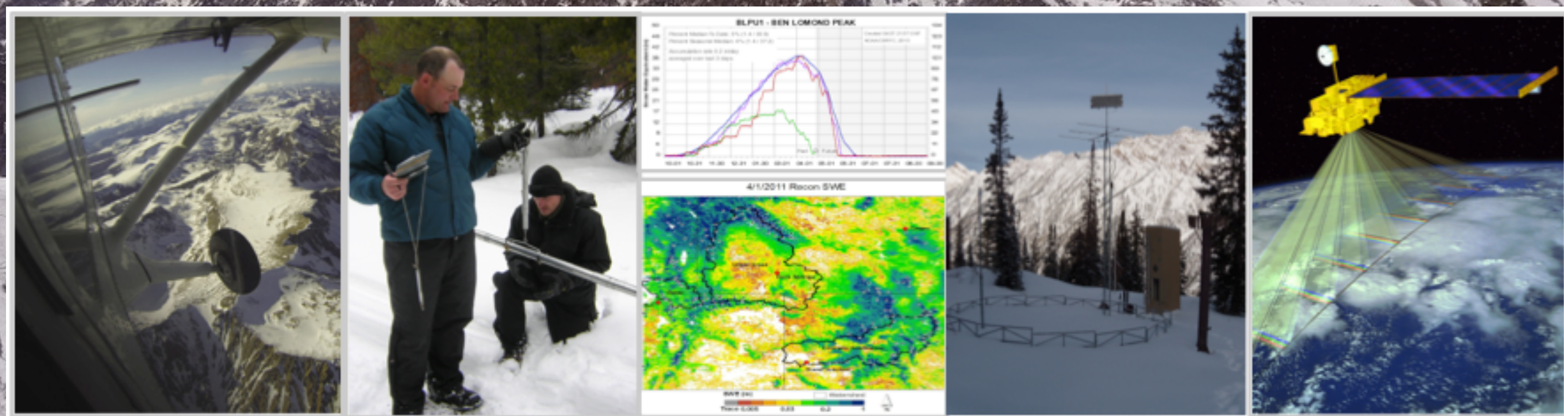
Western Water Assessment

CIRES

University of Colorado **Boulder**

http://wwa.colorado.edu

Measuring and modeling our snow water resource



West Jordan, Utah – August 11, 2015

Background Photo: Jim Steenburgh, Wasatch Weather Weenies

NIDIS

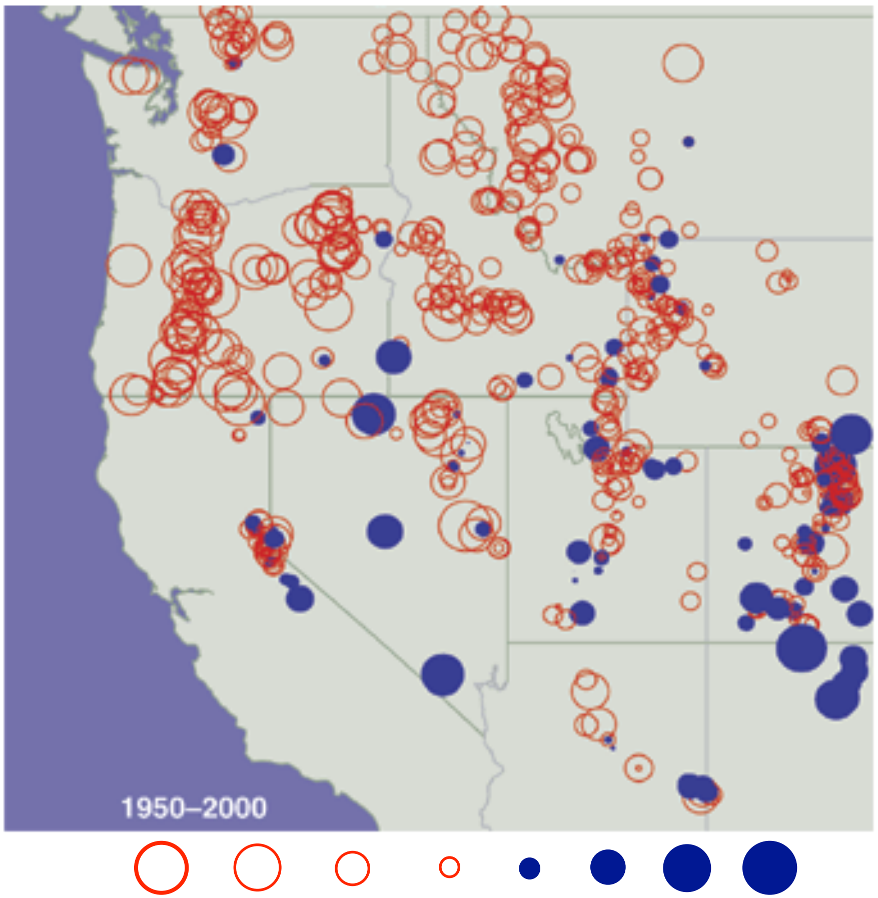
NRCS Natural Resources Conservation Service Snow Survey

