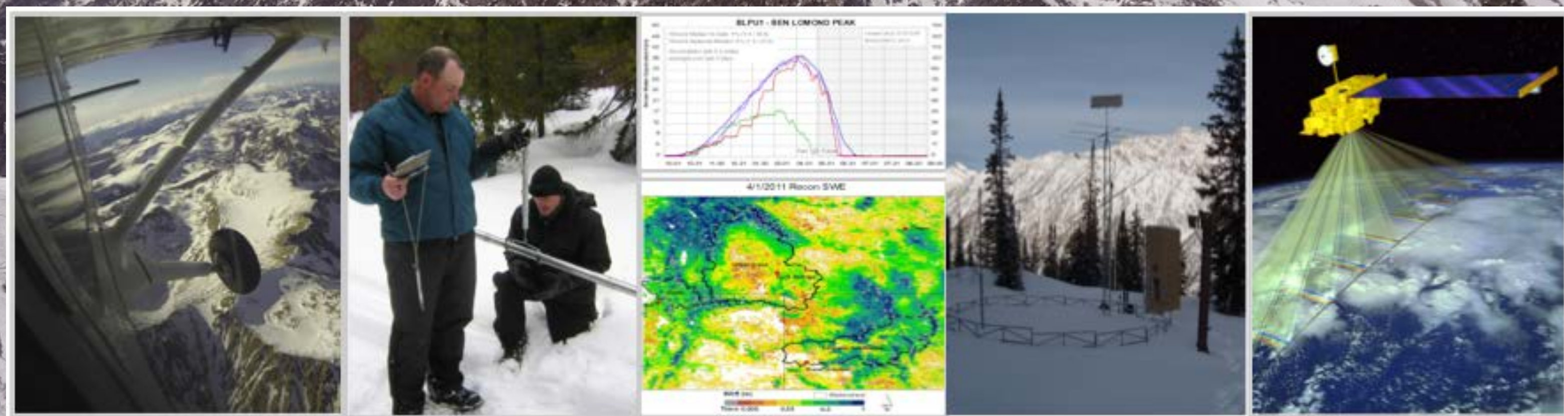
http://wwa.colorado.edu

Measuring and modeling our snow water resource



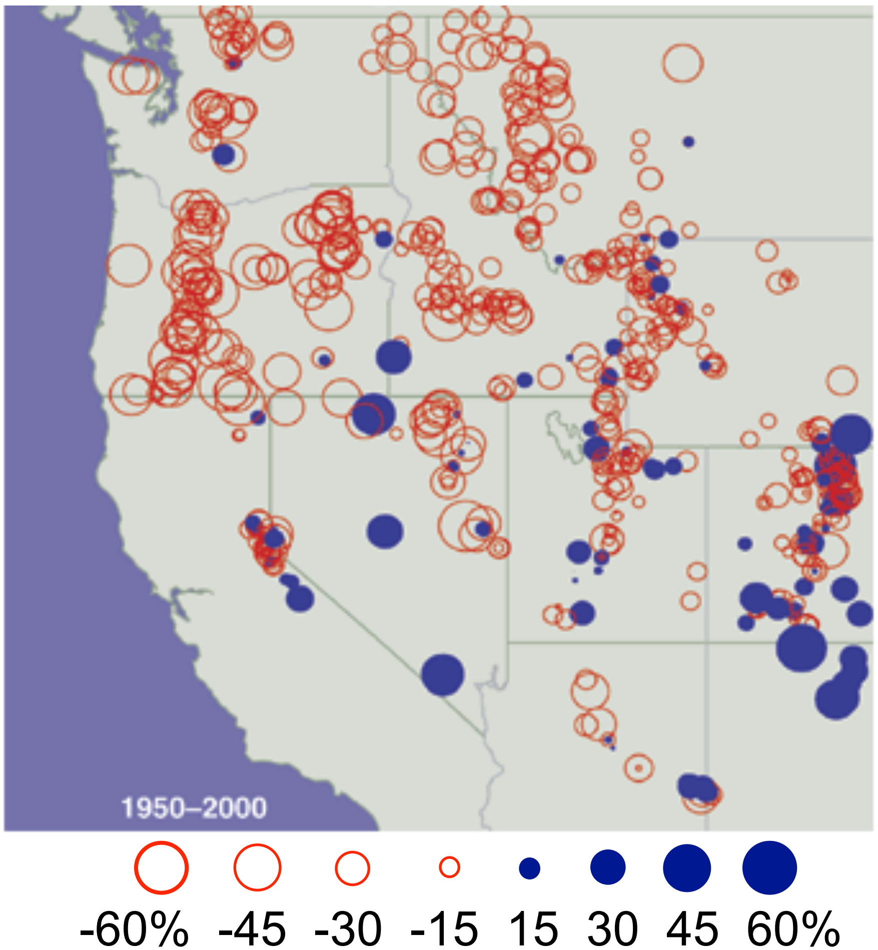
Lander, WY – August 27, 2015

Administering Wyoming's Water Resources

Photo: Jim Steenburgh, Wasatch Weather Weenies

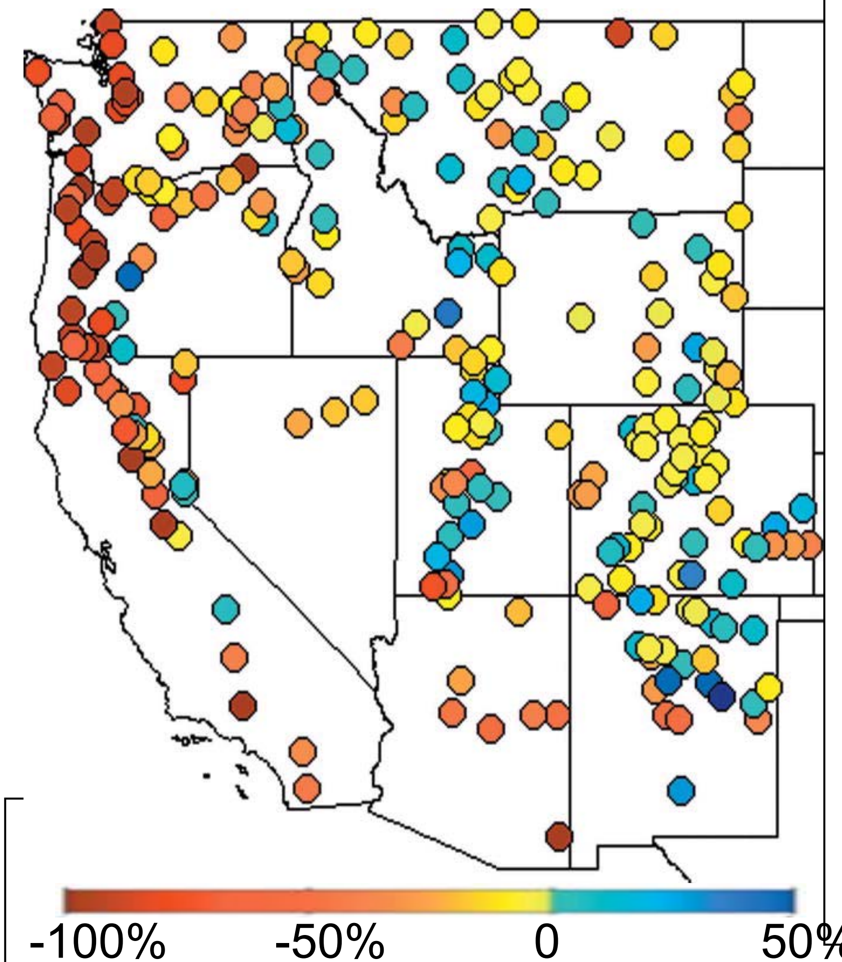
Snowpack Trends: 1950 - 2000

Percent change in April 1 snow water equivalent



Service, 2004

