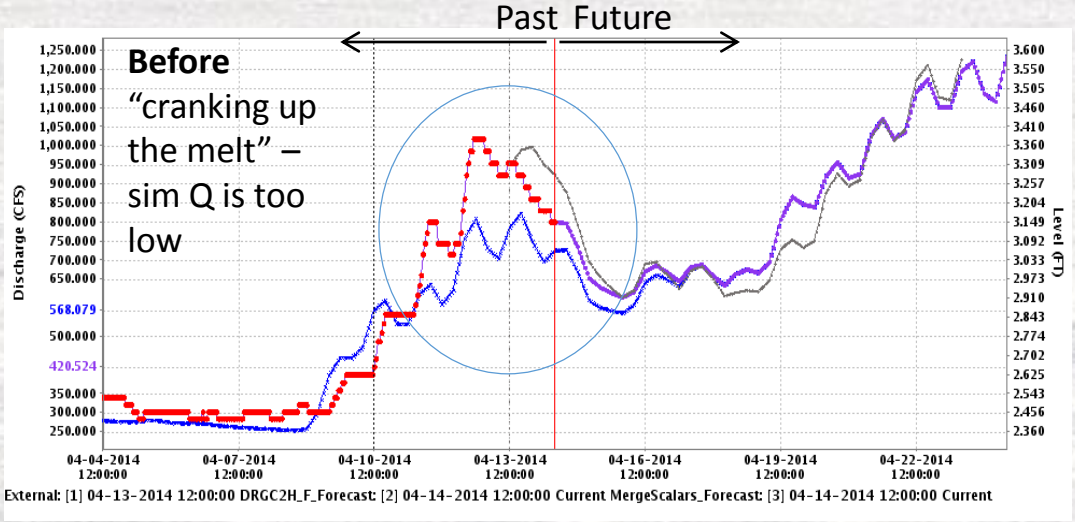
- CBRFC uses Operational Snow Model – SNOW17
- Temperature-index model (air temperature used as proxy for energy/radiation)
- Calibrated (1980's – present)
- This approach breaks down when conditions deviate from average
- Dustier than average snowpack brings earlier snowmelt than what SNOW17 predicts
- Larger streamflow prediction errors are correlated with dustier years

Ongoing research indicates that this [dust] is a major factor contributing to operational river runoff forecast errors in the Colorado River Basin [Bryant et al., 2013]

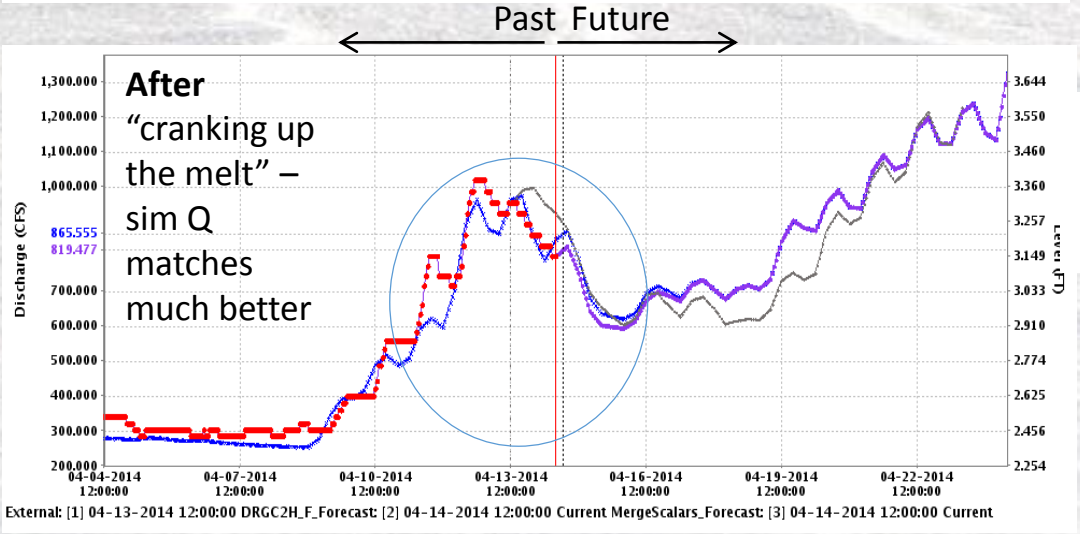
Furthermore, it has been shown that variation in the rate at which river flows in the eastern portion of the Upper Colorado River Basin *is controlled by variability in dust radiative forcing and not by variations in spring air temperatures* [Painter, Skiles, Deems, and others, submitted]