Colorado Basin River Forecast Center CBRFC

Jordan Valley Water Conservancy District

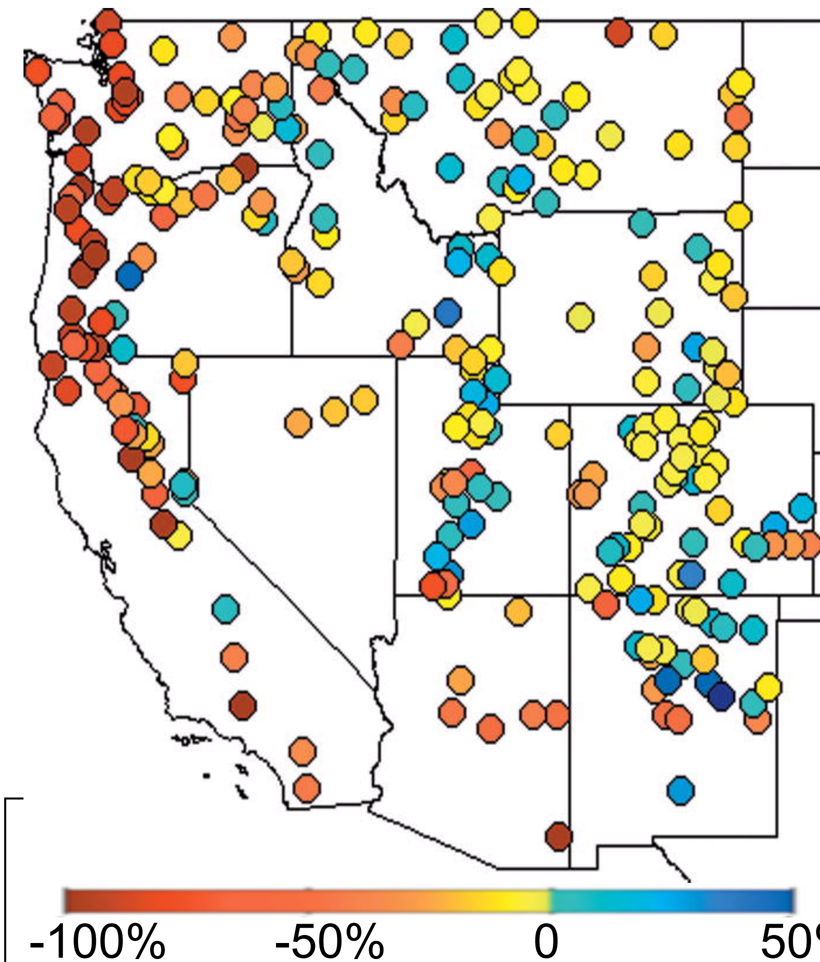
Snowpack Trends: 1950 - 2000

Percent change in April 1 snow water equivalent



Service, 2004

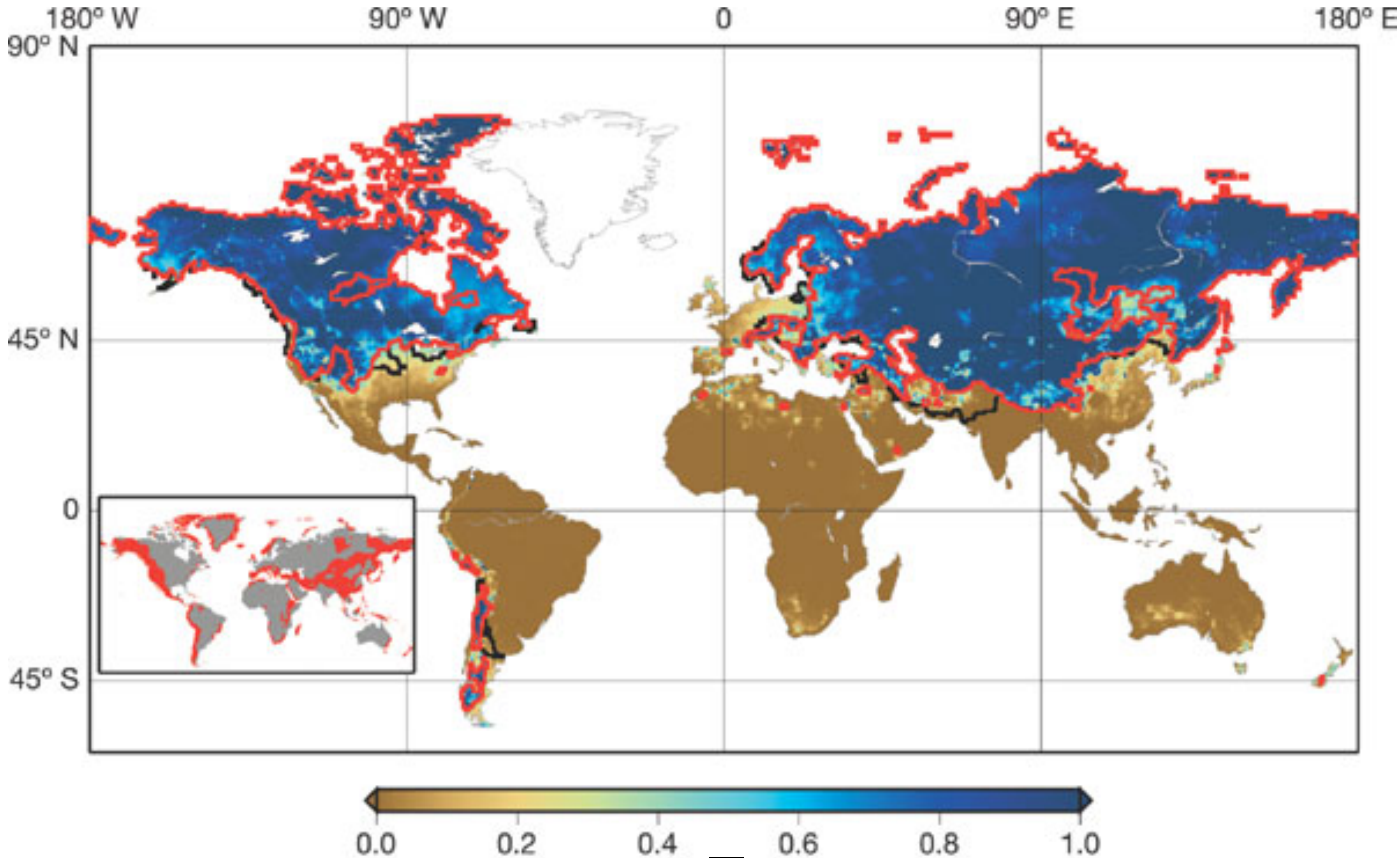
Percent change in snowfall to rainfall



Knowles et al., 2006

Importance of Snowmelt Runoff

1/6th of the population and 1/4th of GDP



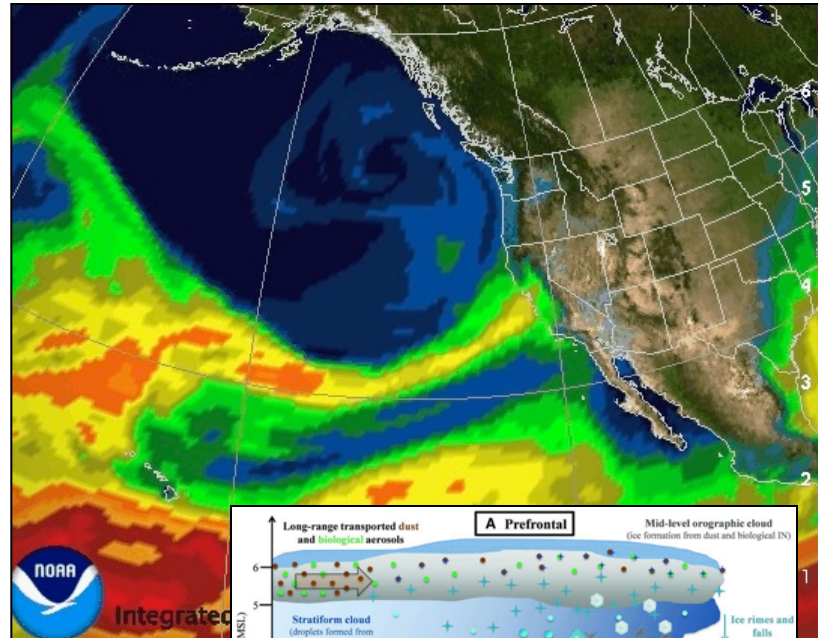
Snowfall / Runoff Ratio

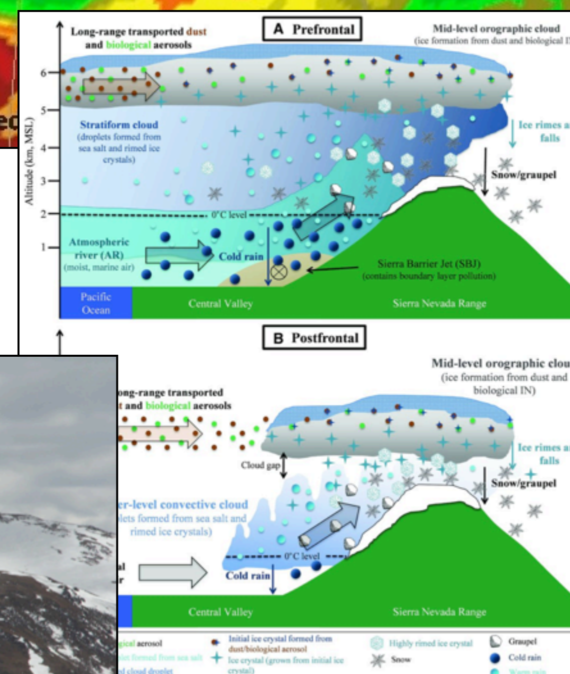
Barnett et al., 2005 - Nature

Snow accumulation

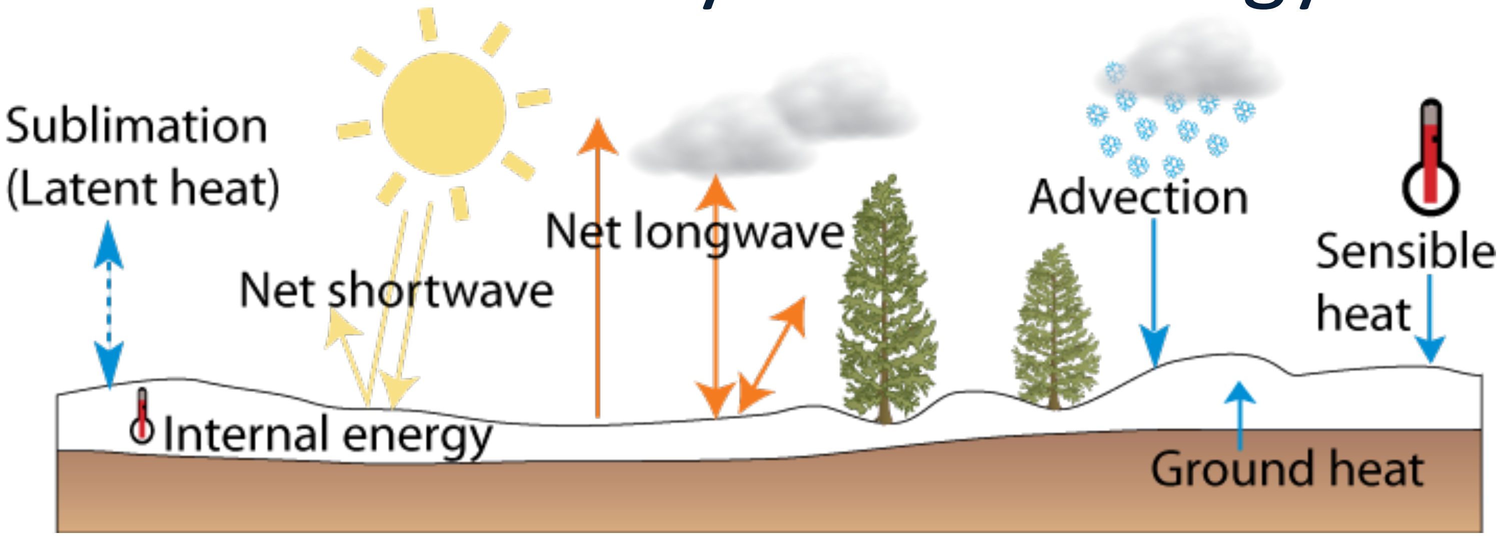
depends on:

- Storm track
- Storm synoptics
- Air temperature & moisture
- Orientation of moisture flux relative to topography
- Orographic enhancement
- Wind redistribution
- …