Percent change in snowfall to rainfall

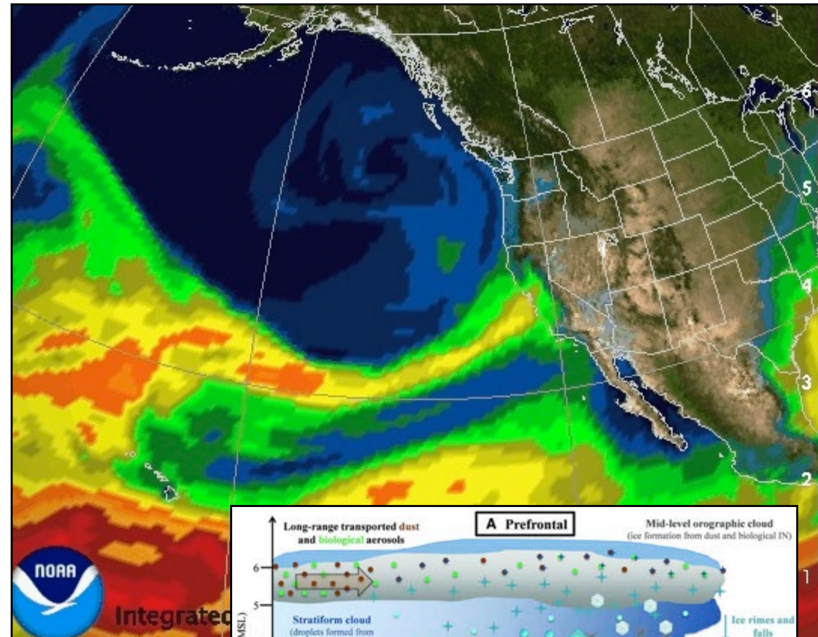


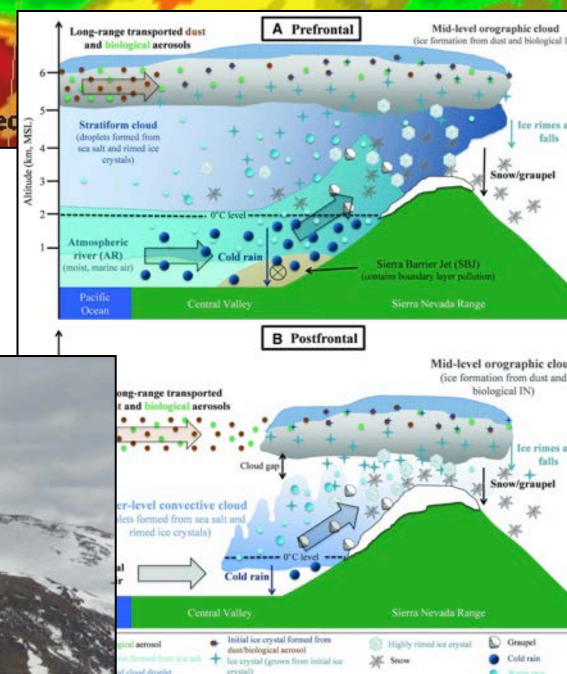
Knowles et al., 2006

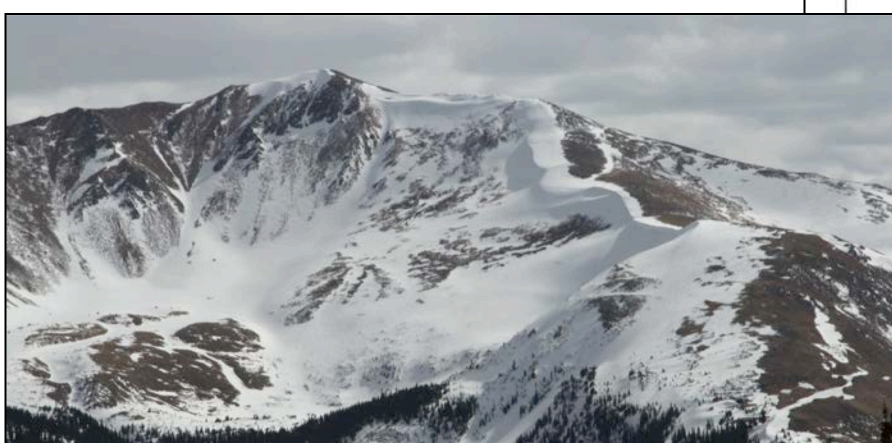
Snow accumulation

depends on:

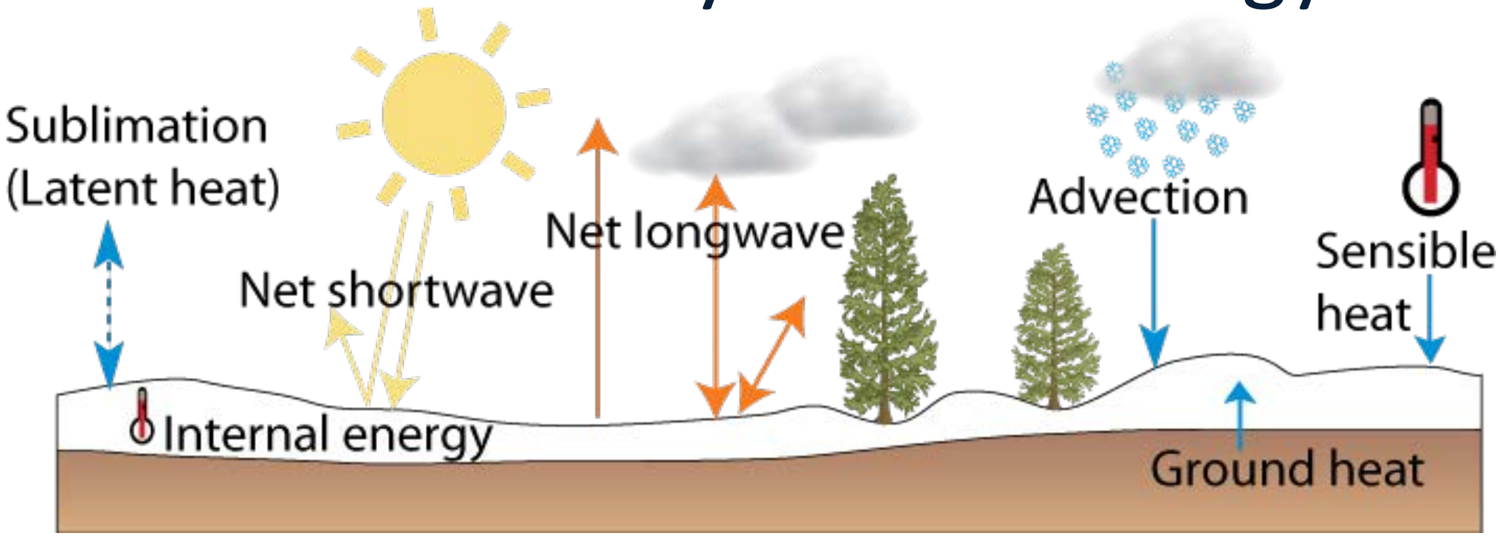
- Storm track
- Storm synoptics
- Air temperature & moisture
- Orientation of moisture flux relative to topography
- Orographic enhancement
- Wind redistribution
- …







