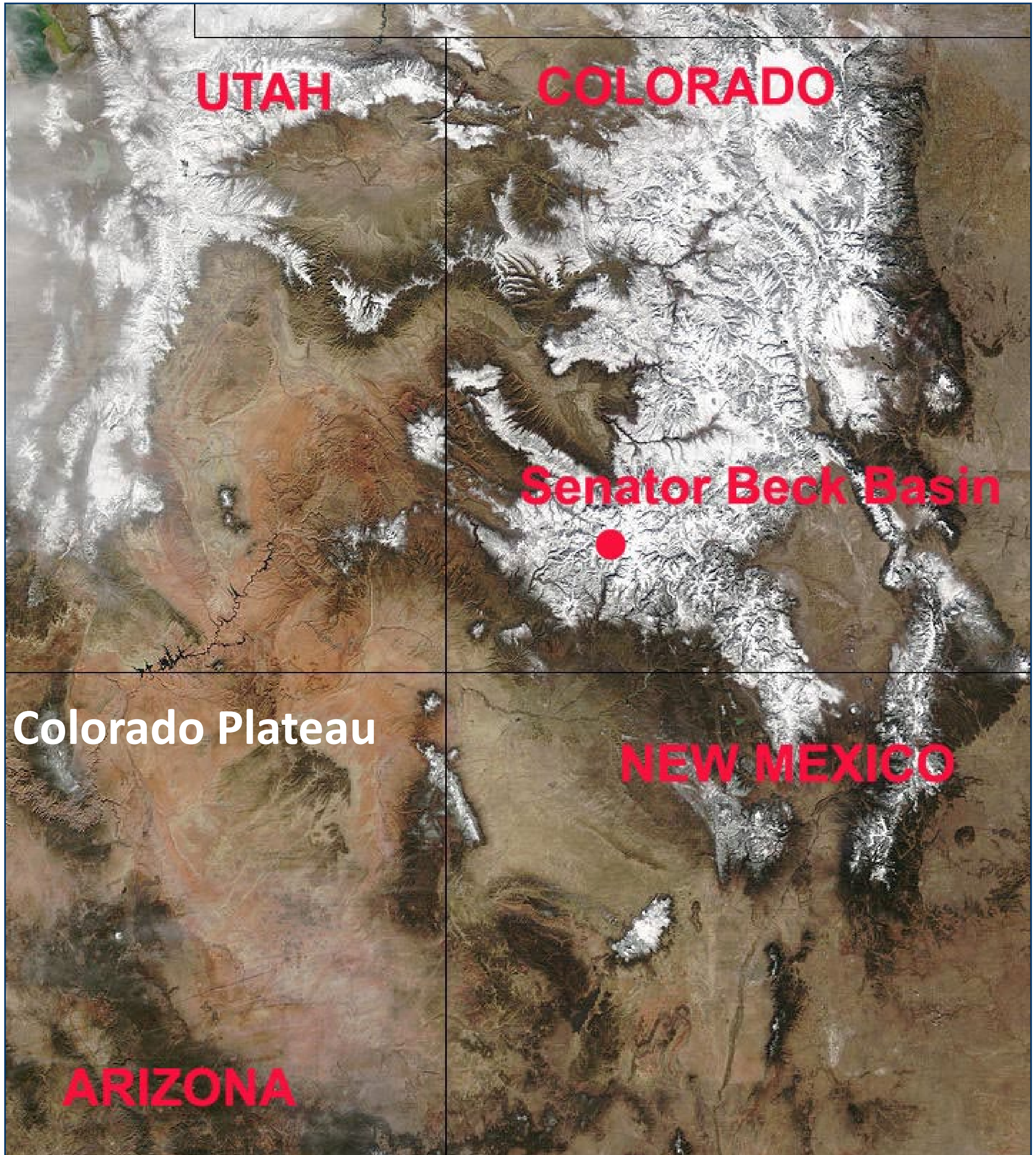
CSAS

Center for Snow & Avalanche Studies

Roaring Fork Conservancy
Basalt, CO
January 30, 2024

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



Snow = Water

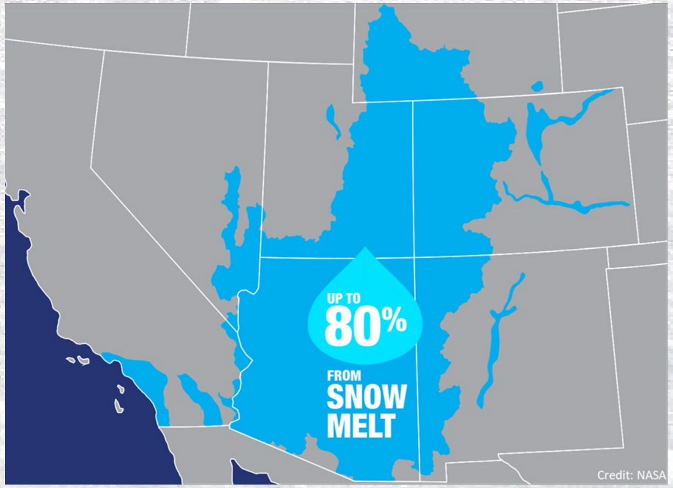
Todays Talk

- Snow
- Measuring Snow
- Snowpack/Climate Trends
- Dust-on-Snow
- Modeling/Forecasting

Why so critical?

- agriculture
- storage
- hydropower
- recreation
- municipal
- industry
- environment
- downstream compacts

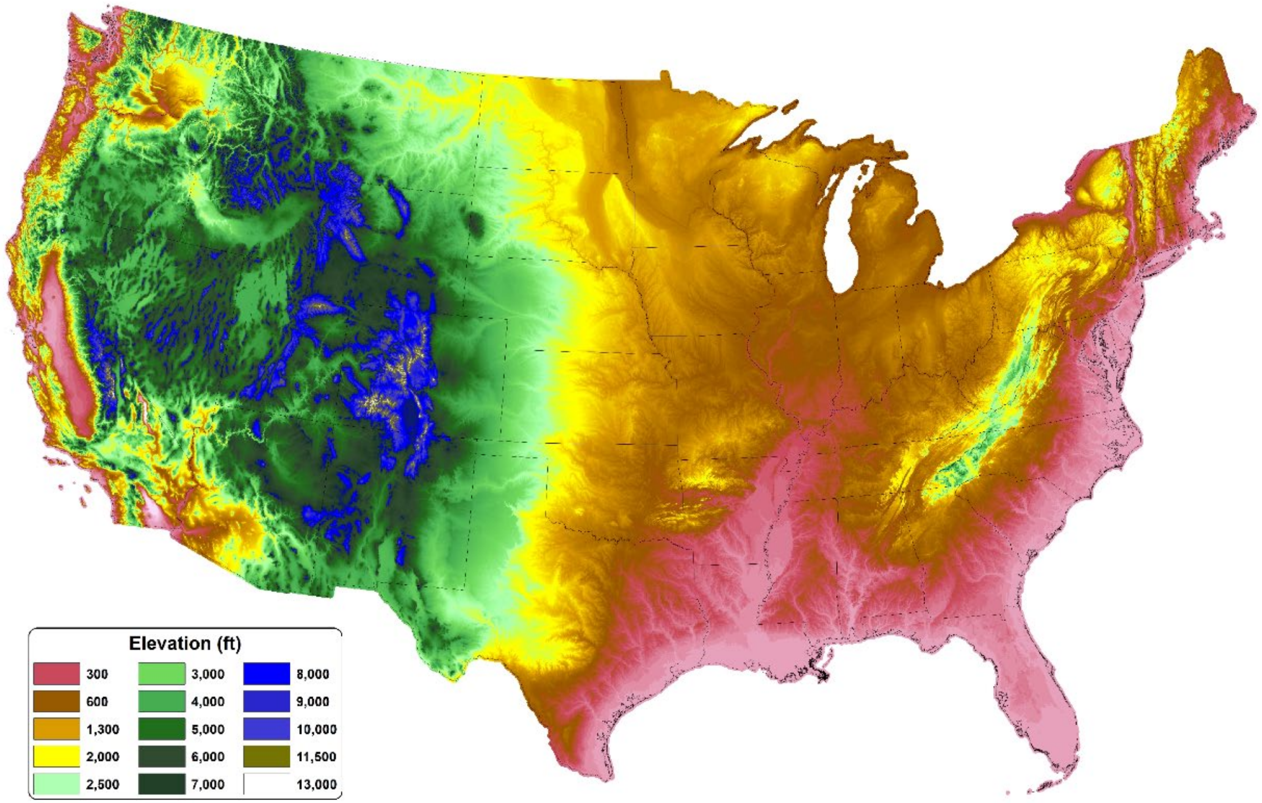
- Most precipitation falls as snow
- Annual peak in the hydrograph
- In the Western United States (U.S.) 80% of the annual discharge originates from snowmelt in the mountain watershed
- About 15% of the surface area of the basin contributes about 85% of the average annual runoff
- 70% of water at Lee’s Ferry, below Lake Powell, comes from Colorado
- Snowpack is natural reservoir & water tower



Credit: NASA

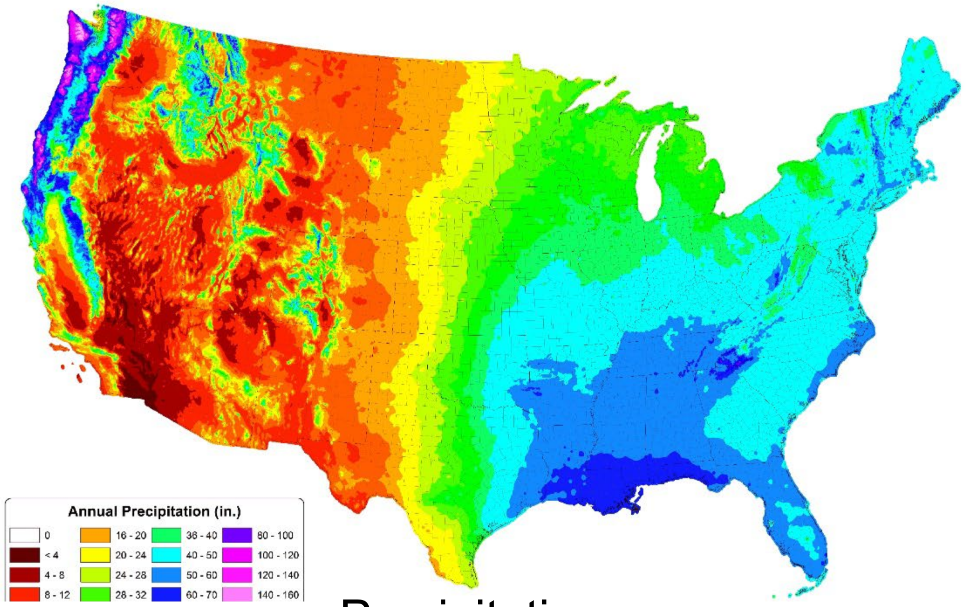
Variability =

- Mid latitude
- Intercontinental
- Elevation, topography



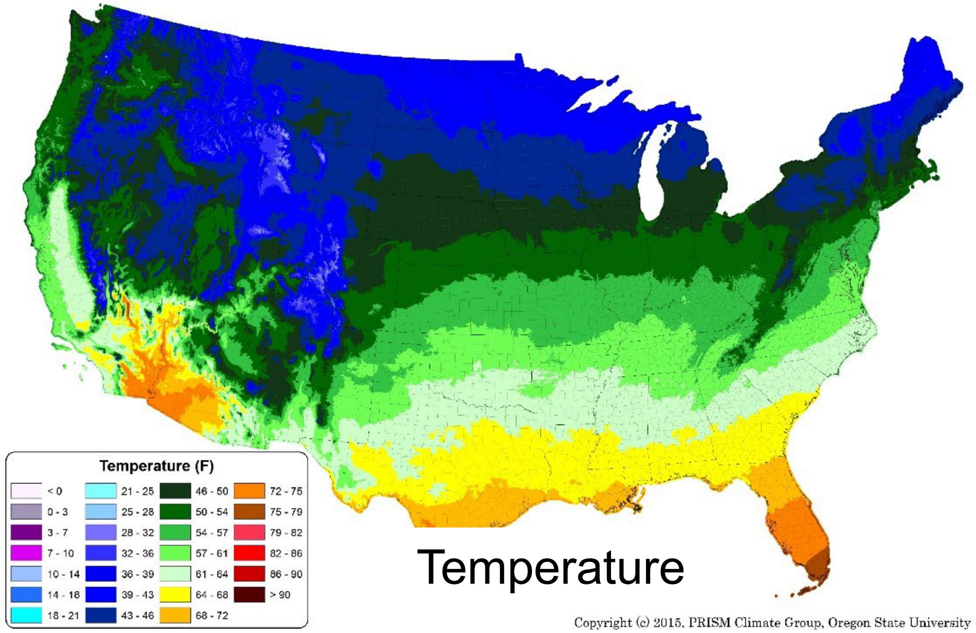
Elevation

30-yr Normal Precipitation: Annual
Period: 1981-2010



Precipitation

30-yr Normal Mean Temperature: Annual
Period: 1981-2010

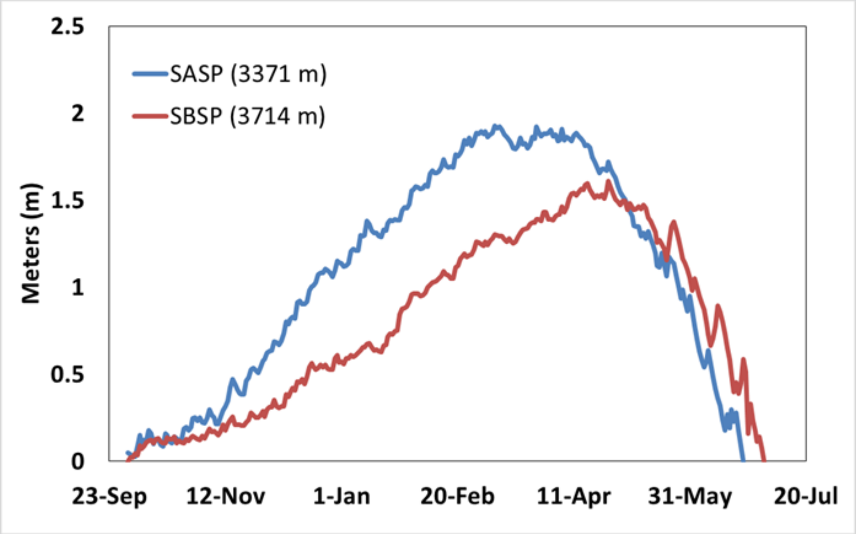


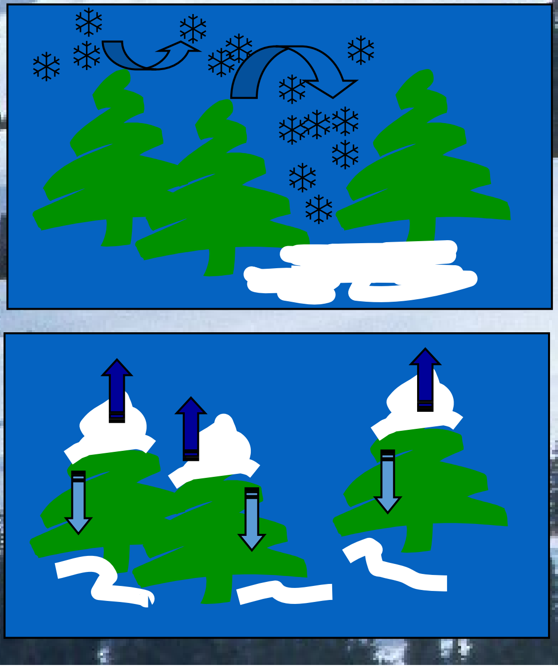
Temperature

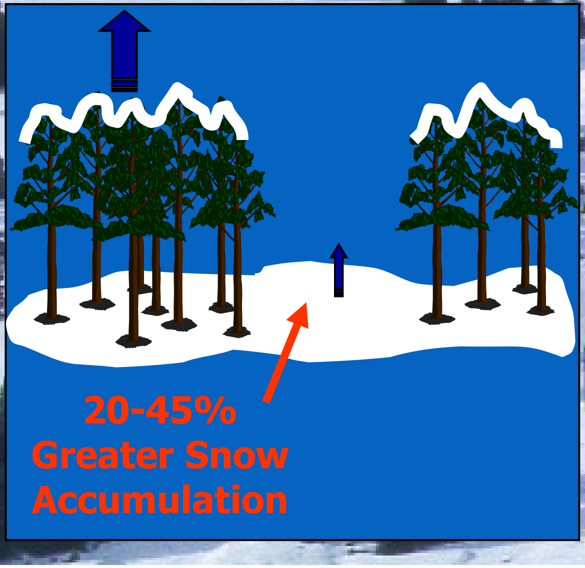
Snow Cover Distribution

Snowpack amount varies in space and time

- Elevation
- Aspect
- Wind Redistribution
- Vegetation and Tree Interception
- Topography



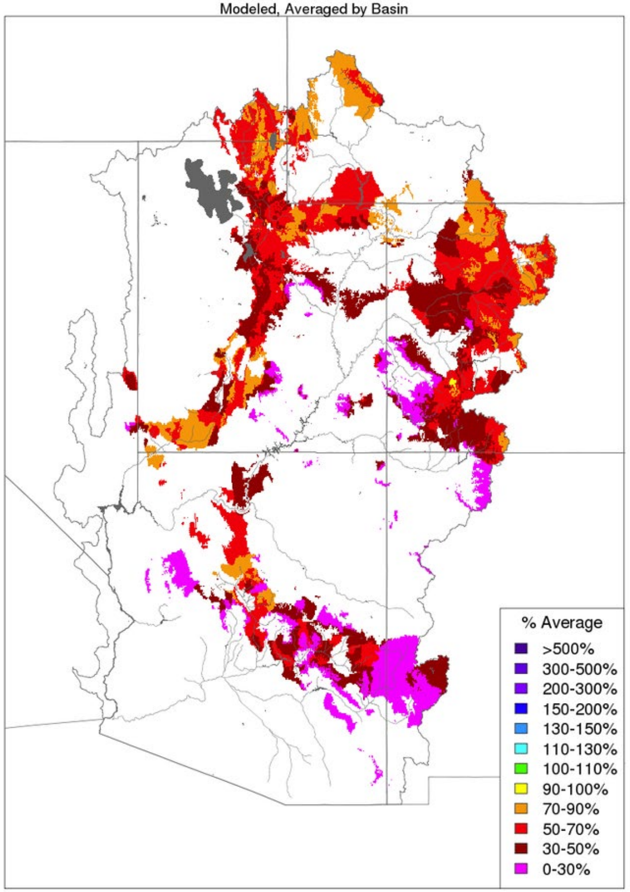




20-45% Greater Snow Accumulation

Soil Moisture - Fall - 2020 (November 15)

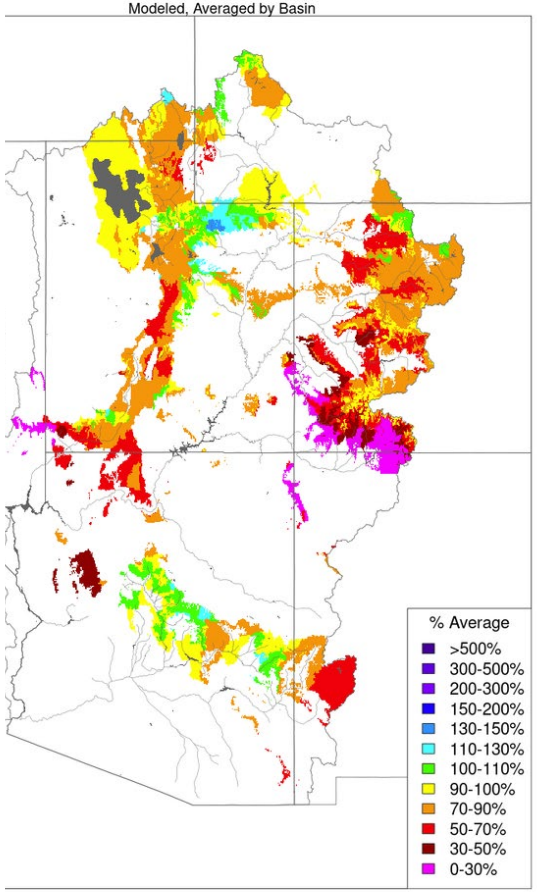
Modeled, Averaged by Basin



Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov

Soil Moisture - Fall - 2021 (November 15)

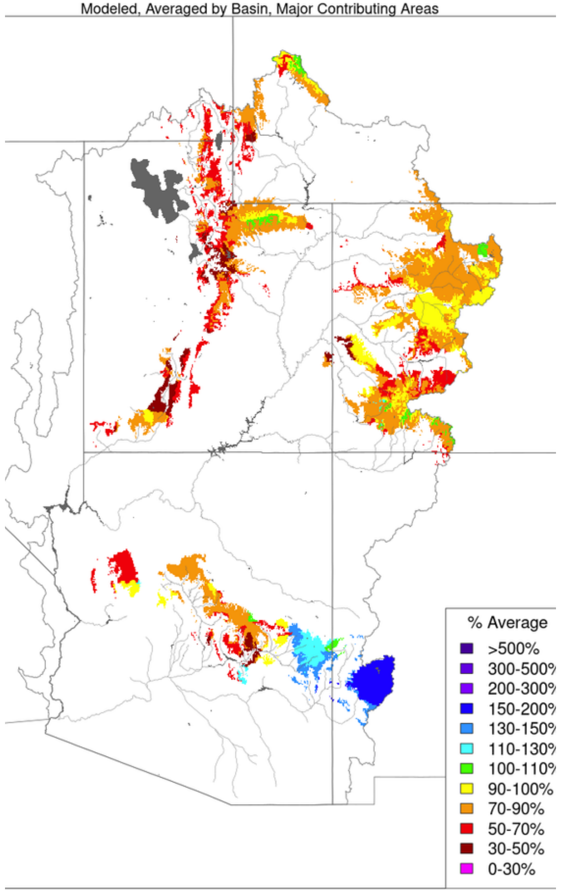
Modeled, Averaged by Basin



Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov

Soil Moisture - Fall - 2022 (November 02)

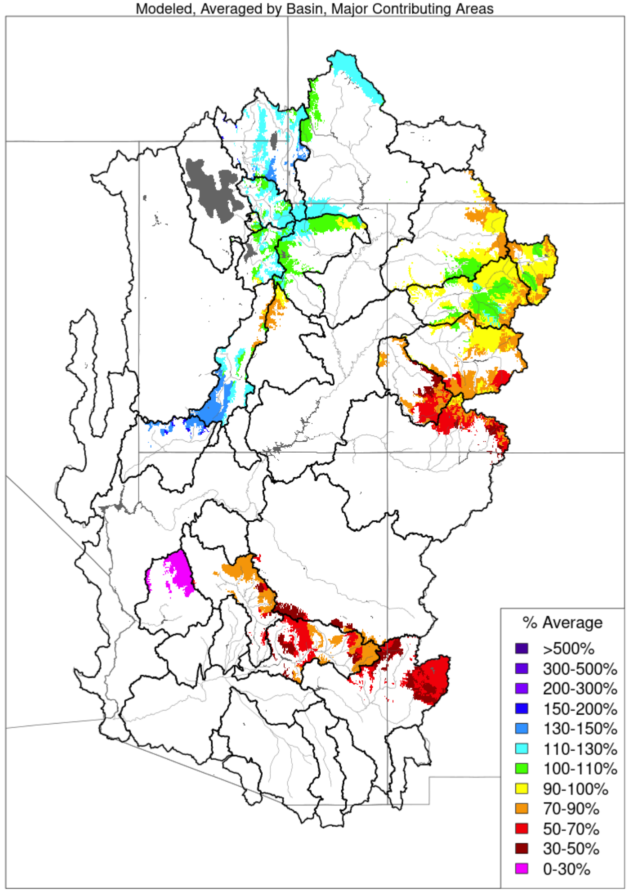
Modeled, Averaged by Basin, Major Contributing Areas



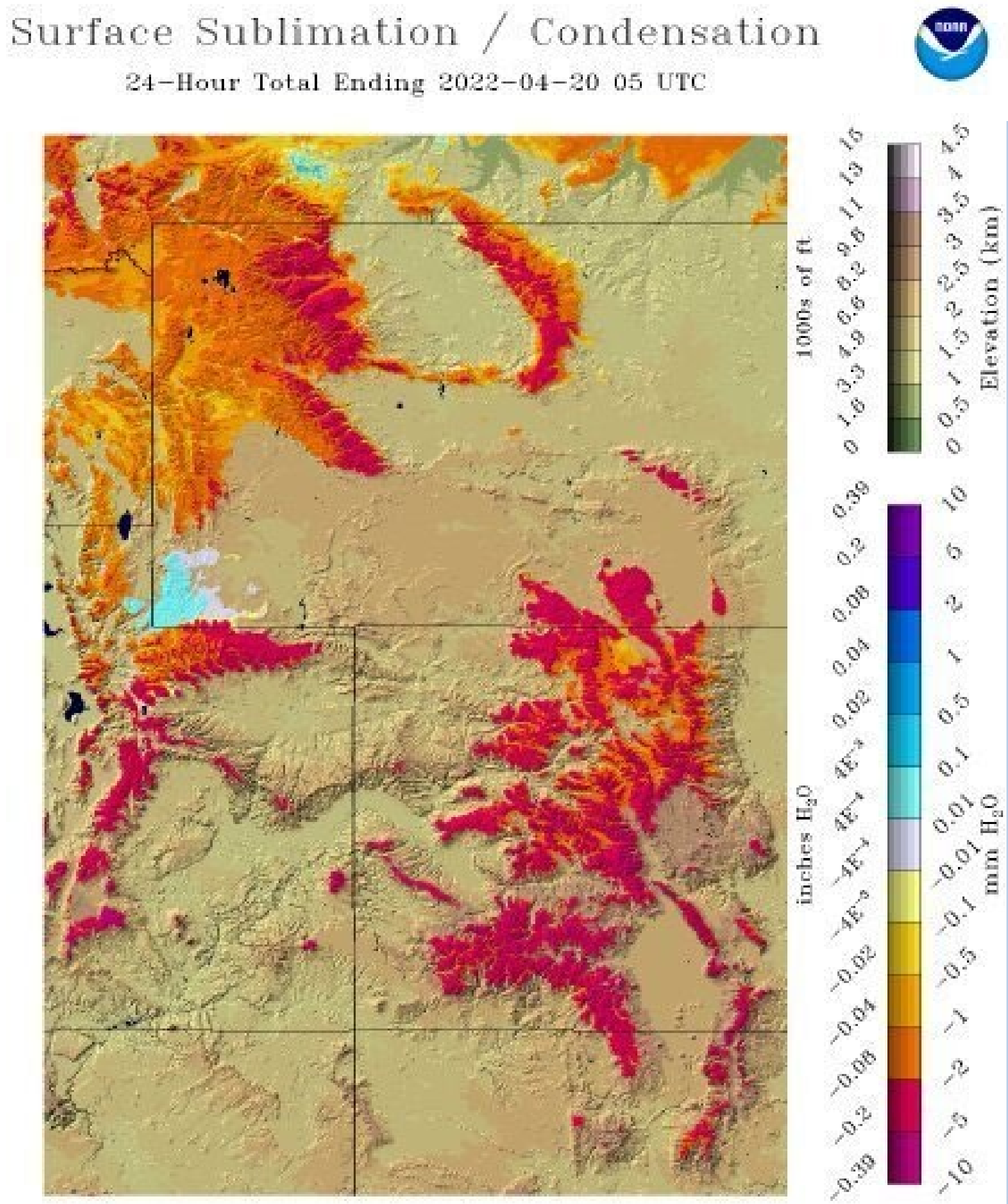
Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov

Soil Moisture - Fall - 2023 (November 15)

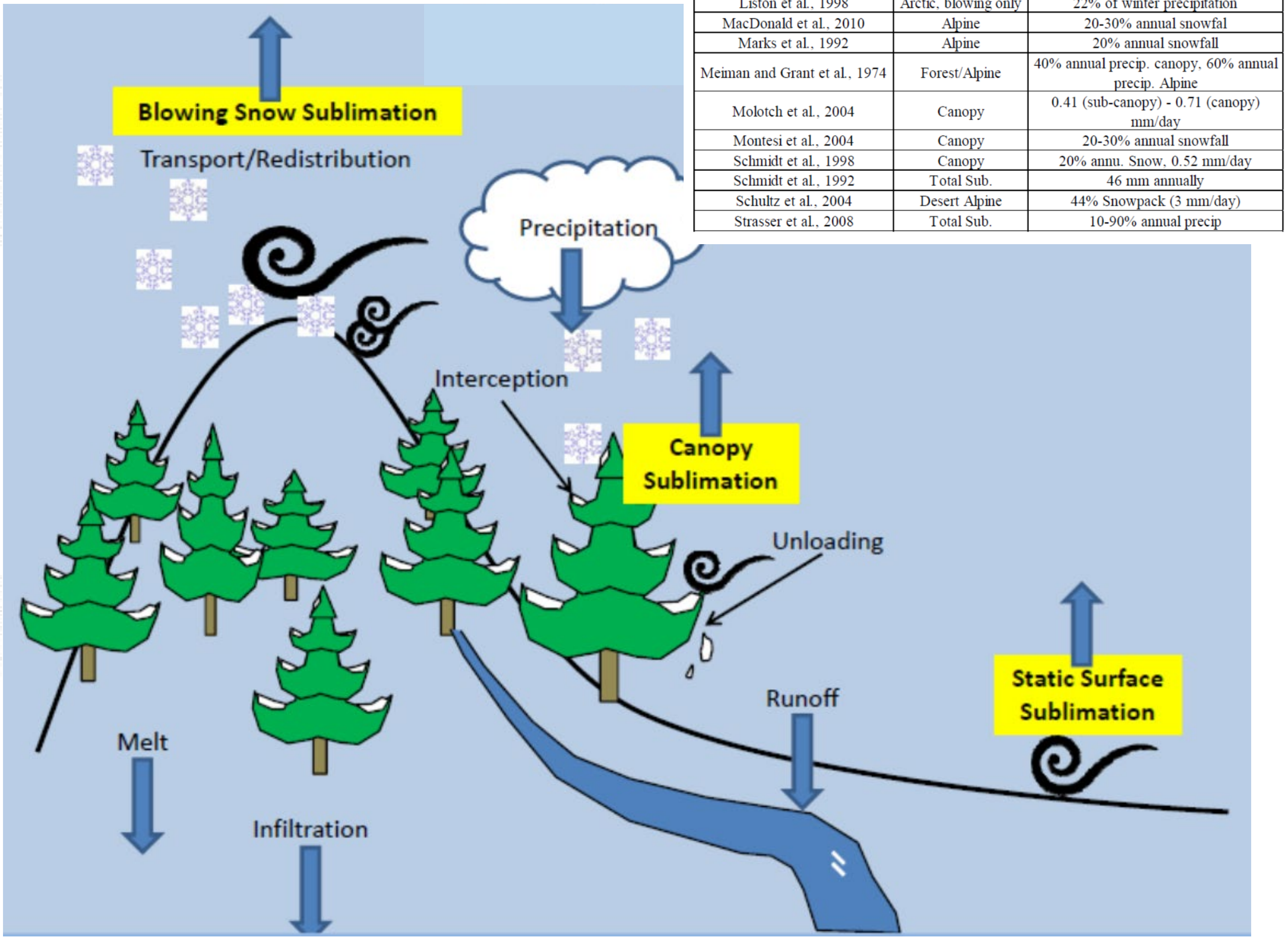
Modeled, Averaged by Basin, Major Contributing Areas



Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov



Author	Type	Amount
Avery et al., 1992	Static	1.56 mm/day (max of 8.52 mm/day)
Harding et al., 1996	Canopy	4 mm in 36 hours
Hood et al., 1994	Static and blowing	15% annual precip.
Kattleman et al., 1991	Alpine	1-2 mm/day, 18% ann. Precip.
Lundberg et al., 1994	Canopy	0.3 mm/hr
Liston et al., 1998	Arctic, blowing only	22% of winter precipitation
MacDonald et al., 2010	Alpine	20-30% annual snowfal
Marks et al., 1992	Alpine	20% annual snowfall
Meiman and Grant et al., 1974	Forest/Alpine	40% annual precip. canopy, 60% annual precip. Alpine
Molotch et al., 2004	Canopy	0.41 (sub-canopy) - 0.71 (canopy) mm/day
Montesi et al., 2004	Canopy	20-30% annual snowfall
Schmidt et al., 1998	Canopy	20% annu. Snow, 0.52 mm/day
Schmidt et al., 1992	Total Sub.	46 mm annually
Schultz et al., 2004	Desert Alpine	44% Snowpack (3 mm/day)
Strasser et al., 2008	Total Sub.	10-90% annual precip



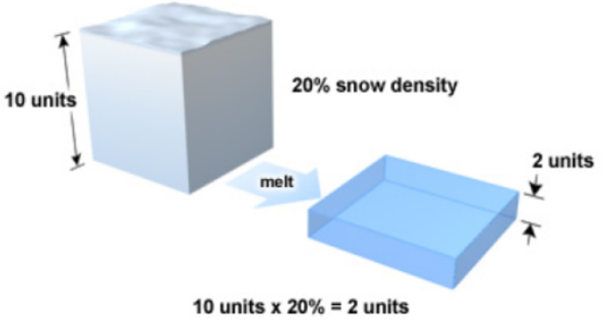
OWP OFFICE OF WATER PREDICTION

National Snow Analysis

Snow Measurement

Hydrologists are most interested in the snow water equivalent (SWE) of snow

Snow Water Equivalent (SWE)



©The COMET Program

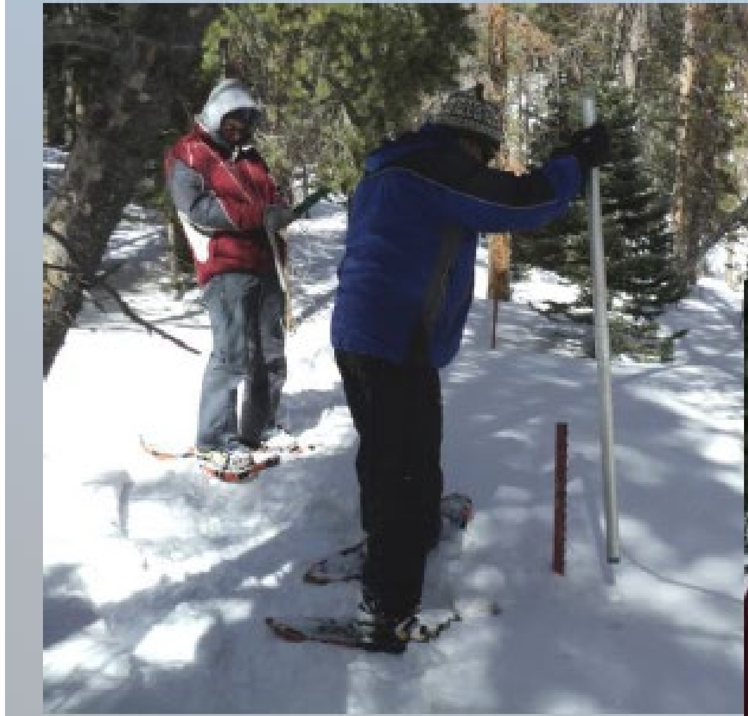
- Precipitation
  - Snowfall
- Snow on the ground
  - Depth
  - Density
  - SWE

Snow Pits

Snow Courses with Snow Tube

Snow Pillows, SNOTEL Stations

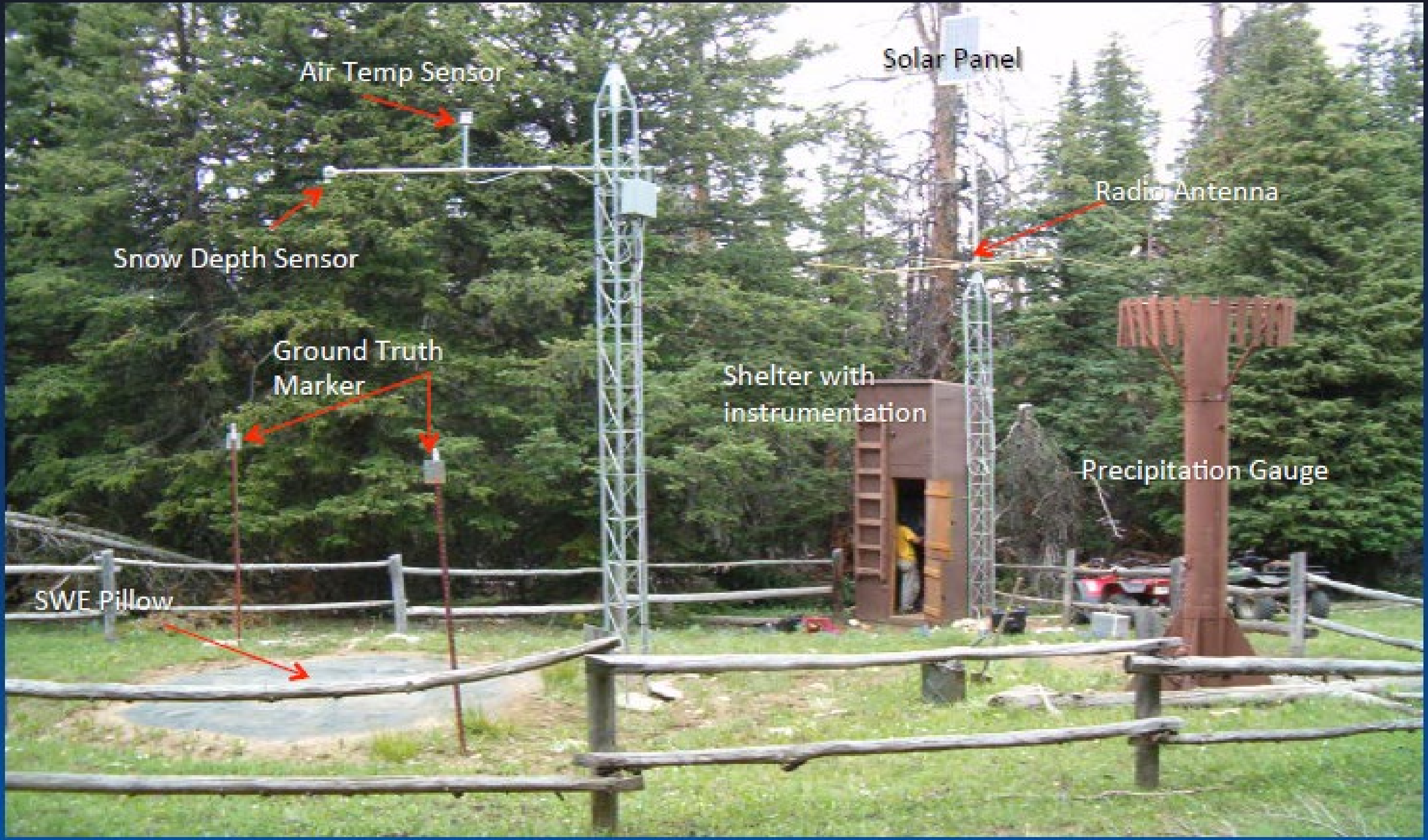
NRCS Snow course



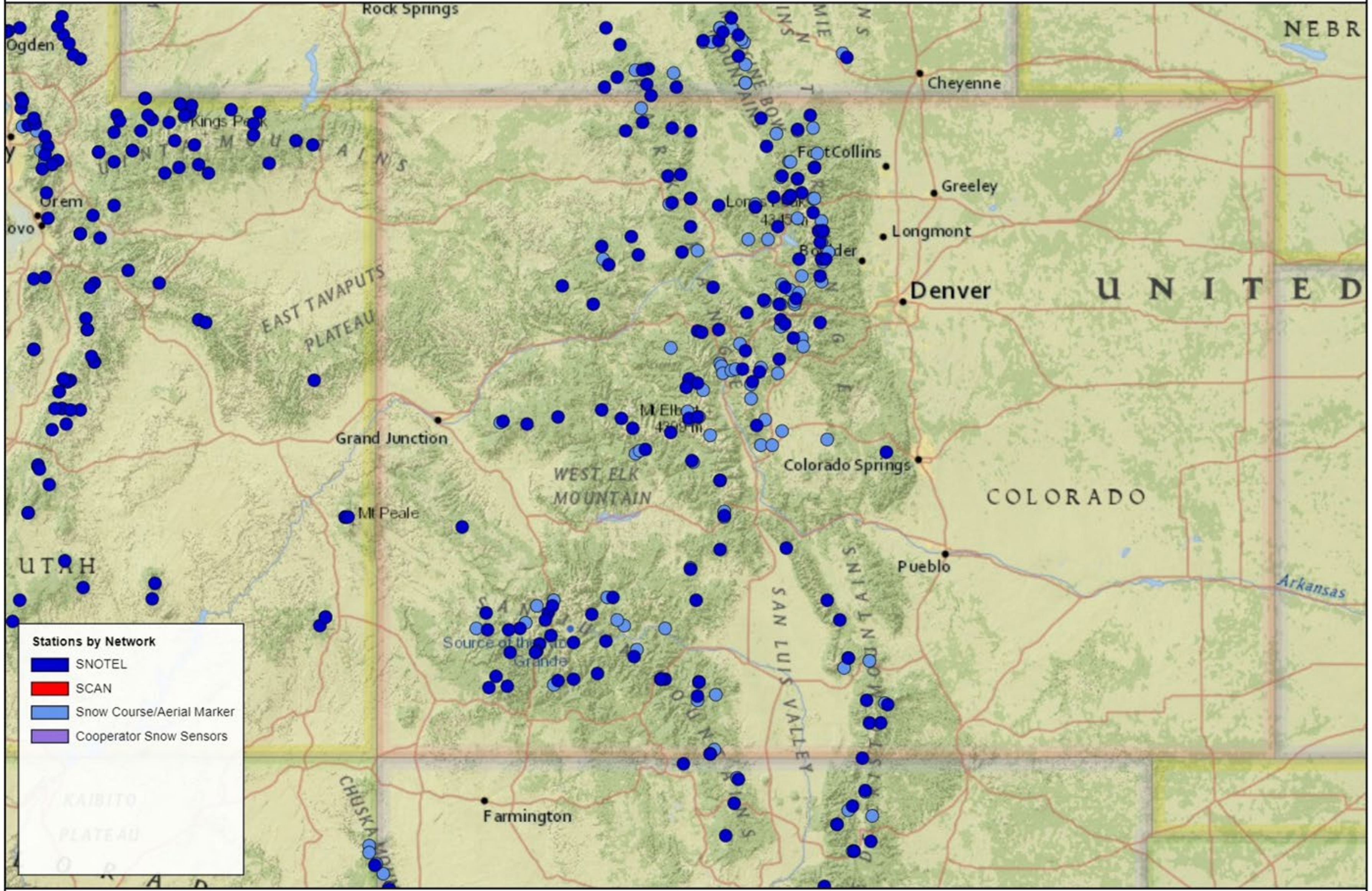
weigh sample, subtract weight of sample tube, result is SWE in inches of water

Idarado Snow Course

Anatomy of a SNOTEL site



Stations by Network



USDA Natural Resources Conservation Service
United States Department of Agriculture

N

0 10 20 40 60 80 100 Miles

Created 1-04-2020

snow station data

snow course measurements

- higher spatial representation/coverage
- lower temporal resolution
- statistics (compute variability)

SNOw TELemetry (SNOTEL)

- lower spatial representation/coverage
- higher temporal resolution
- additional measurements collected

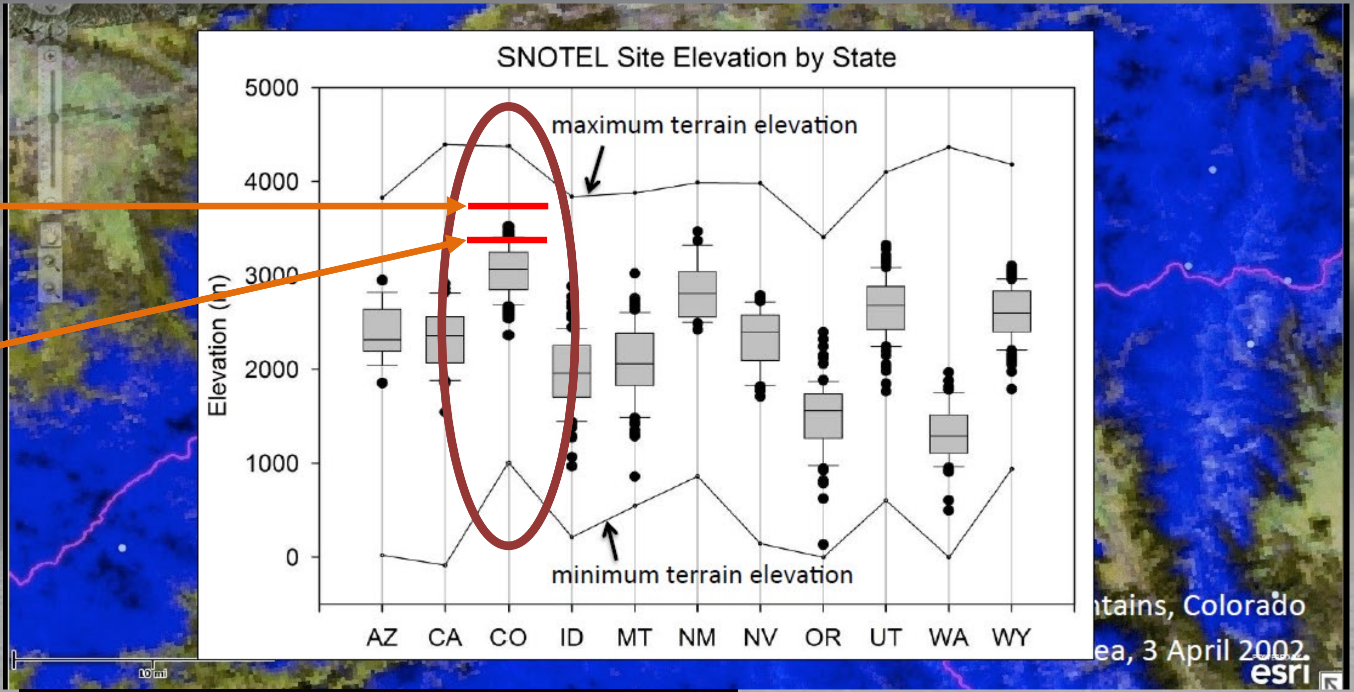
Additional Considerations

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

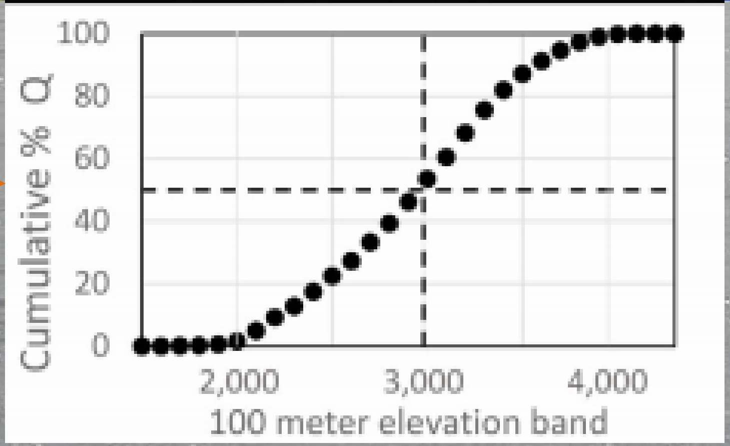
Center for Snow and Avalanche Studies
Helping Fill the Monitoring Gap at Higher Elevations

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

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



Upper Colorado River Basin: 50% of streamflow is generated above 9,843’ (3,000 m)



Snowpack monitoring workshop for drought planning and Streamflow Forecasting: Broomfield, Colorado. September 9, 2015. http://wwa.colorado.edu/events/workshops/COsnow2015.html . Measuring and Modeling our Snow Water Resources
Presented by Jeff Deems & Noah Molotch

Upper Colorado River Basin: 40% of streamflow is generated above all SNOTEL’s

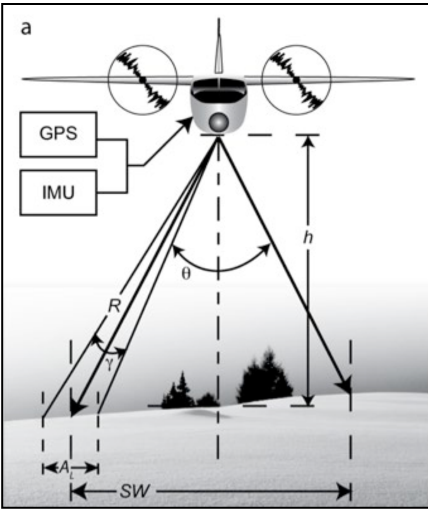
Airborne Snow Observatory (ASO)

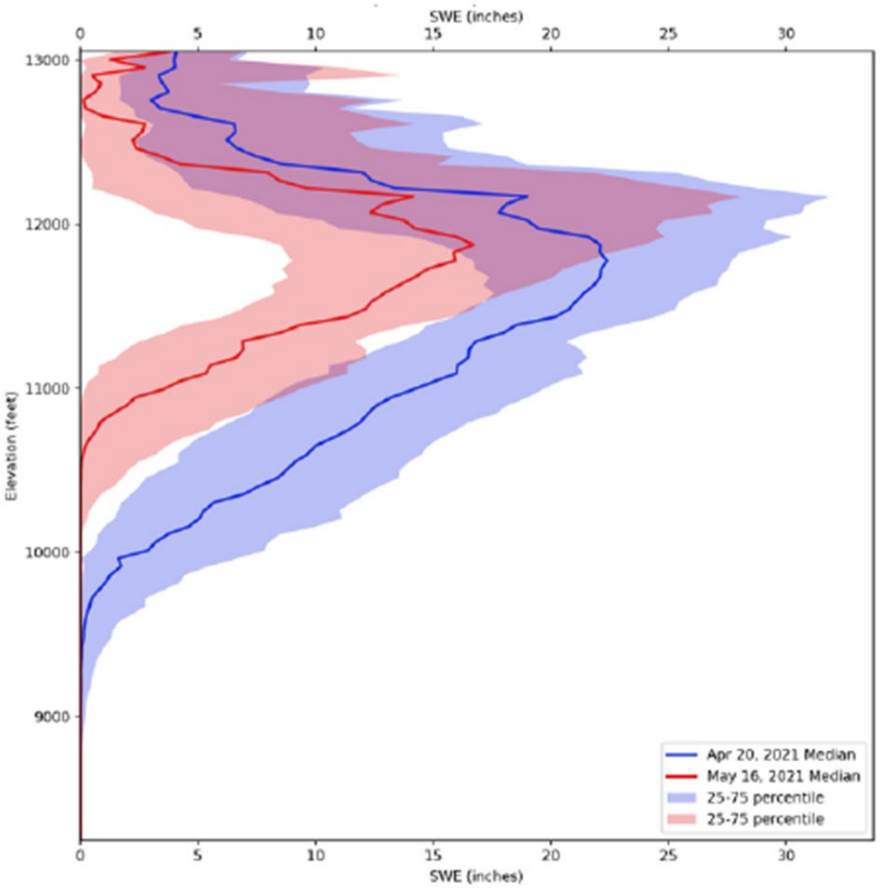
Snow Depth & SWE from LiDAR

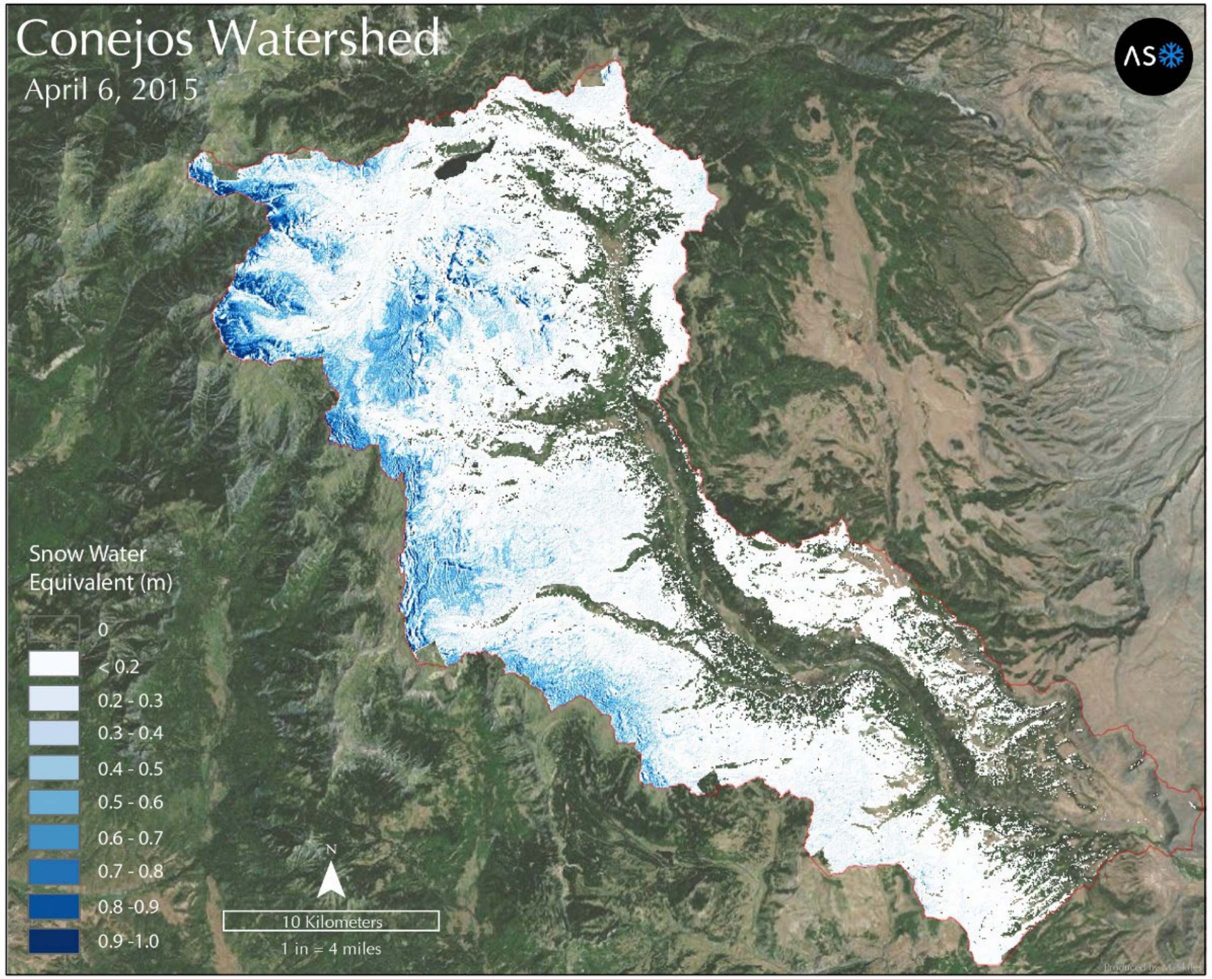
- Majority of SWE spatial variability due to snow depth
- Depth can be measured by differential elevation mapping
  - collect snow-free & snow-covered data sets
- Apply obs/modeled density (SWE = depth * density)

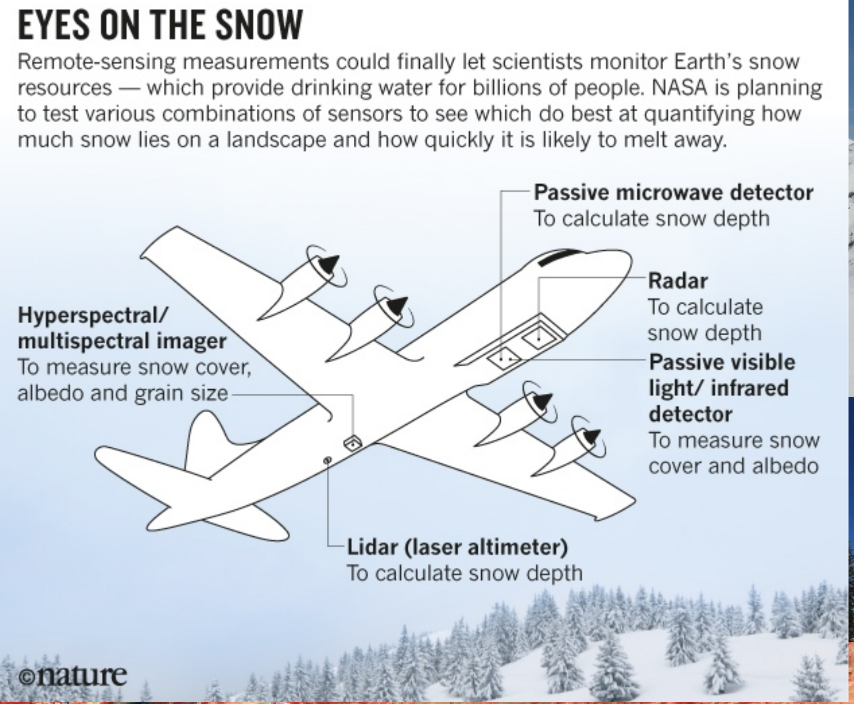
LiDAR-derived snow depth, Colorado (Deems et al., 2013)

ASO LiDAR-derived SWE









EYES ON THE SNOW

Remote-sensing measurements could finally let scientists monitor Earth's snow resources — which provide drinking water for billions of people. NASA is planning to test various combinations of sensors to see which do best at quantifying how much snow lies on a landscape and how quickly it is likely to melt away.