Snow melt is driven by surface energy balance



Change in internal energy

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

Melt energy

Albedo

Shortwave radiation

Net Longwave radiation

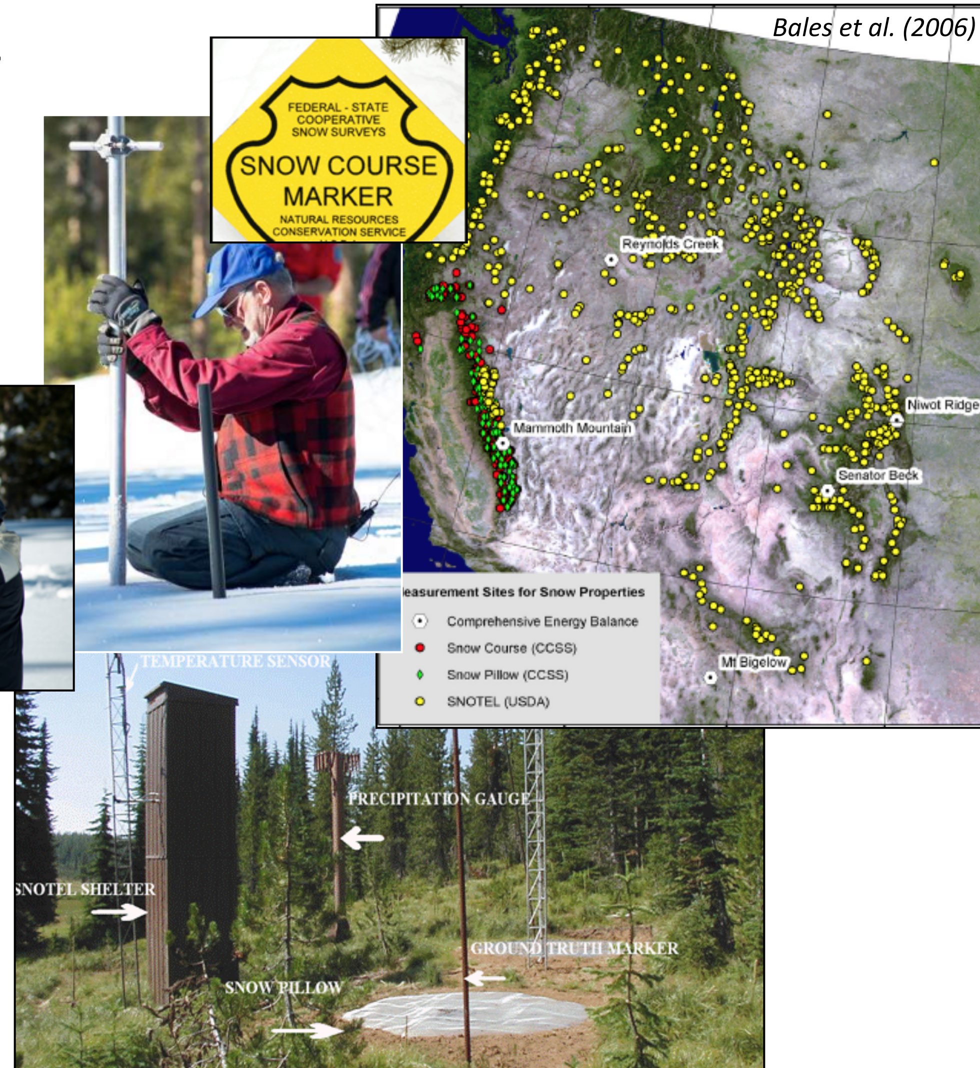
Sensible heat/advection

Latent heat

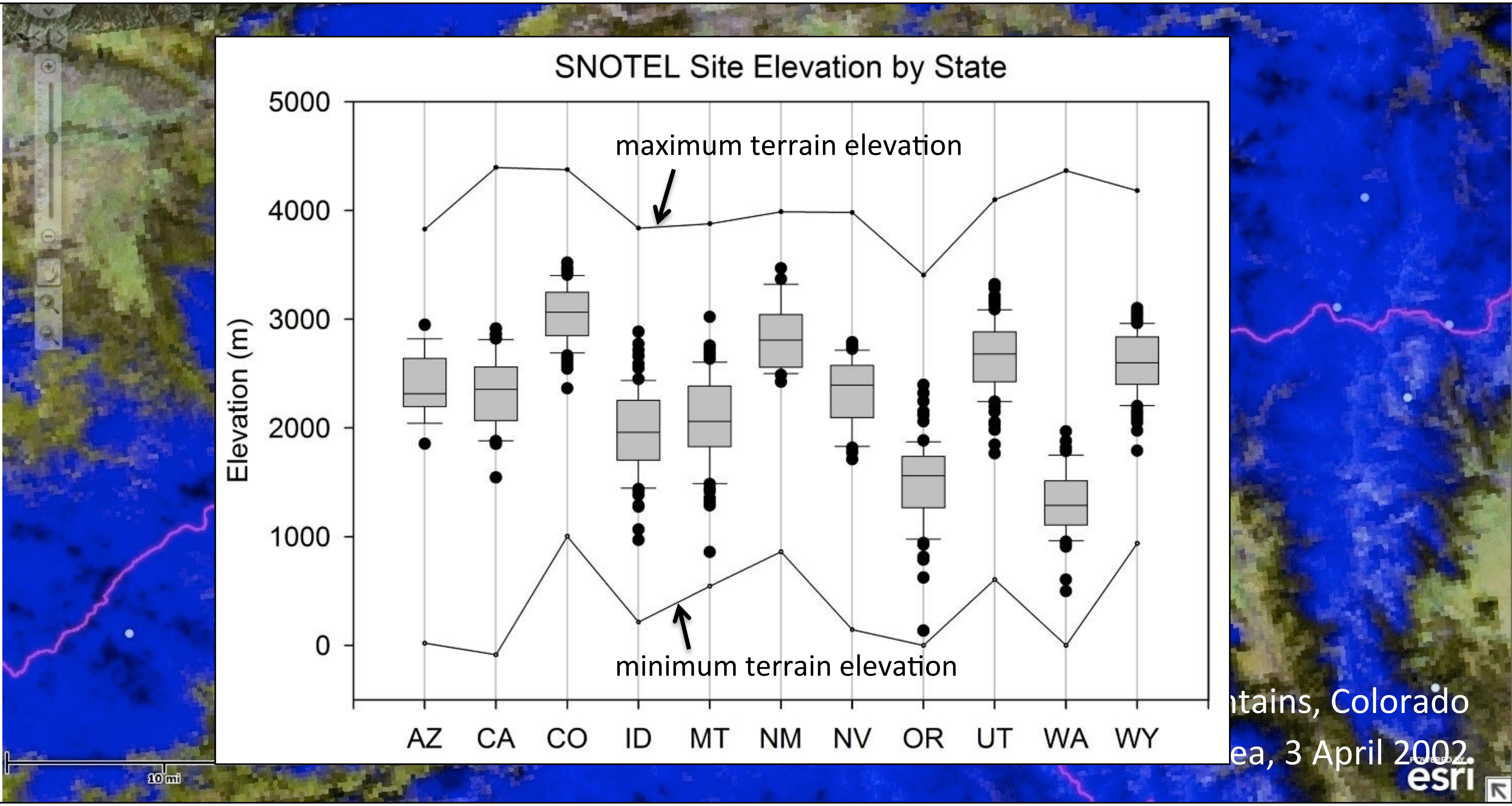
Ground heat

Operational Snow Monitoring

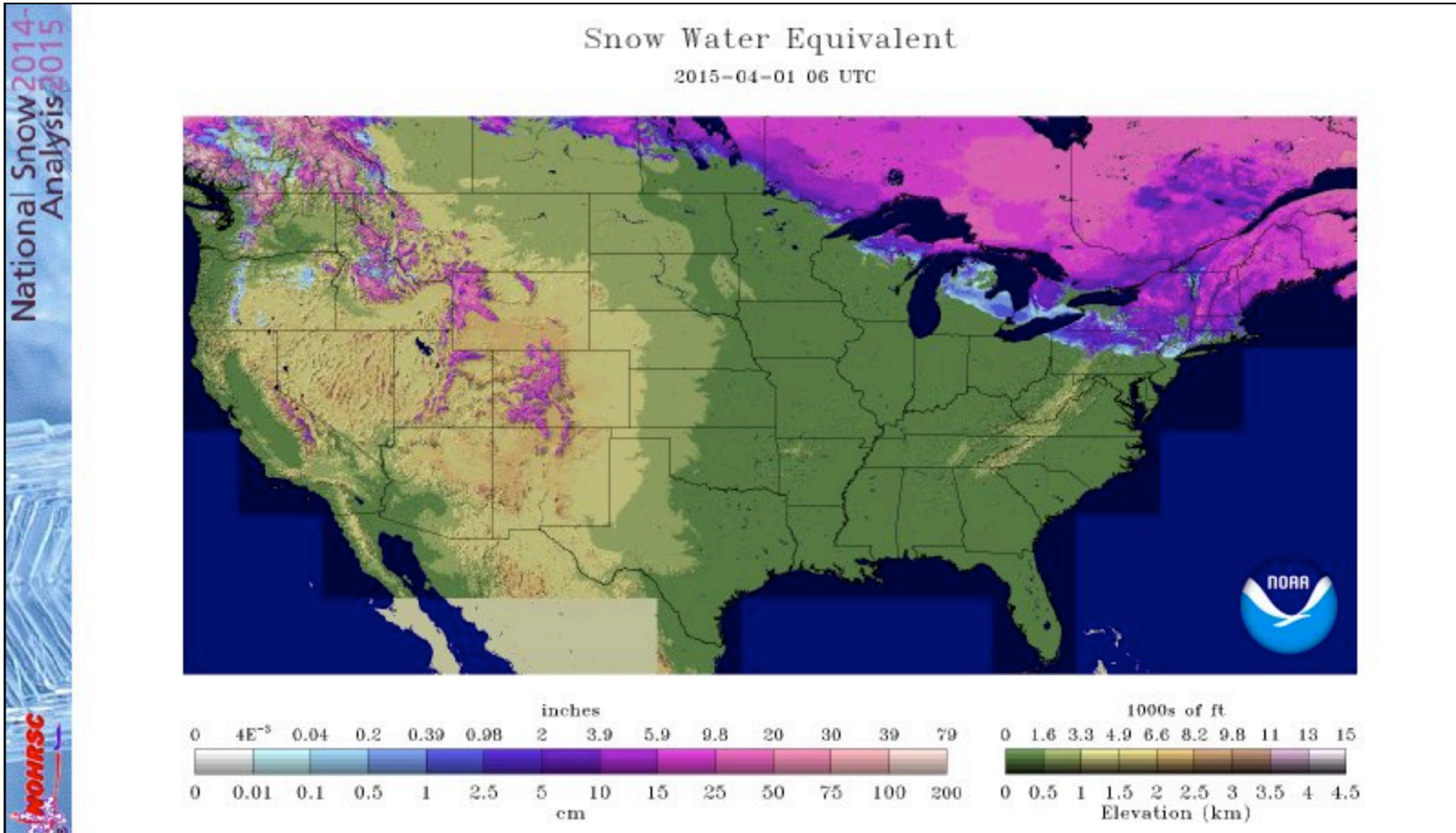
- Snowmelt provides 75-80% of water supply in western US
- Snow Water Equivalent (SWE) is measured at manual snow courses & automatic SNOTEL snow pillows
- Manual & automated measurements are used for statistical & index forecasts
- Measurements



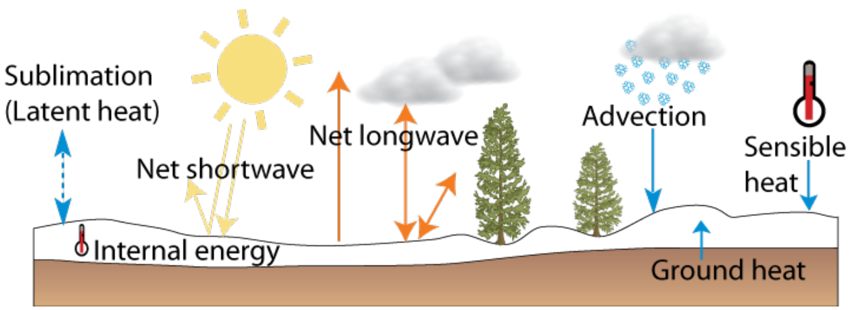
Operational Snow Monitoring



National Weather Service: SNODAS



Snowmelt & runoff simulation & forecasting



Temperature index model

- e.g. CBRFC; SAC/SNOW-17
- *Q = f(T_{air}*melt factor)*
- Calibrated to observations

Statistical forecast

- e.g. NRCS
- *Q = f(SWE)*
- Calibrated to years in period of record

Physically-based model

- e.g. PRMS

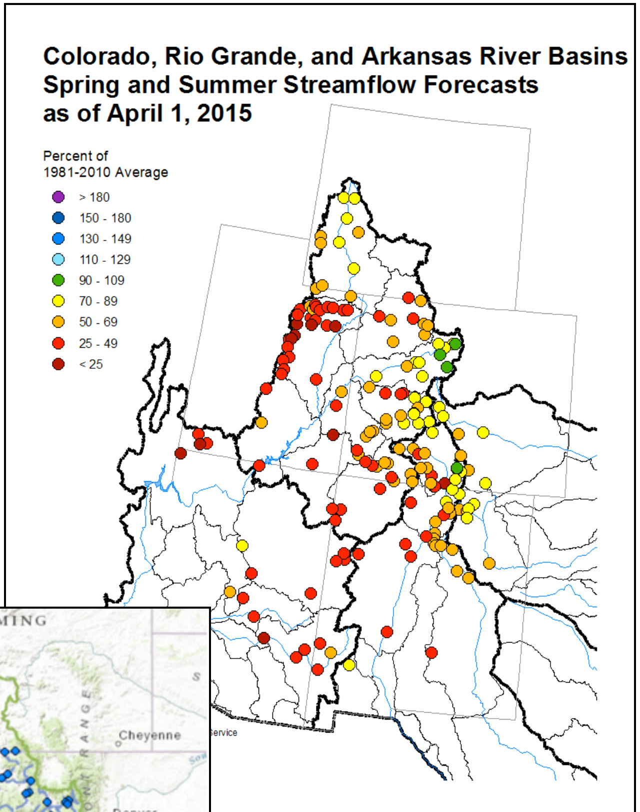
$$Q_m + \frac{dU}{dT} = (1-\alpha)S + L^* + Q_s + Q_v + Q_g$$

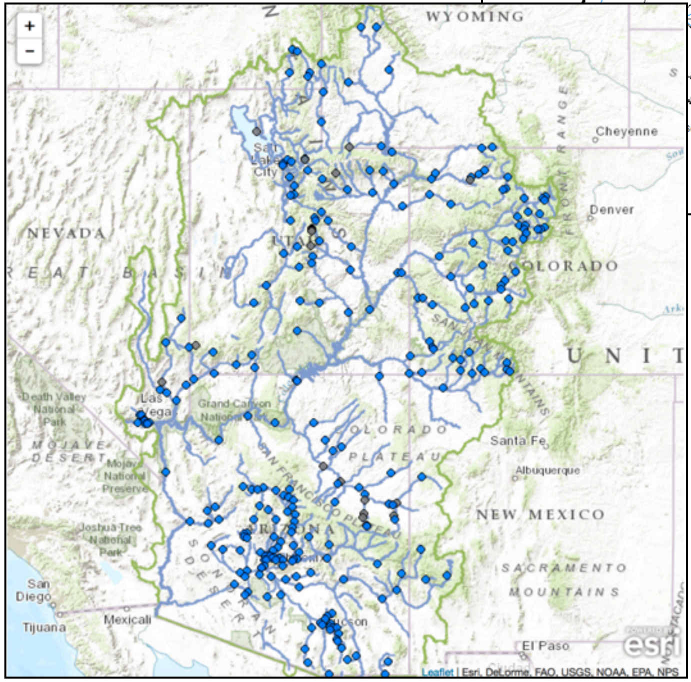
- Common research tool

Operational forecasting

- Statistical streamflow forecast (e.g. NRCS)
  - Regression-based
  - Relates winter/spring SWE obs to spring/ summer streamflow
- Temperature index runoff forecast (e.g. CBRFC)
  - Calibrated relationship between air temperature & snowmelt

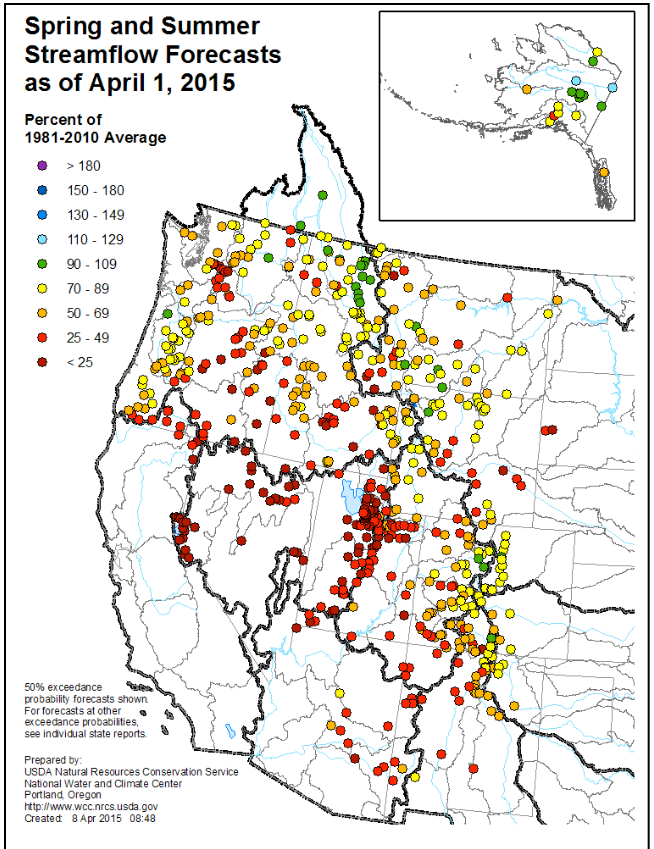
** Both methods assume calibrations apply to current conditions*





Index Forecasts

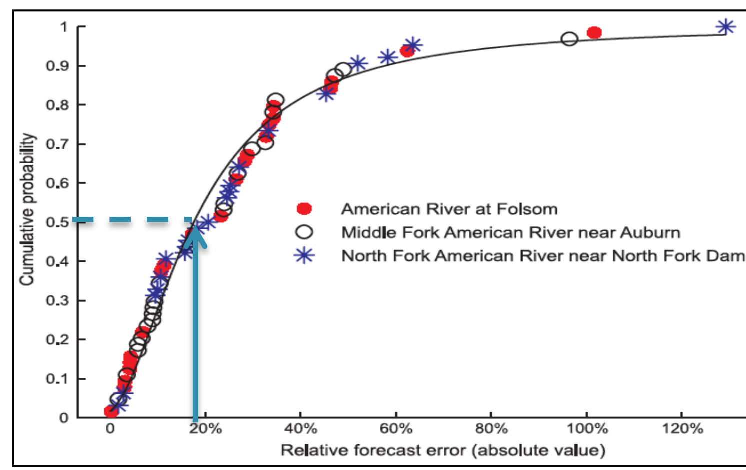
Statistical forecasts are vulnerable to unusual conditions