Snow melt is driven by surface energy balance



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

Change in internal energy

Melt energy

Albedo

Shortwave radiation

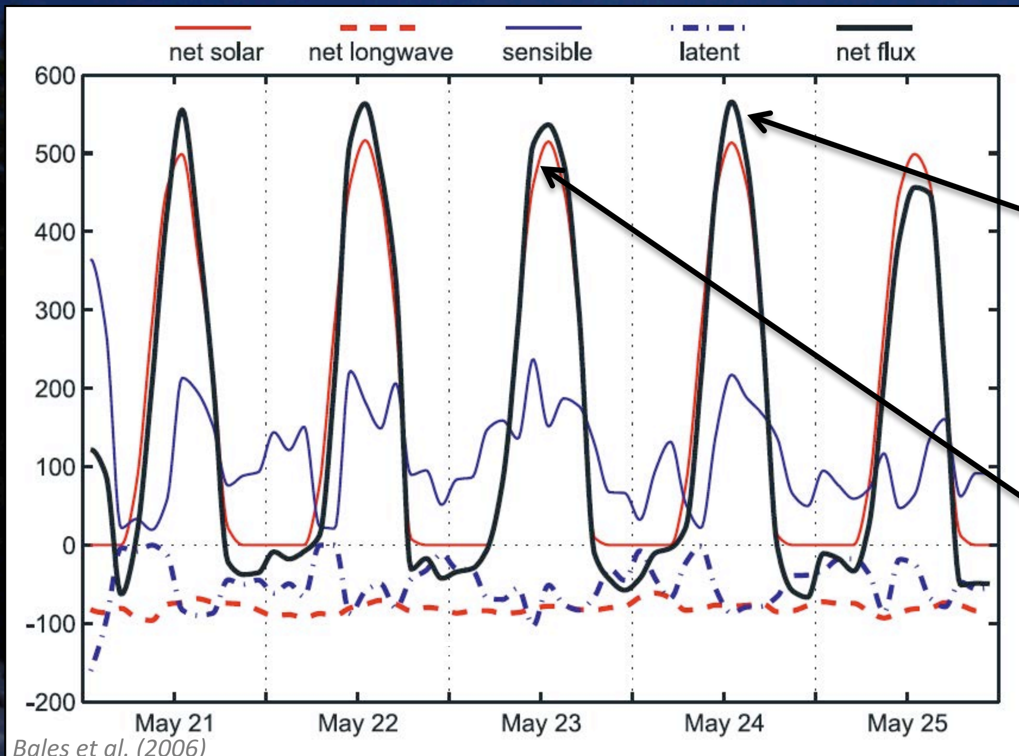
Net Longwave radiation

Sensible heat/advection

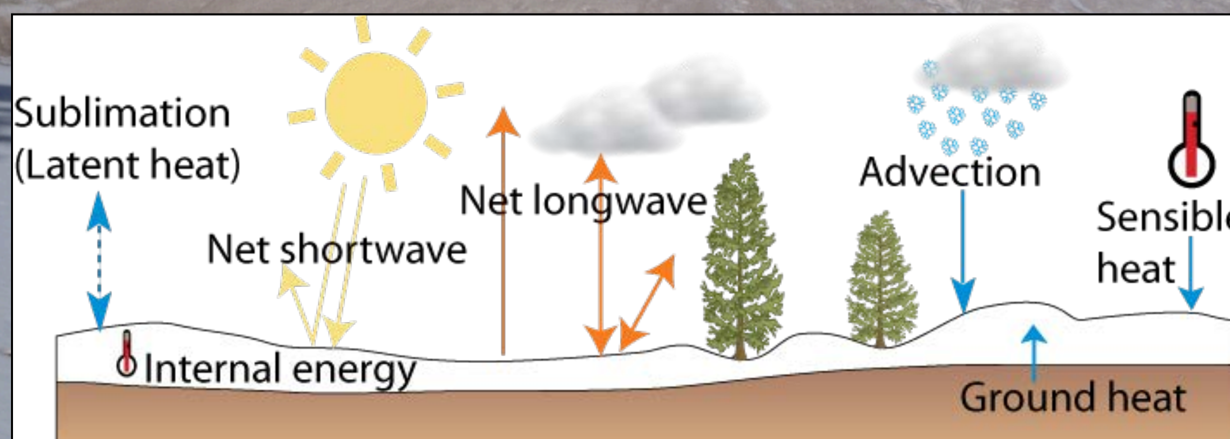
Latent heat

Ground heat

Solar radiation controls snowmelt



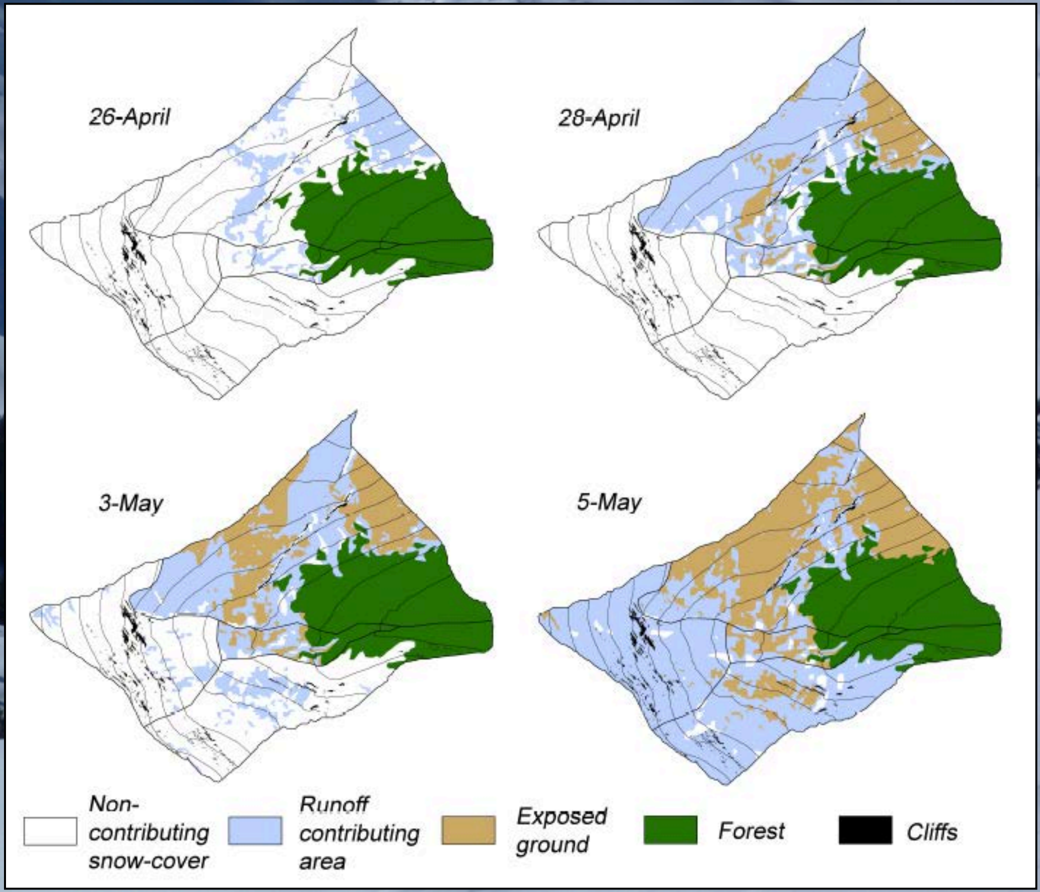
Bales et al. (2006)



April 2010
Senator Beck Basin, San Juan Mountains

Snow accumulation patterns control melt volume & timing

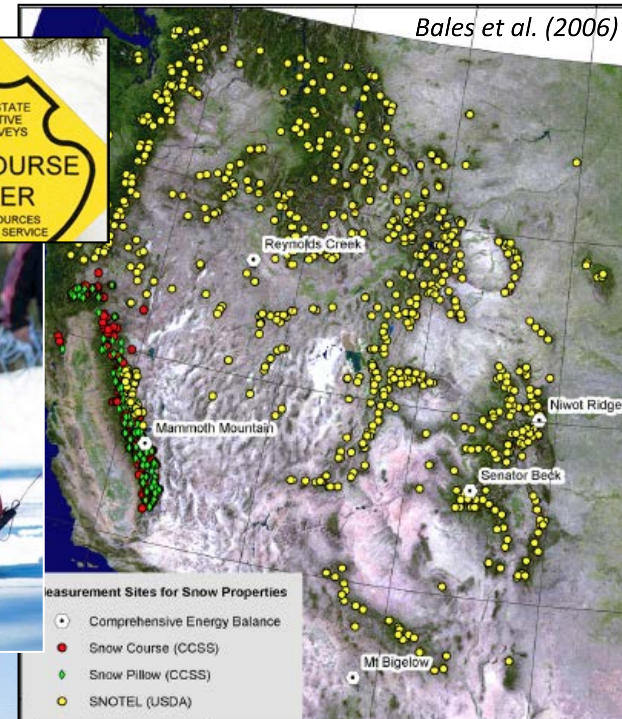
- different spatial patterns can produce the same values at point locations
- distribution of SWE + terrain drivers of energy balance determine melt & runoff patterns