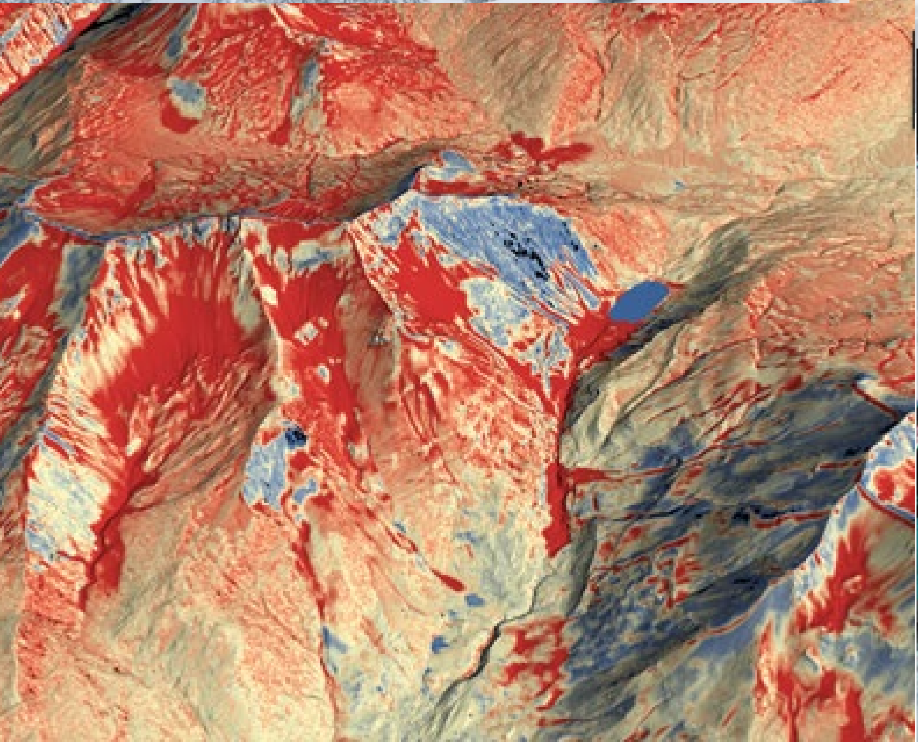
Passive microwave detector
To calculate snow depth

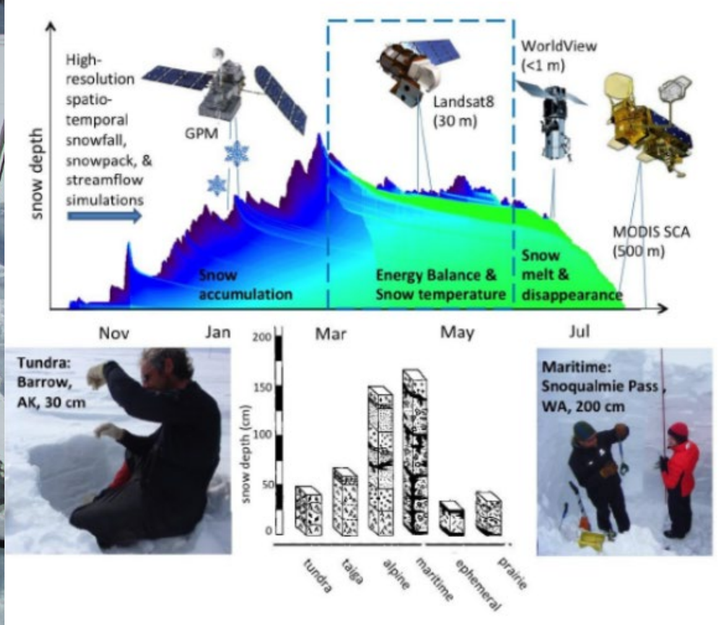
Radar
To calculate snow depth

Hyperspectral/ multispectral imager
To measure snow cover, albedo and grain size

Passive visible light/ infrared detector
To measure snow cover and albedo

Lidar (laser altimeter)
To calculate snow depth





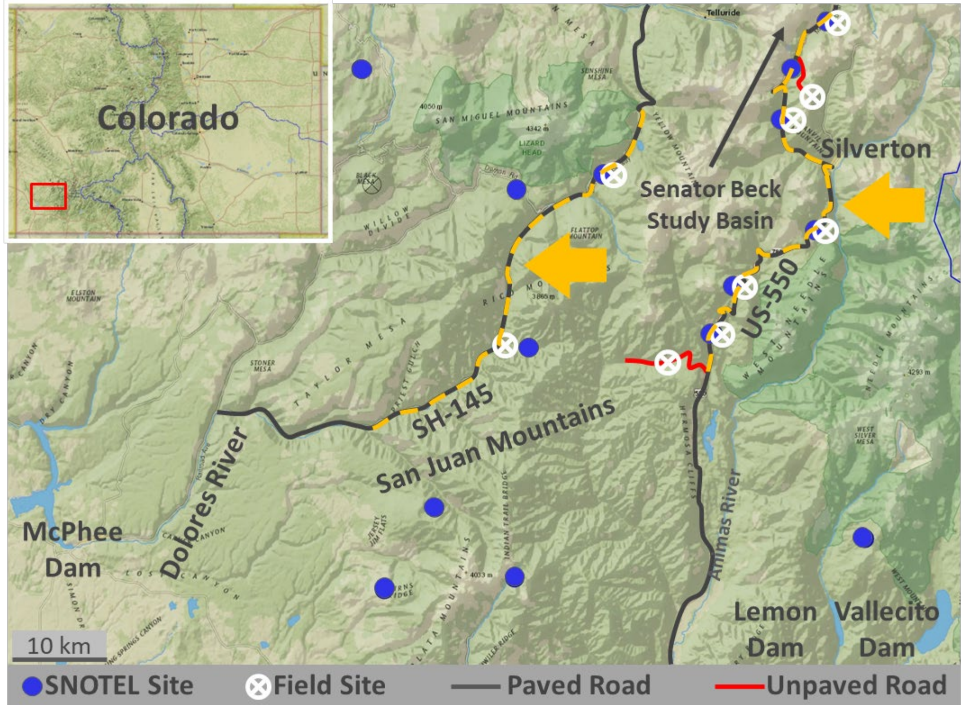
Snow Water Supply Forecasting Program

Demonstration and Evaluation of a Cosmic Ray Neutron Rover as an Emerging Snow Monitoring Technology for Improved Water Management

BUREAU OF RECLAMATION

CSAS

- Cosmic rays produce high-energy/fast neutrons in the atmosphere. When these neutrons interact with hydrogen, their energy is moderated. CRN sensor passively counts epithermal/fast neutrons. Count is inversely proportional to the quantity of hydrogen near the sensor
- Animas, Uncompahgre, and Dolores basins
- Wide range of accessible elevations and variable snowpack
- Highly-instrumented Senator Beck Study Basin

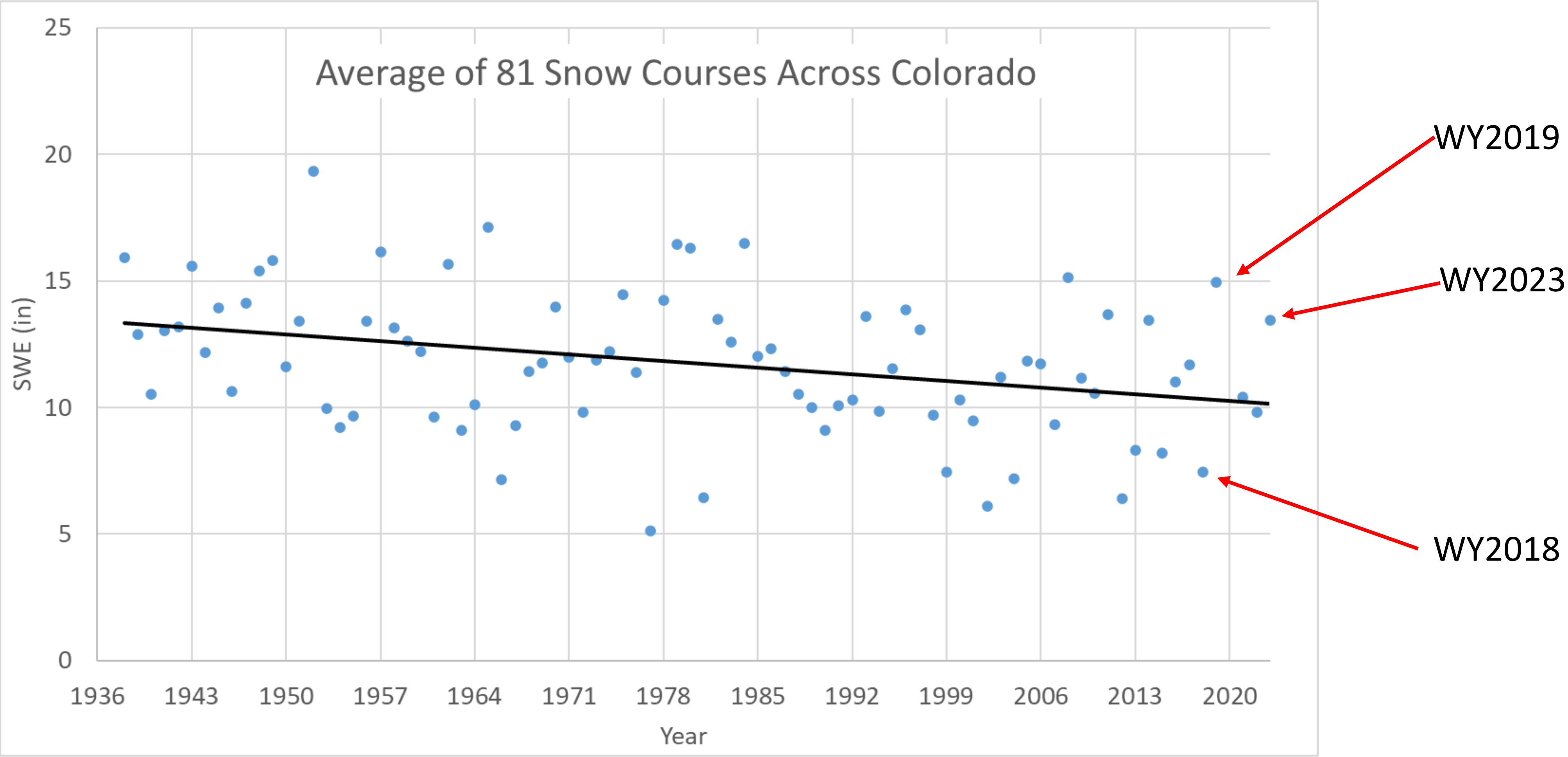


Benefits of CRN Rover

- Provides SWE with a *footprint* not achieved by traditional in-situ methods
- *Mobility* allows data collection where and when it is most critical
- Rapid data collection (~1 minute)
- *Highest sensitivity* occurs when SWE observations are most important for runoff predictions (late in season)

Less Snow

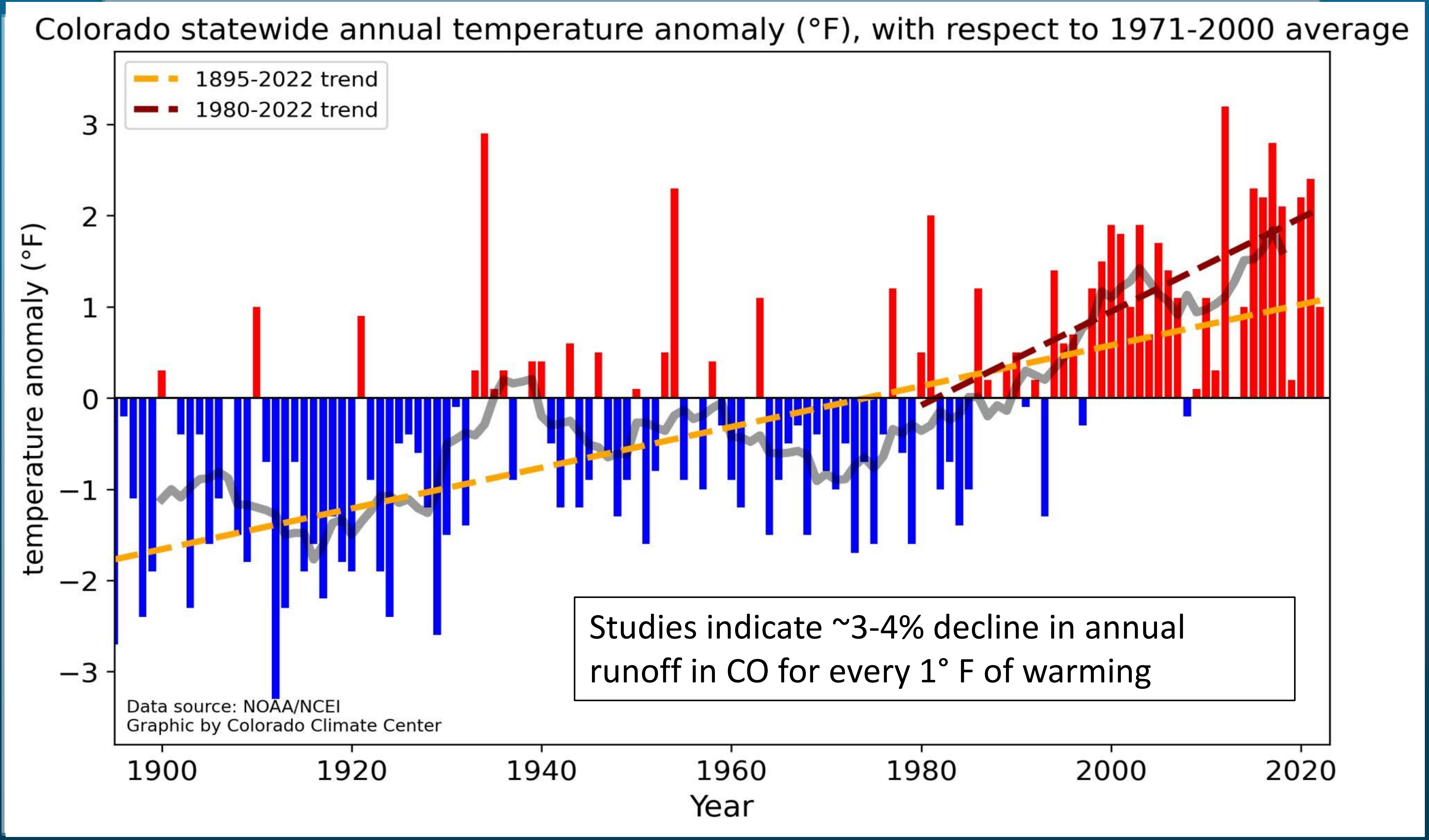
- In Western US over the last 40 years snowpack has diminished by 41%
- Snow season has become 34 days shorter on average
- In Colorado annual snowcourse data taken April 1st since 1959 show 20-60% decline



WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

http://wwa.colorado.edu

Colorado has warmed by 2°F in 30 years



Studies indicate ~3-4% decline in annual runoff in CO for every 1° F of warming

Data source: NOAA/NCEI
Graphic by Colorado Climate Center

Source: Updated from Lukas et al., *Climate Change in Colorado*, 2014; Data (1900-2017): NOAA NCEI; http://www.ncdc.noaa.gov/cag/; (2018) METDATA/gridMET (U. of Idaho) rescaled to match NOAA NCEI average (https://app.climateengine.org/)

Colorado Dust-on-Snow Program

SASP
May 13, 2013

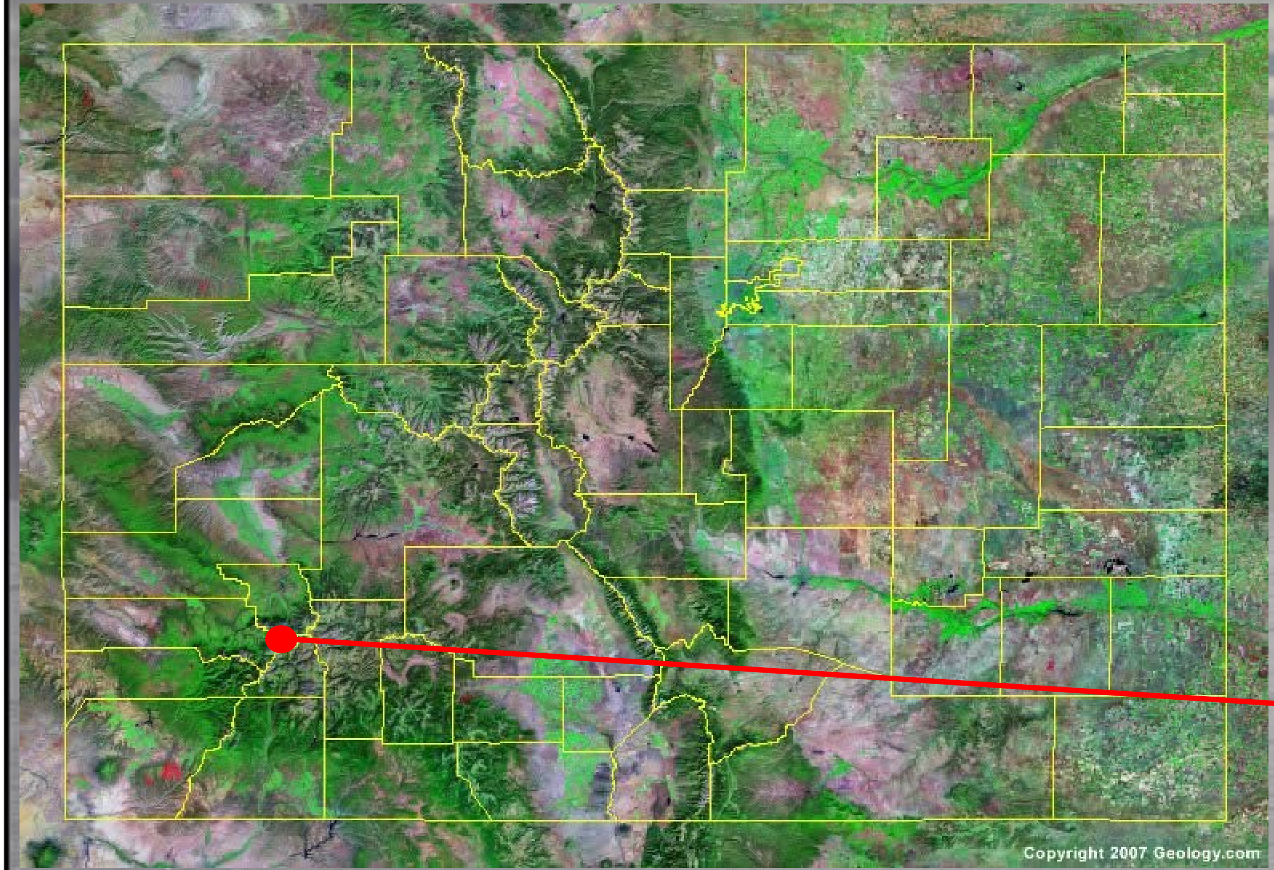
May 12, 2009 – from Peak 13,510', Senator Beck Basin Study Area