Colorado Basin River Forecast Center (CBRFC)
Snowmelt Forecast Errors and Dust

- Consider Information From
  - Historical Analysis
  - Field Observations
    - CSAS dust-on-snow data
  - Remote Sensing
  - Weather Forecast
- Operators at CBRFC make manual melt factor adjustments based on observed dust radiative forcing information



Recent Obs Q
Model Sim
Official Fcst Q



Recent Obs Q
Model Sim
Official Fcst Q

Credit: plots courtesy B. Bernard (CBRFC)

What is in the works? ……

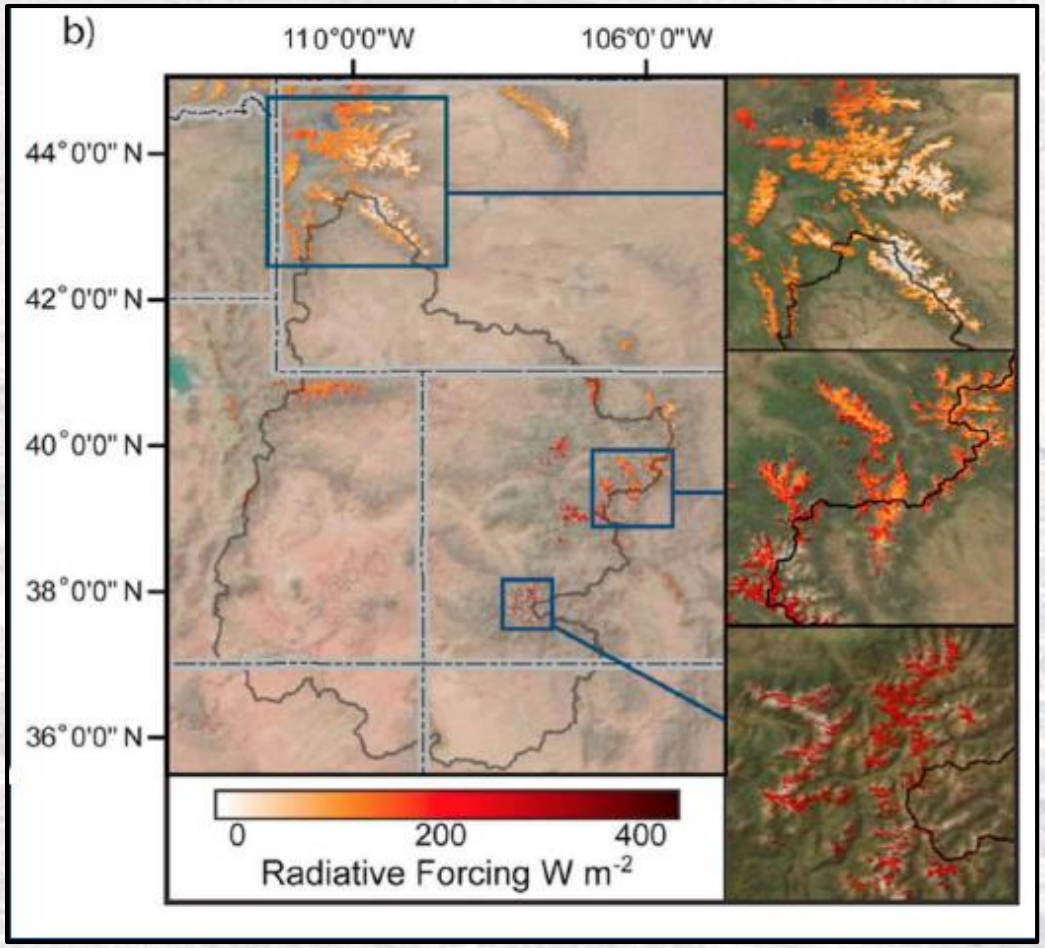
Jet Propulsion Laboratory and CBRFC Partnership (2013-)