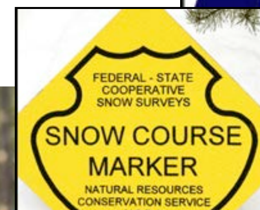


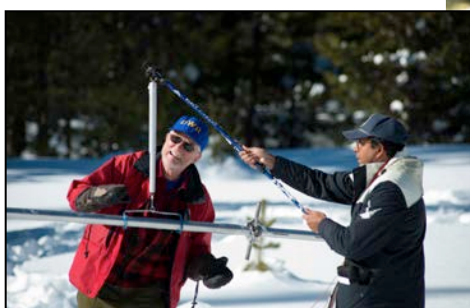
DeBeer & Pomeroy, 2010 HESS

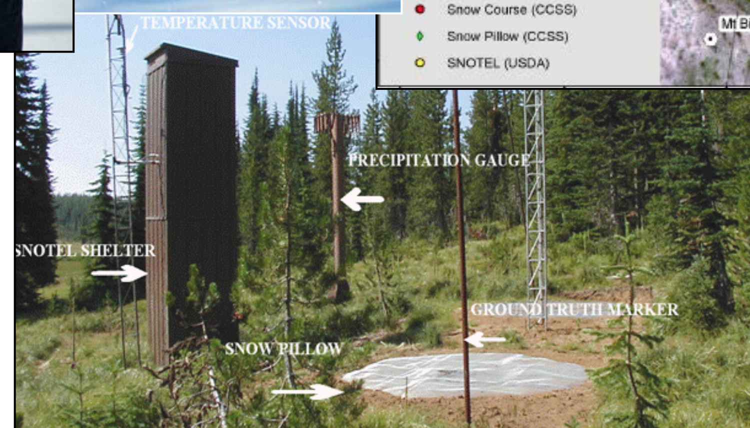
Operational Snow Monitoring

- 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

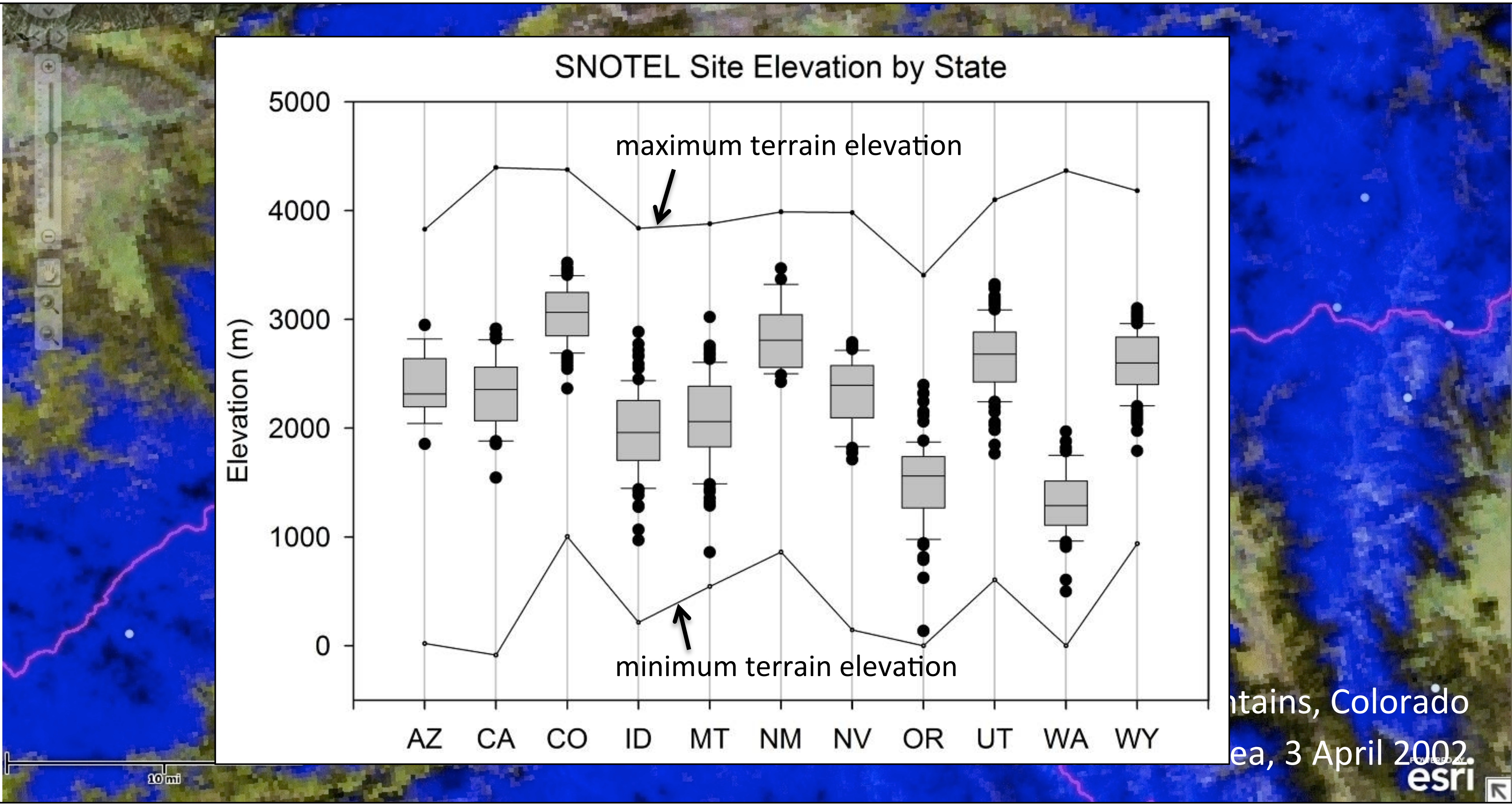




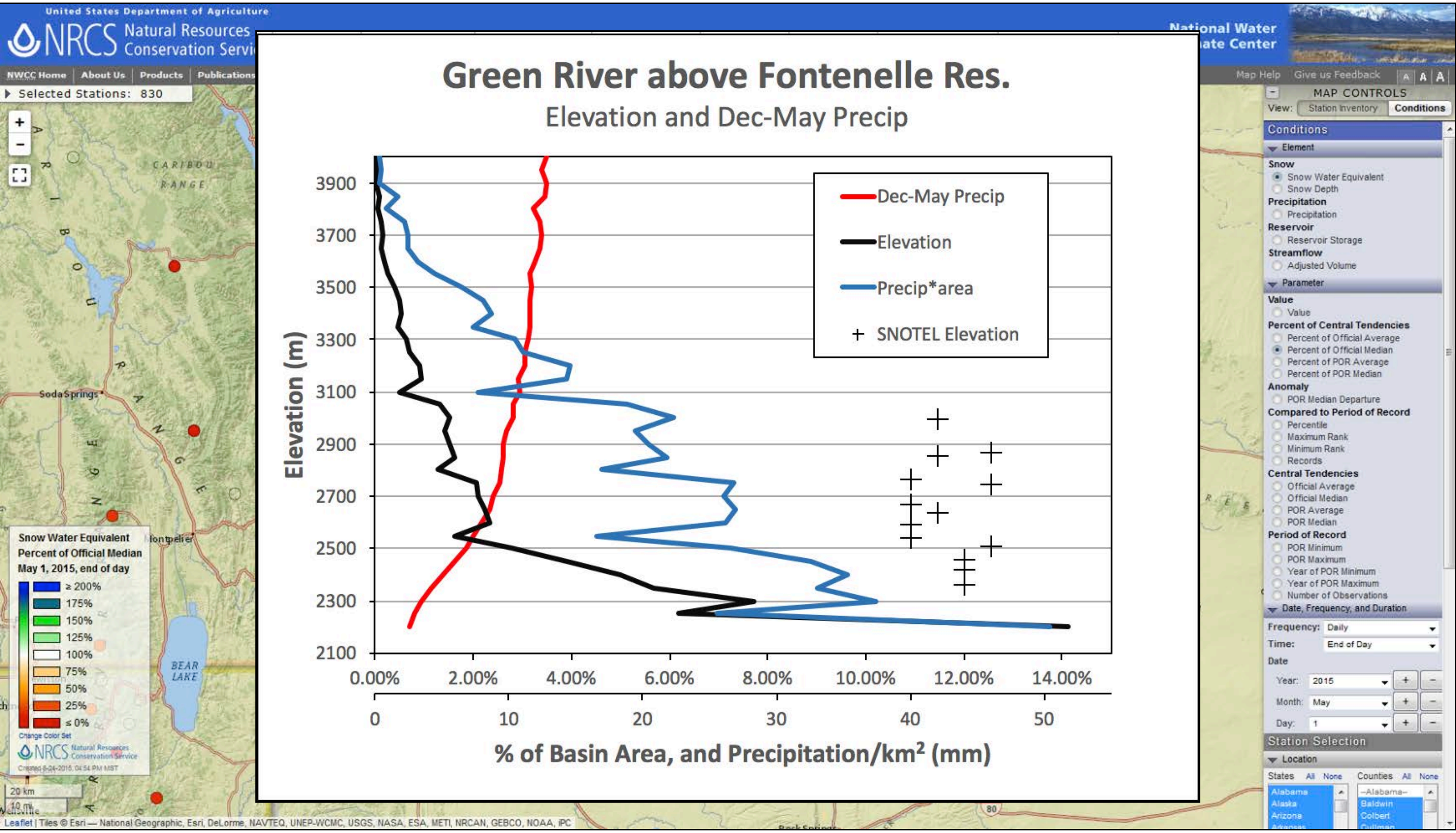




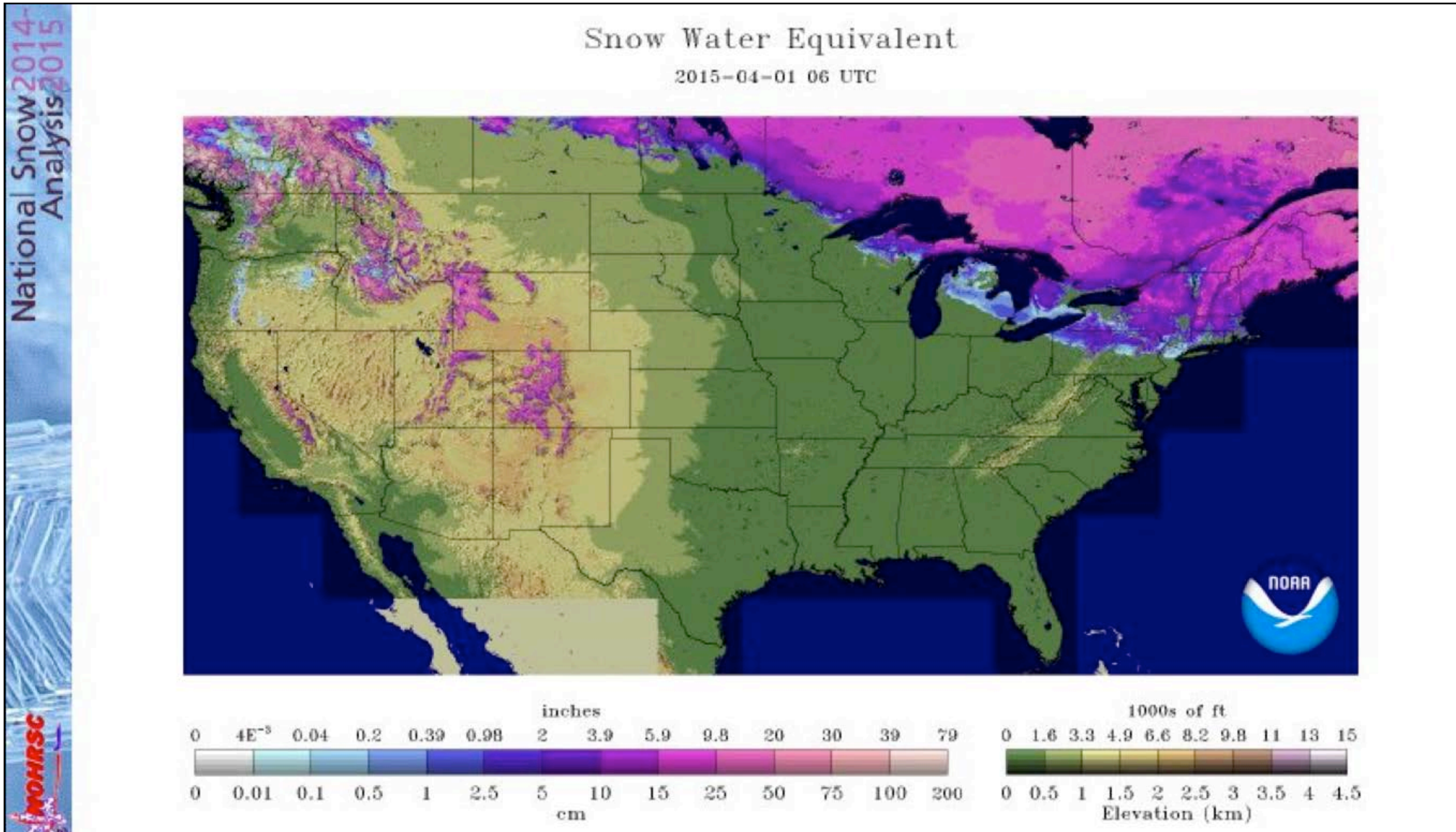
Operational Snow Monitoring



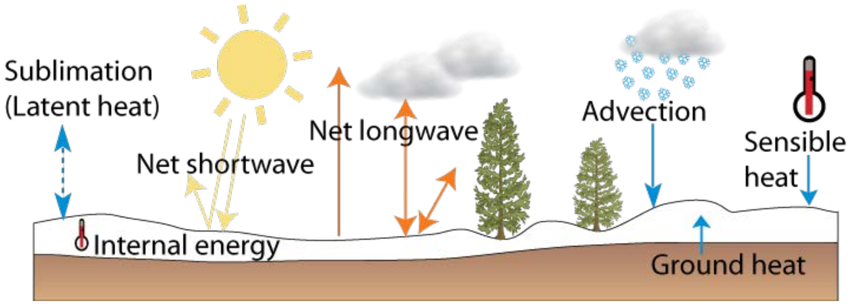