variation from calibration period conditions causes forecast errors

- snow distribution/timing
- snow reflectance/albedo

American River, CA
1 April Forecast for April-July runoff

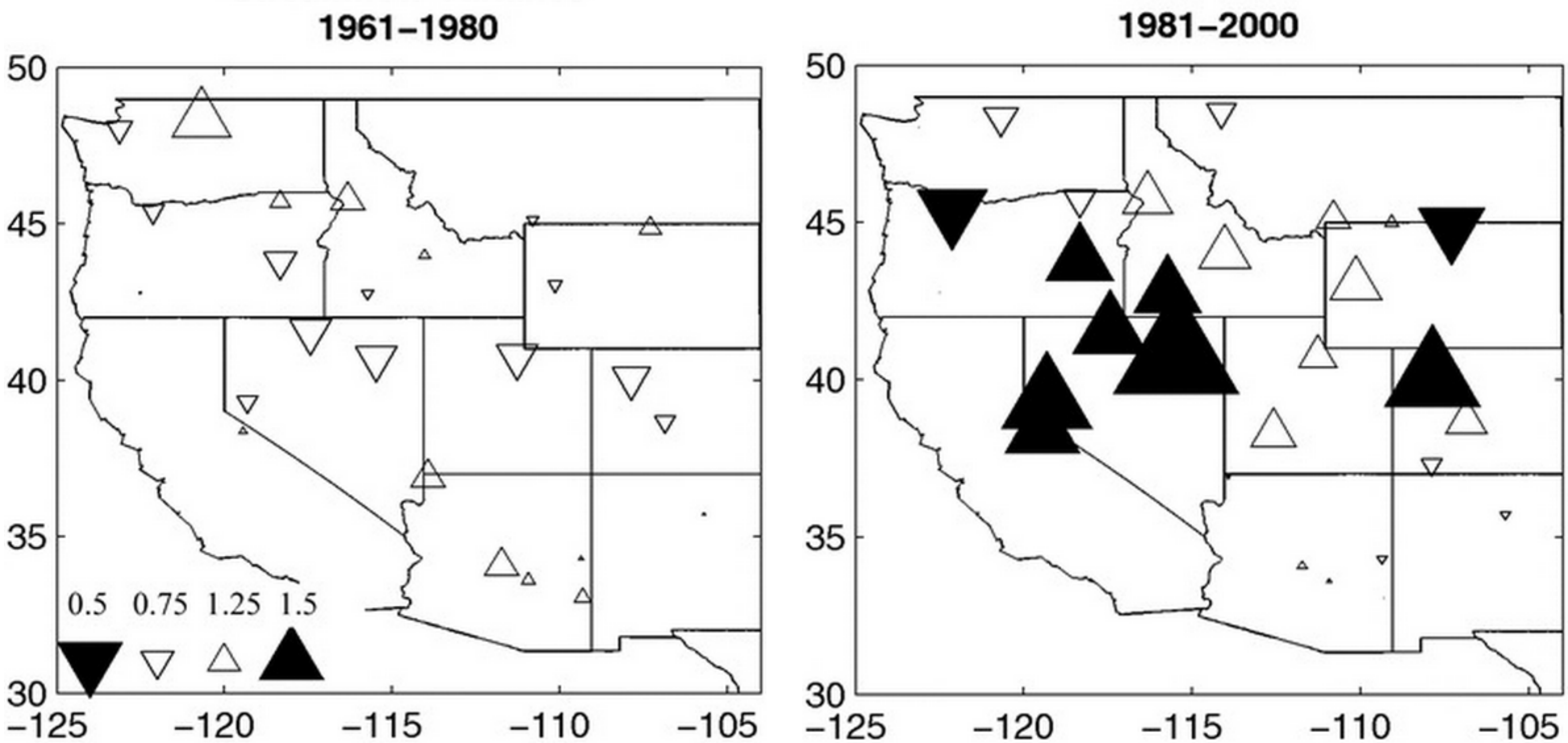


Dozier (2011)

Median forecast error 18%
80th %ile error 39%.

Forecast error sources

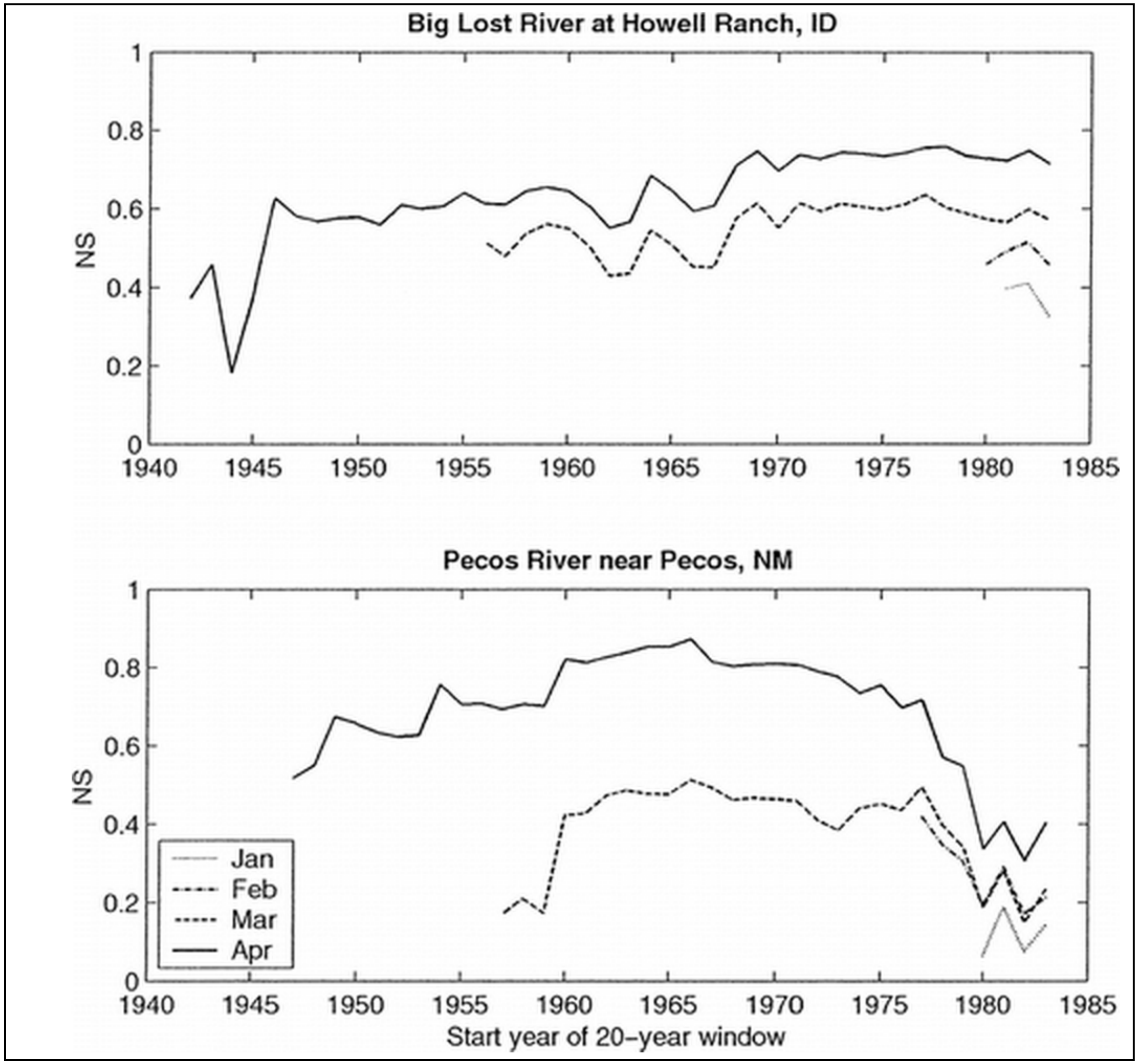
Streamflow variance is increasing



Pagano et al., 2002 – J. of Hydrometeorology

Forecast error sources

Nash-Sutcliffe Forecast skills have decreased at many forecast points in the West due to increased climate variability