Snow Properties from MODIS

- Snow Covered Area (SCA)
- Grain size
- Albedo
- Dust radiative forcing

The Result

- SWE adjustments based on SCA
- Melt factor adjustments based on dust forcing



Other efforts……National Water Model

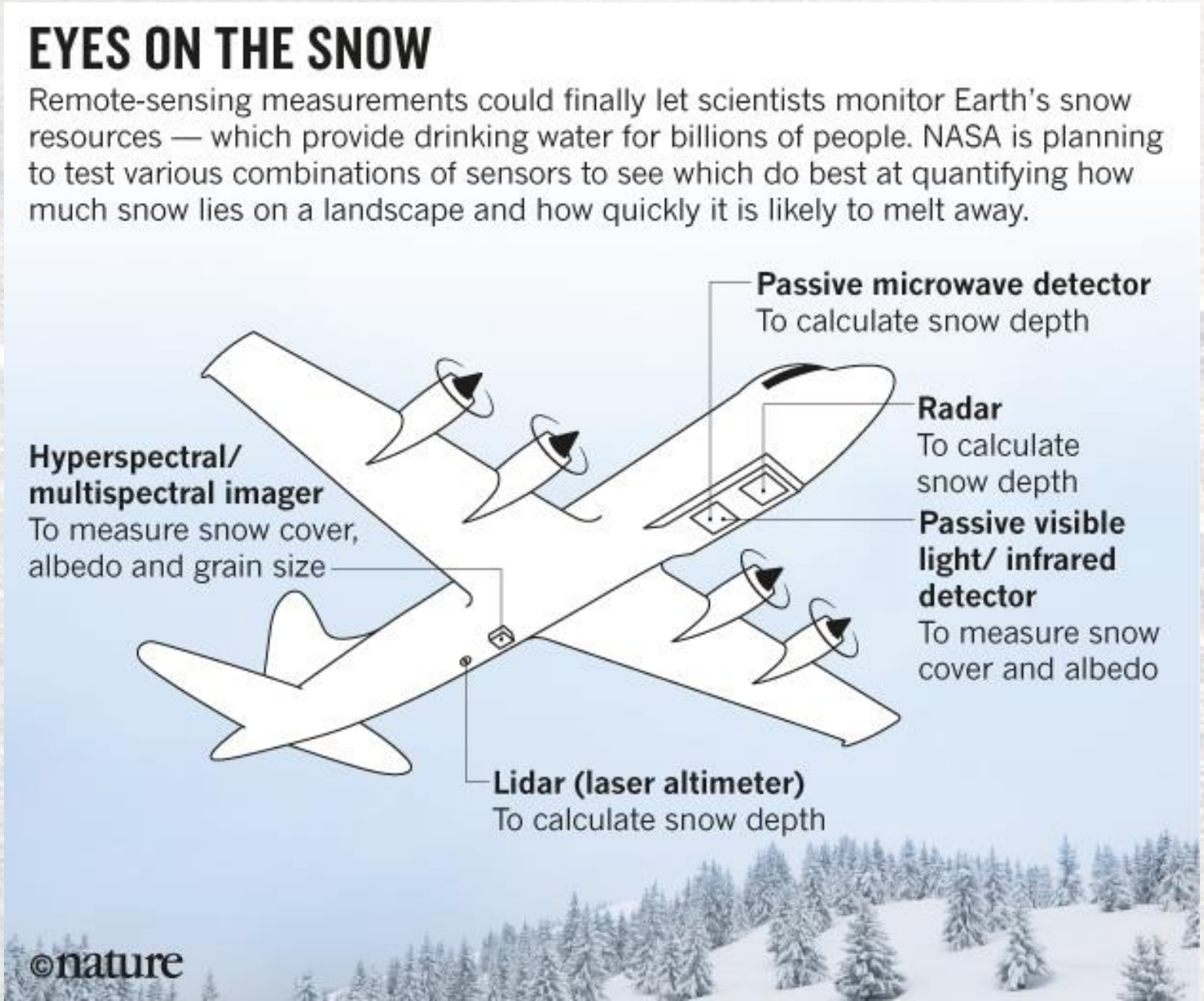
Center for Snow and Avalanche Studies

Mountain System Monitoring

- Detecting Regional Climate Change
- Collecting Integrative Datasets
  - Over 10 years of data
  - Data used for hydrologic modeling, satellite (and airborne) ground validation, and forecasting
  - Helping understand mountain meteorology and physics
- Colorado Dust-on-Snow (CODOS) Program
  - Provide water community with updates
    - Presence of dust in snowpack
    - Where dust is located in snowpack