Operational Snow Monitoring



National Weather Service: SNODAS



Snowmelt & runoff simulation & forecasting



Temperature index runoff model

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

Statistical water supply forecast

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

Physically-based hydrology model

- e.g. PRMS

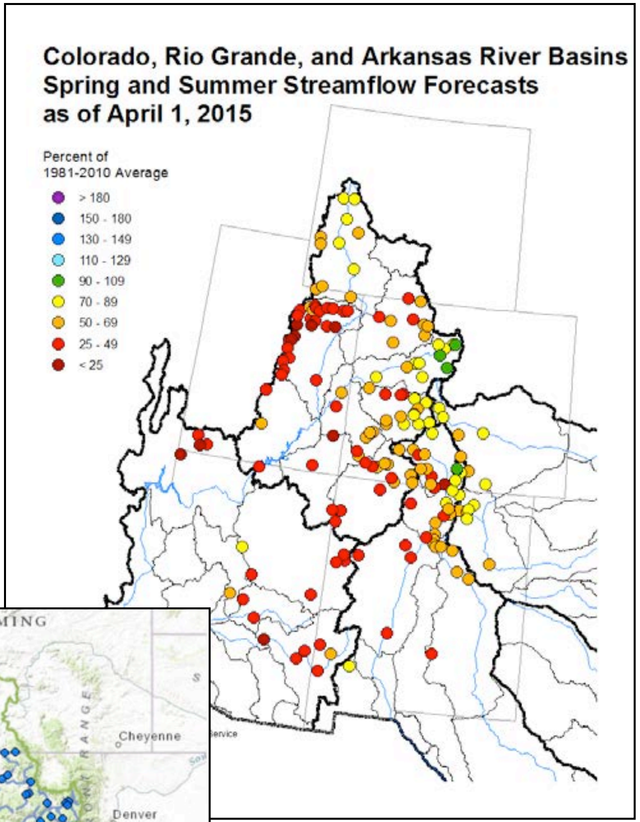
$$Q_m + \frac{dU}{dT} = (1-\alpha)S + L^* + Q_s + Q_v + Q_g$$