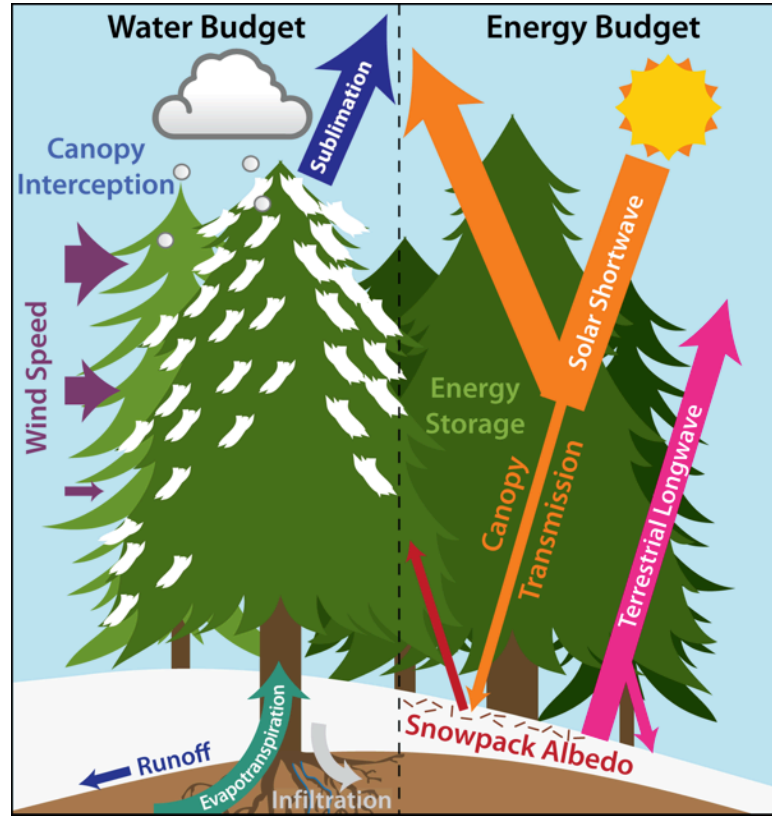


Pagano et al., 2002 – J. of Hydrometeorology

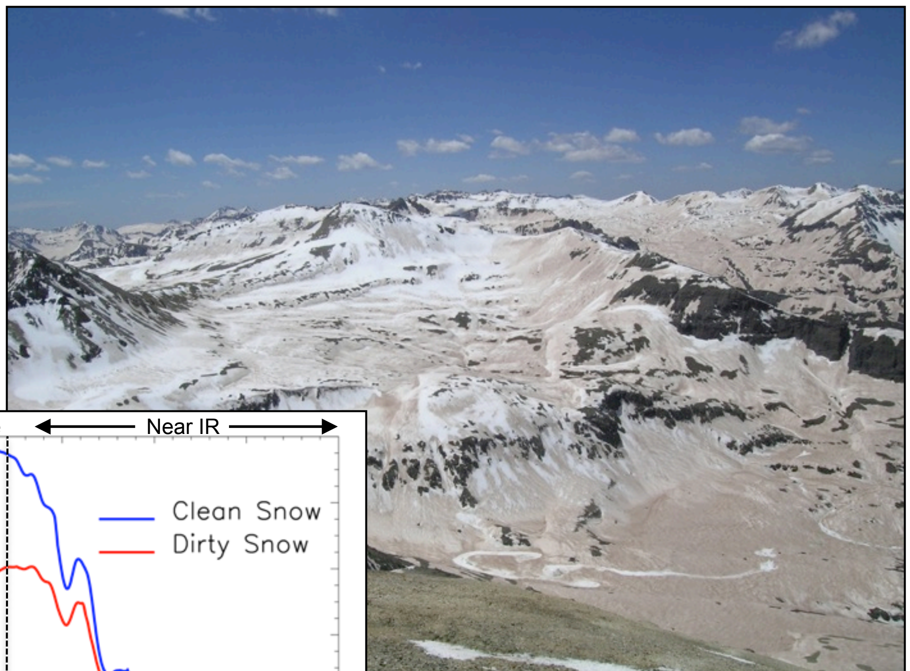
Forecast error sources

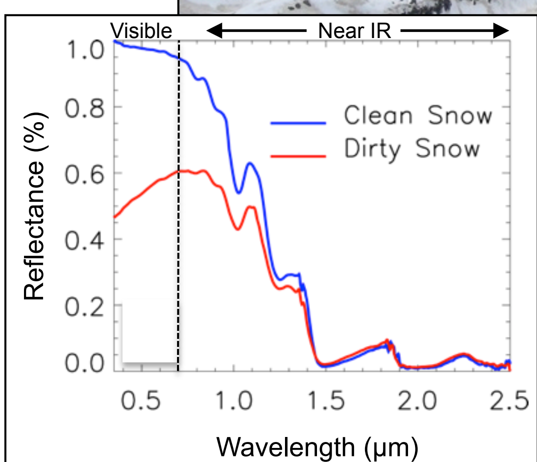
Land cover change/bark beetle

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



Pugh and Gordon, *Hydrological Processes*





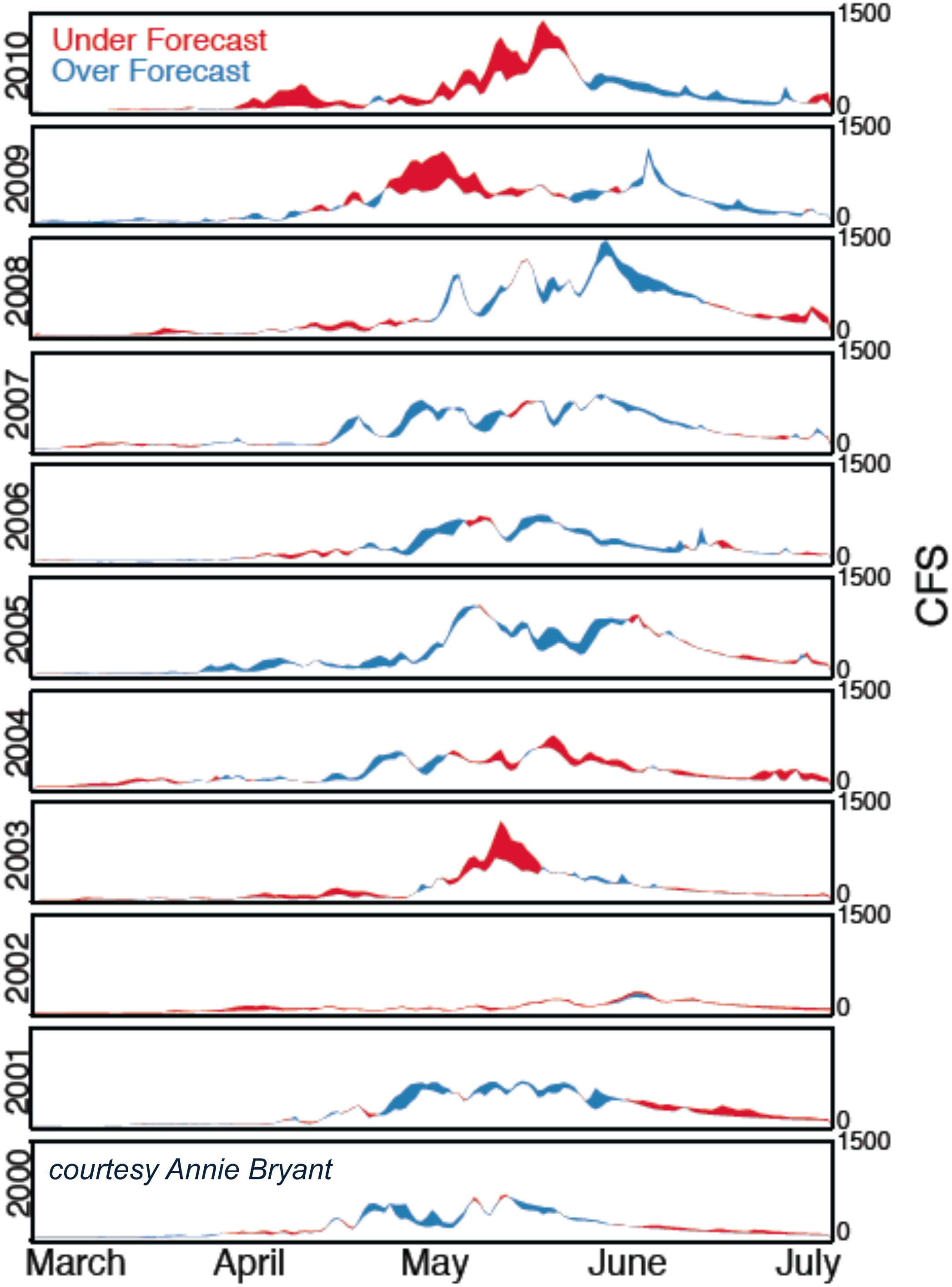
Dust on snow

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

Dust implications for runoff forecasting

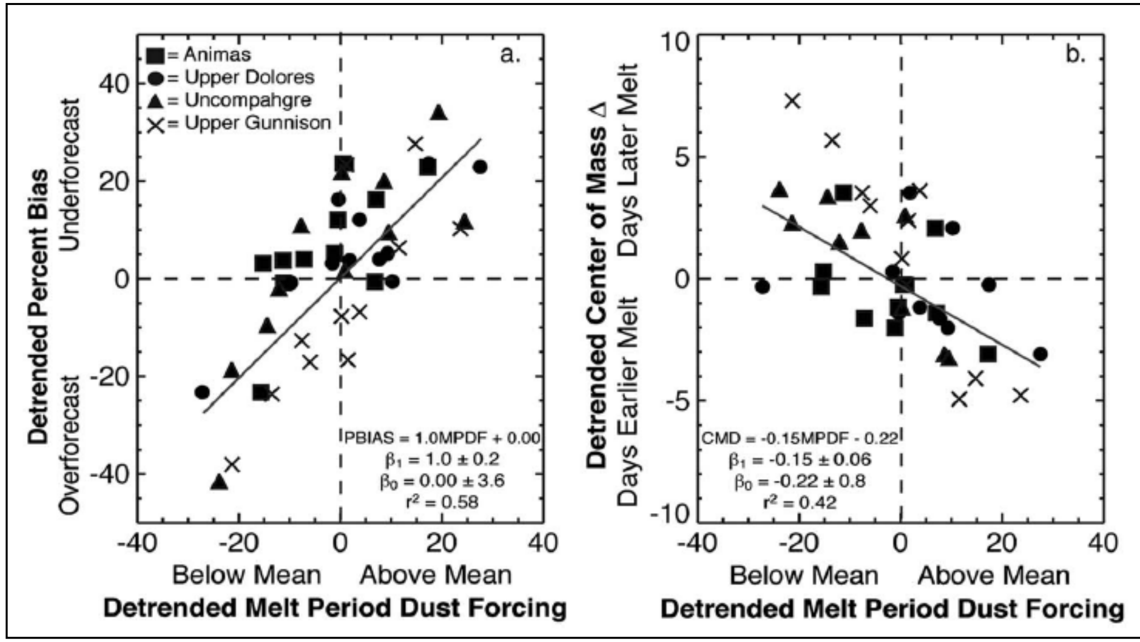
Index models are vulnerable to dust forcing variability

- index-based models rely on the current conditions being well-represented in the calibration period
- example: SNOW-17 / SAC-SMA underpredicts early snowmelt streamflow in years with heavy dust loading



Dust forcing correlated to forecast errors

- melt period dust forcing derived from MODIS
- SNOW-17 appears to be calibrated to moderate dust
  - high dust:
    - underforecast volume
    - late peak
  - low dust:
    - overforecast volume
    - early peak



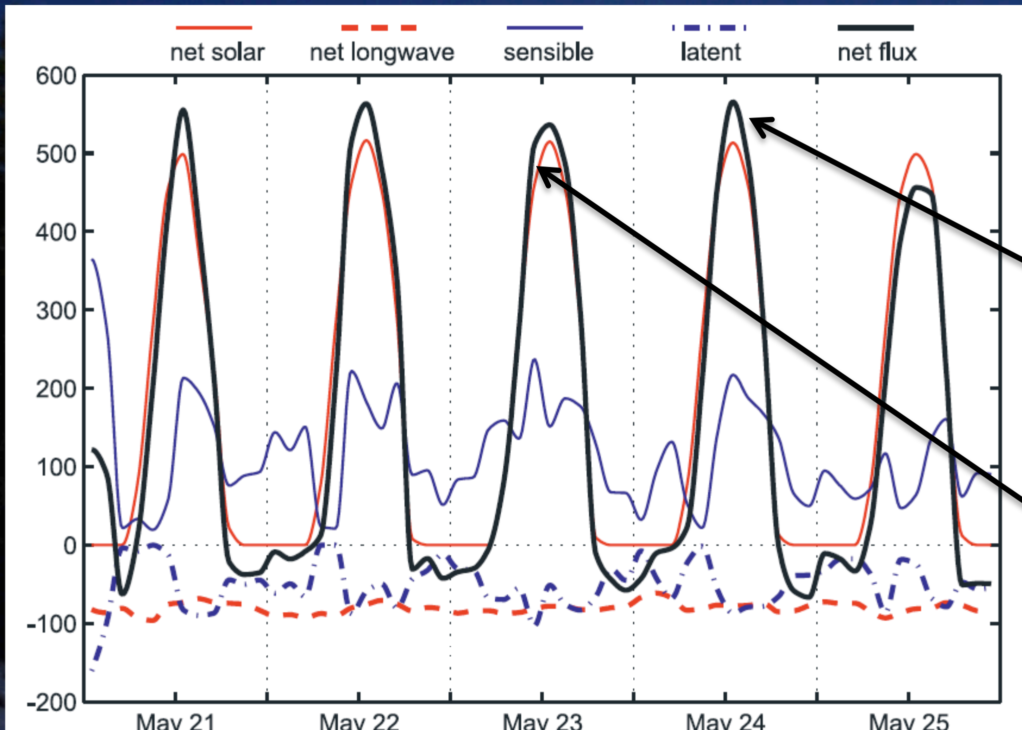
Impact of dust radiative forcing in snow on accuracy of operational runoff prediction in the Upper Colorado River Basin

Ann C. Bryant,[1] Thomas H. Painter,[2] Jeffrey S. Deems,[3,4] and Stacie M. Bender[5]

GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 3945–3949, doi:10.1002/grl.50773, 2013

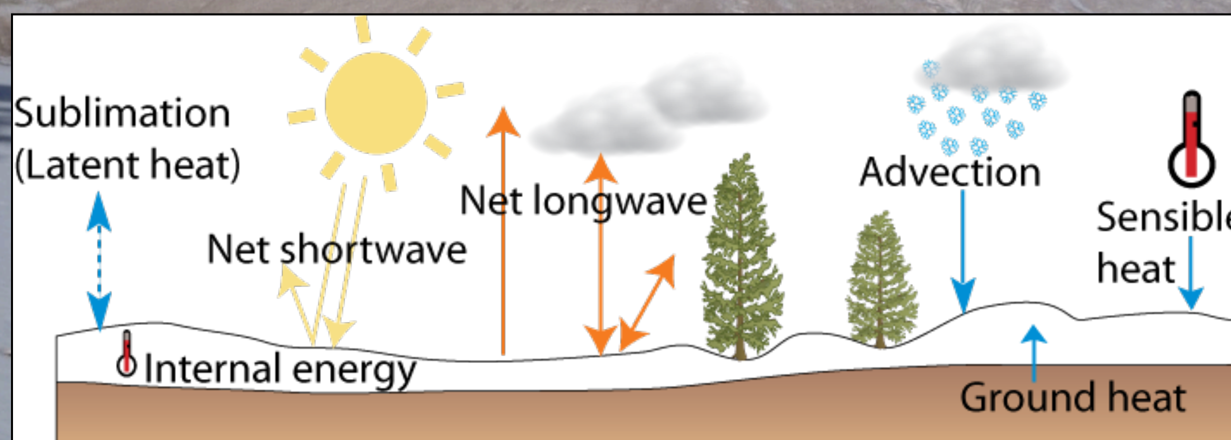
- need dynamic melt factor adjustment or energy balance model

Solar radiation controls snowmelt



Bales et al. (2006)