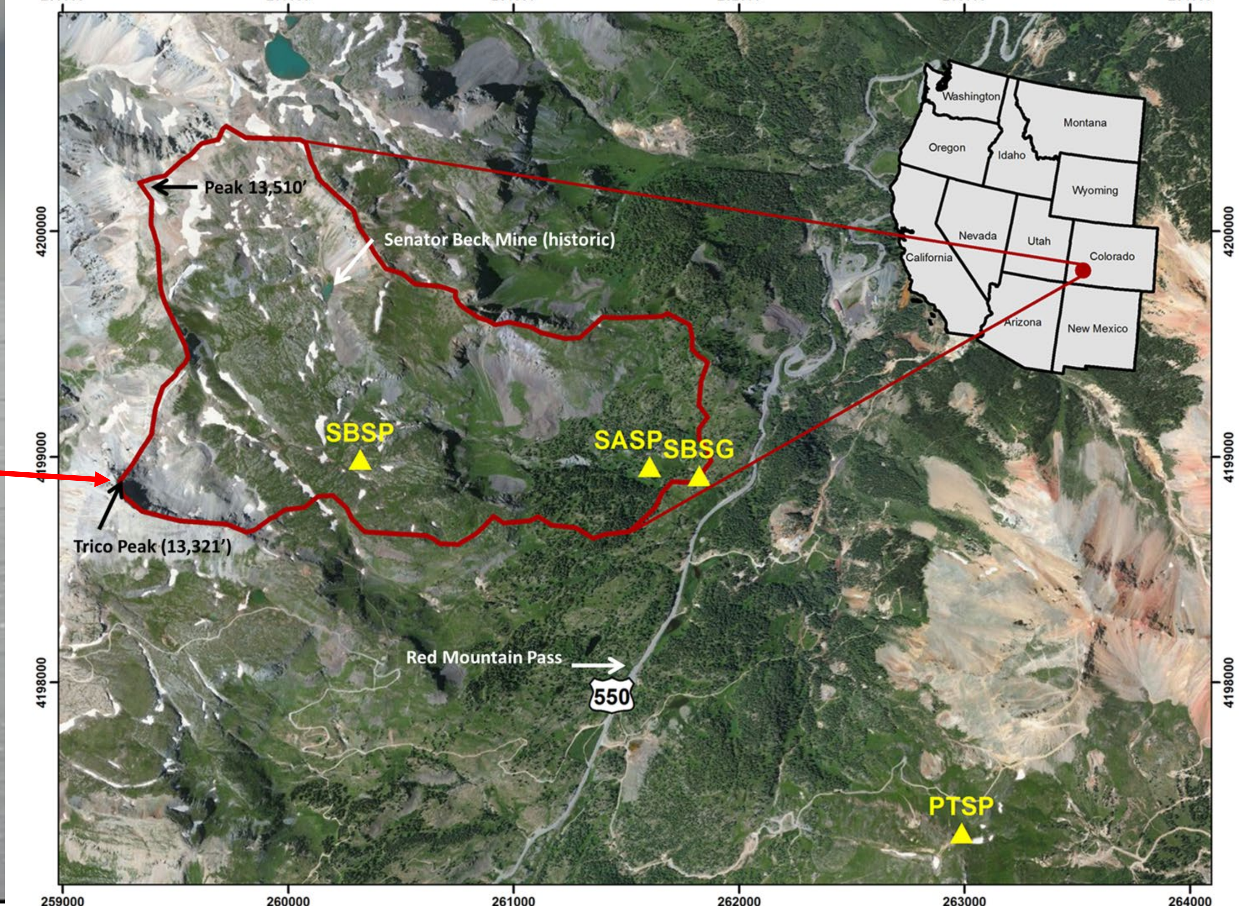
Wolf Creek
May 2, 2019

SASP
MAY 5, 2018

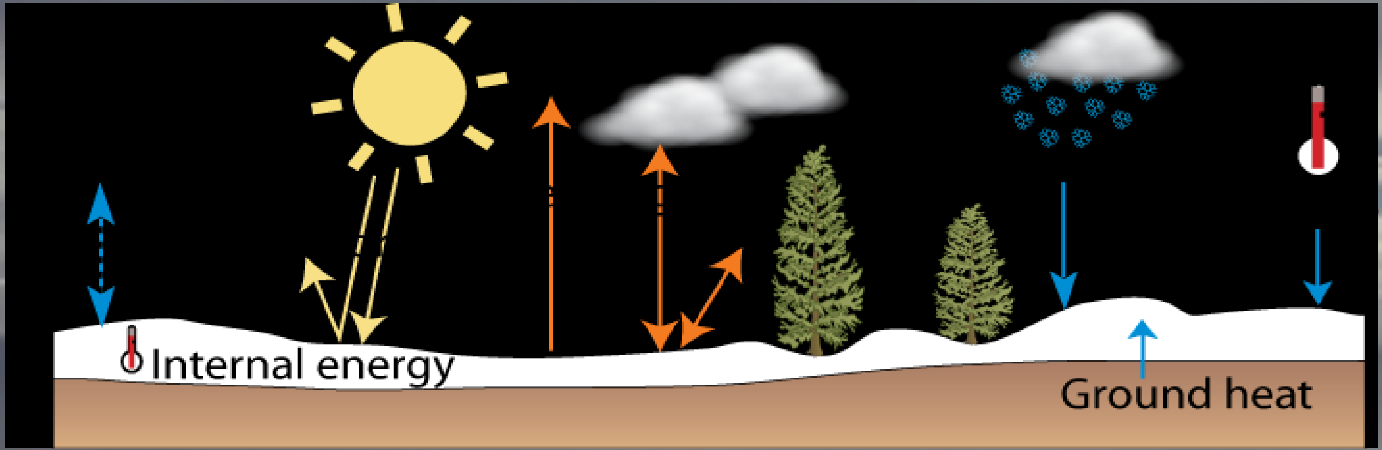
Center for Snow and Avalanche Studies

Senator Beck Study Basin





Snow melt is driven by surface energy balance



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

Change in internal energy

Energy available for melt

Albedo

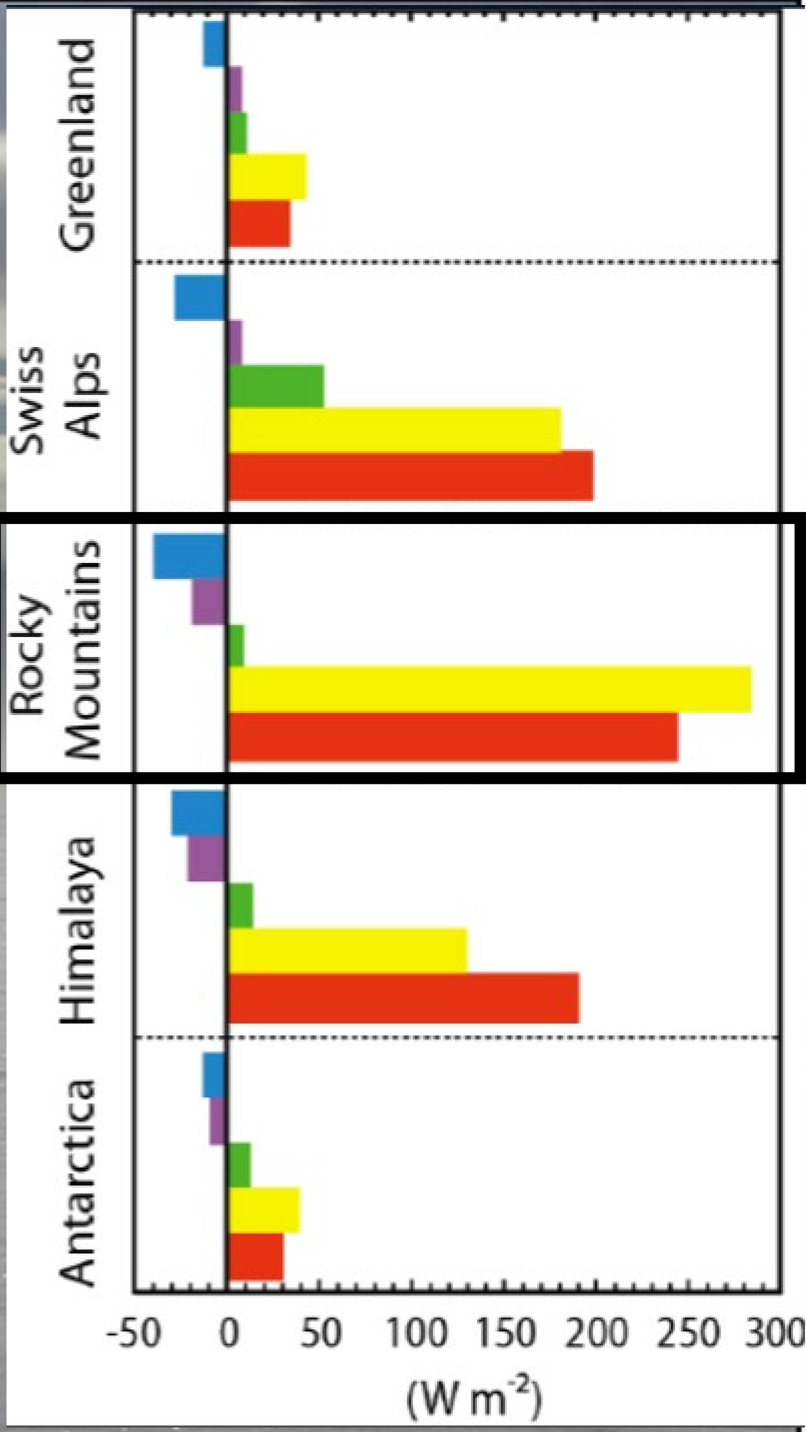
Shortwave radiation

Longwave radiation

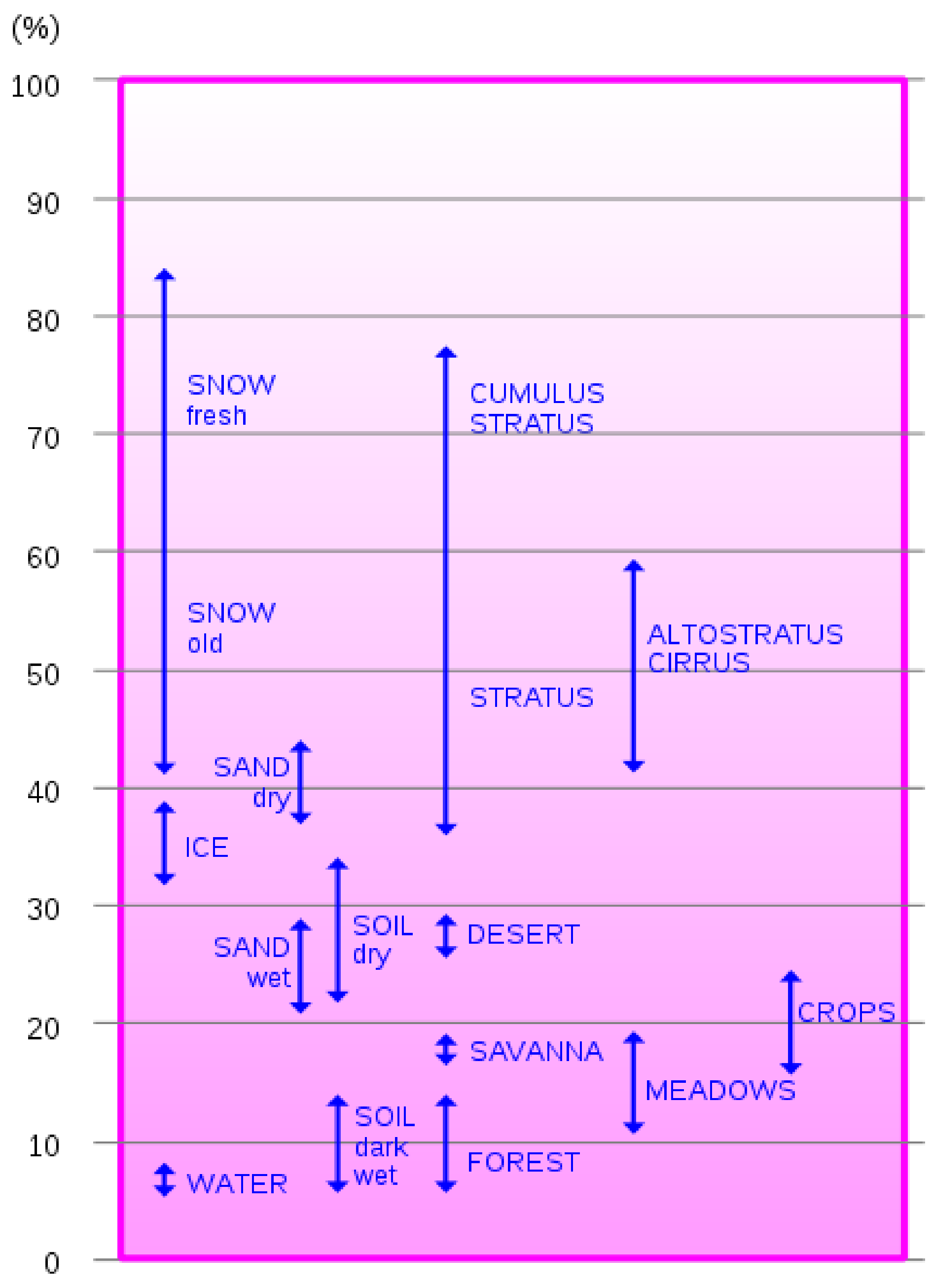
Sensible heat/advection

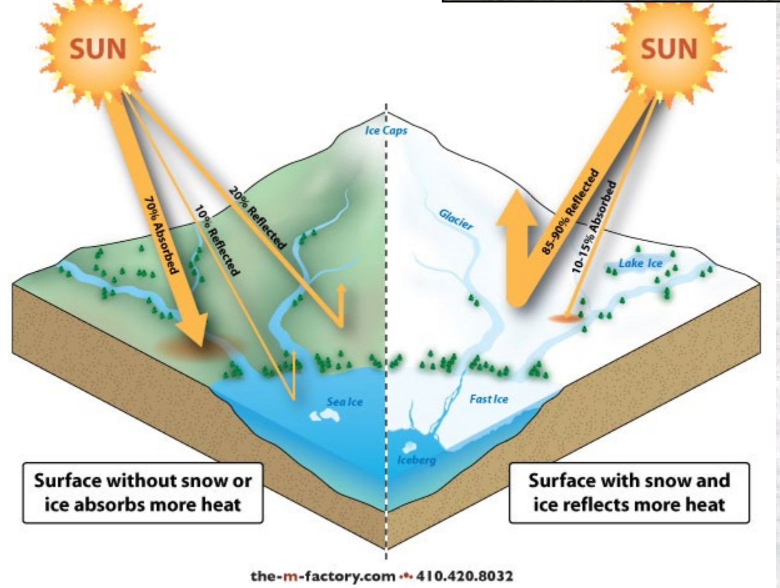
Latent heat

Ground heat

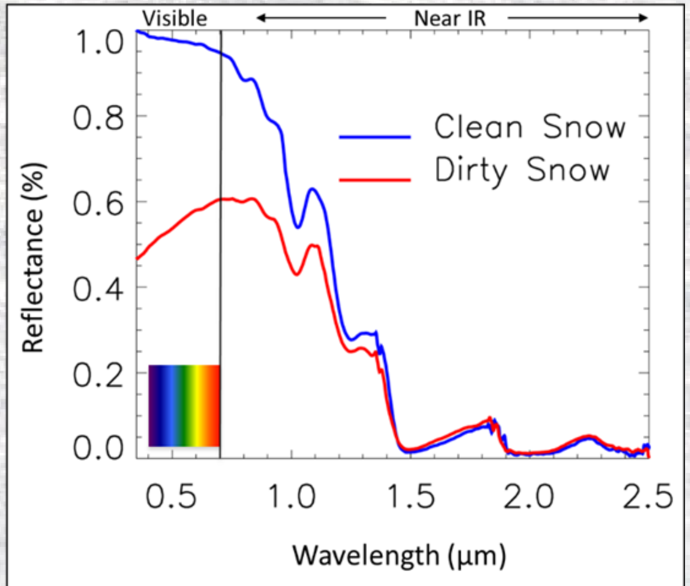


……..*Solar radiation (not air temperature) drives snowmelt!!*





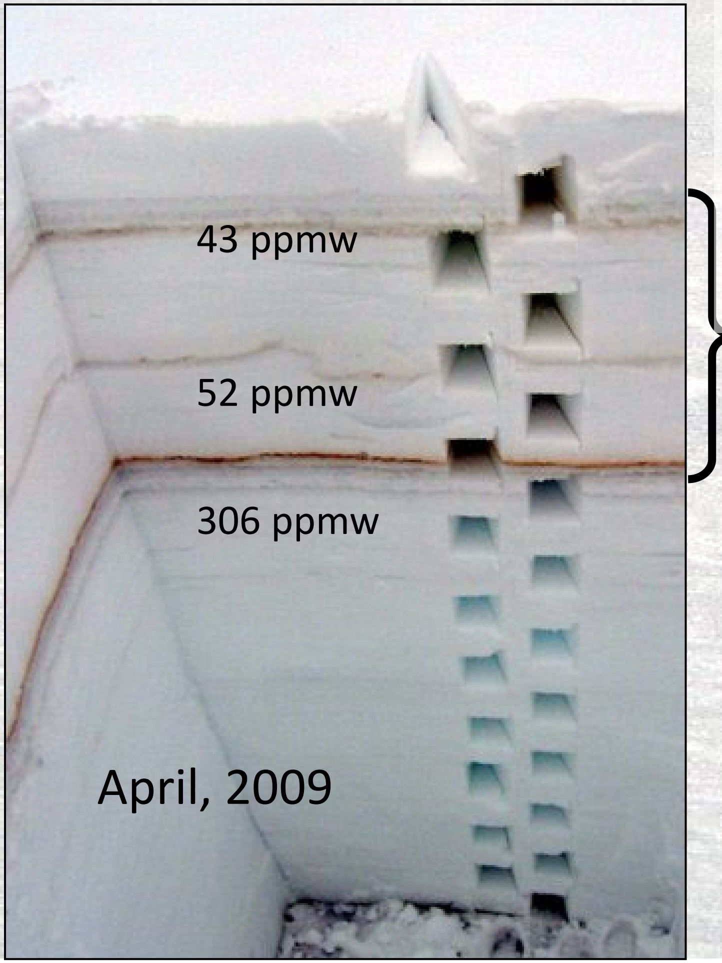
the-m-factory.com • 410.420.8032



Effects of Dust-on-Snow Snowmelt and River Forecasting

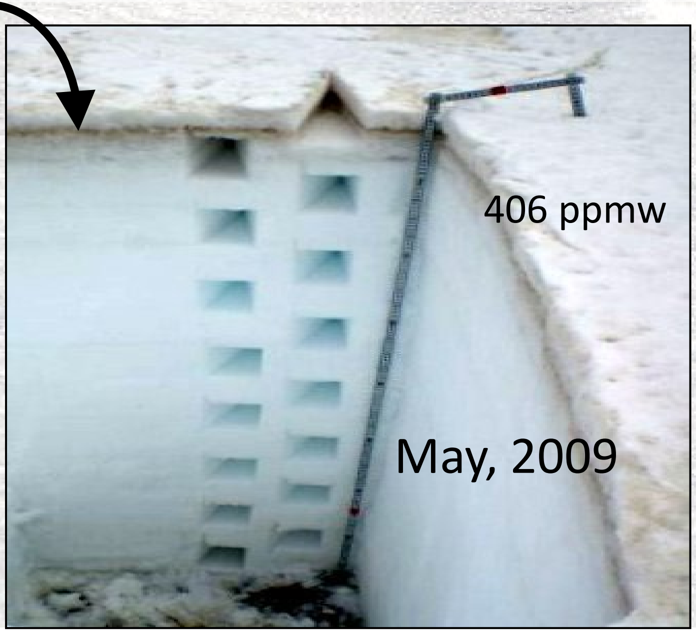
Dust accumulates on surface

Rabbit Ears Pass, Colorado



Dust-on-Snow Effects

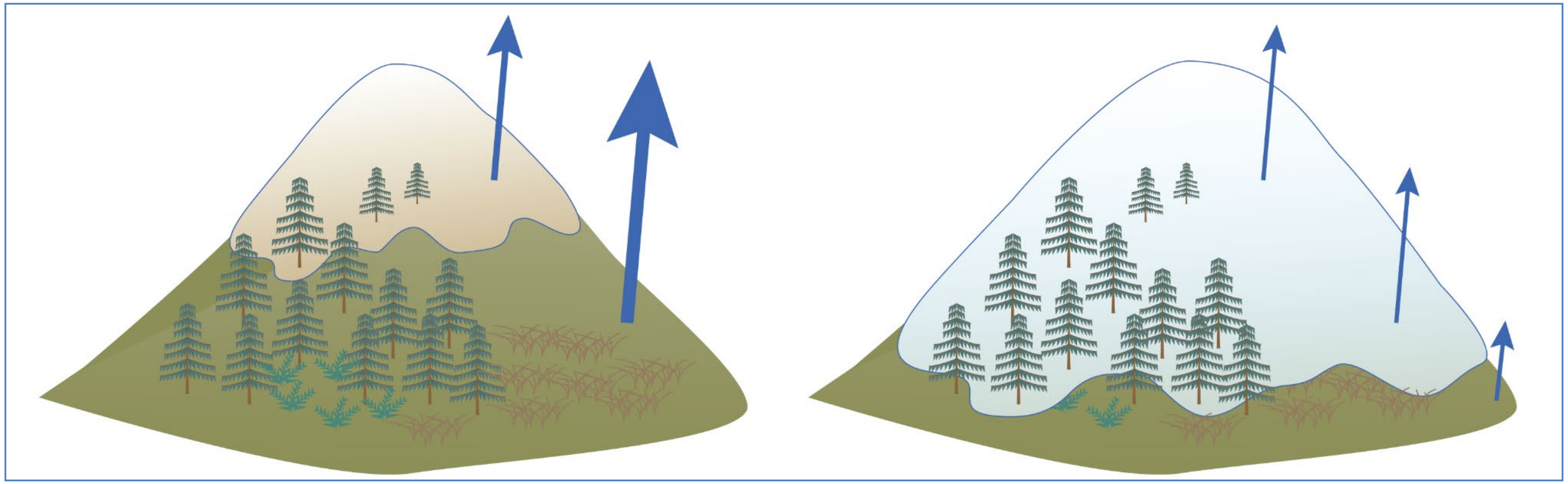
- Timing of snowmelt
- Rate of snowmelt
- Reduce total runoff yields




Silverton
April 3, 2013

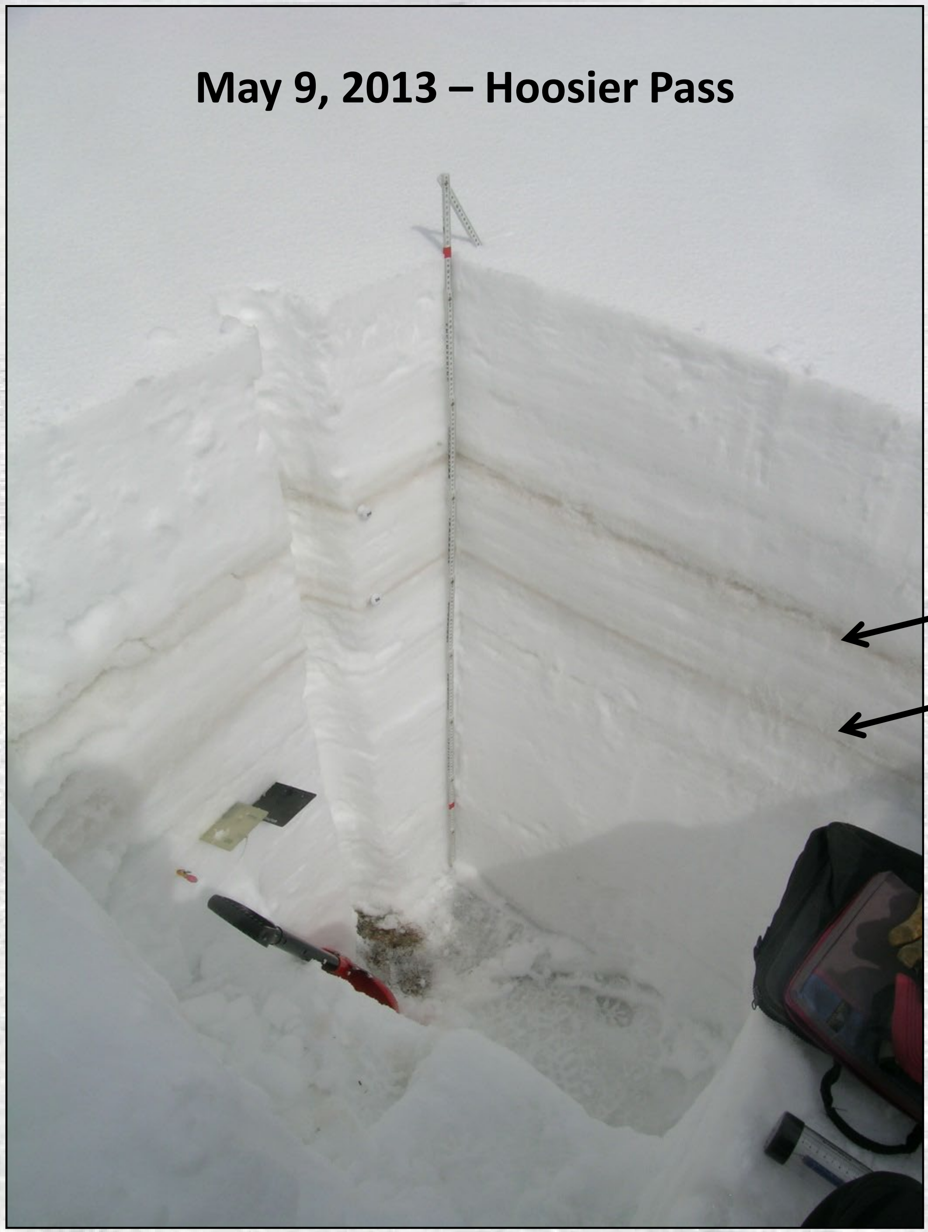

Near Aspen
April 3, 2009

Longer growing season increases ET

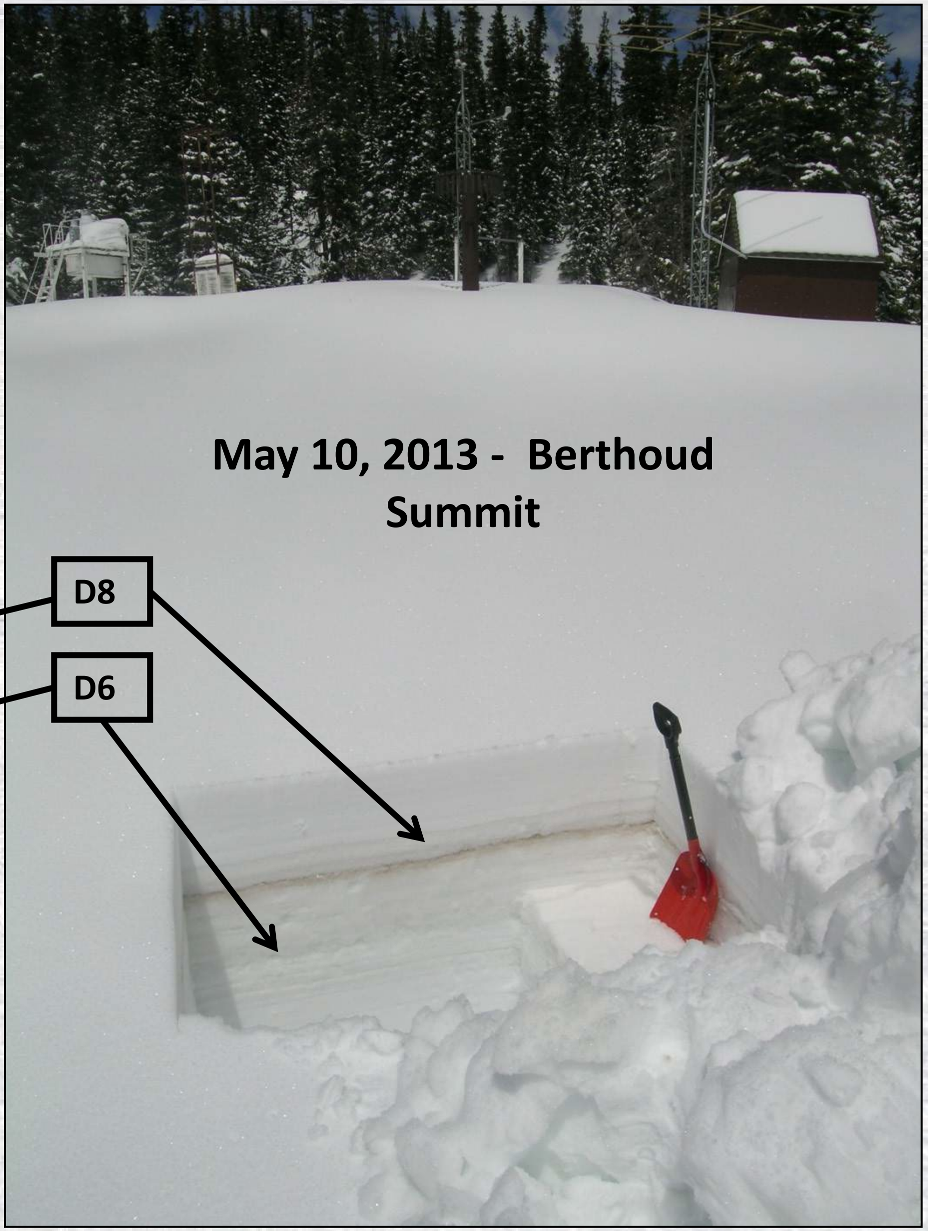


Painter, Deems, *et al.*, *PNAS* (2010)

Dust-on-Snow Events are Extensive *but* Not Always Apparent

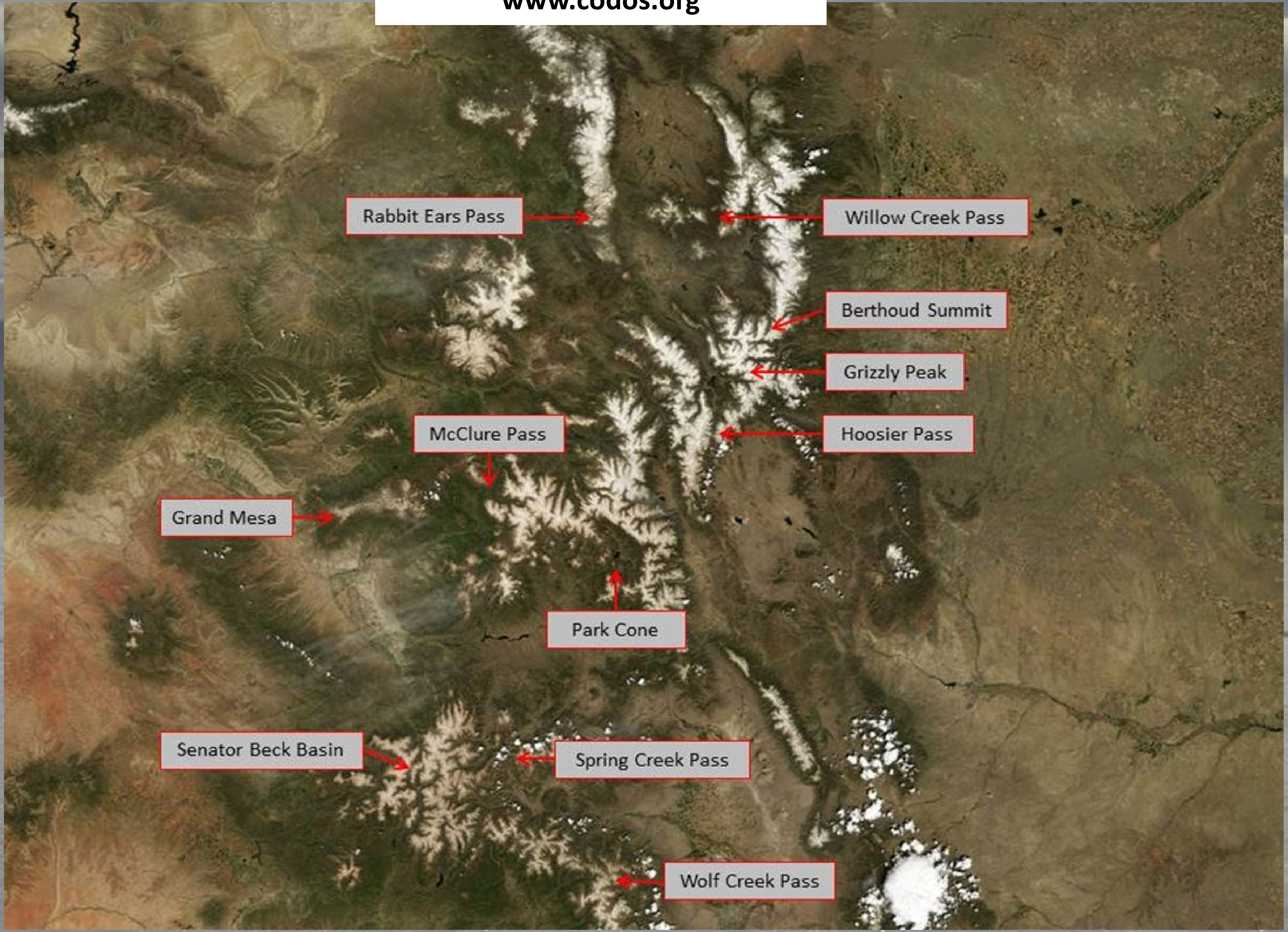


May 9, 2013 – Hoosier Pass



May 10, 2013 - Berthoud Summit

Colorado Dust-on-Snow Program
www.codos.org



AGU PUBLICATIONS

Geophysical Research Letters

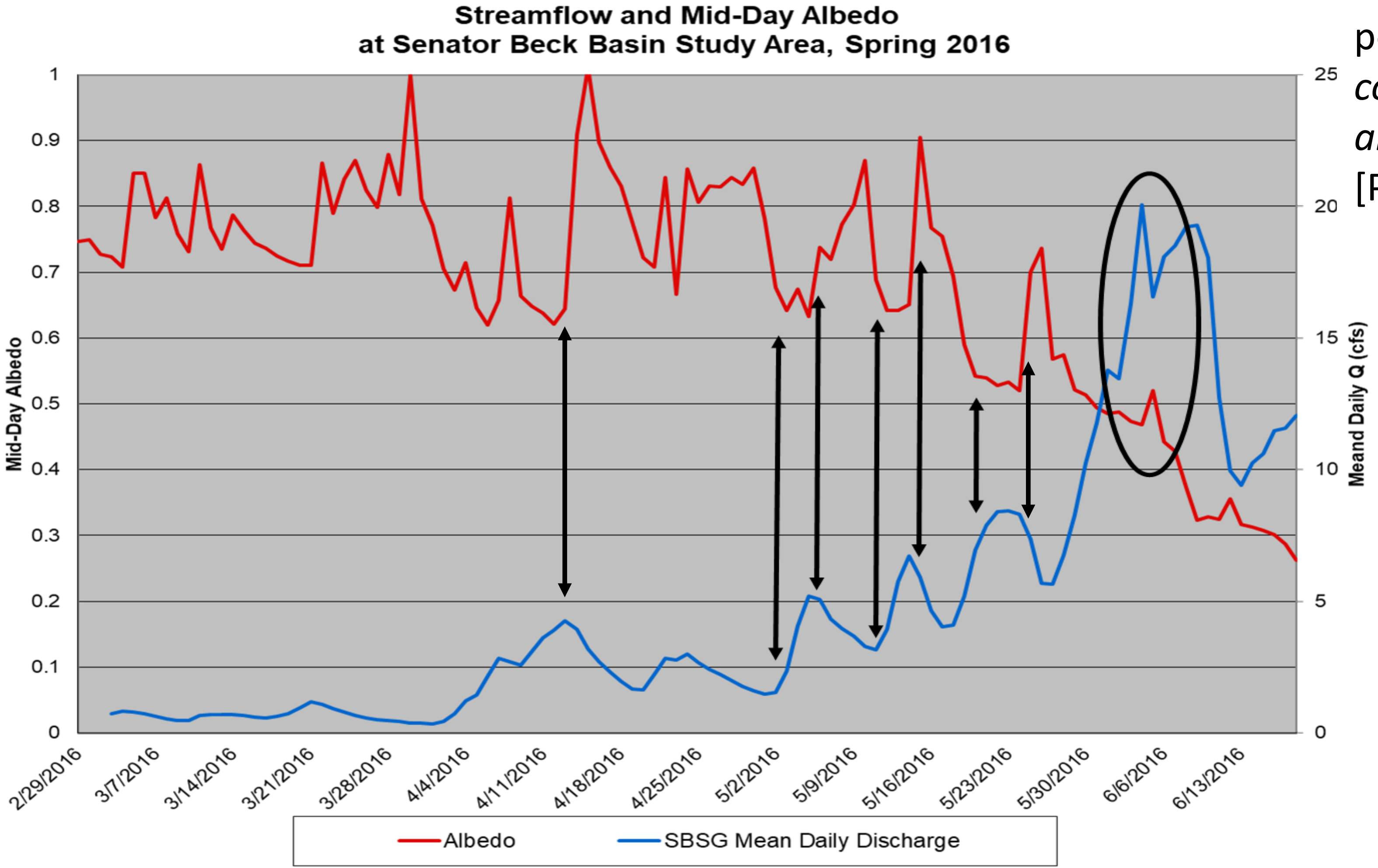
RESEARCH LETTER

10.1002/2017GL075826

Key Points:

- Radiative forcing by dust on snow

Variation in Rising Limb of Colorado River Snowmelt Runoff Hydrograph Controlled by Dust Radiative Forcing in Snow



Streamflow and Mid-Day Albedo
at Senator Beck Basin Study Area, Spring 2016

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]

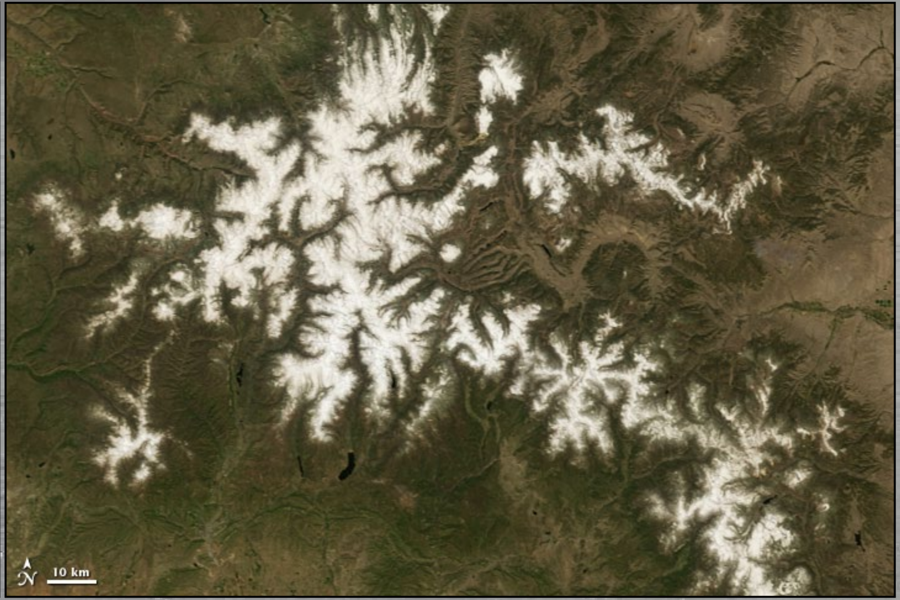
ontrol

Dust-on-Snow

Controls on Snowmelt

Knowing the MAGNITUDE and TIMING/INTENSITY of snowmelt runoff requires knowing

SNOW WATER EQUIVALENT & SNOW ALBEDO



May 31, 2008

Landscape-Scale Dust Deposition

May 18, 2009

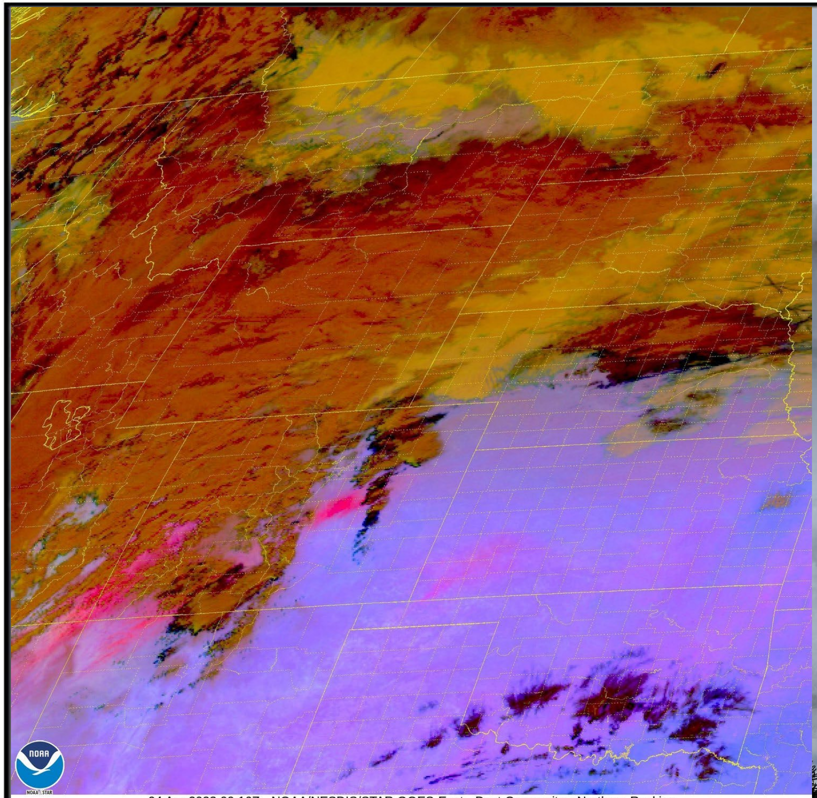

04 Apr 2023 00:16Z - NOAA/NESDIS/STAR GOES-East - Dust Composite - Northern Rockies

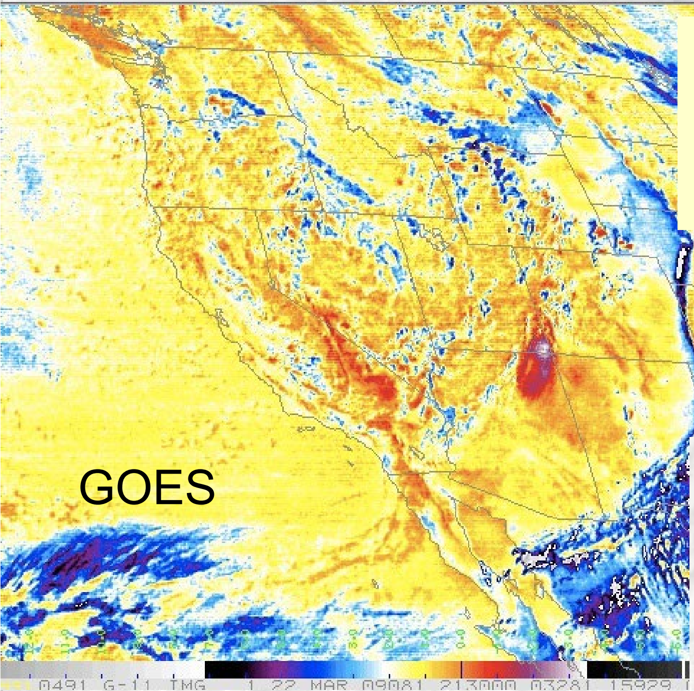

Photo by Steve Hunter, City of Aspen


Grand Mesa, April 20, 2023

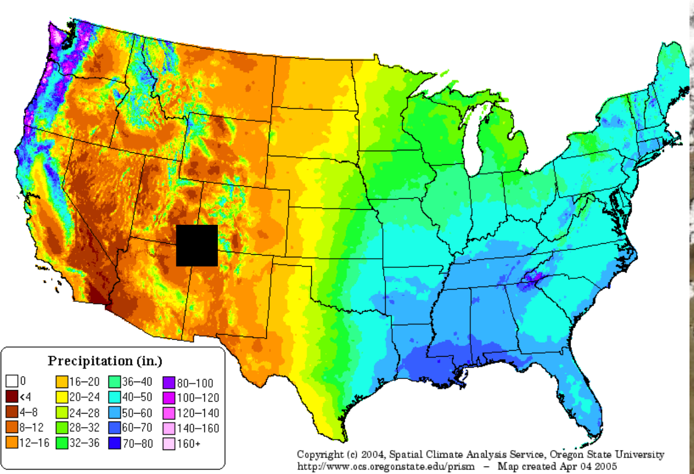

Image courtesy of Jeff Deems Airborne Snow Observatories


Wolf Creek Pass

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



Precipitation: Annual Climatology (1971–2000)

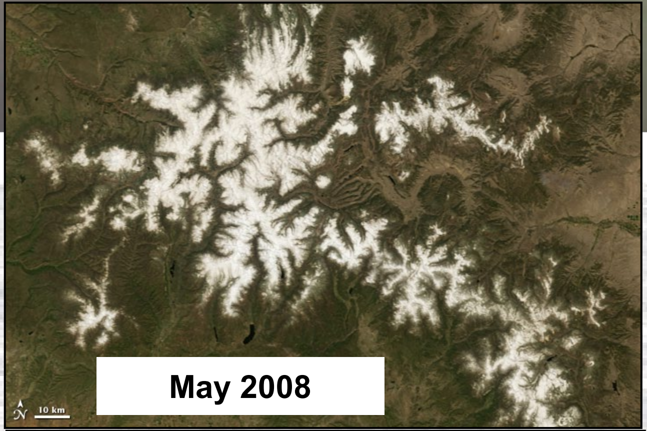


Copyright (c) 2004, Spatial Climate Analysis Service, Oregon State University
http://www.ocs.oregonstate.edu/prism – Map created Apr 04 2005

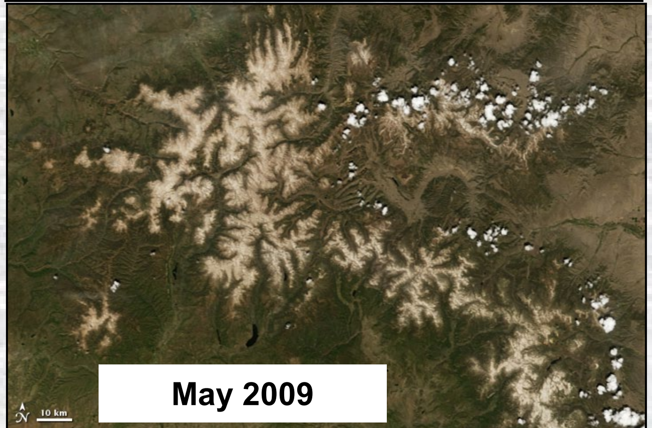
MODIS image
April 3, 2009
Northeastern Arizona