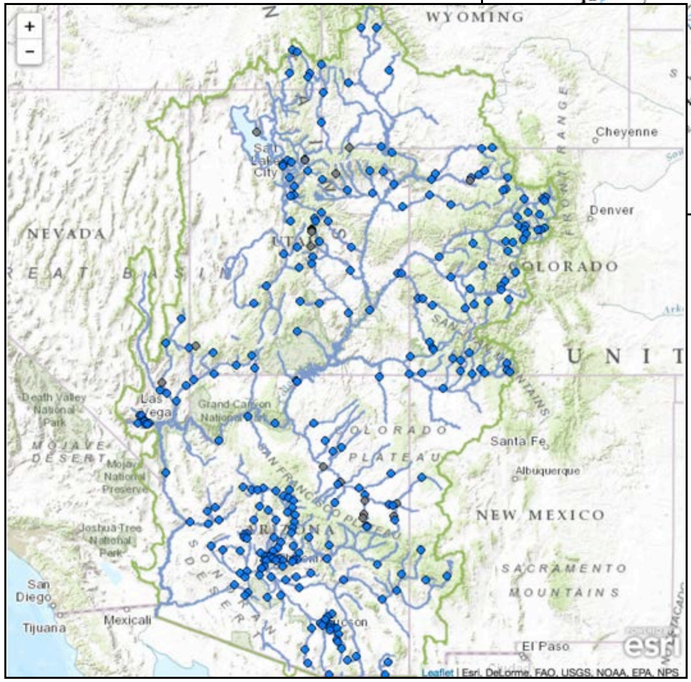
- Common research tool

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

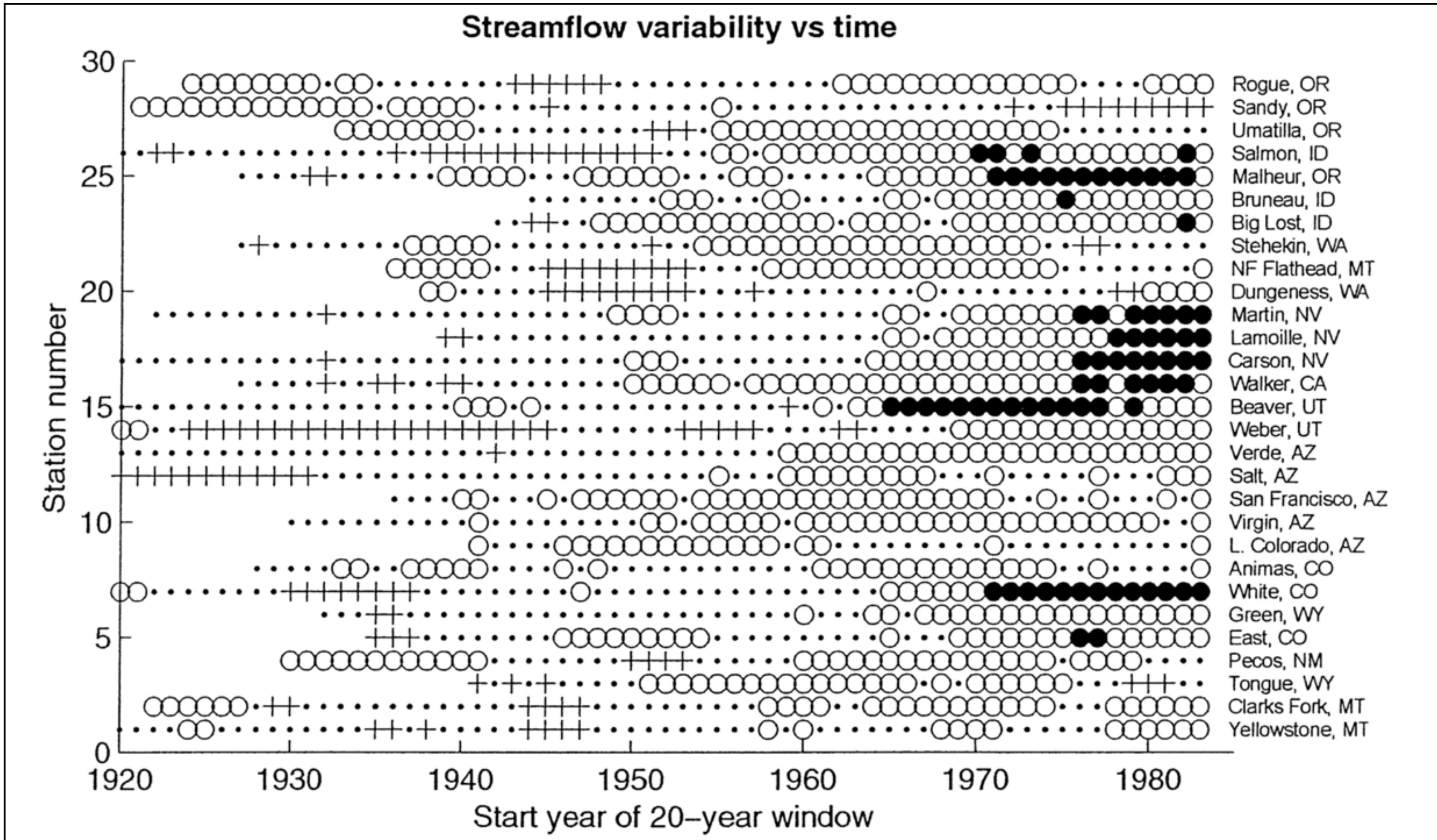
** Both methods assume calibrations apply to current conditions*





Forecast error sources

Streamflow variance is increasing

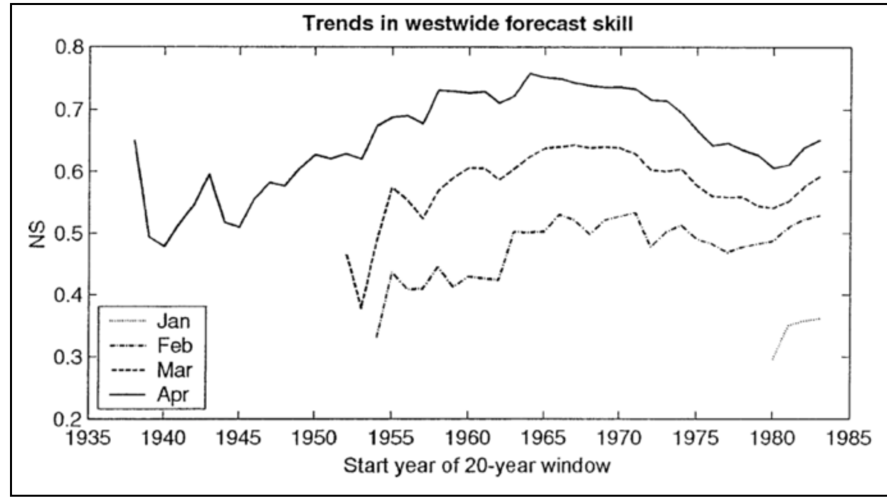


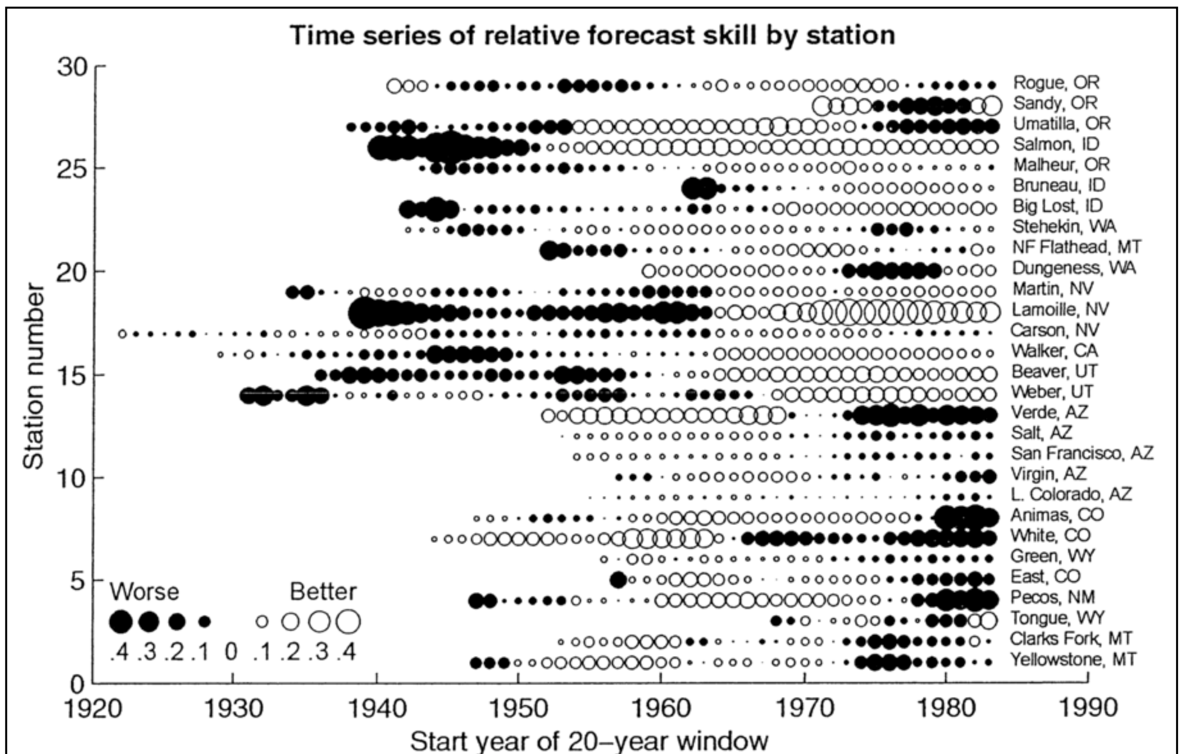
Pagano et al., 2004 – J. of Hydrometeorology