repeat, spatially explicit maps of snow albedo are needed



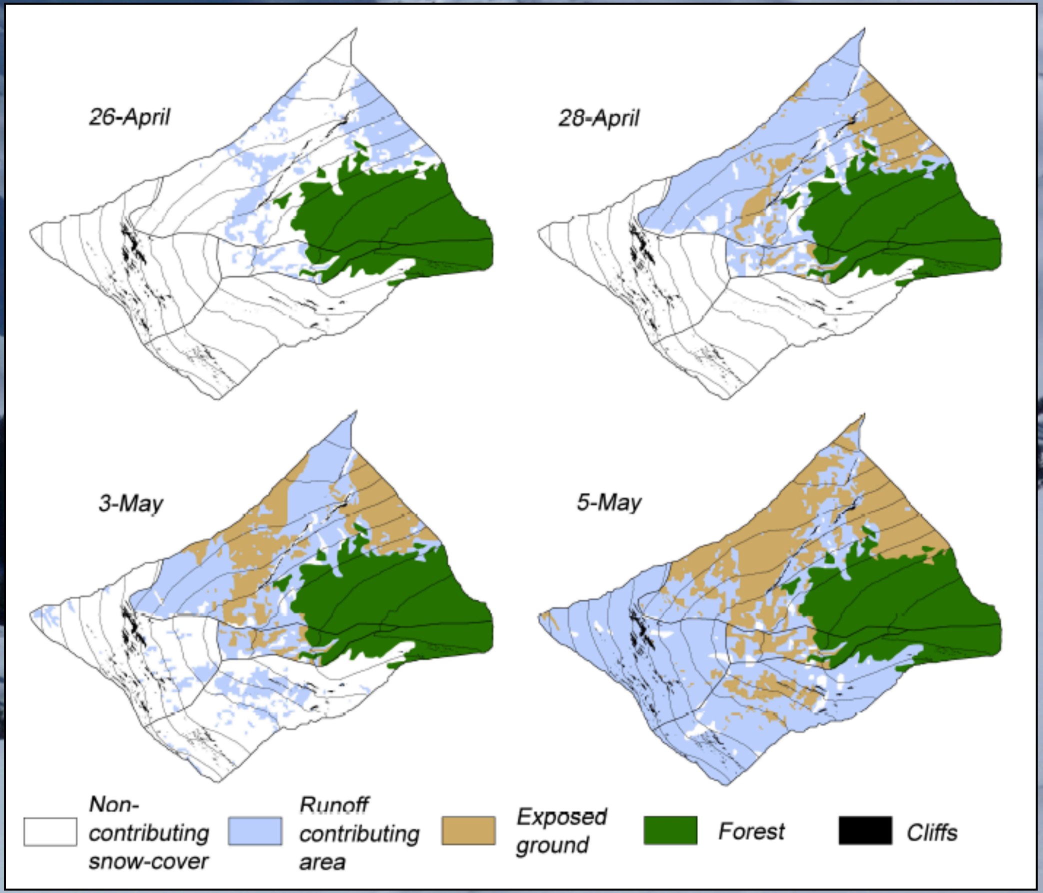
April 2010

Senator Beck Basin, San Juan Mountains

Snow accumulation patterns control melt volume & timing

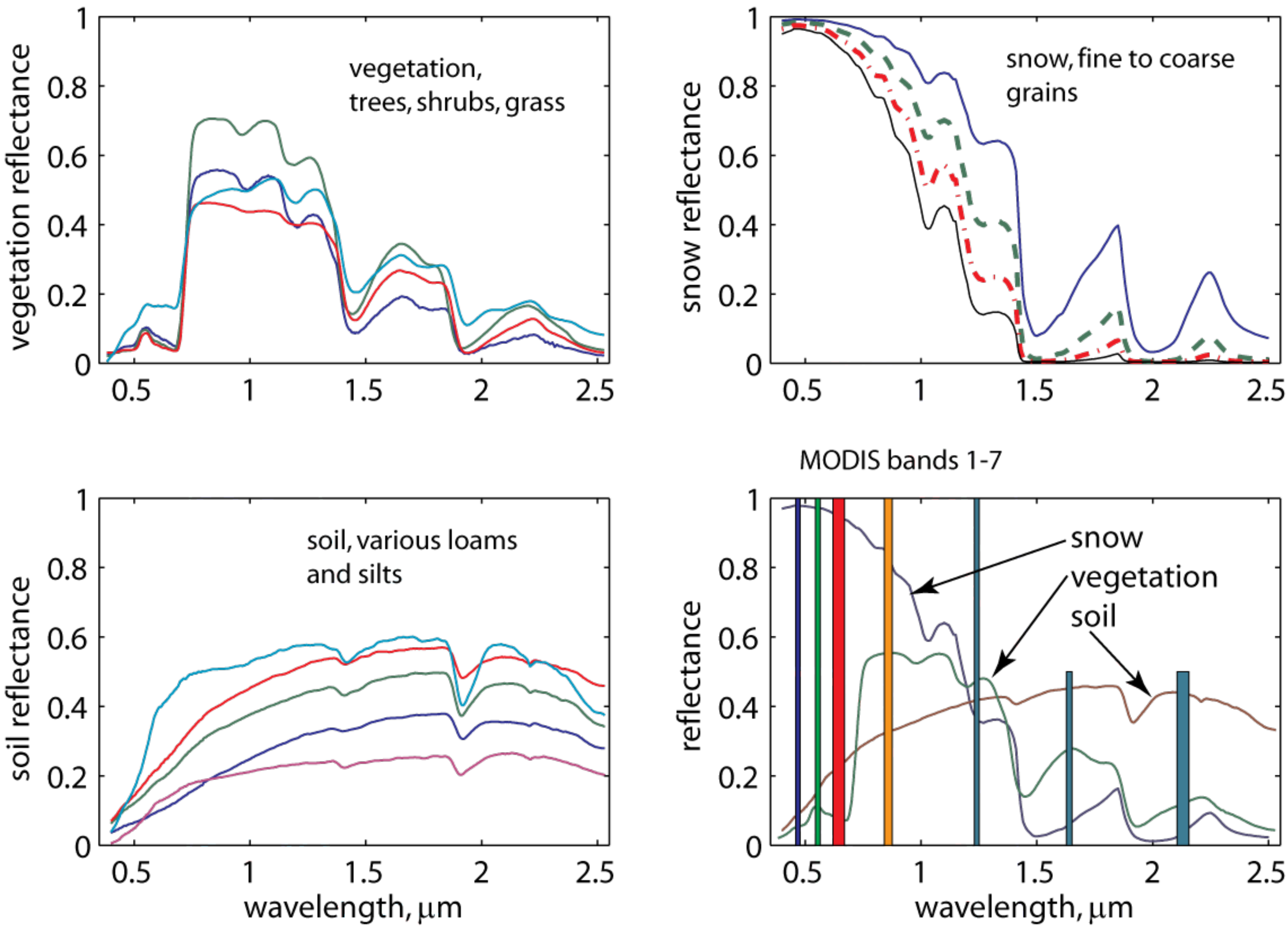
- different spatial patterns can produce the same values at point locations
- distribution of SWE + terrain drivers of energy balance determine melt & runoff patterns

repeat, spatially explicit maps of snow depth/SWE are needed

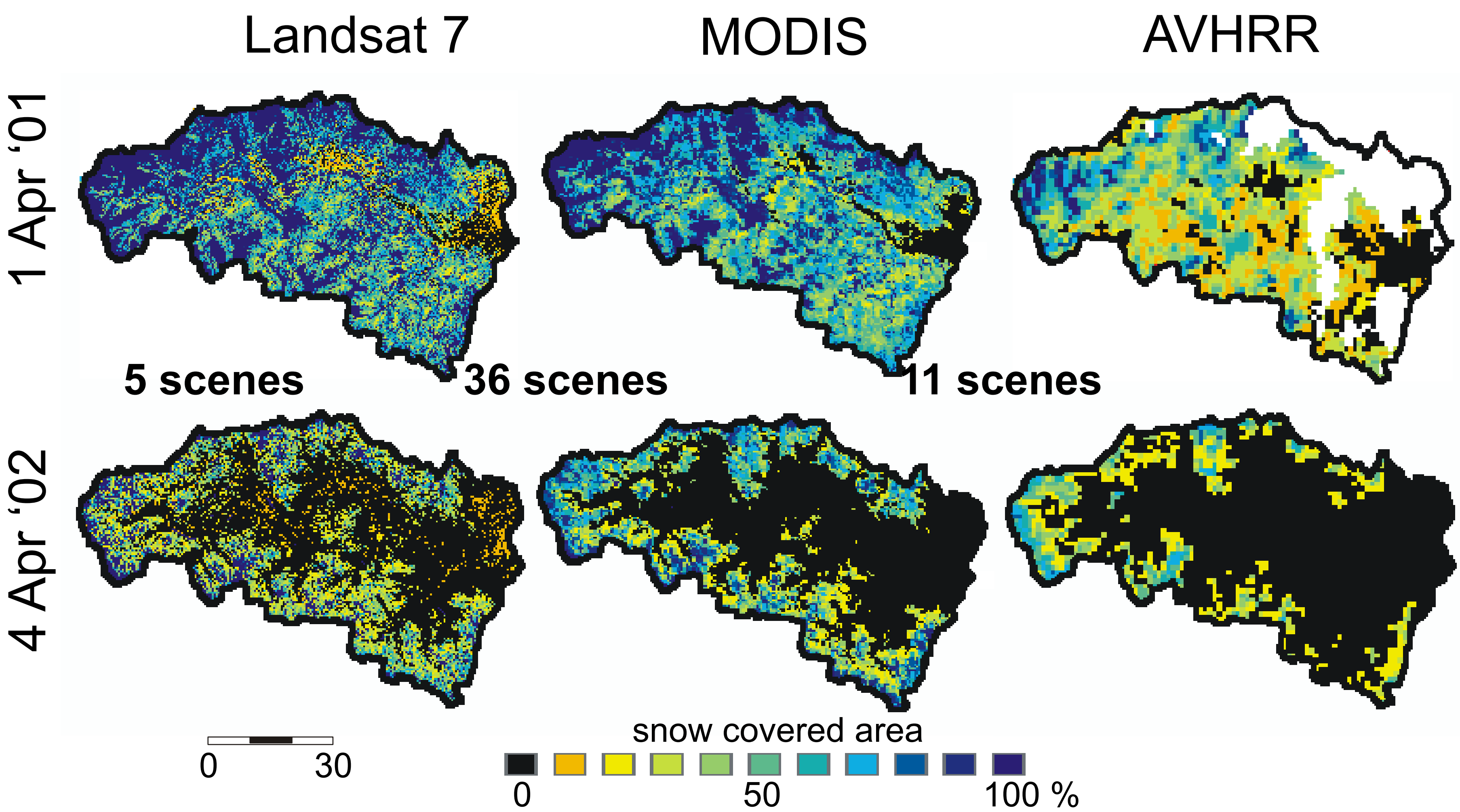


DeBeer & Pomeroy, 2010 HESS

Optical remote sensing

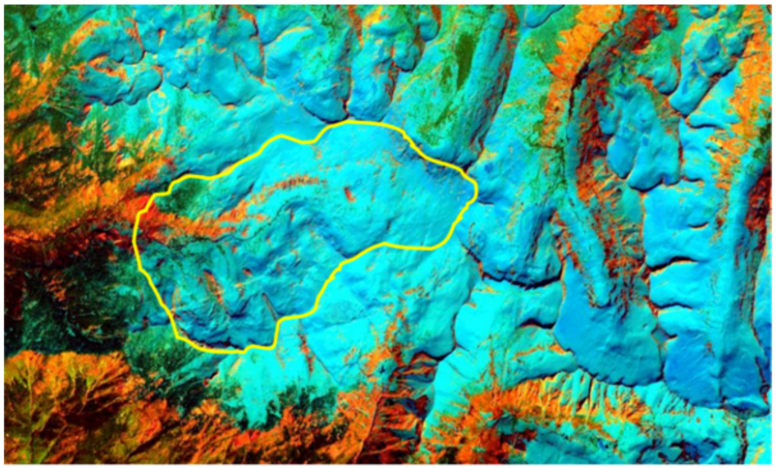


Snow Covered Area (SCA)