Dust from NE Arizona is deposited on Colorado mountain snow cover

2010

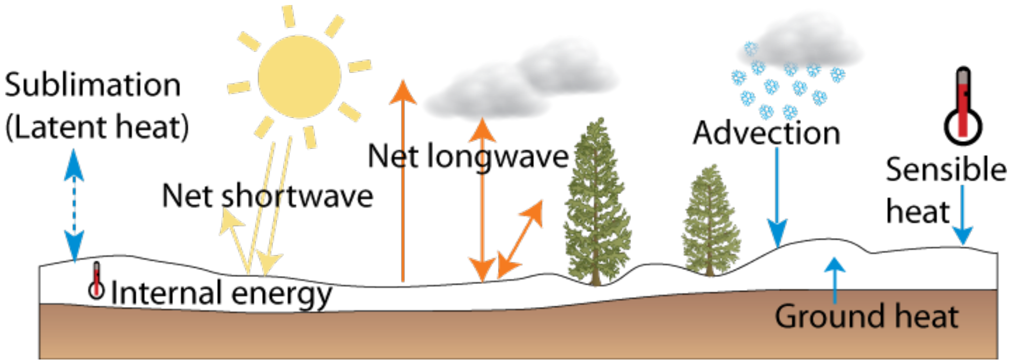


May 2008



May 2009

Snowmelt & runoff simulation & forecasting



Temperature index runoff model

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

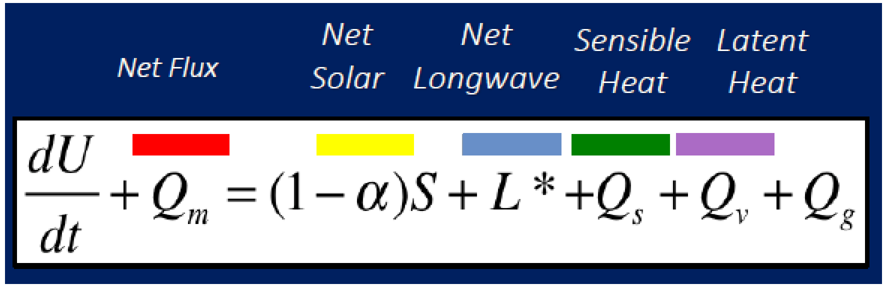
Statistical water supply forecast

- 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. WRF



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

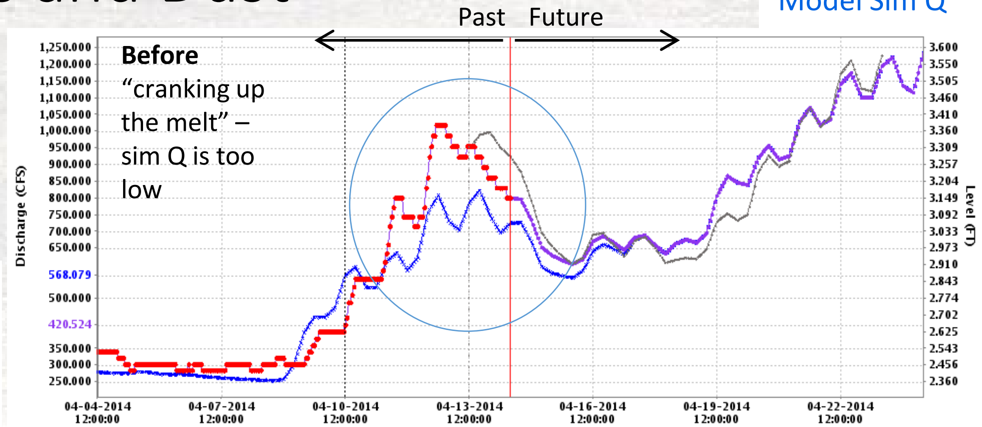
- Common research

Colorado Basin River Forecast Center (CBRFC)

Snowmelt Forecast Errors and Dust

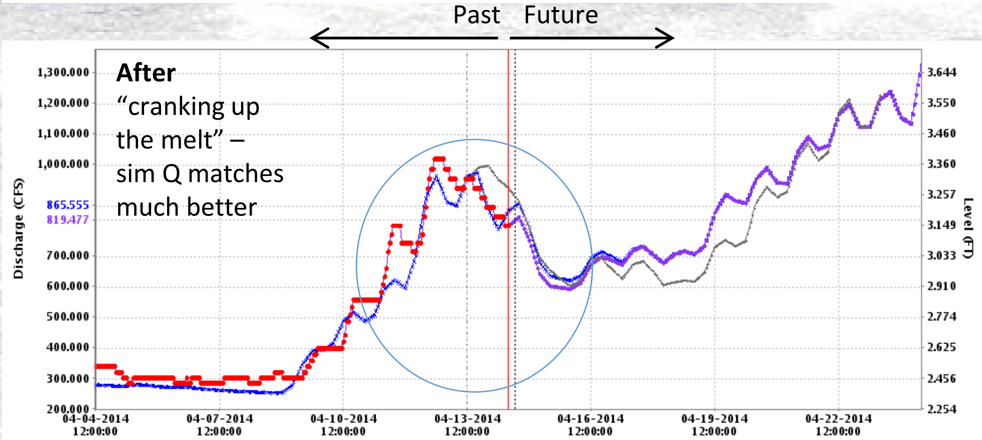
- CBRFC uses SNOW17 temperature-index model
- This approach breaks down when conditions deviate from average
- Dustier than average snowpack brings earlier snowmelt than what SNOW17 predicts
- Larger streamflow prediction errors are correlated with dustier years

Official Fcst Q
Recent Obs Q
Model Sim Q



Before
"cranking up the melt" – sim Q is too low

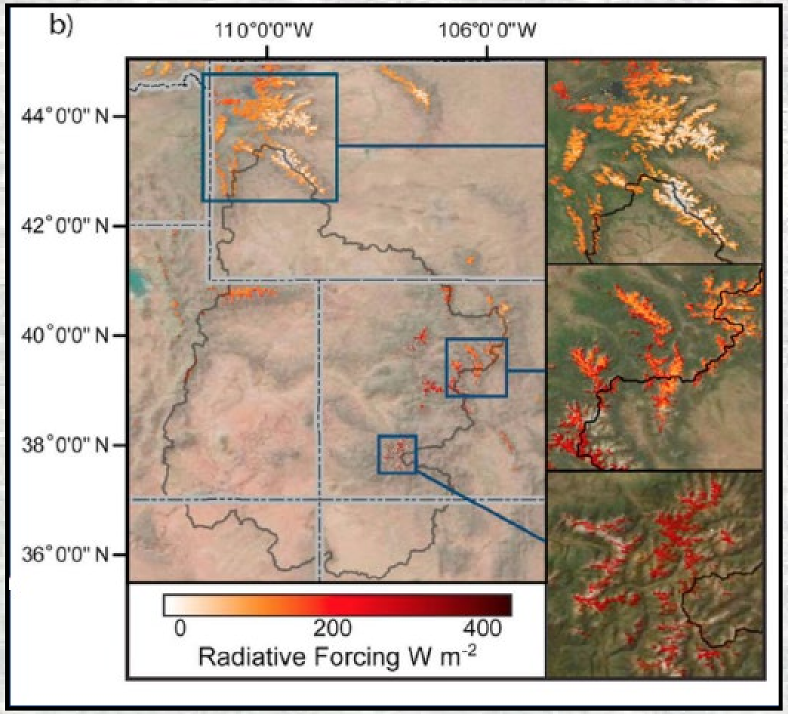
External: [1] 04-13-2014 12:00:00 DRGC2H_F_Forecast: [2] 04-14-2014 12:00:00 Current MergeScalars_Forecast: [3] 04-14-2014 12:00:00 Current

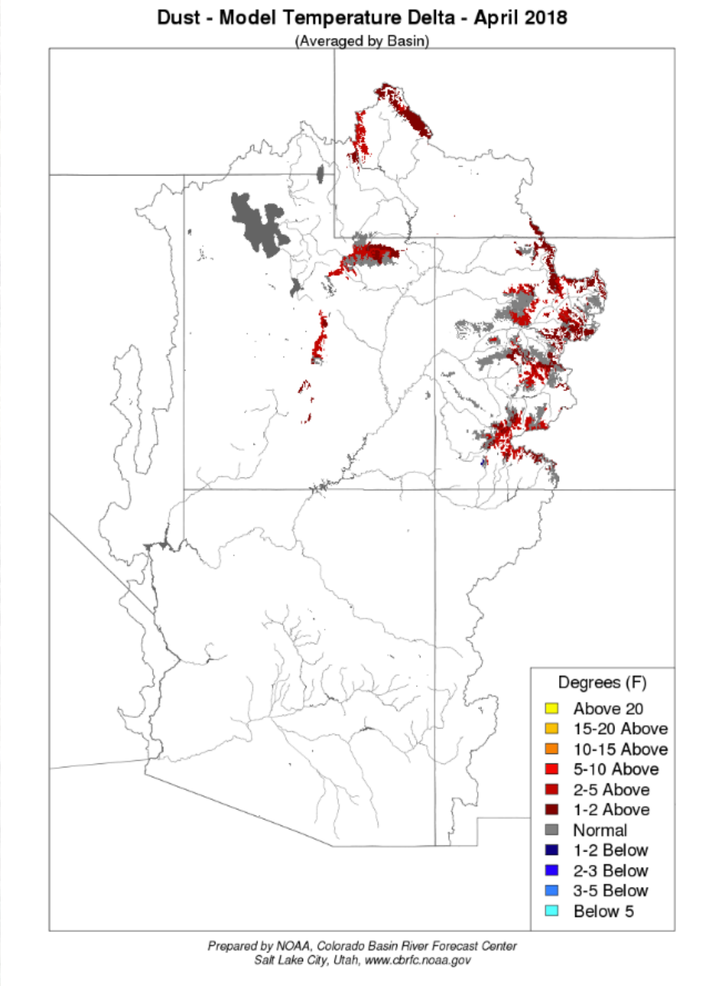


After
"cranking up the melt" – sim Q matches much better

External: [1] 04-13-2014 12:00:00 DRGC2H_F_Forecast: [2] 04-14-2014 12:00:00 Current MergeScalars_Forecast: [3] 04-14-2014 12:00:00 Current

Credit: plots courtesy B. Bernard (CBRFC)





Dust - Model Temperature Delta - April 2018
(Averaged by Basin)

Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov

- West Gulf RFC: Do not make adjustments based on dust observations.

WWW.SNOWSTUDIES.ORG
WWW.CODOS.ORG

jderry@snowstudies.org
Cell # 970-231-6595

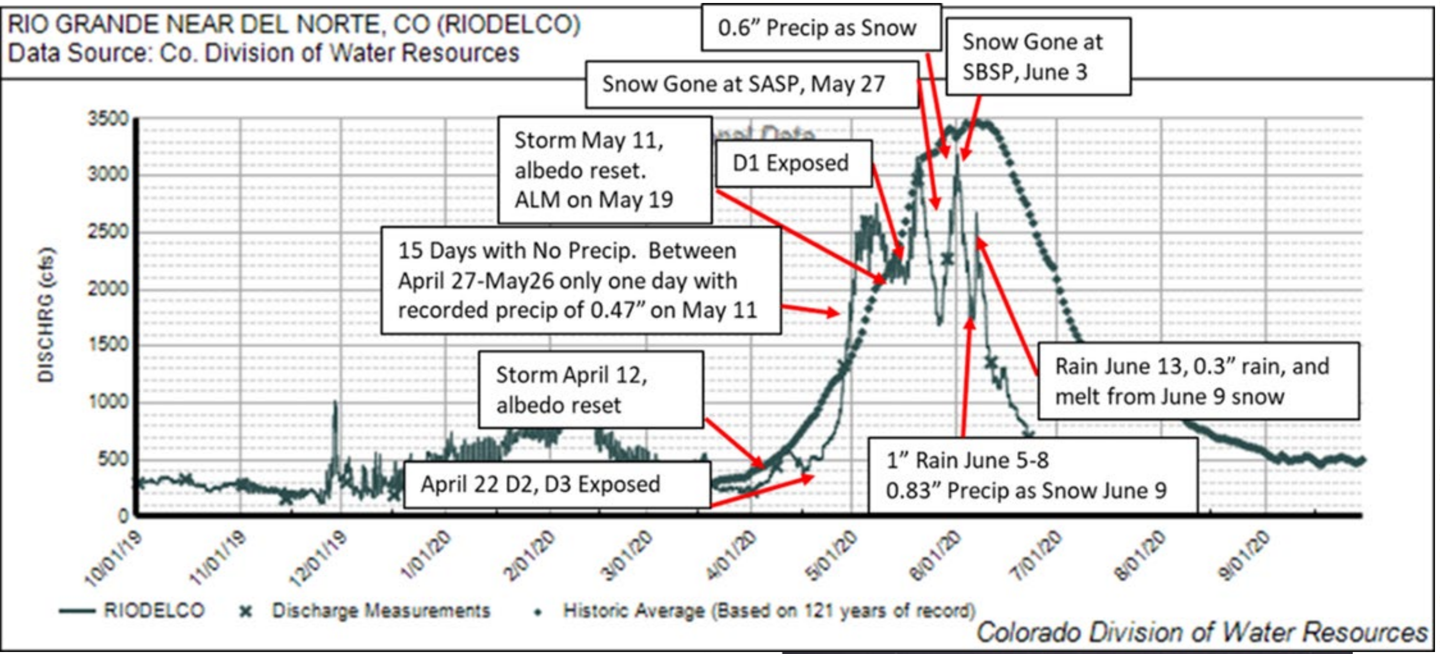
The Center for Snow and Avalanche Studies (CSAS) is home to "CODOS", the Colorado Dust-on-Snow program, an applied science effort on behalf of Colorado and regional water management agencies. CSAS operates the Senator Beck Basin study area at Red Mountain Pass as the primary sentry site for the CODOS program. With direct funding from stakeholders, CSAS monitors the presence/absence of dust layers at **11** mountain pass locations throughout Colorado. Using those observations, data from nearby Snotel sites, and weather forecasts, the CODOS program issues a series of "Update" analyses of how dust-on-snow is likely to influence snowmelt timing and rates during the runoff season.

WATER YEAR 2024 UPDATES

- September 20, 2023: "Snow School For Water Professionals", Season Summary

WATER YEAR 2023 UPDATES

- September 5, 2023: WY2023 Season Summary
- June 8, 2023: Observations from Senator Beck
- June 4, 2023: Observations from Swamp Angel
- June 2, 2023: Observations from Southern CODOS Sites
- May 30, 2023: Snowmelt as we Head into June
- May 23, 2023: Still Lot's of Snow to Melt, Front Range Obs
- May 10, 2023: Warm Up, Cool Down, Repeat
- April 29, 2023: Time-Out is Over
- April 21, 2023: Observations at the Southern CODOS Sites
- April 17, 2023: Observations at Front Range Sites
- April 6, 2023: Nature of Runoff Season Just Altered Dramatically, Land Health Thoughts
- April 3, 2023: Dust Event #4, More Coming
- March 24, 2023: Word For WY2023, "Epic"
- March 18, 2023: CODOS Tour Observations - Lot's O'Snow, Min Dust
- March 10, 2023: A Tad Bit More Dust, Storms Coming In
- March 1, 2023: March 1 Update, Dust Enhanced Runoff Classification, Current Conditions, Looking Towards Spring
- February 26, 2023: Big Storm, Mild Dust
- February 17, 2023: Snowpack Update
- February 1, 2023: Workshop Information & Zoom Link


RIO GRANDE NEAR DEL NORTE, CO (RIODELCO)
Data Source: Co. Division of Water Resources

0.6" Precip as Snow

Snow Gone at SBSP, June 3

Snow Gone at SASP, May 27

Storm May 11, albedo reset. ALM on May 19

D1 Exposed

15 Days with No Precip. Between April 27-May26 only one day with recorded precip of 0.47" on May 11

Storm April 12, albedo reset

Rain June 13, 0.3" rain, and melt from June 9 snow

April 22 D2, D3 Exposed

1" Rain June 5-8
0.83" Precip as Snow June 9

Colorado Division of Water Resources

Forest Fires

Water Resources Research

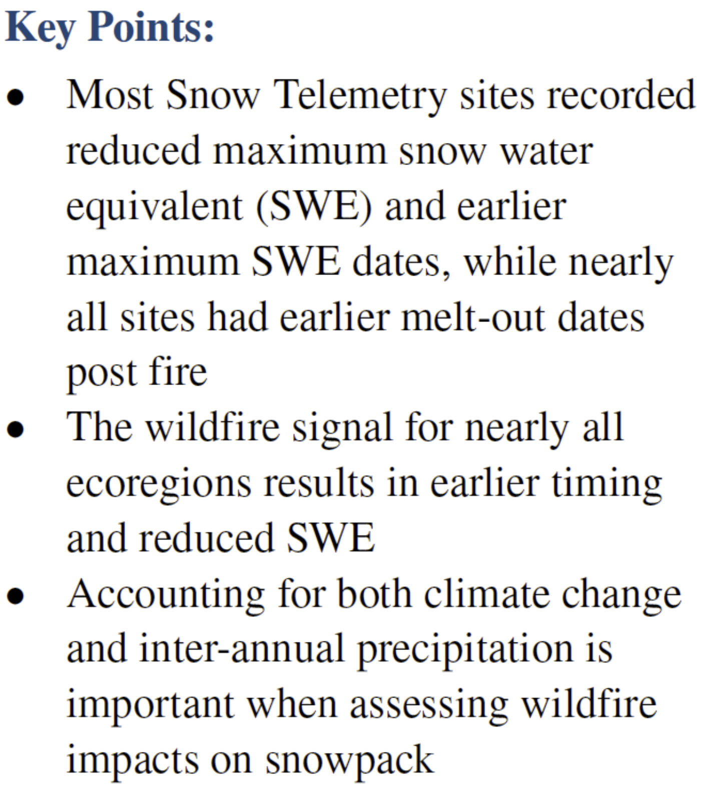
RESEARCH ARTICLE

10.1029/2021WR031569

Key Points:

Wildfire Impacts on Snowpack Phenology in a Changing Climate Within the Western U.S.

Jeremy Giovando[1,2] and Jeffrey D. Niemann[2]



Key Points:

- Most Snow Telemetry sites recorded reduced maximum snow water equivalent (SWE) and earlier maximum SWE dates, while nearly all sites had earlier melt-out dates post fire
- The wildfire signal for nearly all ecoregions results in earlier timing and reduced SWE
- Accounting for both climate change and inter-annual precipitation is important when assessing wildfire impacts on snowpack

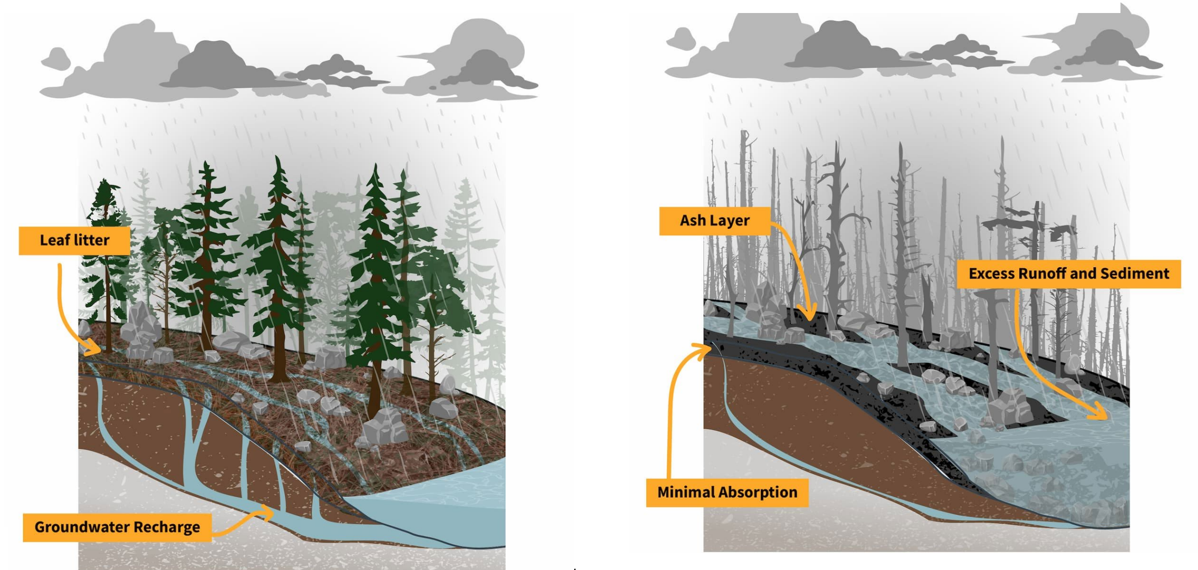
RESEARCH ARTICLE | EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES

Increasing wildfire impacts on snowpack in the western U.S.

Stephanie K. Kampf, Daniel McGrath, Megan G. Sears, +2, and John C. Hammond Authors Info & Affiliations

Water Quality:

- Increased sediment and nitrate, phosphorus, dissolved organic carbon, and manganese
- Eutrophication, stream habitat alteration, metals mobilization in reservoirs
- Impaired water-treatment efficiency



'data.usgs.gov/visualizations/fire-hydro/index.html#/

Aridification – Not Drought

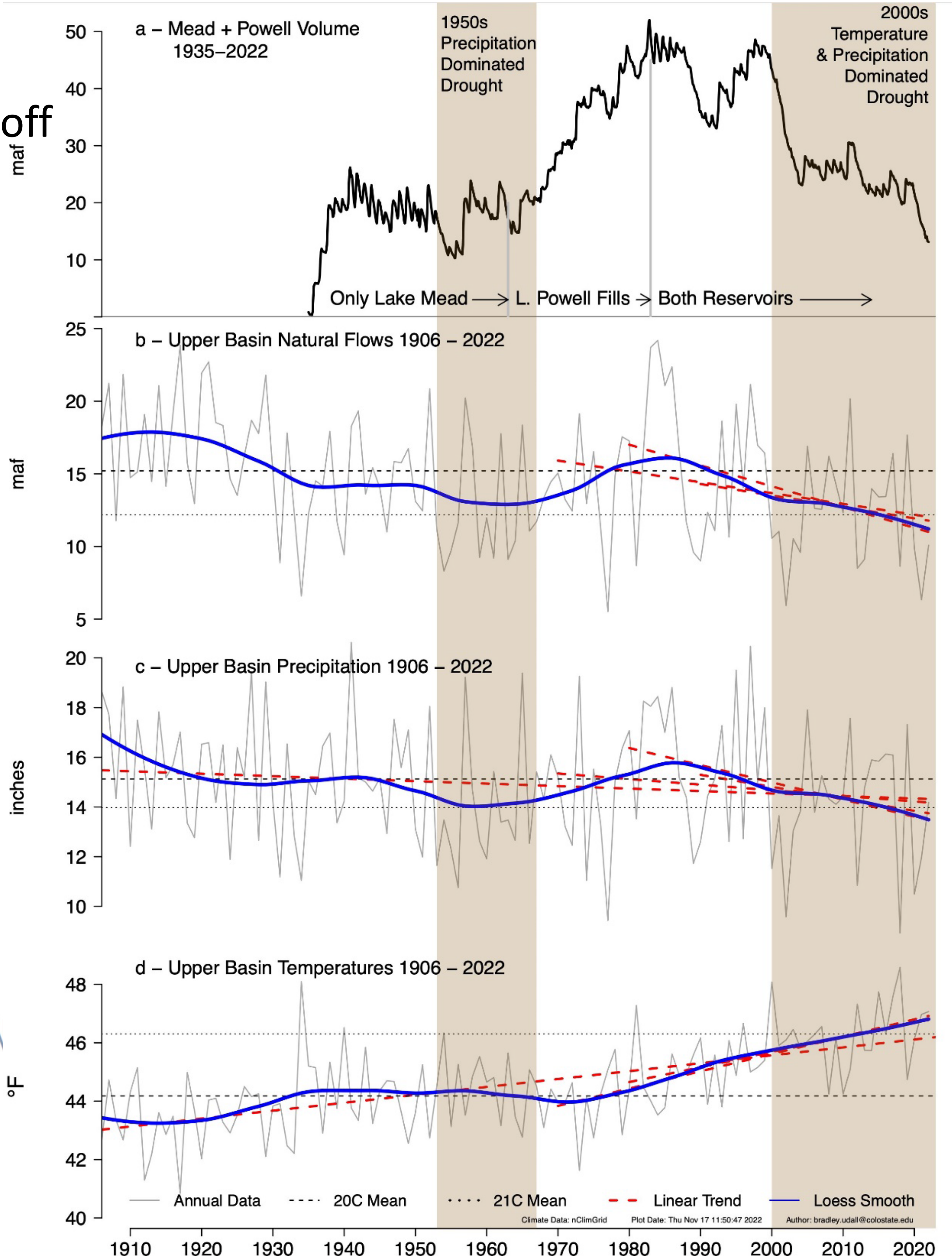
- Declining snowpack and earlier runoff
- Higher temperatures: > 1.25 °C
- Drying Soil
- Thirsty atmosphere (holds more moisture)
- Moving storm tracks
- Shorter winters

- Temp can be a major flow driver in addition to precip
- Since 1988 flows have been less than expected given winter precip
- Warm temps exacerbated modest precip deficits in the Millennium Drought

AGU PUBLICATIONS

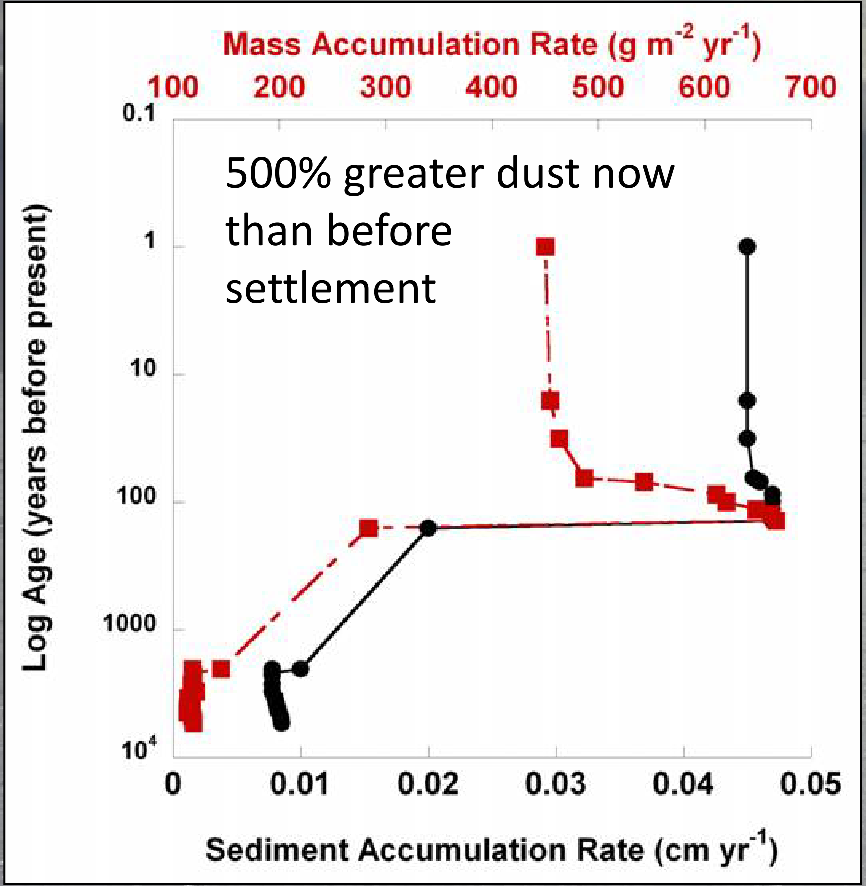
The twenty-first century Colorado River hot drought and implications for the future

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



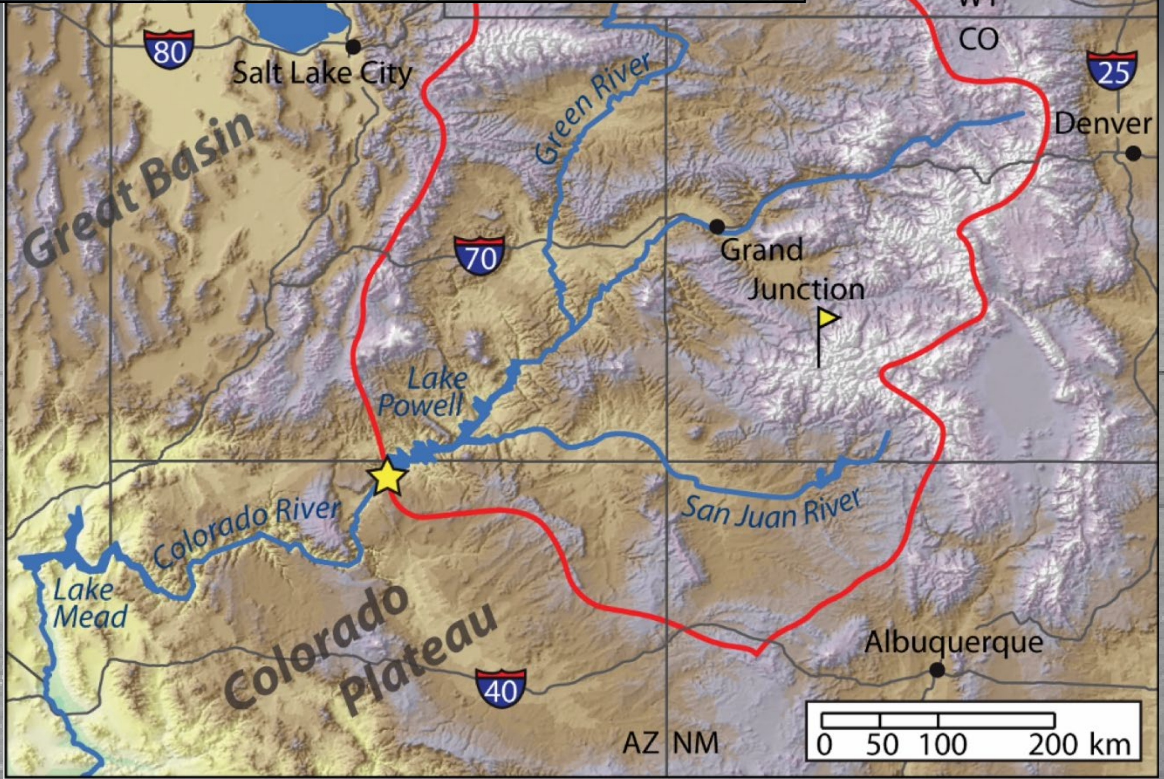
- Precipitation declines only partially explain
  - ~ 2/3 of the loss
- Temperature increases explain the remainder
  - ~ 1/3 of the loss
- Why?
  - More Evaporation
  - Thirstier Atmosphere
- Temperature-Induced Losses
  - Now = ~6%
  - 2050 = ~20%
  - 2100 = ~35%

Dust deposition increased after settlement



500% greater dust now than before settlement

Neff *et al.* (2008) Nature Geosciences



Plant Community Monitoring

Snow amount and distribution greatly influences vegetation composition, abundance, and distribution.