    - When dust emergence will likely occur
  - Improves
    - Timing of snow melt forecasts
    - Rate of snow melt forecasts
    - Total runoff estimates

CSAS

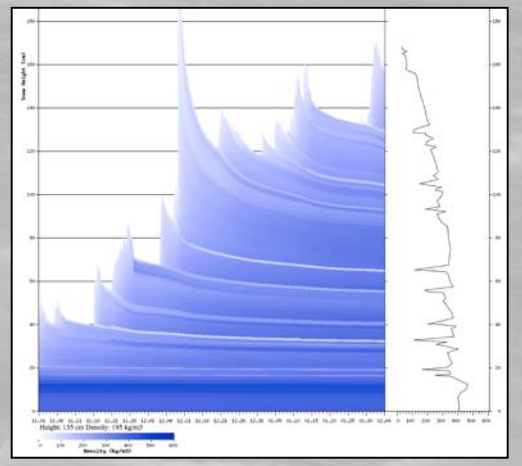
NASA SnowEx Project: https://snow.nasa.gov/snowex



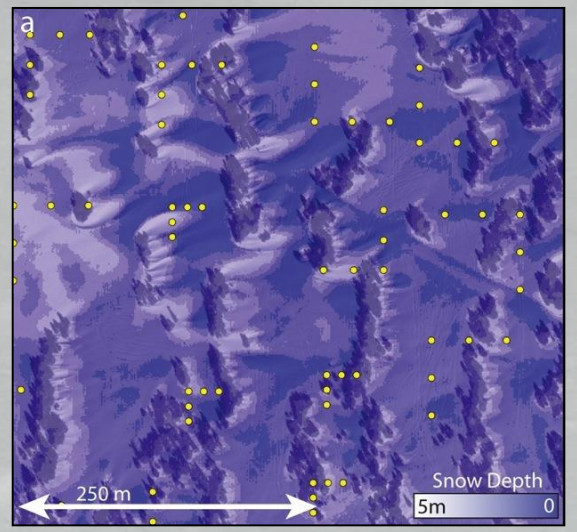
NASA Airborne Snow Observatory (ASO)

Snow Depth & SWE from LiDAR

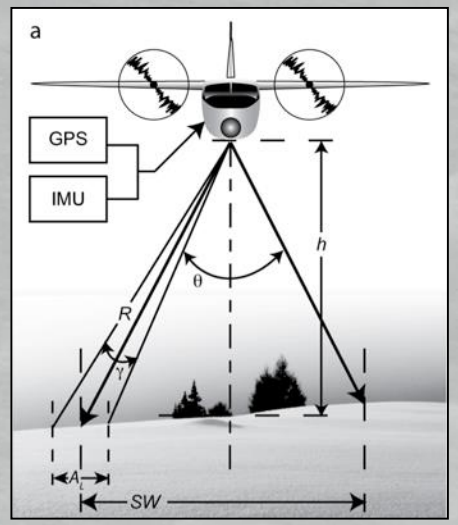
- Majority of SWE spatial variability due to snow depth
- Depth can be measured by differential elevation mapping
  - collect snow-free & snow-covered data sets
  - classify & remove vegetation points
  - subtract snow-free from snow-covered
- Apply obs/modeled density
  - SWE = depth * density
  - SNOTEL/manual obs + snow model can estimate density well