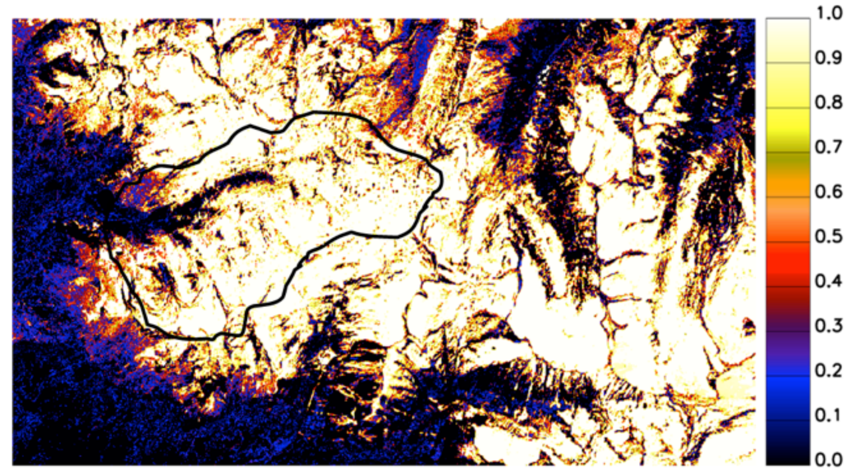


Snow Properties & SCA
Sierra Nevada, CA

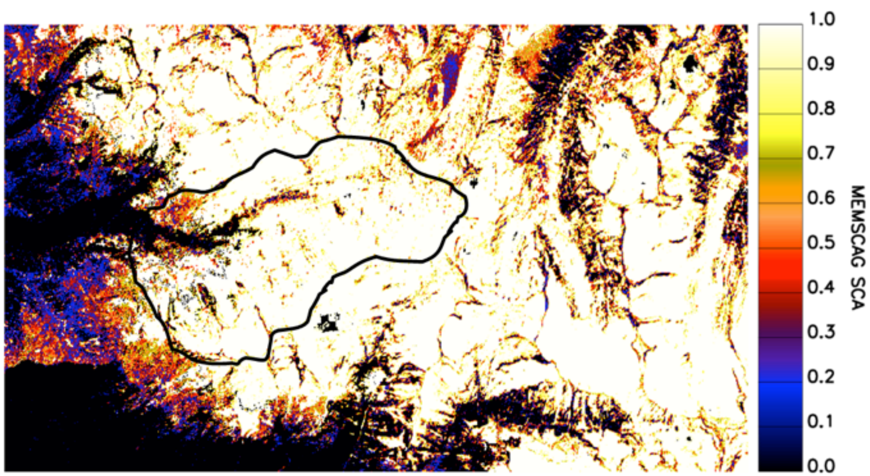
AVIRIS



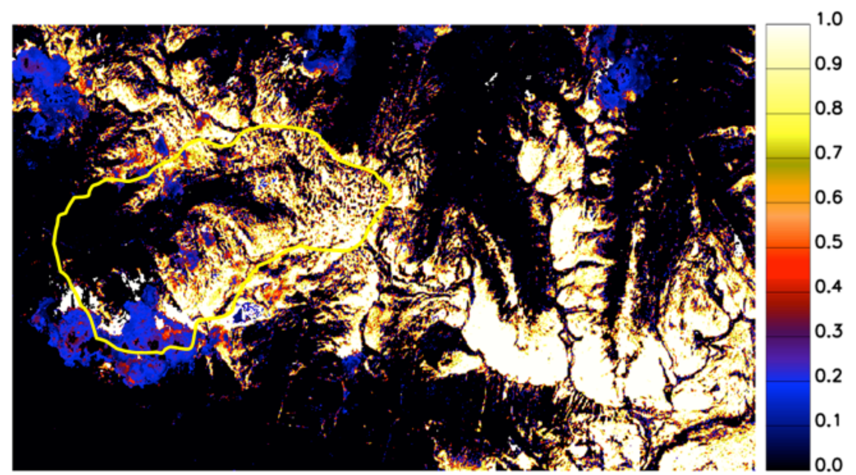
21 May 1997



05 May 1997

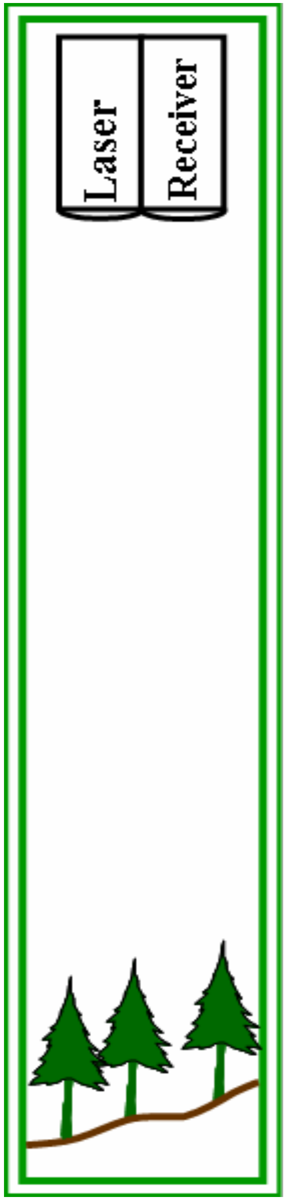


18 June 1997

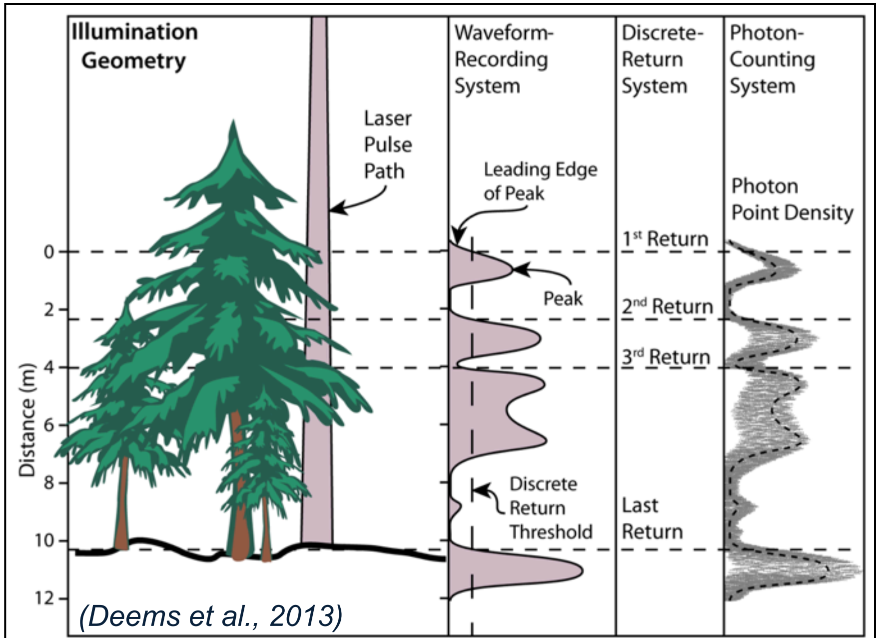


20 km

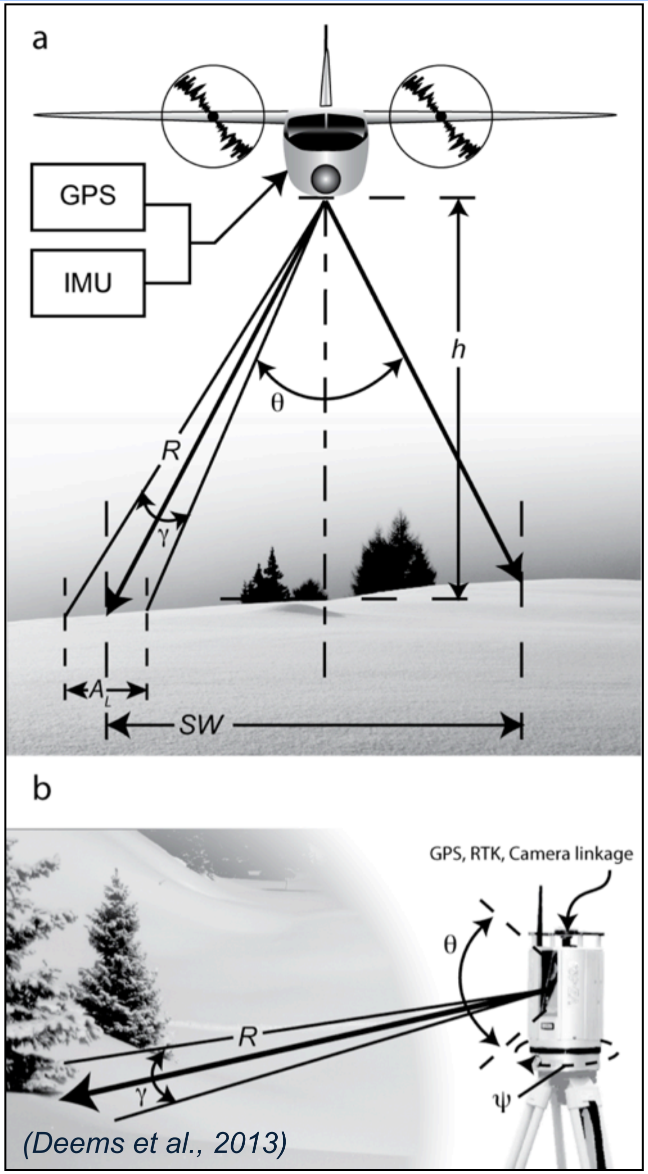
LIDAR surface elevation mapping



- measures time-of-flight to target
  - Hundreds of kHz pulse rate
- GPS system allows precise positioning of each laser shot
- product: high-resolution surface elevation map



(Deems et al., 2013)

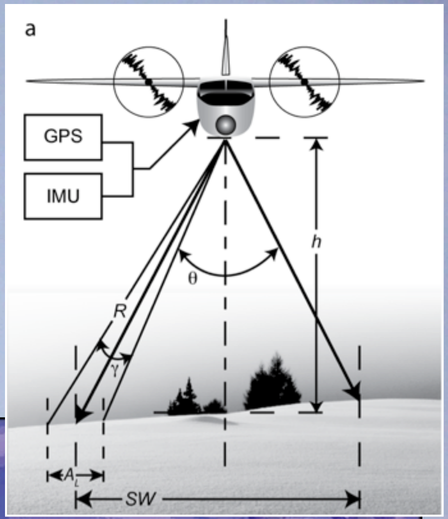


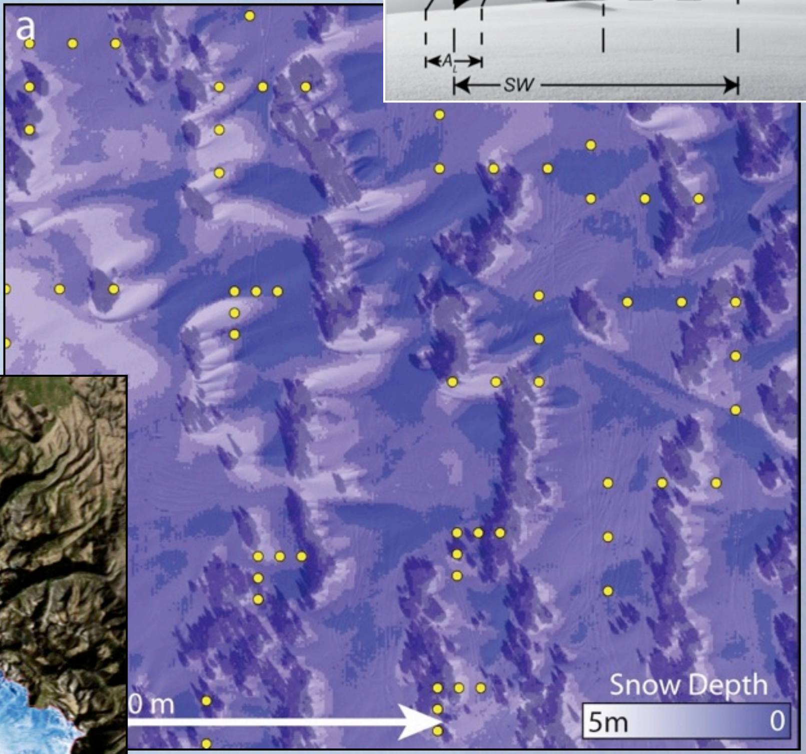
(Deems et al., 2013)

beam spread allows sub-canopy mapping in forests

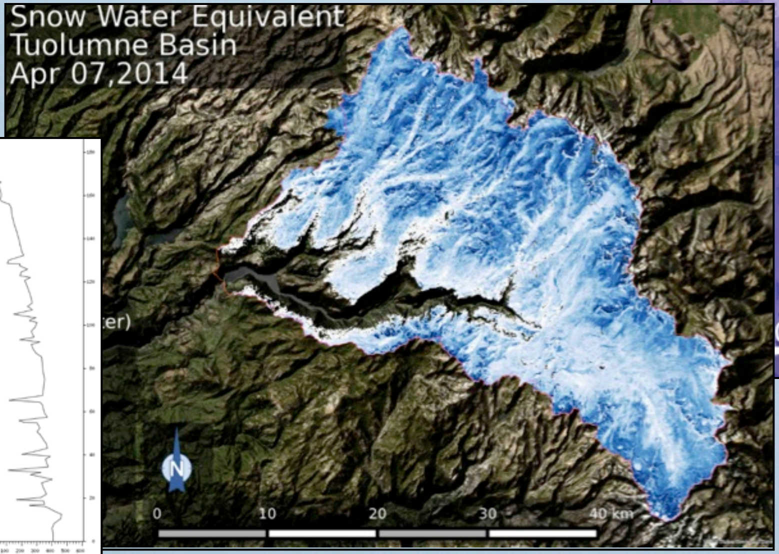
Snow depth & SWE from LiDAR

- 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

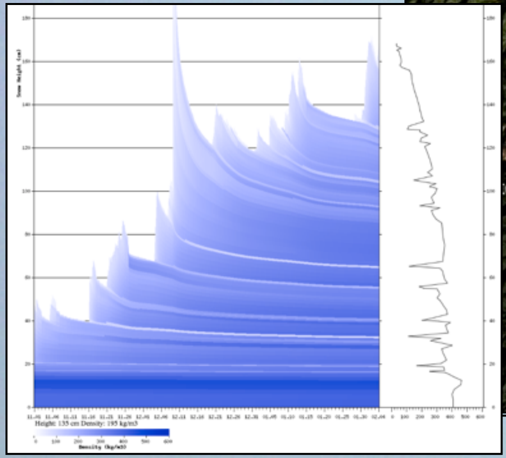




LiDAR-derived snow depth, Colorado (Deems et al., 2013)