Alpine regions are considered one of the most vulnerable ecosystems in the face of climate change, yet we have very few sites with quantitative data

Colorado Natural Heritage Program

2004

2014

2021

AGU PUBLICATIONS

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

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

Aridification – Not Drought

- Temp can be a major flow driver in addition to precip
- Since 1988 flows have been less than expected given winter precip
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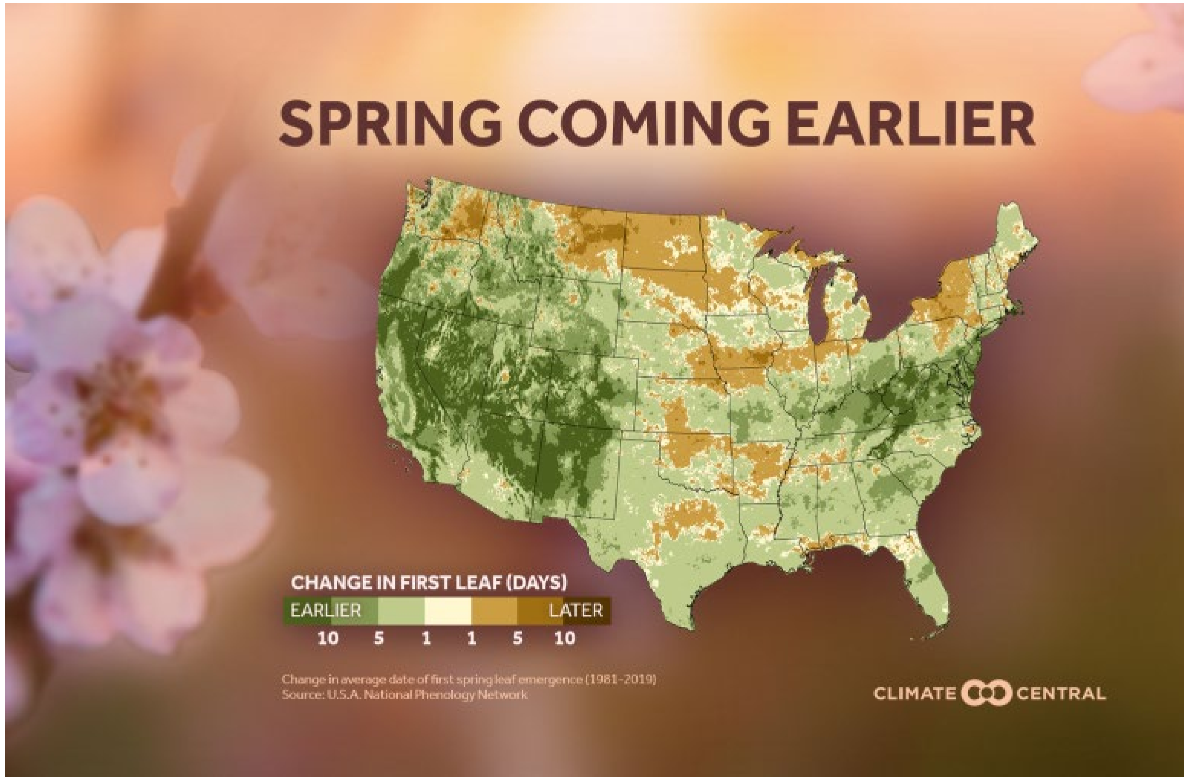
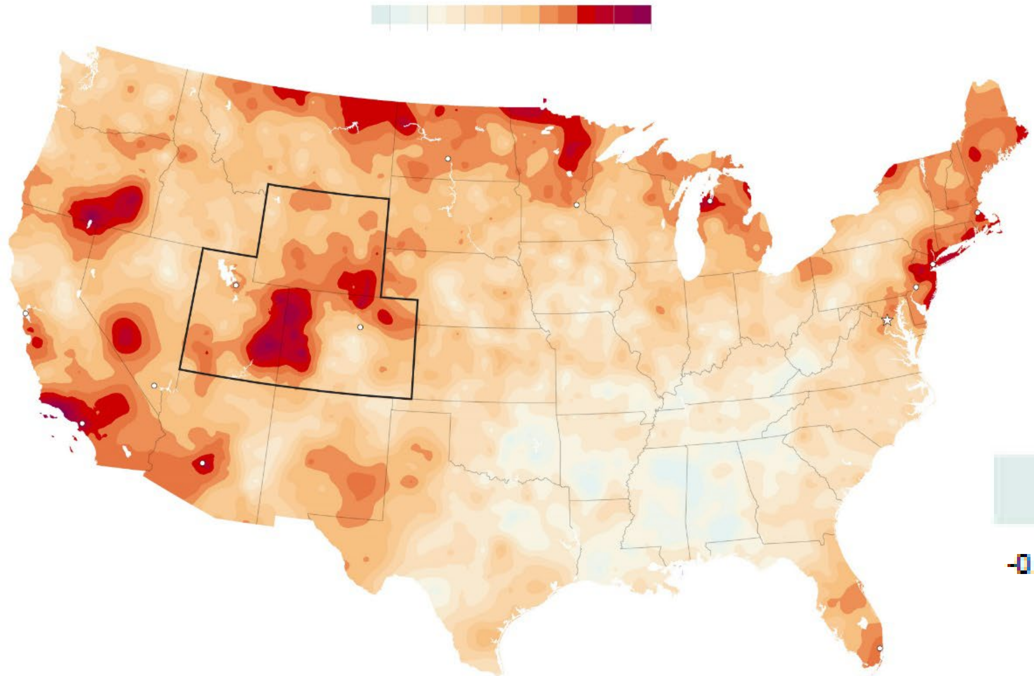


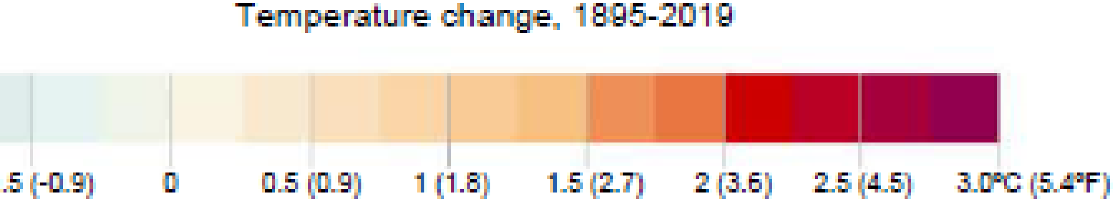
Change in average date of first spring leaf emergence (1981-2019)
Source: U.S.A. National Phenology Network

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

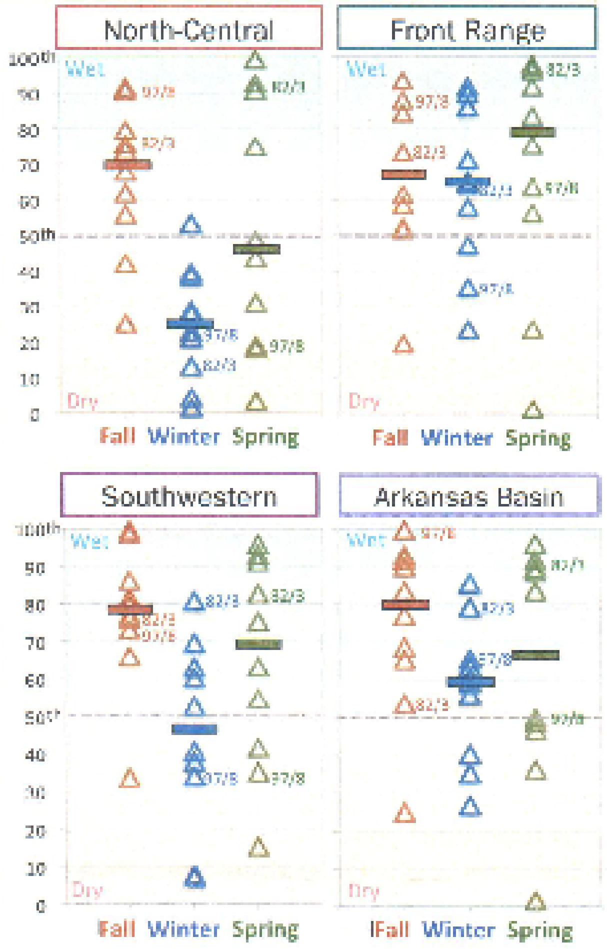
March 27, 2008

NRDC





EL NIÑO IMPACTS FOR COLORADO Fall, Winter, Spring 2015–16

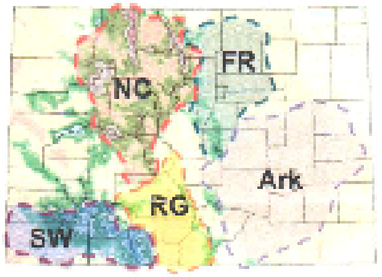


The open triangles show the percentile ranks (100th=wettest; 50th =median, 1st= driest) for seasonal precipitation during and after the 10 strongest fall El Niño conditions since 1915, relative to all years in the record. The bars show the median outcome of the 10 years. 82/3 = 1982–83 El Niño; 97/8 = 1997–98 El Niño (Figure: WWA & NOAA PSD)

Across Colorado, past strong El Niño events have often brought above-normal precipitation in the fall (Sep–Nov) and spring (Mar–May), but less so in winter (Dec–Feb).

- In the **North-Central** mountains—the headwaters of the Colorado, Gunnison, Yampa, White, North Platte, and South Platte—fall is more often wet than dry, spring is split evenly, but *winter* is drier than normal in 9 of 10 cases.
- For the **Front Range**, there is a tendency towards wetter conditions in all seasons, especially in spring. Major (>18") snowstorms are also much likely during El Niño.
- In the **Arkansas Basin**, the wet tendencies are similar to the Front Range, though strongest in fall.
- In **Southwestern** Colorado, fall is consistently wetter than normal; spring slightly less so; winter is split between wet and dry. (The **Rio Grande Basin** follows a similar pattern.)
- *There has been a wide range of outcomes in all seasons.*

Colorado Region Locator Map

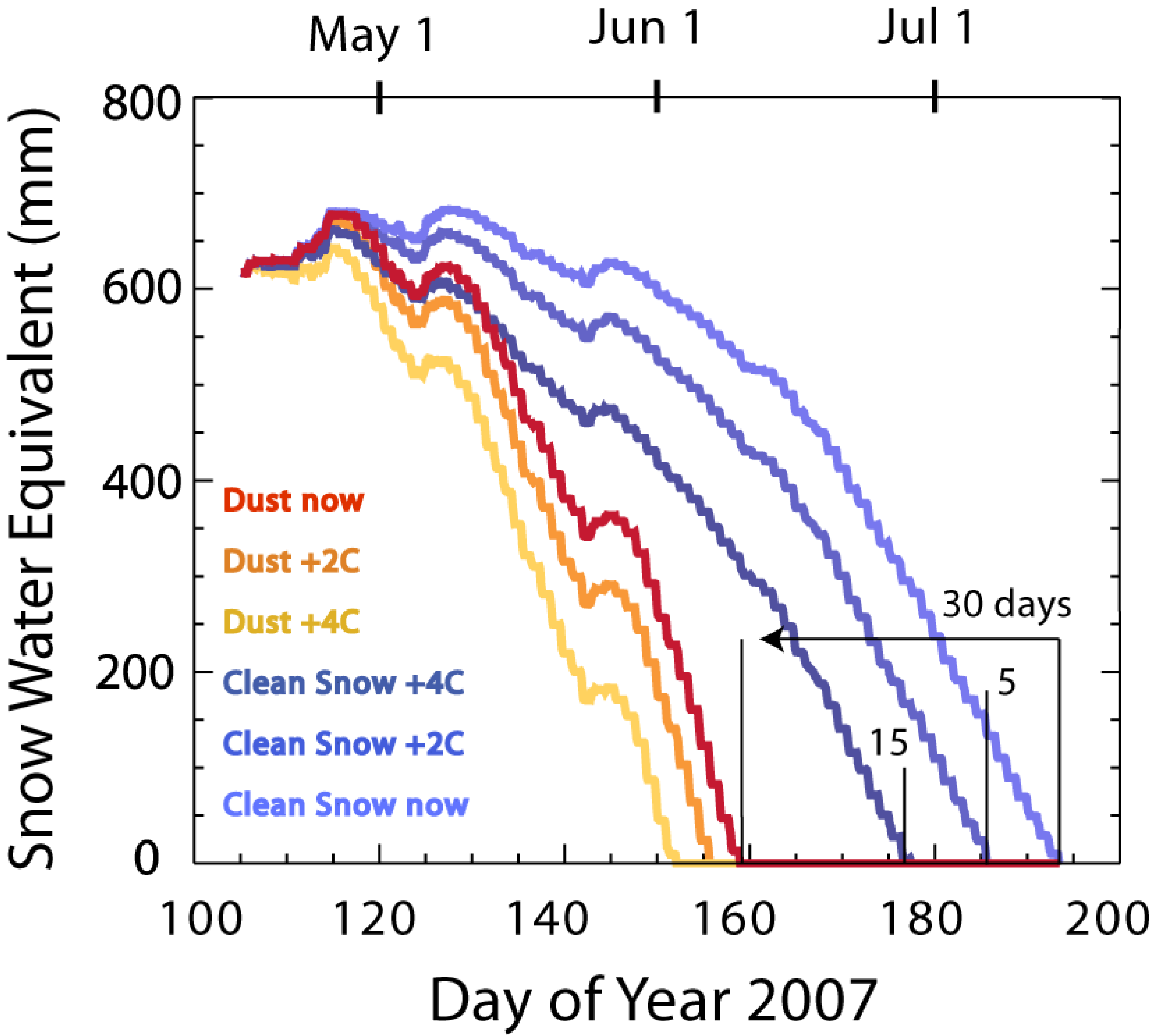


Colorado's spring snowpack and annual runoff also have tended to be above normal in past strong El Niño events. Overall, the pronounced wet tendency in fall and spring precipitation has balanced out the dry tendency for winter in the North-Central and Southwestern regions. In most of the strongest past El Nino events, May 1 snow-water equivalent (SWE) and water-year runoff *(below)* have both been above normal in Colorado's major river

Resources for monitoring ENSO and its Impacts for Colorado

NOAA - ENSO Blog
www.climate.gov/news-features/department/enso-blog

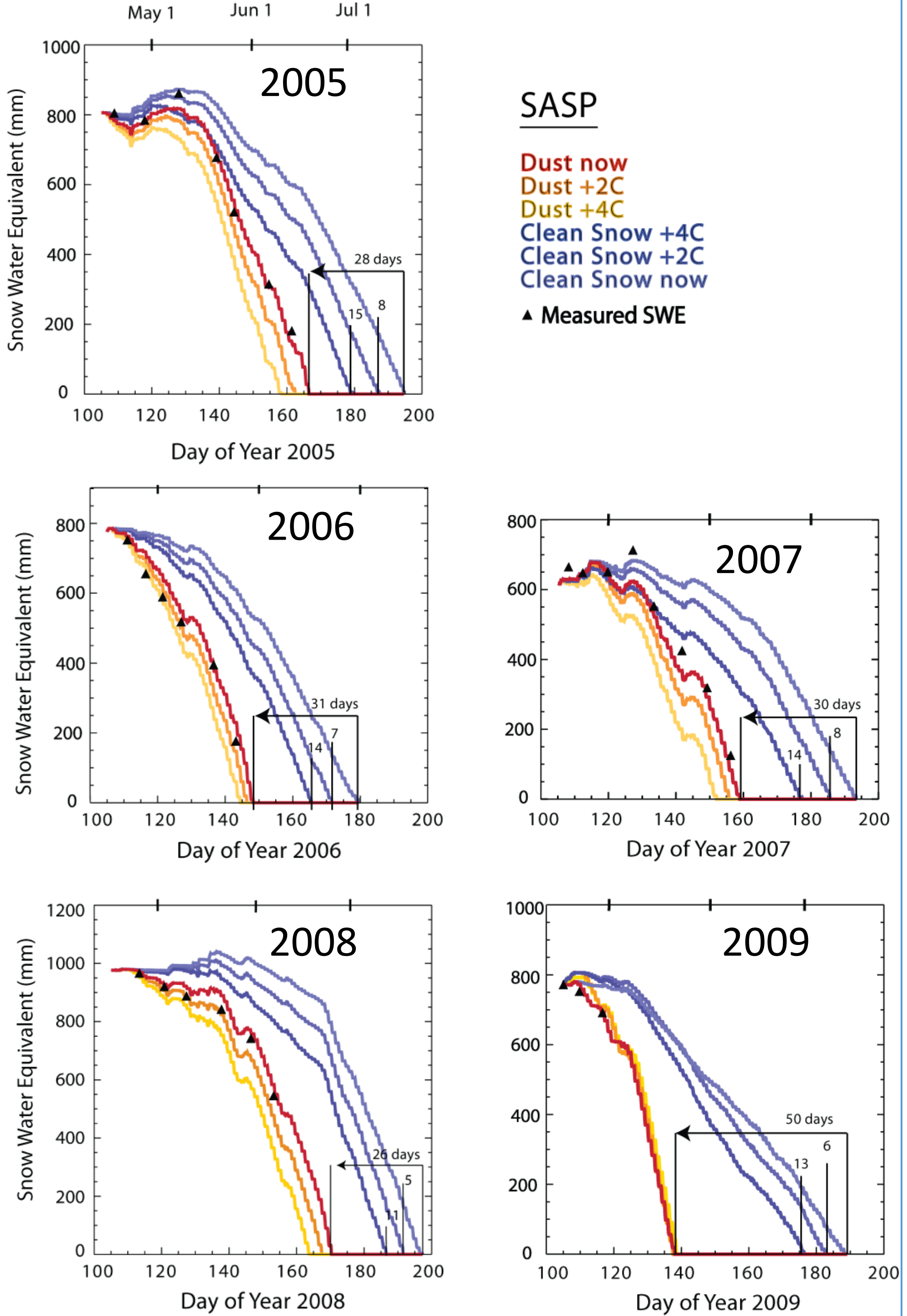
PSD - MEI Homepage
www.esrl.noaa.gov/psd/enso/mei/

May 1
Jun 1
Jul 1
800
600
400
200
0
Snow Water Equivalent (mm)
100
120
140
160
180
200
Day of Year 2007
Dust now
Dust +2C
Dust +4C
Clean Snow +4C
Clean Snow +2C
Clean Snow now
30 days
15
5

Dust enhances snowmelt

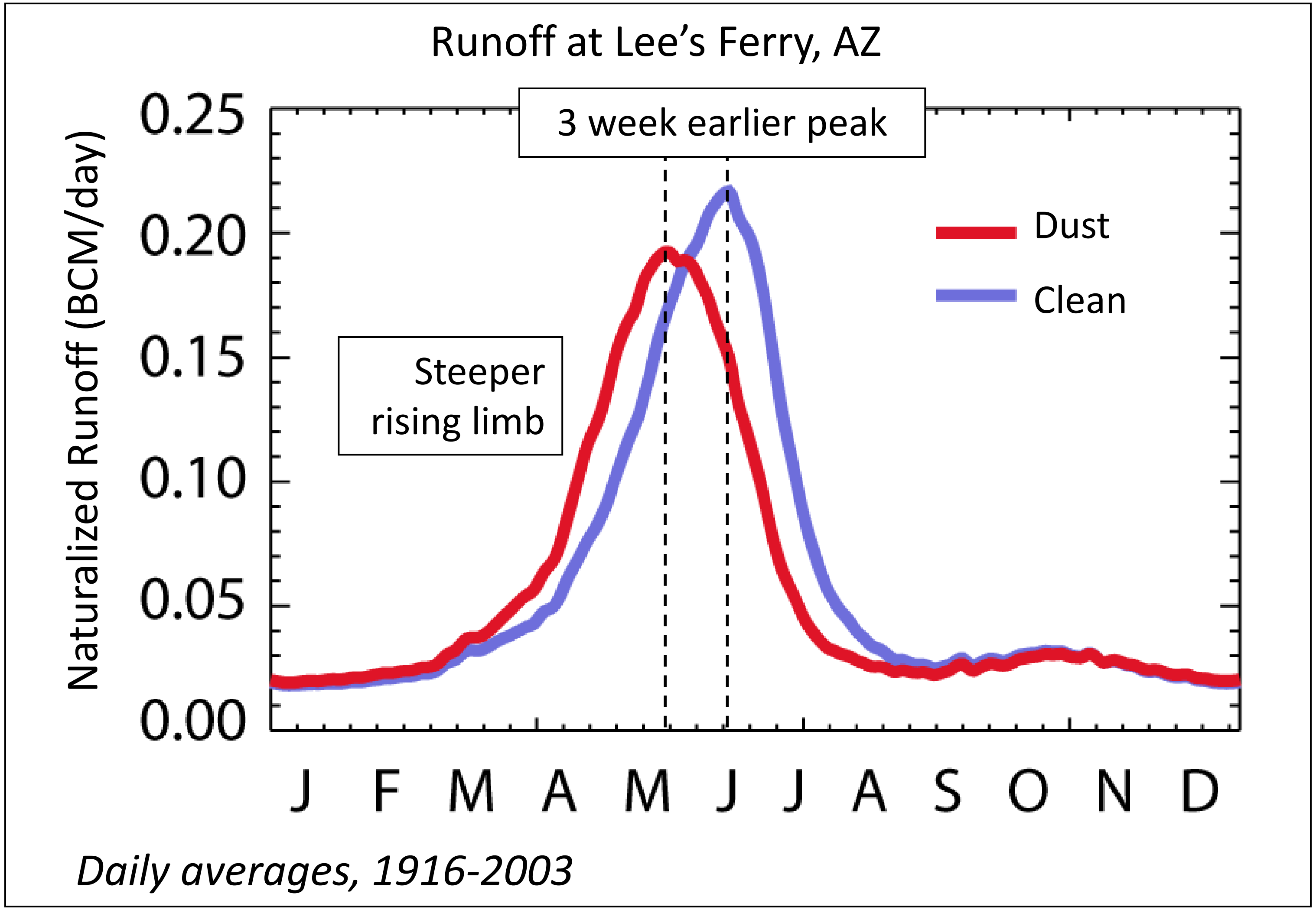
Swamp Angel Study Site:
observed & modeled SWE

Year	# dust events	# spring dust events	# days melt advanced
2003	3	1	-
2004	3	3	-
2005	4	4	28
2006	8	6	31
2007	8	6	30
2008	9	9	26
2009	12	9	50
2010	9	8	-



Skiles *et al.* (*in prep*)

Early melt shifts hydrograph

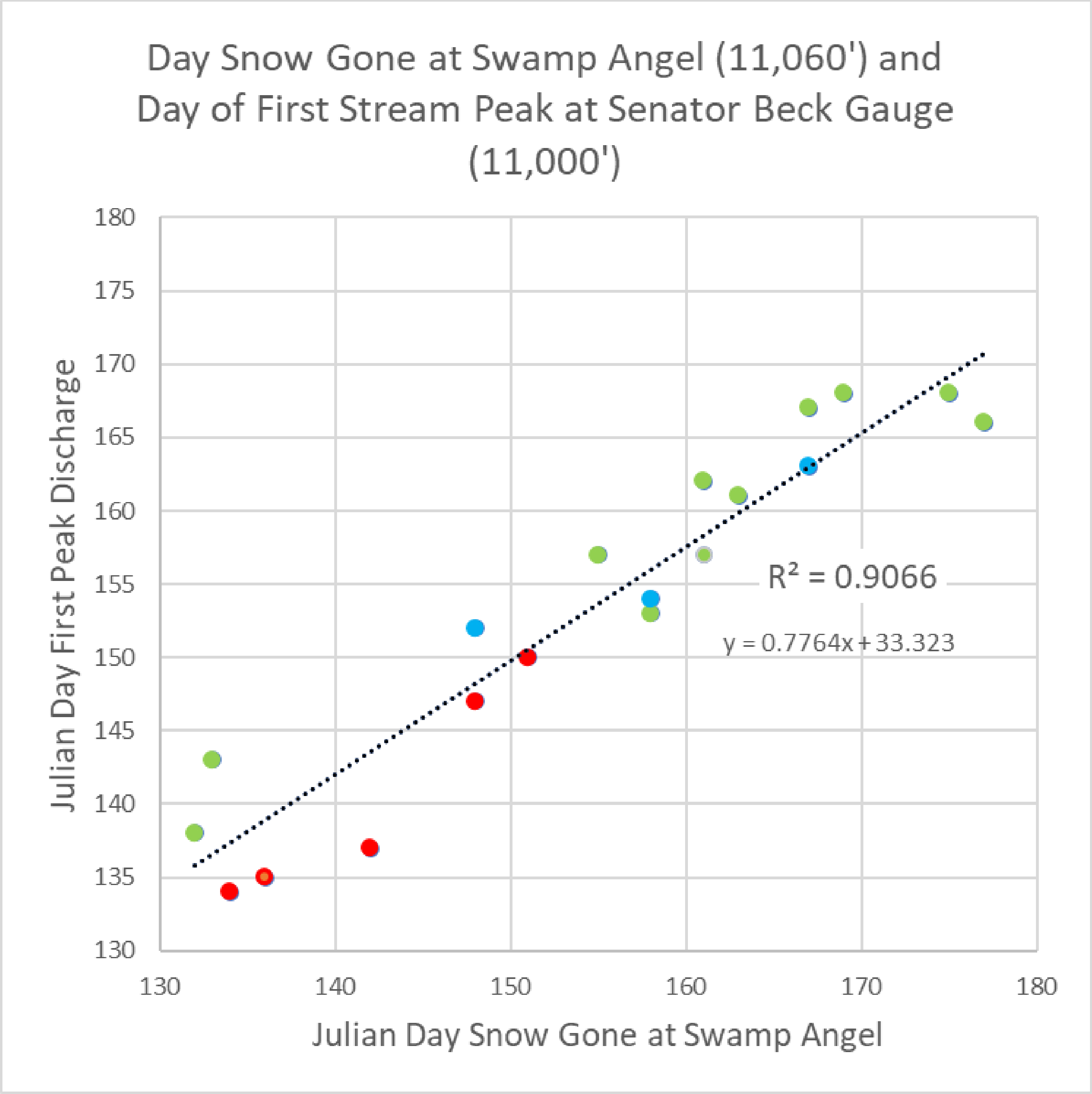

Runoff at Lee’s Ferry, AZ

3 week earlier peak

Steeper rising limb

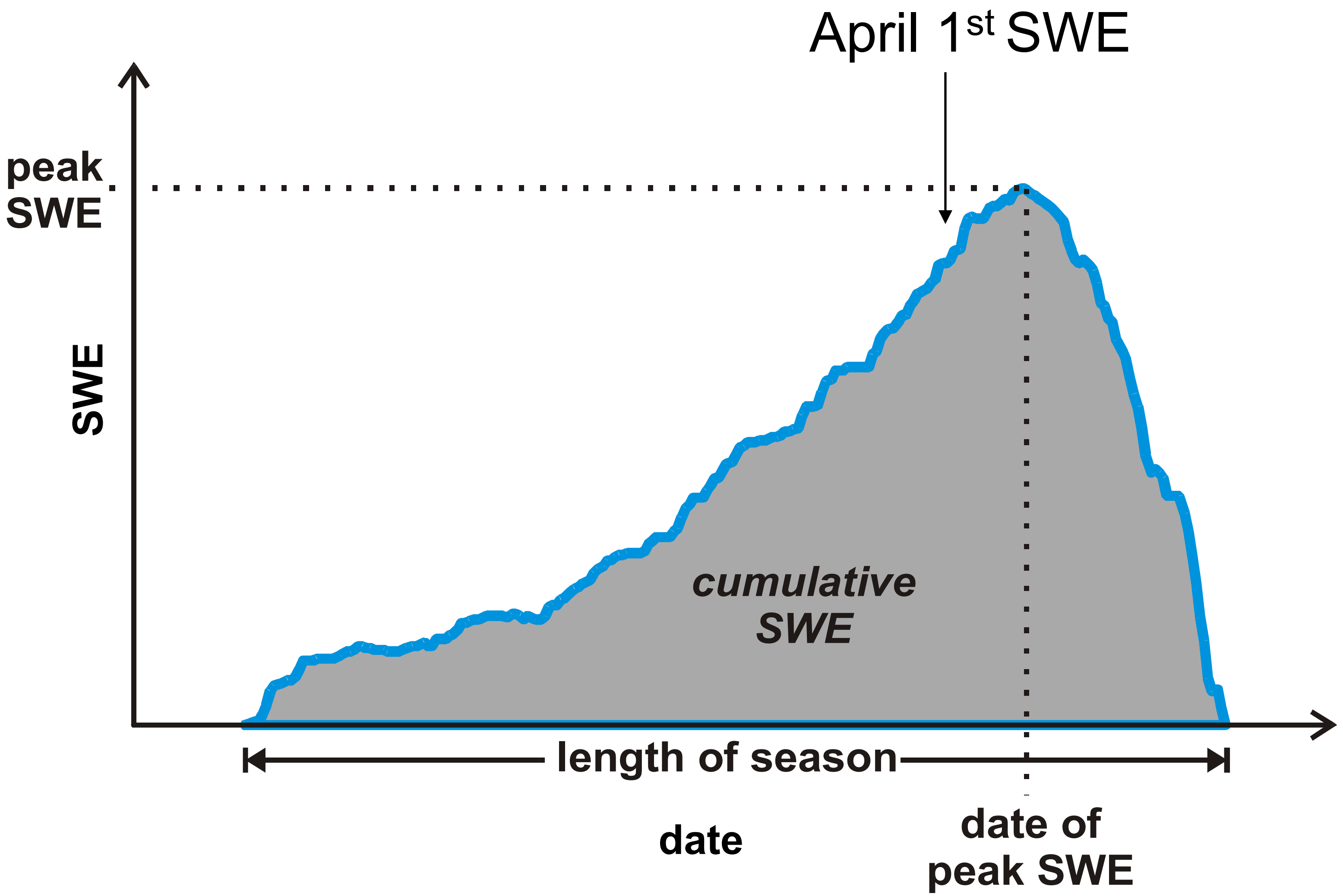
Daily averages, 1916-2003

Painter, Deems, *et al.*, *PNAS* (*2010*)



Day Snow Gone at Swamp Angel (11,060') and Day of First Stream Peak at Senator Beck Gauge (11,000')