Forecast error sources

Climate variability

- Forecast skill has decreased at many forecast points in the West due to increased climate variability
- Trends in forecast skill vary over time and by location



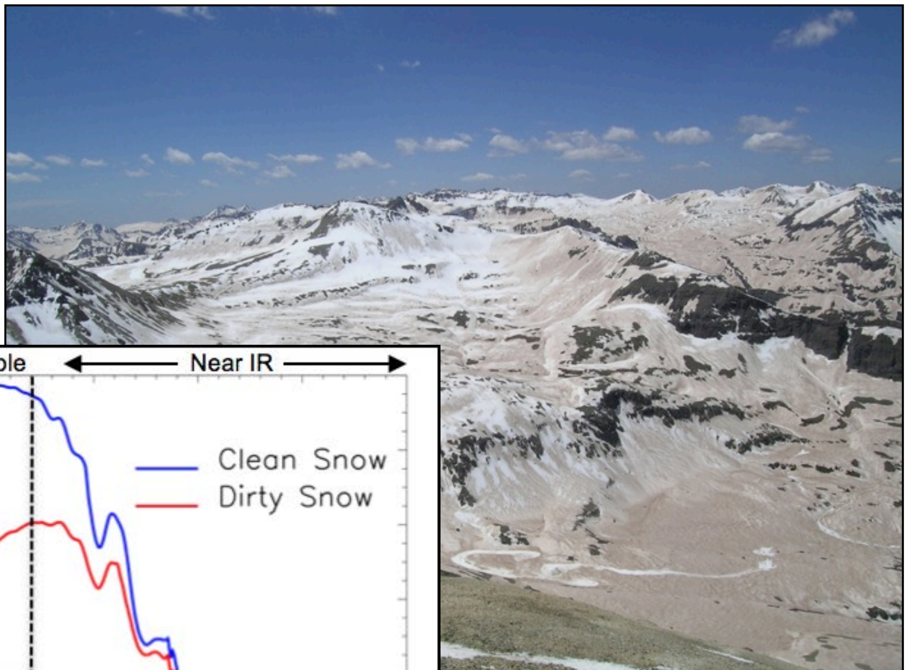


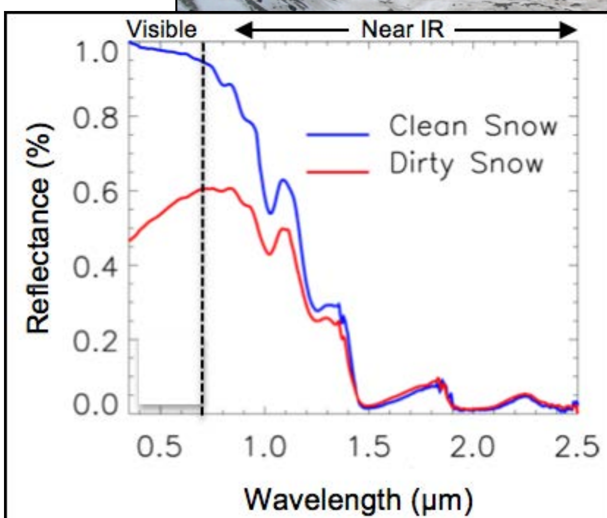
Pagano et al., 2004 – J. of Hydrometeorology

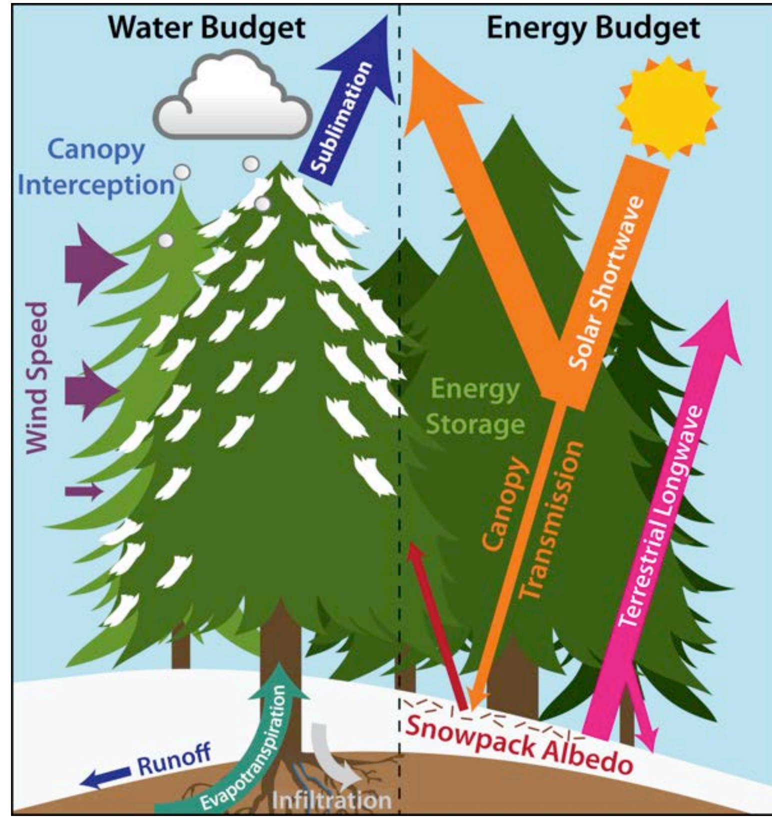
Forecast error sources

Land cover change/bark beetle

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







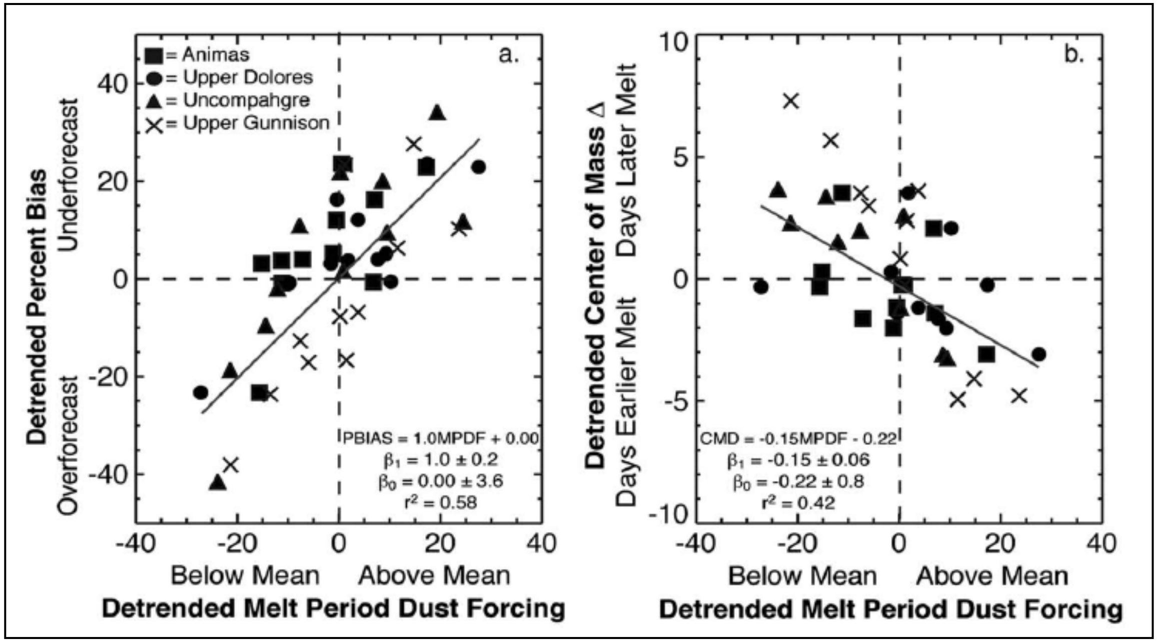
Pugh and Gordon, *Hydrological Processes*