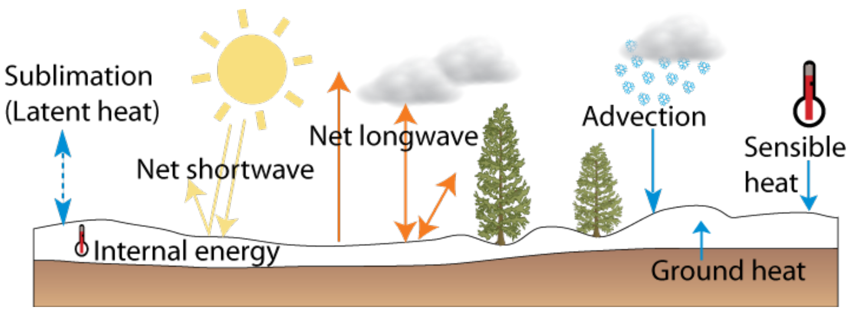


ASO LiDAR-derived SWE



SNOWPACK model, courtesy CAIC

Integrating spatial snow products with snowmelt & runoff simulations



Statistical forecast

- NRCS
- *Q = f(SWE)*
- Calibrated to years in period of record

Temperature index model

- E.g. CBRFC/SNOW-17
- $Q = f(T_{air} * \text{melt factor})$
- Calibrated to observations

Energy balance model

- E.g. PRMS

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

- Common research tool

Integration of spatial snow products & models:

Index-based models

Watershed	3/29/15 % Avg to Date	3/29/15 SWE (in)	3/23/14 SWE (in)	3/23/14 thru 3/29/15 Change in SWE (in)
AMERICAN	12.78	1.44	2.38	-0.95
FEATHER	0.98	0.10	0.35	-0.25
KAWEAH	14.06	1.10	0.98	0.11
KERN	3.84	0.32	1.31	-0.99
KINGS	11.00	1.70	3.87	-2.17
TAHOE	5.87	1.32	7.31	-5.99
MERCED	21.72	2.53	2.47	0.06
OWENS	7.91	0.45	1.31	-0.86
SAN JOAQUIN	21.24	3.60	5.19	-1.59
STANISLAUS	14.07	2.04	4.48	-2.44
TRUCKEE	3.06	0.48	2.29	-1.81
TUOLUMNE	31.42	4.84	5.76	-0.93
YUBA	3.50	0.38	1.16	-0.78
COSUMNES	0.04	0.00	0.11	-0.11
MOKELUMNE	9.28	0.99	3.24	-2.26
TULE	0.02	0.00	0.02	-0.02
WEST WALKER RIVER	16.98	1.93	3.91	-1.99
EAST WALKER RIVER	8.78	0.85	2.70	-1.85
WEST FORK CARSON RIVER	5.87	0.77	5.75	-4.97
EAST FORK CARSON RIVER	2.19	0.25	3.98	-3.73

TB20150528_swe.report_OUT.txt

```
calculate basin water volume in snowpack
*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*
Tuolumne River Basin
Airborne Snow Observatory
Date: 05/28/2015
surveyed area:                          1175.54
snow covered area (km^2):               396.557
percent snow coverage :                 33.7342
volume of snowpack water (m^3):     5.34373e+007
volume of snowpack water (acre-ft):     43322.3
-- -- -- -- -- -- -- -- -- -- -- -- -- --
mean swe (m):                          0.134753
mean depth (m):                        0.283495
max depth (m):                          4.60309
min rho  (kg/m^3):                      218.189
max rho  (kg/m^3):                      591.896
mean rho (kg/m^3):                      485.464
*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*
file used:
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\USCATB20150528f1a1\TB20150528_SUPERswe_50p0m_agg
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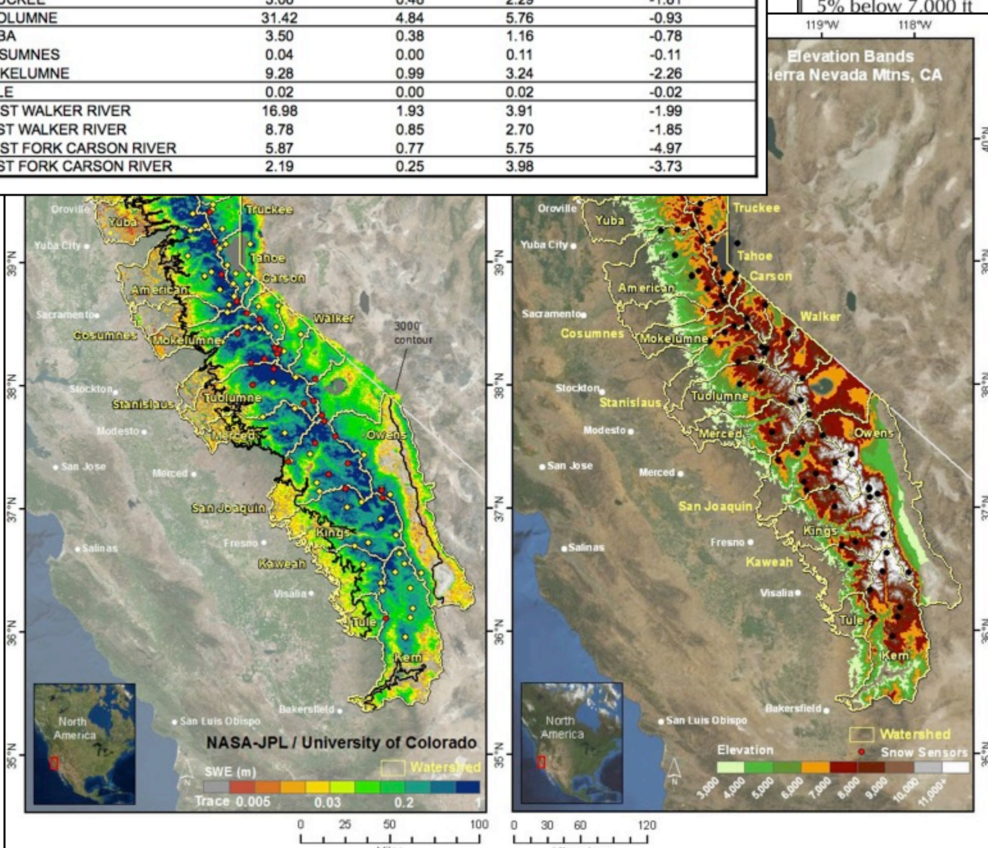
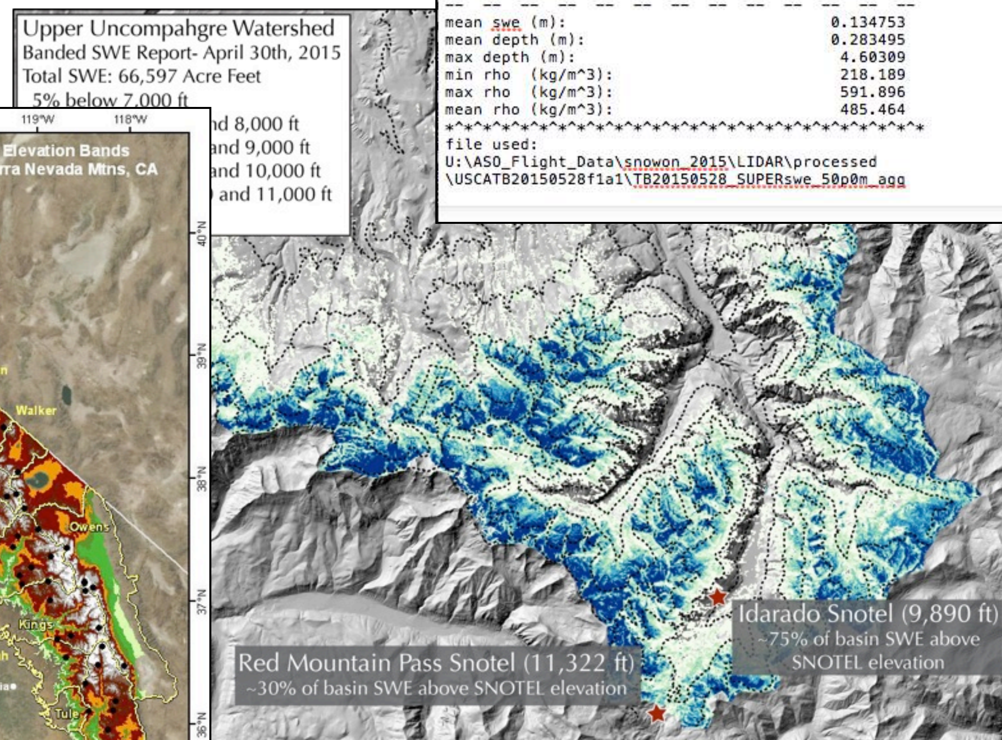
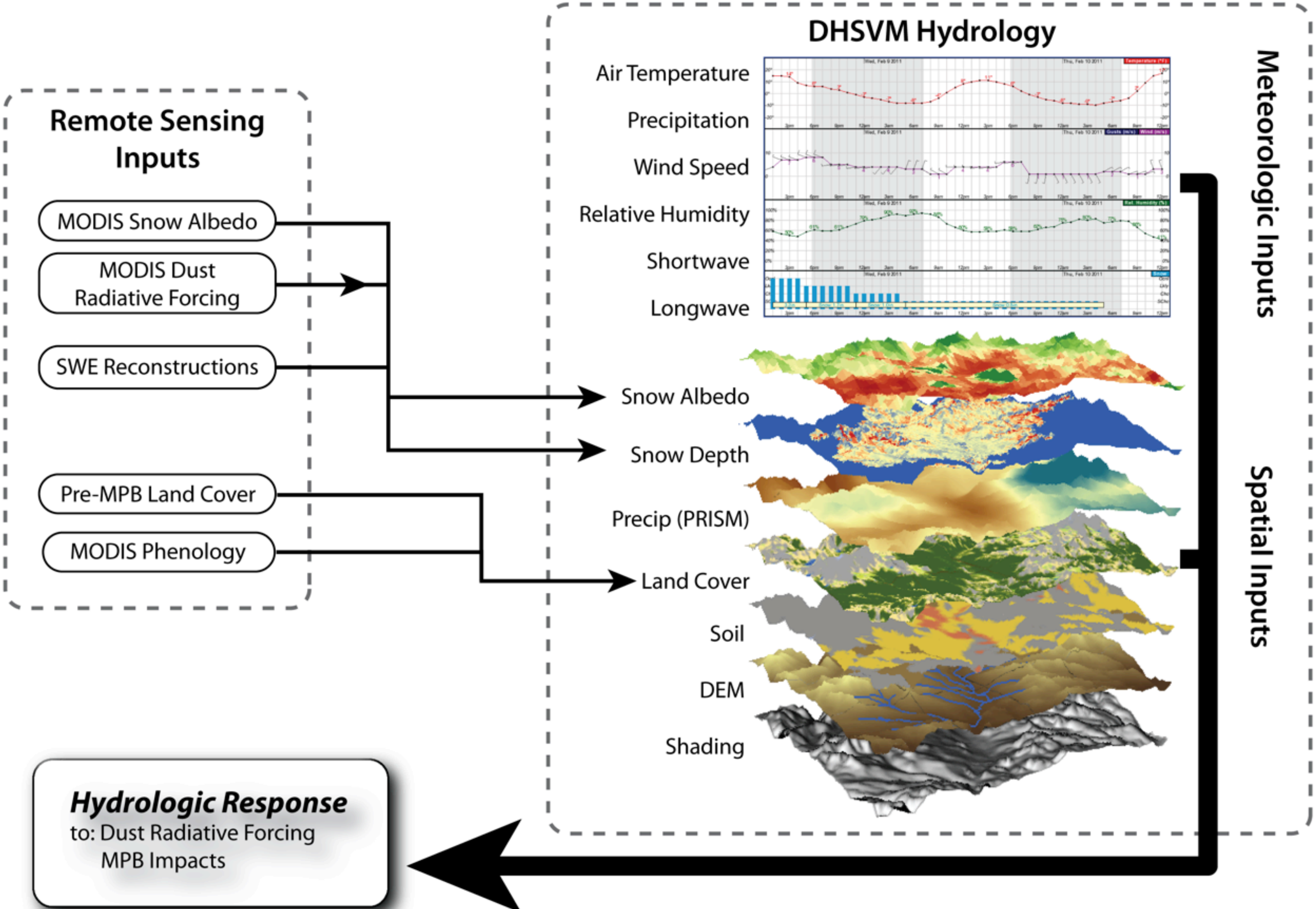




Integration of spatial snow products & models:

Distributed energy balance models



Spatial products to be discussed

JPL MODIS/MODSCAG products

- SCA, albedo, & grain size
- Dust radiative forcing

SWE Reconstruction

- Range/regional-scale retrospective & real-time

Airborne Snow Observatory snow depth, SWE, albedo

- Watershed-scale near-real time airborne measurements