SWE descriptor variables



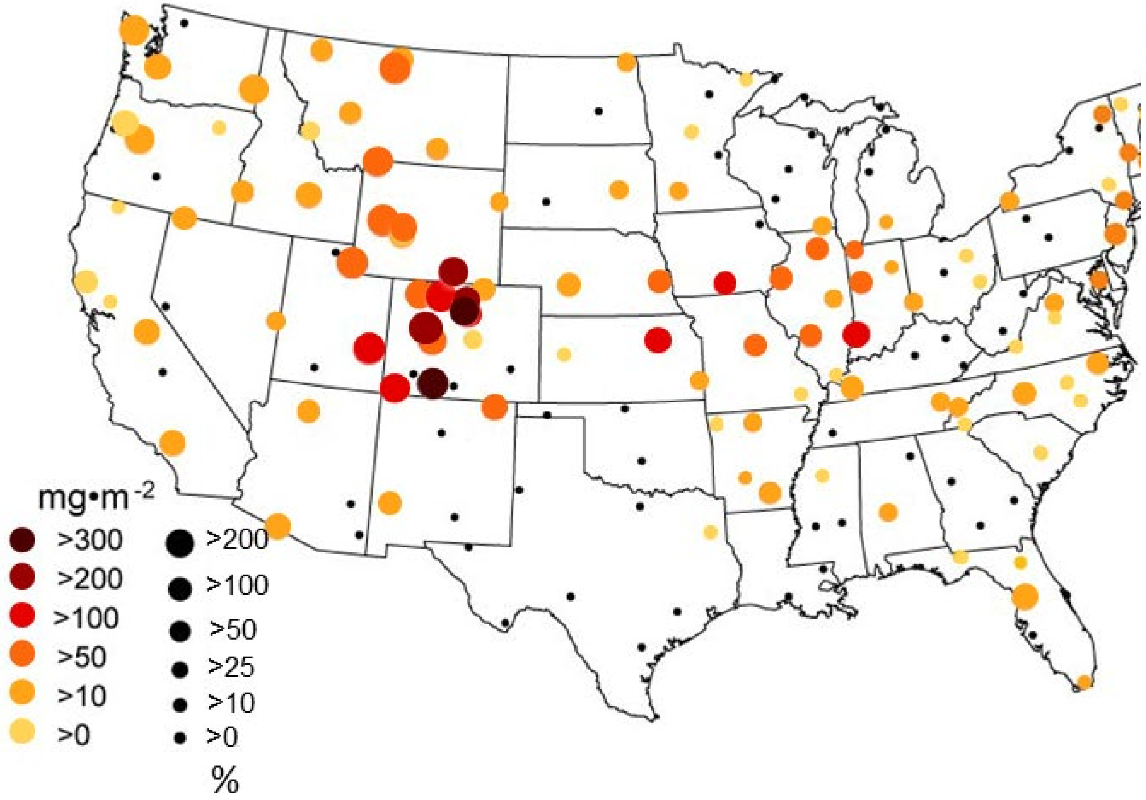
Dust deposition increasing since mid-90’s

J. Brahney, A.P. Ballantyne, C. Sievers, J.C. Neff. Increasing Ca2+ deposition in the western US: the role of mineral aerosols. *Aeolian Research* (2013), http://dx.doi.org/10.1016/j.aeolia.2013.04.003

Increasing aeolian dust deposition to snowpacks in the Rocky Mountains inferred from snowpack, wet deposition, and aerosol chemistry

David W. Clow [a, *], Mark W. Williams [b], Paul F. Schuster [c]

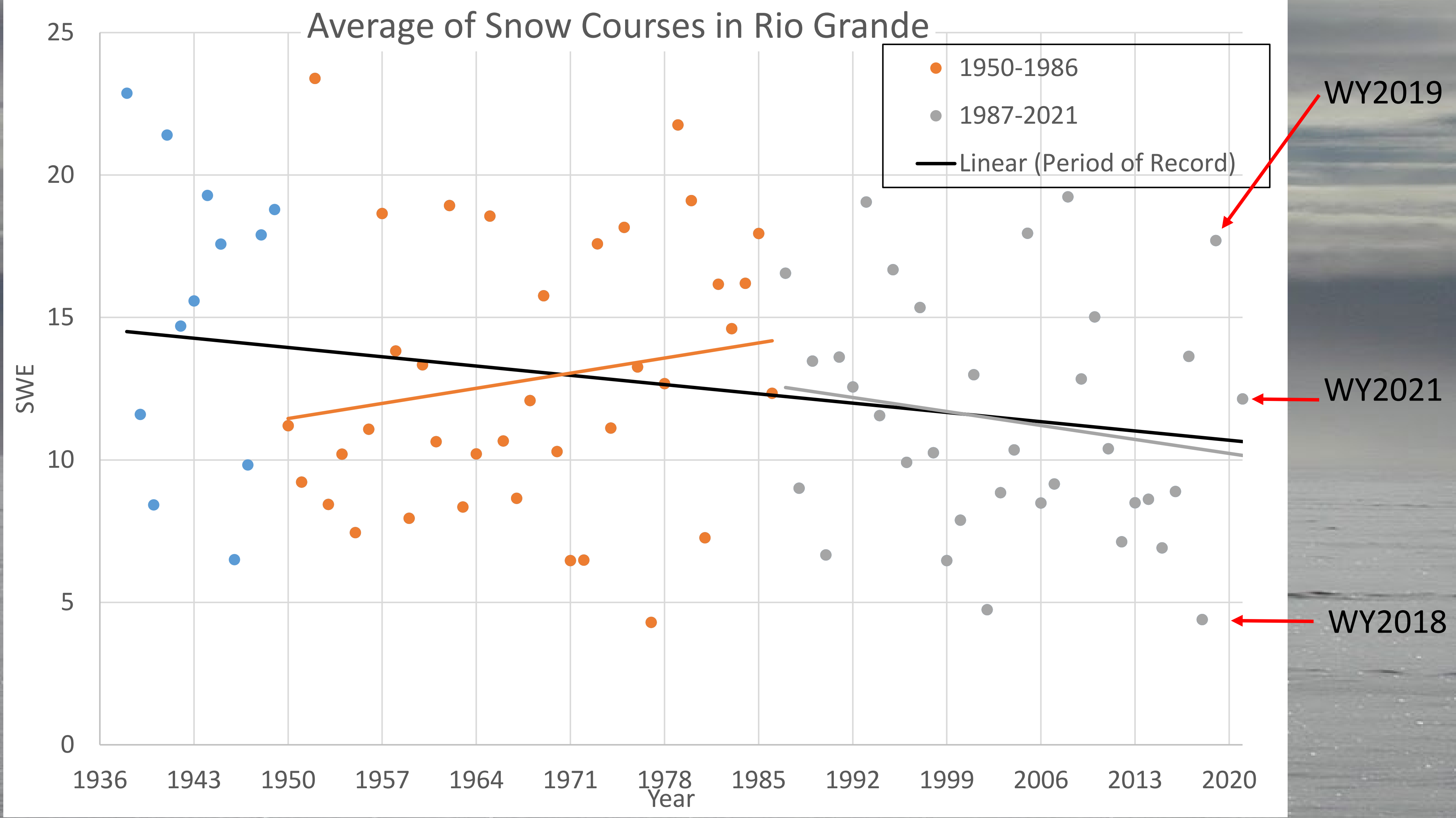
[a] Colorado Water Science Center, United States Geological Survey, Denver Federal Center, MS 415, Denver, CO 80225, USA
[b] Department of Geography, University of Colorado at Boulder, UCB 360, Boulder, CO 80309, USA
[c] National Research Program, United States Geological Survey, 3215 Marine St., Boulder, CO 80303, USA



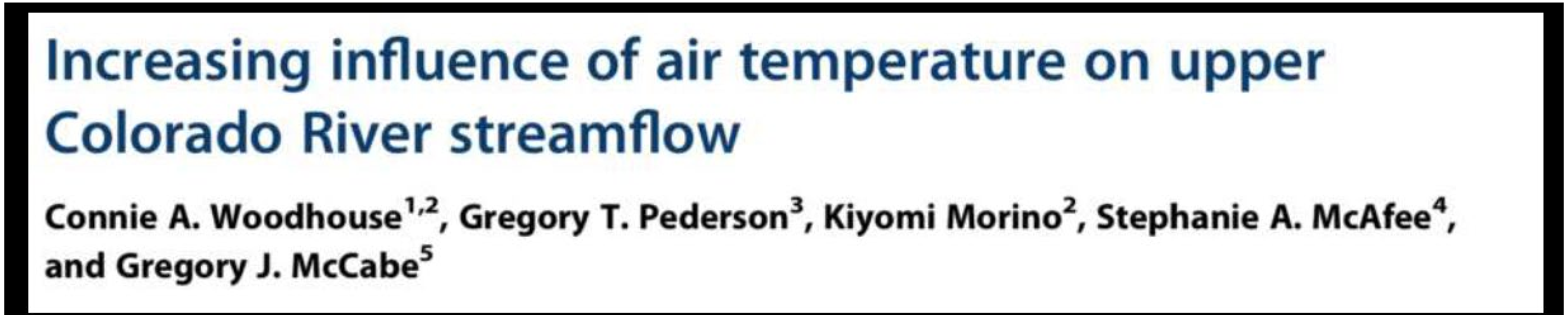
Soil Erosion In The West Is Getting Worse And The Air Is Getting Dustier

By ALI BUDNER • 21 HOURS AGO

About 75% of Rio Grande flows come from snowpack, while monsoon rains produce the rest.



https://labs.waterdata.usgs.gov/visualizations/snow-to-flow/index.html#/



Increasing influence of air temperature on upper Colorado River streamflow

Connie A. Woodhouse[1,2], Gregory T. Pederson[3], Kiyomi Morino[2], Stephanie A. McAfee[4], and Gregory J. McCabe[5]

- Temperature can be a major flow driver in addition to precipitation
- Since 1988 flows have been less than expected given winter precipitation
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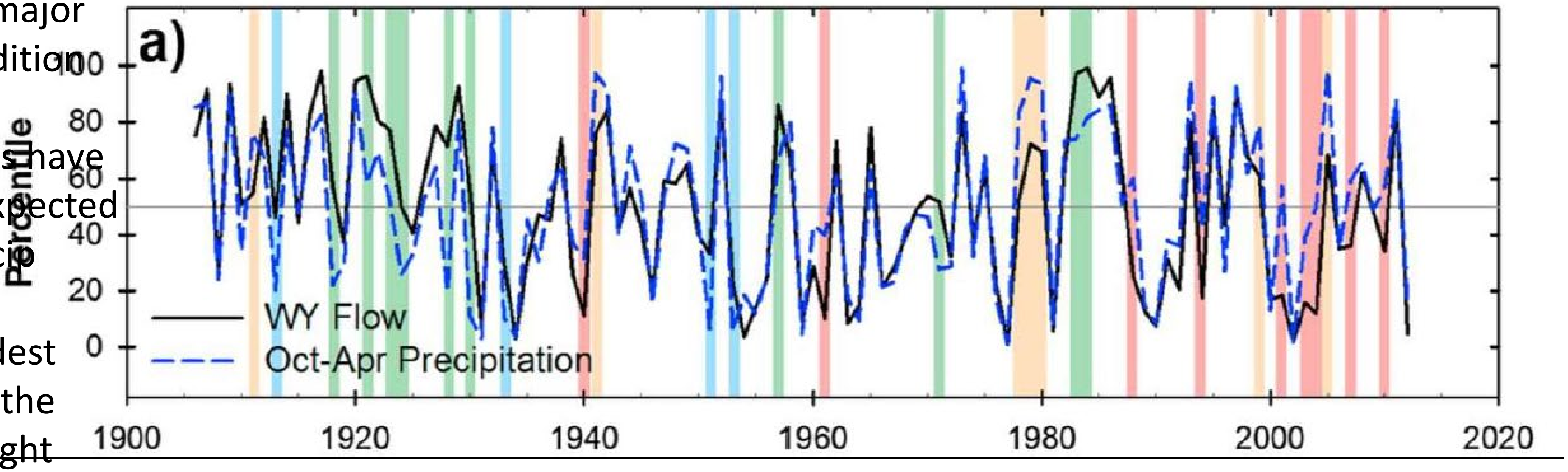


About 60 million people in the Western United States depend on snowmelt.

- Of these, 10—27 million live in areas where it is likely that snowmelt will no longer be able to provide sufficient runoff to meet *summer/fall demand by 2060* (Mankin et al. 2015).

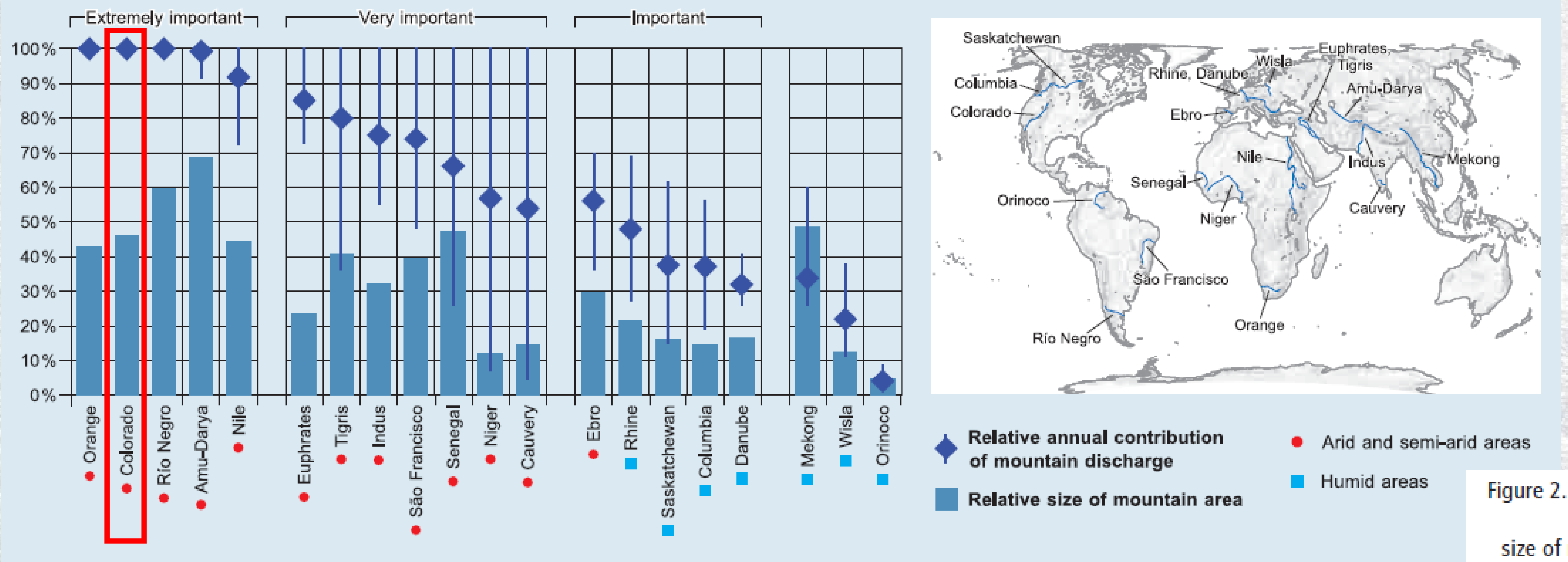


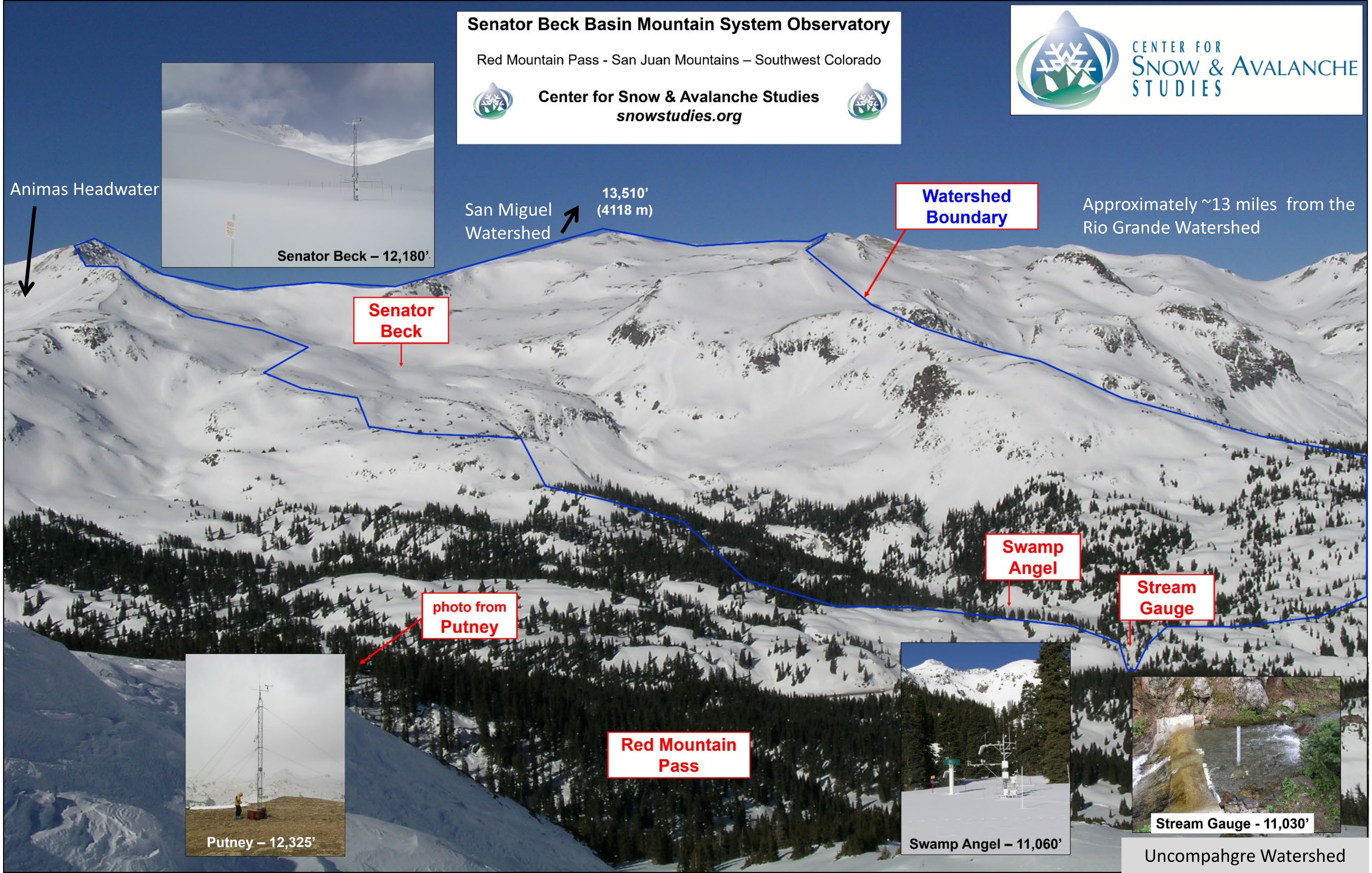
Figure 2.2: Contribution of mountain area to total discharge, and size of mountain area as compared to total basin area for selected rivers world-wide (Viviroli et al 2003).

Senator Beck Basin Mountain System Observatory

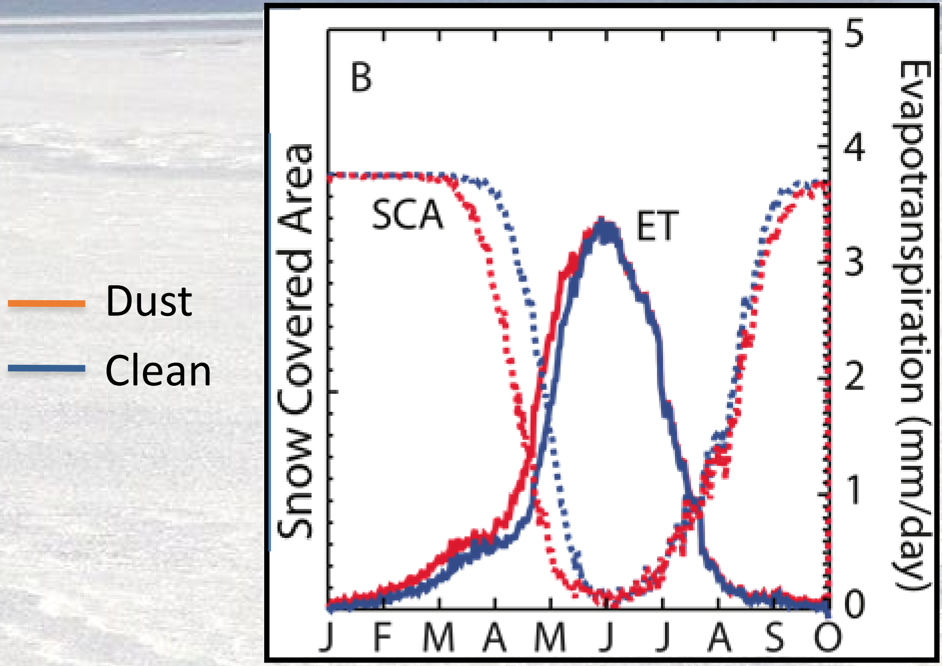
Red Mountain Pass - San Juan Mountains – Southwest Colorado

Center for Snow & Avalanche Studies
snowstudies.org

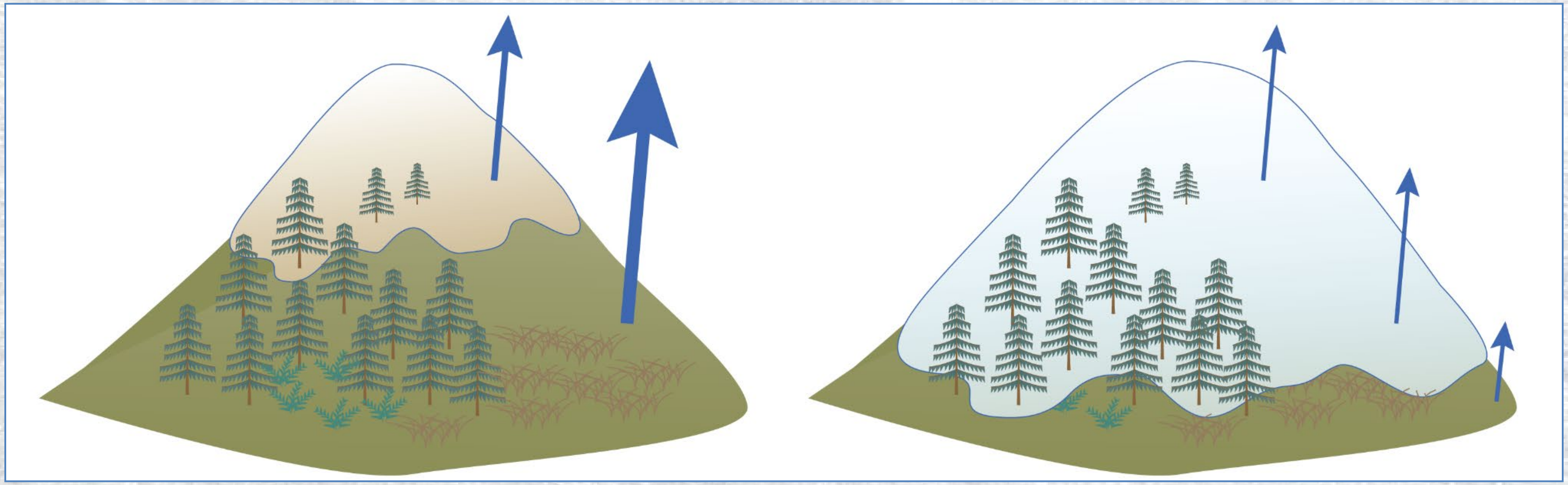
CENTER FOR
SNOW & AVALANCHE
STUDIES



Longer growing season increases ET

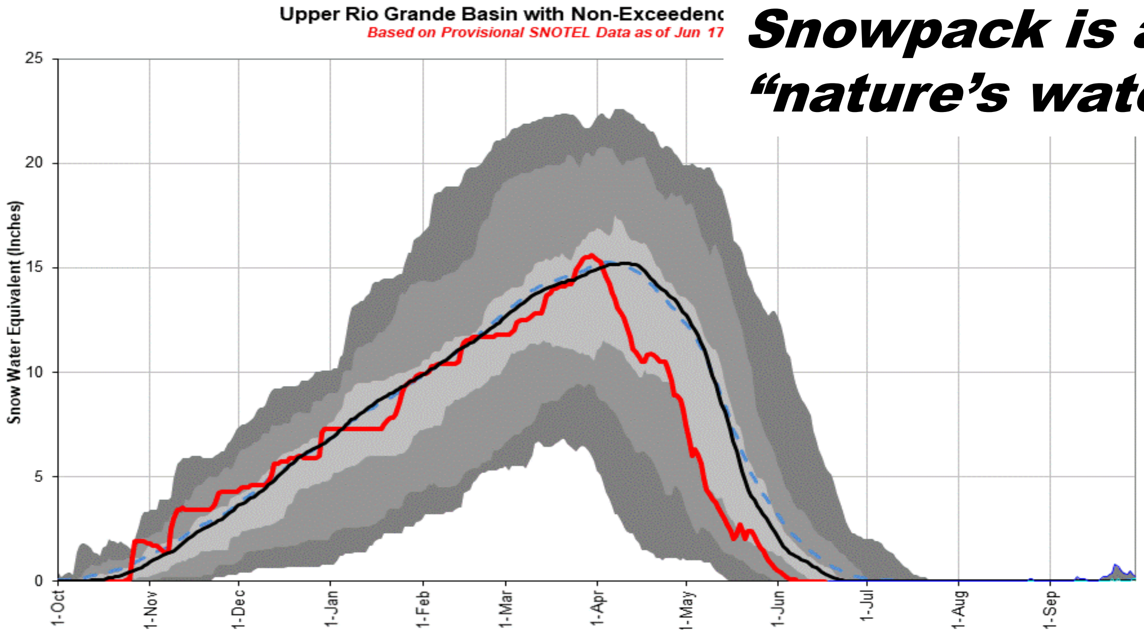


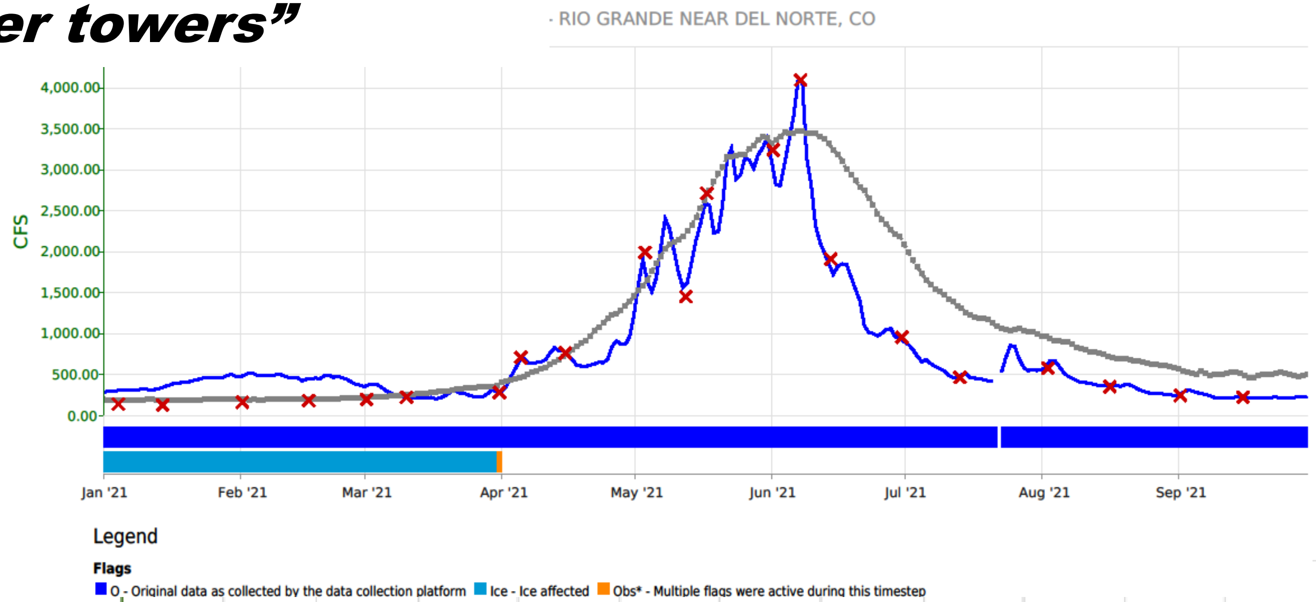
Decrease annual runoff in UCRB by ~ 5% on average

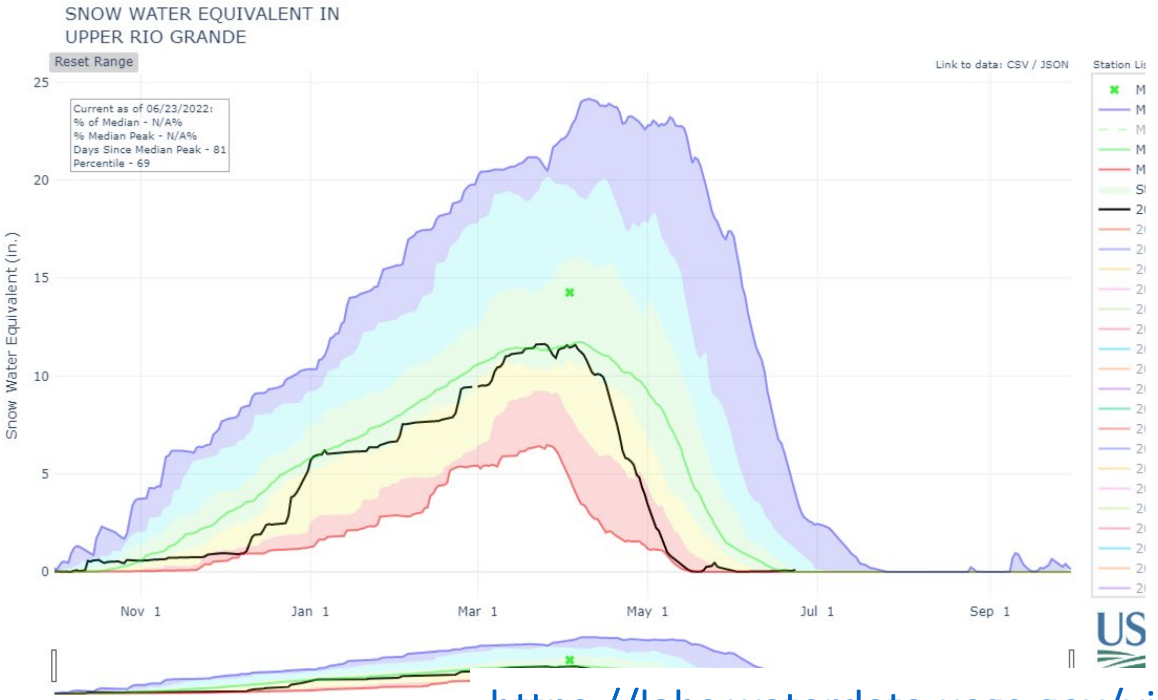


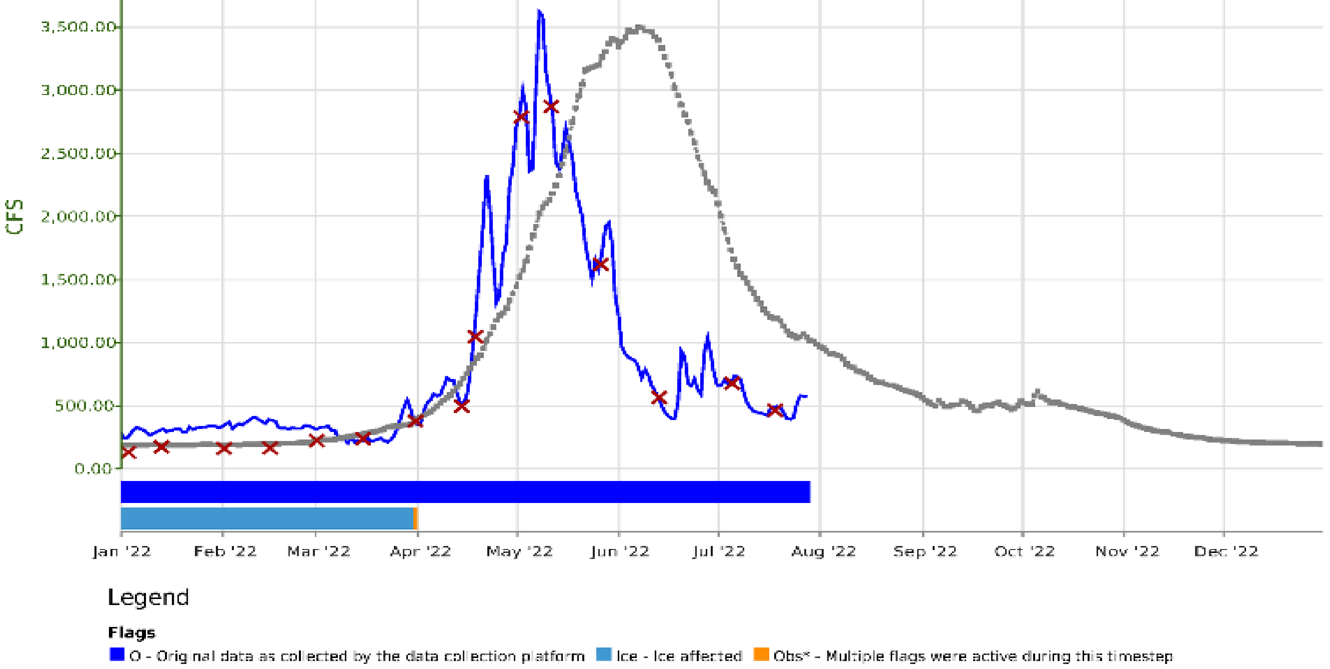
Painter, Deems, *et al.*, *PNAS* (2010)