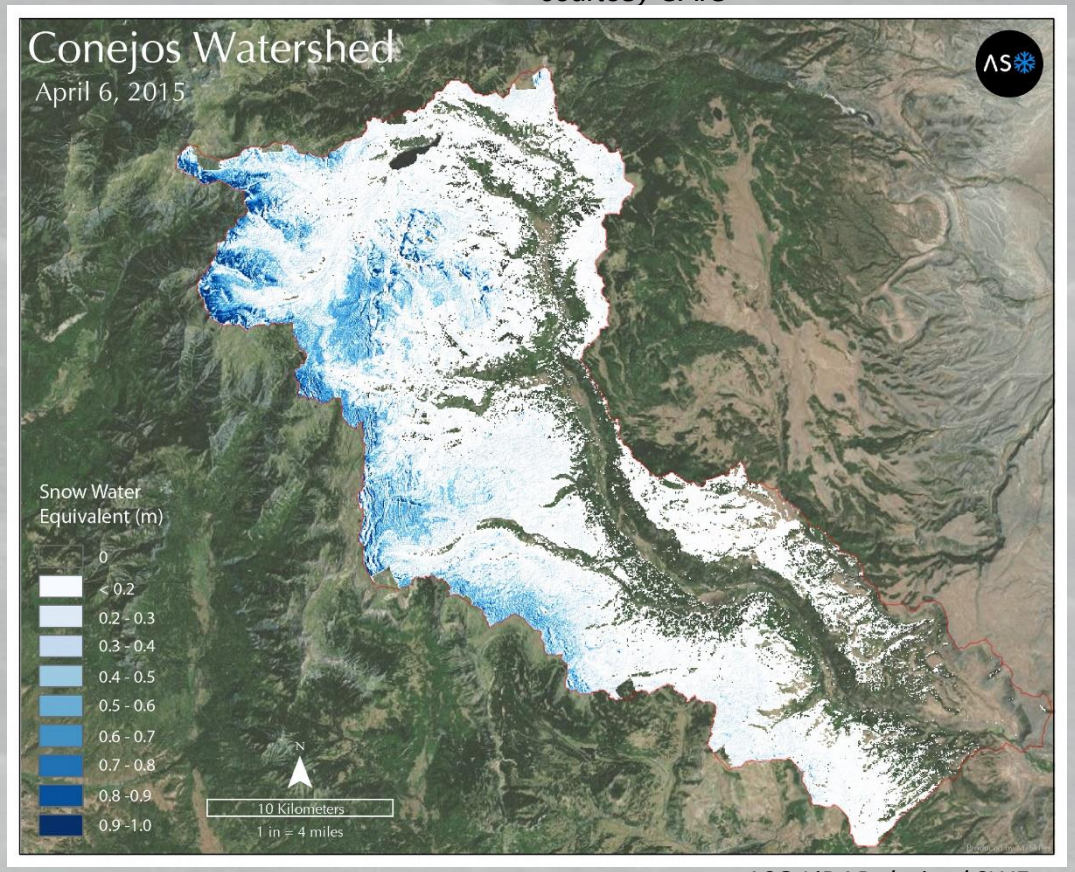


SNOWPACK courtesy CAIC



LiDAR-derived snow depth, Colorado (Deems et al., 2013)