Snowpack is a natural reservoir “nature’s water towers”







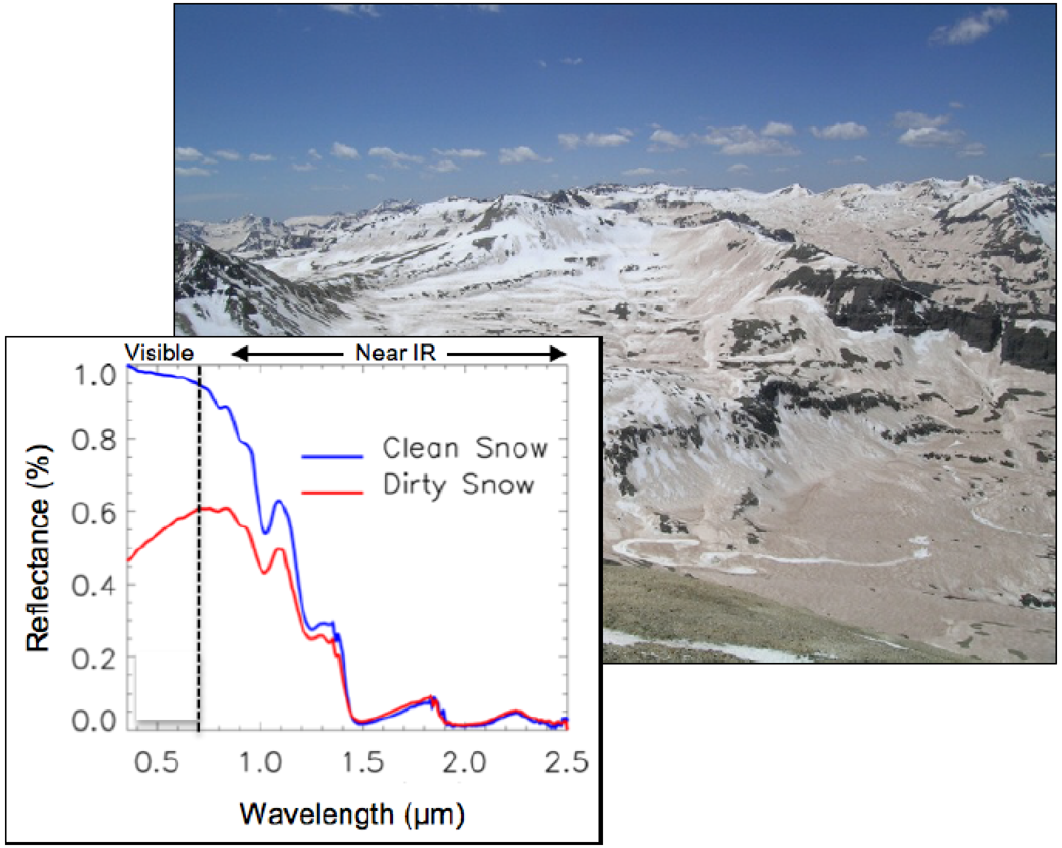


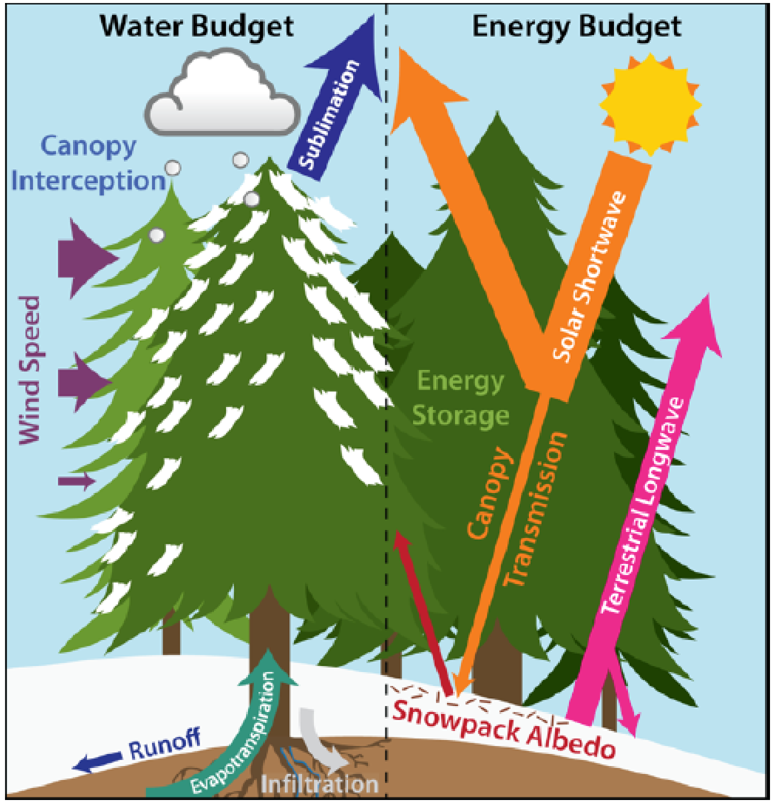
https://labs.waterdata.usgs.gov/visualizations/snow-to-flow/index.html#/

Forecast error sources

Land cover change/bark beetle

- Change in canopy cover over large areas changes snow accumulation & energy balance





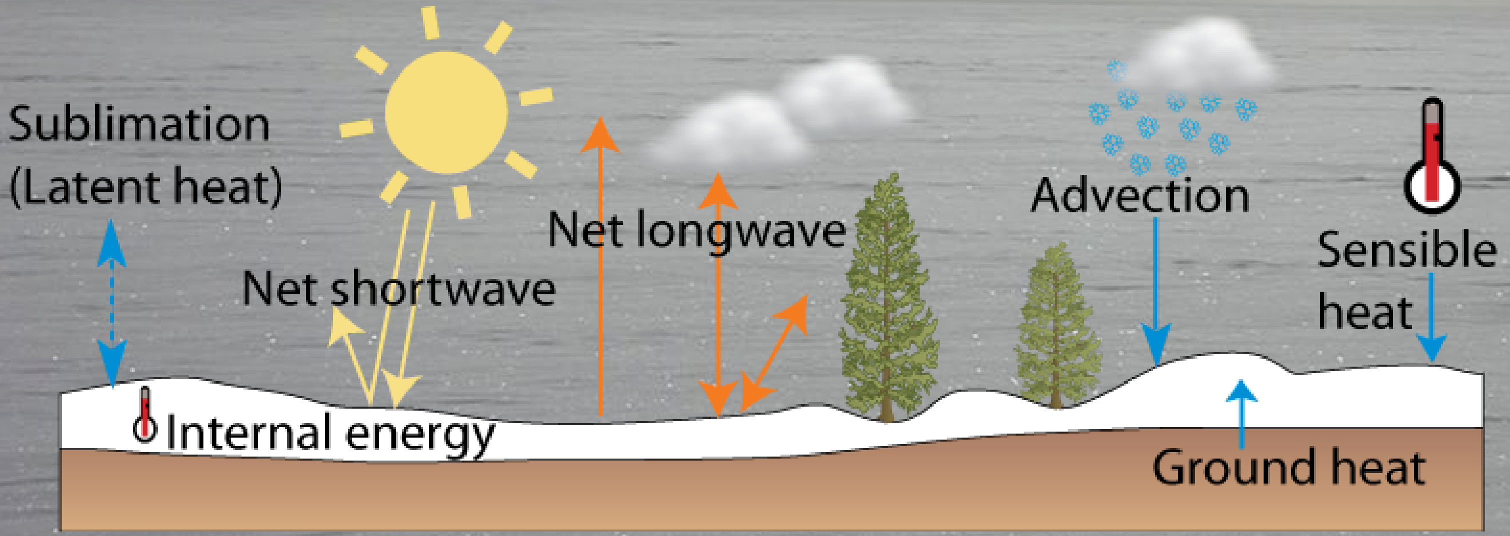
Pugh and Gordon, *Hydrological Processes*

Dust on snow

- Dust strongly increases solar absorption
- Melt shifts earlier
- Decrease in runoff

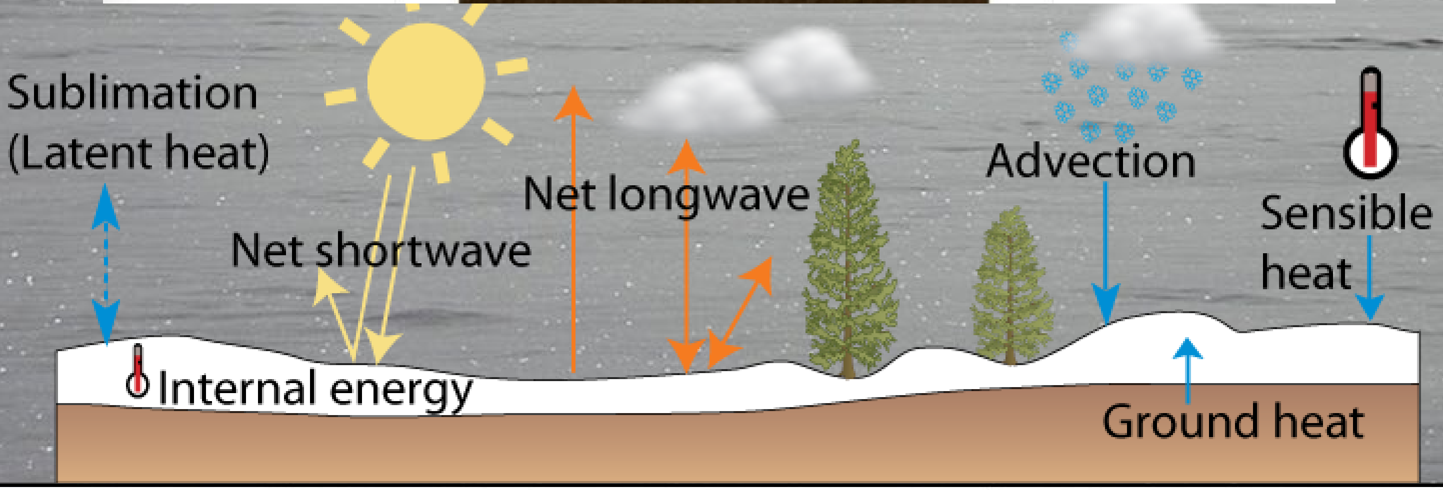
Heat From Rain

- Usually overrated!!
- At rain temperature of 10°C (50°F), it would take 8 inches of rain to melt 1 inch of SWE in an isothermal snowpack.
- Or…What would the temperature need to be if you wanted 1” of rain to melt 1” SWE? 80°F!
- Cold rain can warm snowpack more than warm rain



Heat From Rain

Rain on snow situations are often seen as a "worst case scenario" by forecasters concerned about rapid snowmelt. However, rain falling onto snow does not always cause rapid warming of the snow, or even warming at all. Let's imagine a situation in which rain with a temperature of 10°C is falling at a rate of 10 mm per day. This rain is warm enough that it does not freeze as it trickles down through the snowpack. As the rain moves through the snowpack, it will impart small amounts of heat energy to the snow.



Heat From Rain

Now let's imagine a situation in which cold rain, with a temperature between 0°C and 1°C, is falling. As this cold rain trickles down into the snowpack, it loses heat to the snow and begins to freeze, forming areas of ice.

"Cold" Rain Falling Into Snowpack

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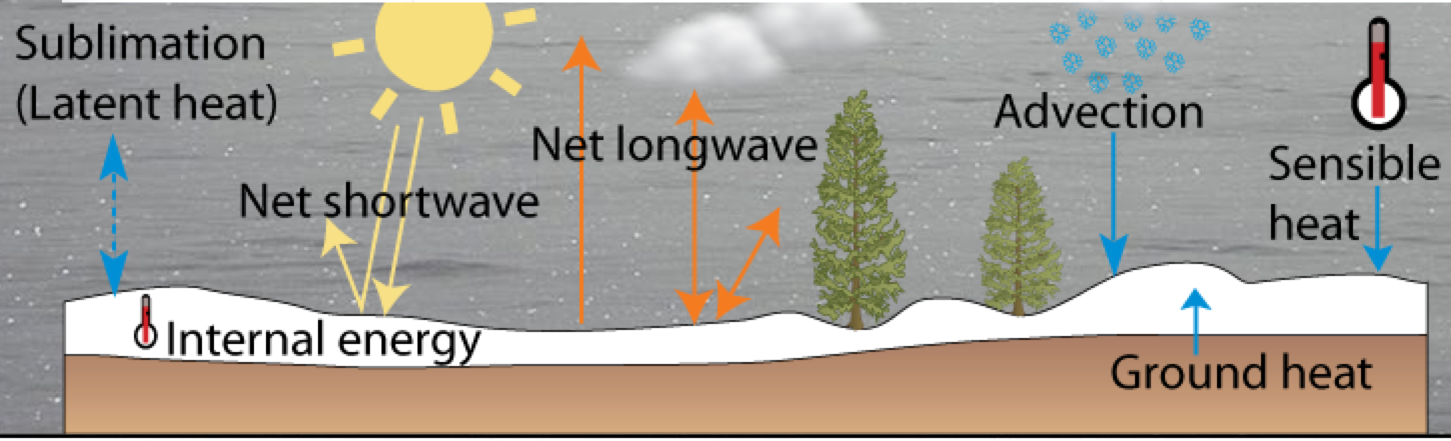
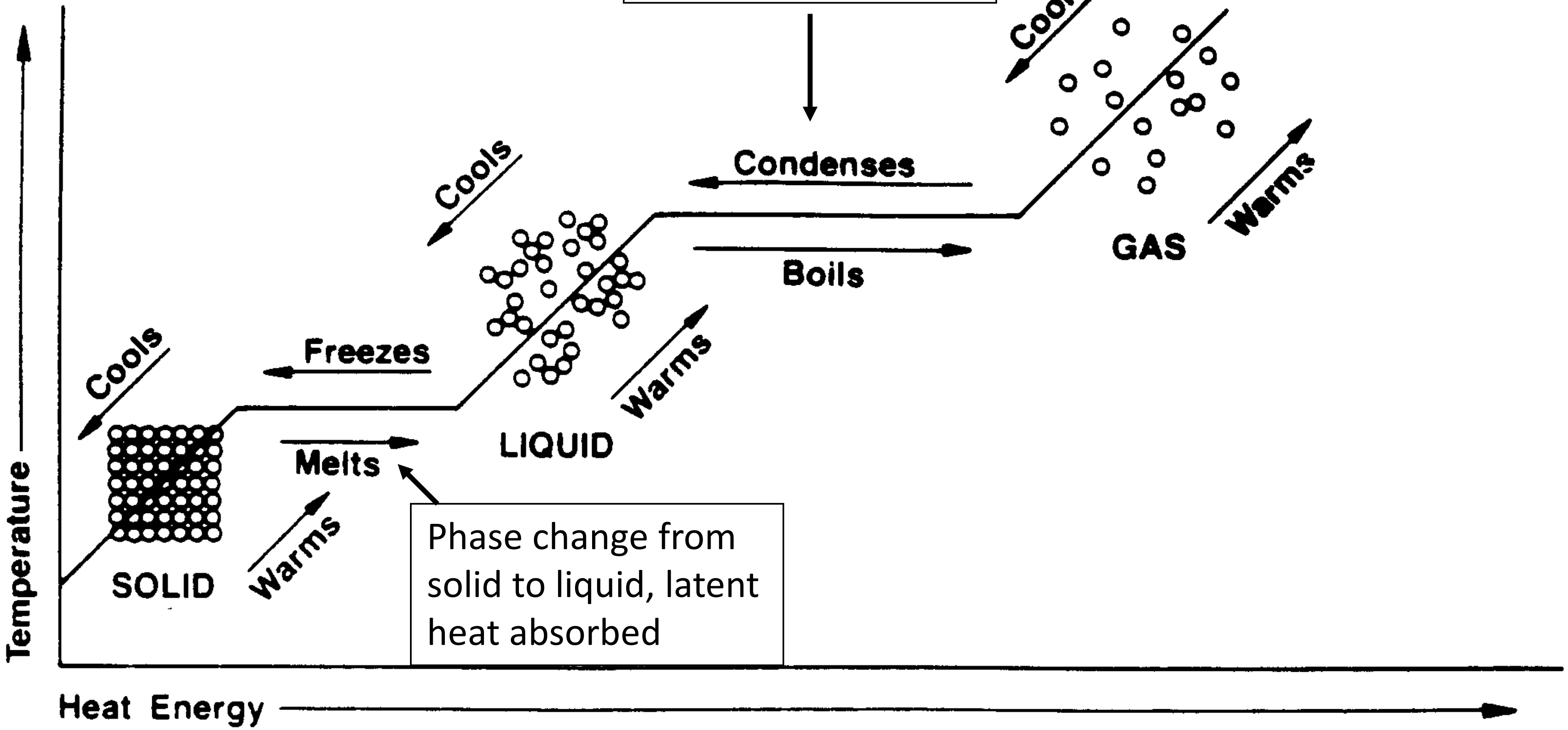
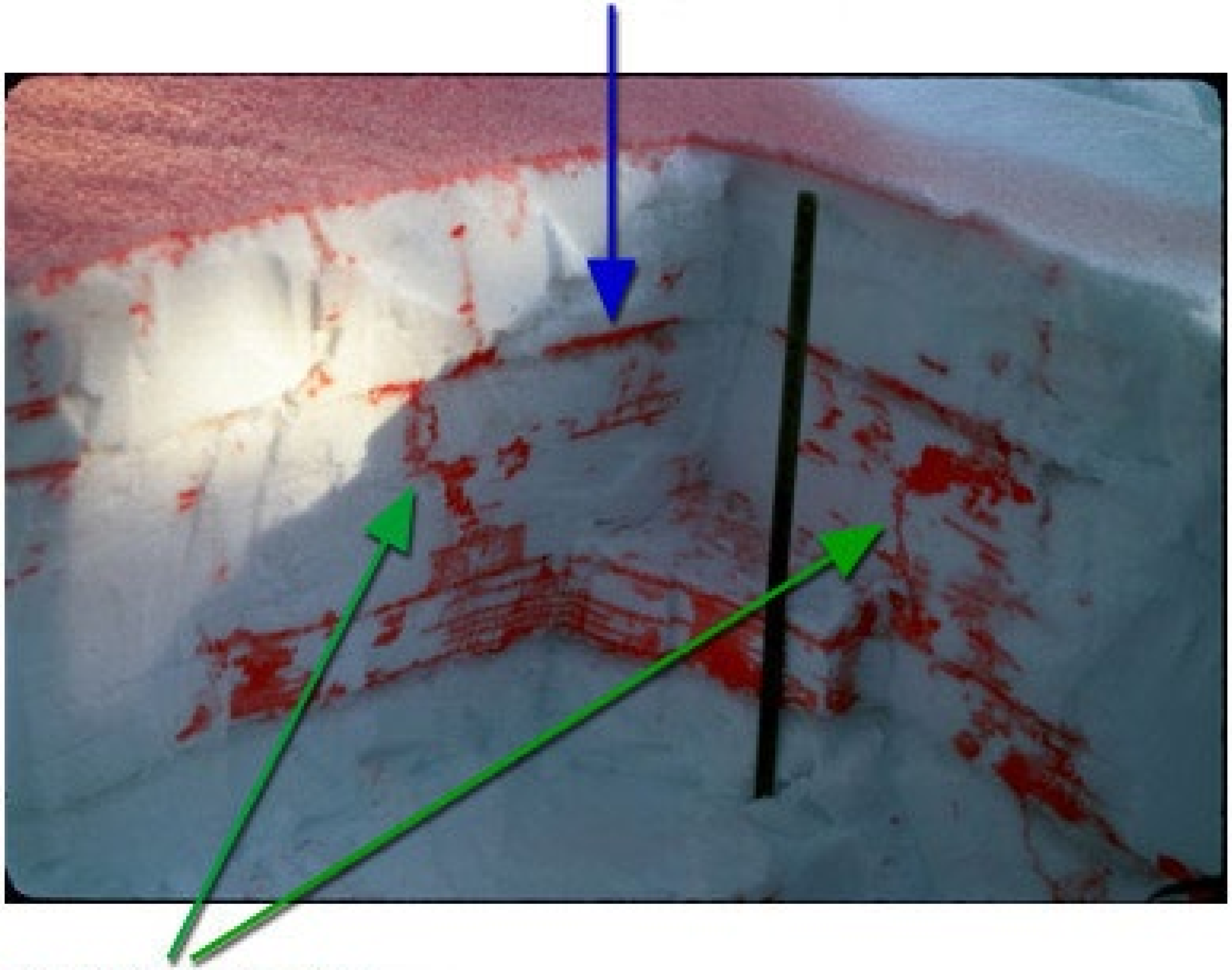


Latent Heat



Phase change from gas to liquid, latent heat is released

Phase change from solid to liquid, latent heat absorbed

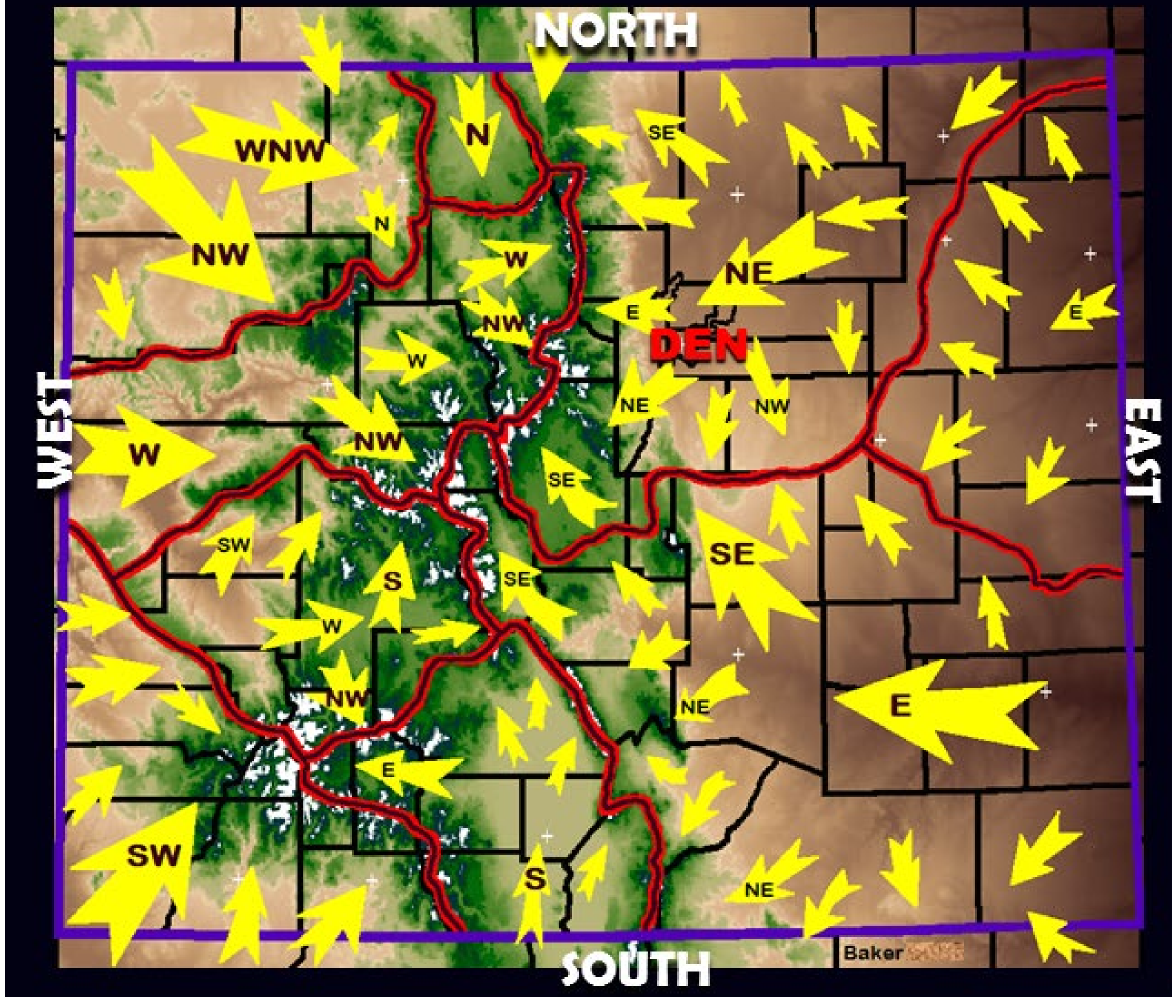


Akumulace vody na nepropustné vrstvě ledové krusty

Preferenční cesty

Jeff Dozier / UCSB / The COMET Program

Optimum Near Ground Wind Components for the Production of Upslope or Orographic Precipitation



In southwest Colorado, the principle upslope wind component is **southwest**.

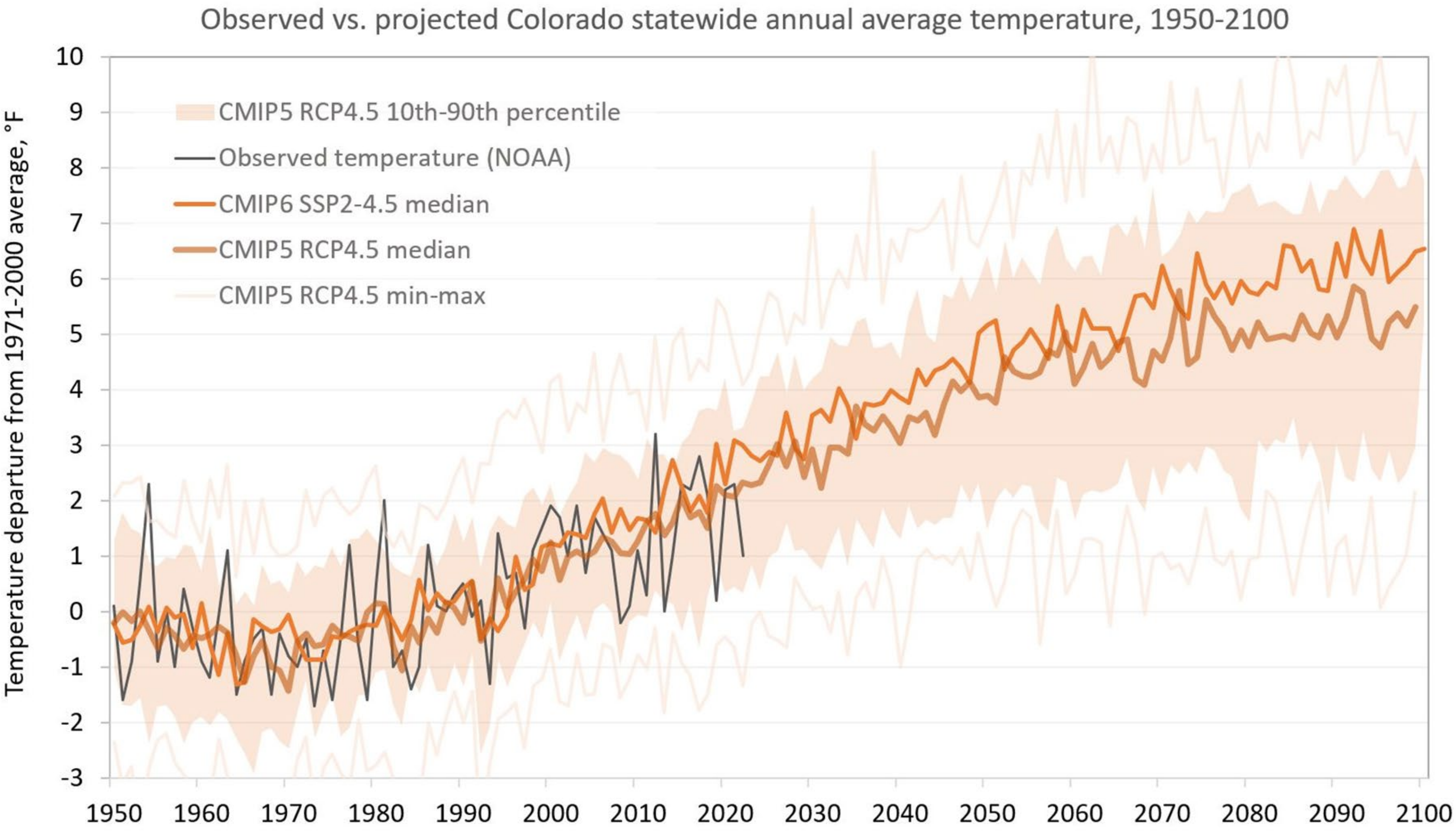
In west-central Colorado, it is principally a **westerly** component.

In northwest Colorado, it is principally a **northwesterly** component.

In northeast Colorado, it is principally an **east-northeast** component.

And, in southeast Colorado, the optimum upslope wind component is **east-southeast**.

Baker - National Weather Service Boulder


Observed vs. projected Colorado statewide annual average temperature, 1950-2100
Temperature departure from 1971-2000 average, °F
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
CMIP5 RCP4.5 10th-90th percentile
Observed temperature (NOAA)
CMIP6 SSP2-4.5 median
CMIP5 RCP4.5 median
CMIP5 RCP4.5 min-max