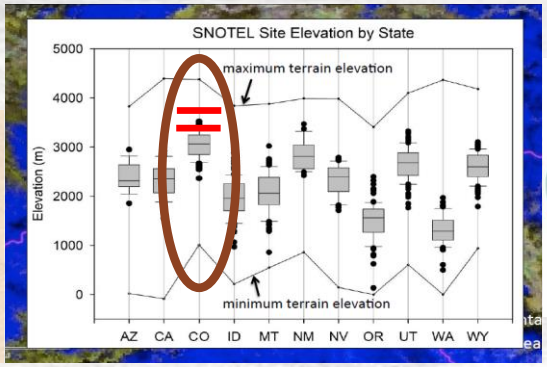


ASO LiDAR-derived SWE

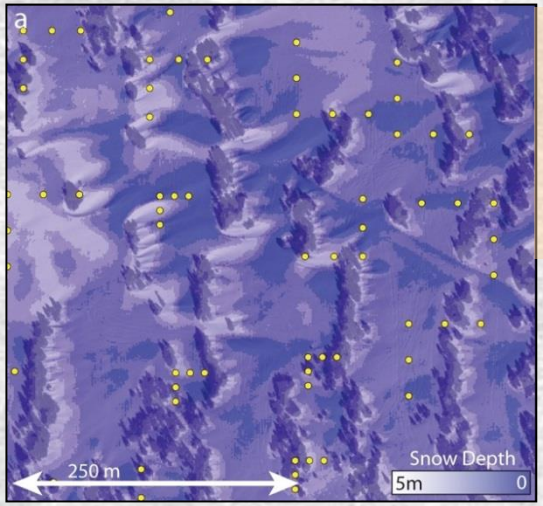
Moving Forward

Improving Data Collection & Models

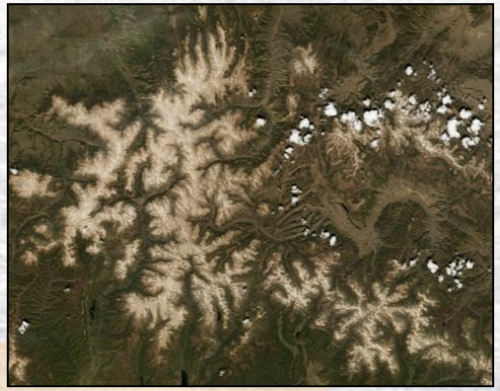
Monitoring at higher elevations



CSAS



Spatial & Temporal Resolution



Albedo → Hydrologic Models

Moving Forward

Research ←→ Application

Awareness & Education

Focused in-person workshops & field days

- CSAS workshop, Watershed Group Events, NRCS Collaborations

Identify relevance to audience, work backwards

- Open Snow –bringing snow science into snow sports
- RFC River Reports/Snowpack Reports in the media

Community Engagement

Youth Education programs

Funding & Leadership

Identify funding streams

Increase buy-in by different sectors to support data collection and model improvement

Watershed groups as leaders

- Winter season engagement
- Geographically distinct audiences, ensures coverage and relevance

Examples of Targeted Education

Snow School for Water Professionals

CSAS, Silverton, CO

Contact Jeff Derry at jderry@snowstudies.org with preferred dates in Feb/March

SCOTT CONDON/THE ASPEN TIMES

Liza Mitchell of the Roaring Fork Conservancy digs a snow pit at the summit of McClure Pass on Sunday.

Public SNOTEL Site Tours

NRCS Collaboration, McClure Pass

RFC Watershed Exploration Series

Snow Science for Kids

RFC Water Education Programs

Other ways YOU can participate & stay informed

Sign up for:

OPEN SNOW

- Local watershed group events
- RFC Weekly River/Snowpack Reports
- CSAS workshop

Reach out to relevant agencies:

NATIONAL SYSTEM OF PUBLIC LANDS
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF LAND MANAGEMENT

NRCS

U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

- University researchers
- Colorado Water Conservation Board
- Local Water Utilities
- Regional Conservation Districts

Give us suggestions:

liza@roaringfork.org // jderry@snowstudies.org

Keep the conversation going – workshop here next year??