Dust on snow

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

Dust 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



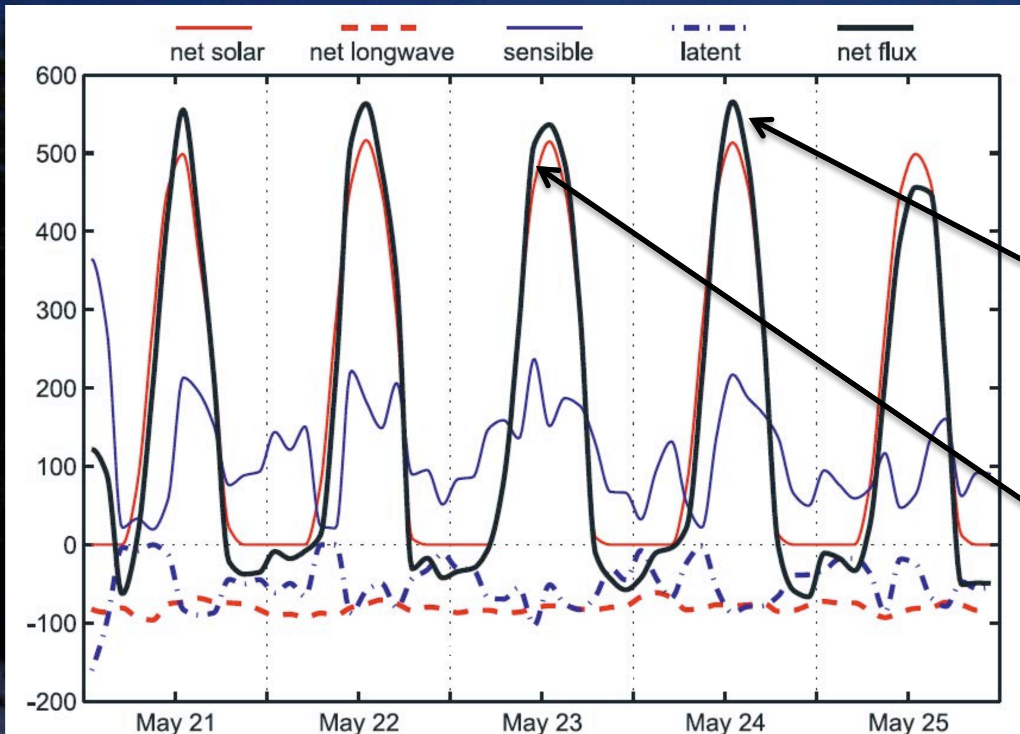
Impact of dust radiative forcing in snow on accuracy of operational runoff prediction in the Upper Colorado River Basin

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

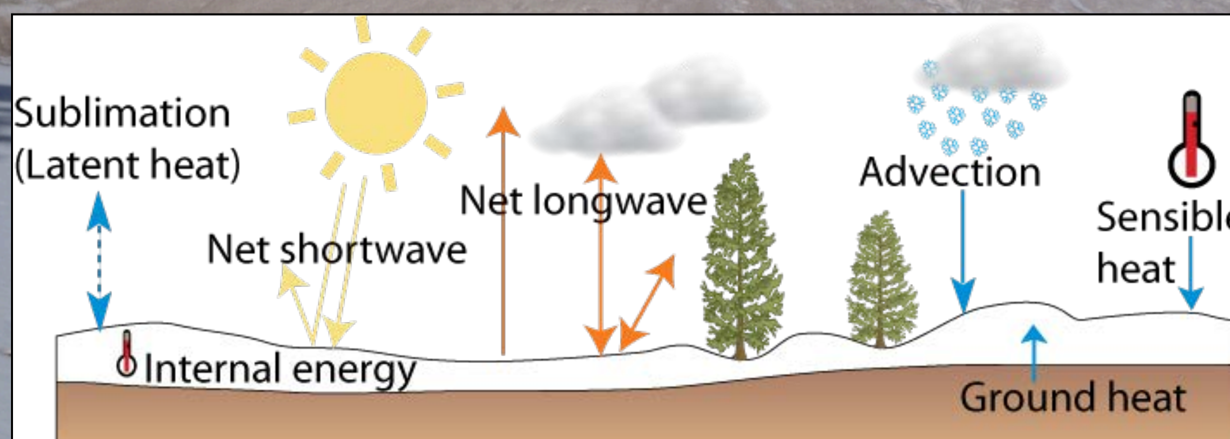
- need dynamic melt factor adjustment or energy balance model

Solar radiation controls snowmelt



Bales et al. (2006)

repeat, spatially explicit maps of snow albedo are needed



April 2010
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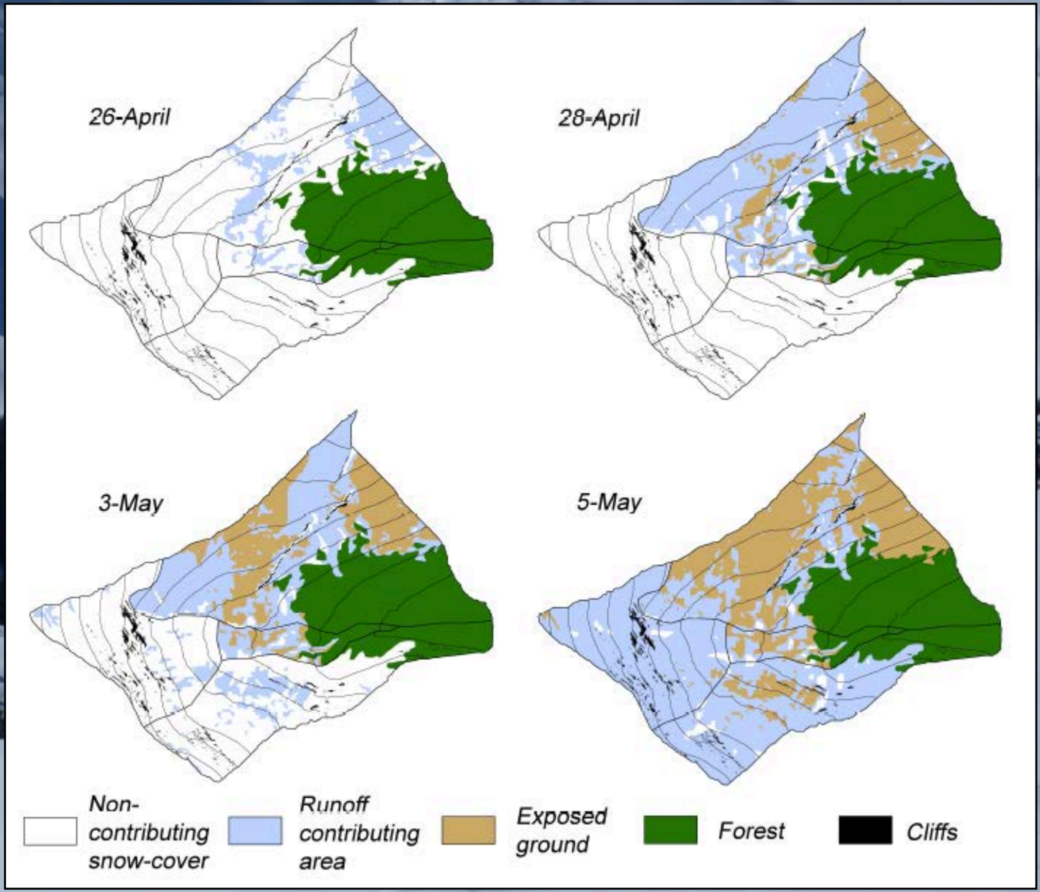
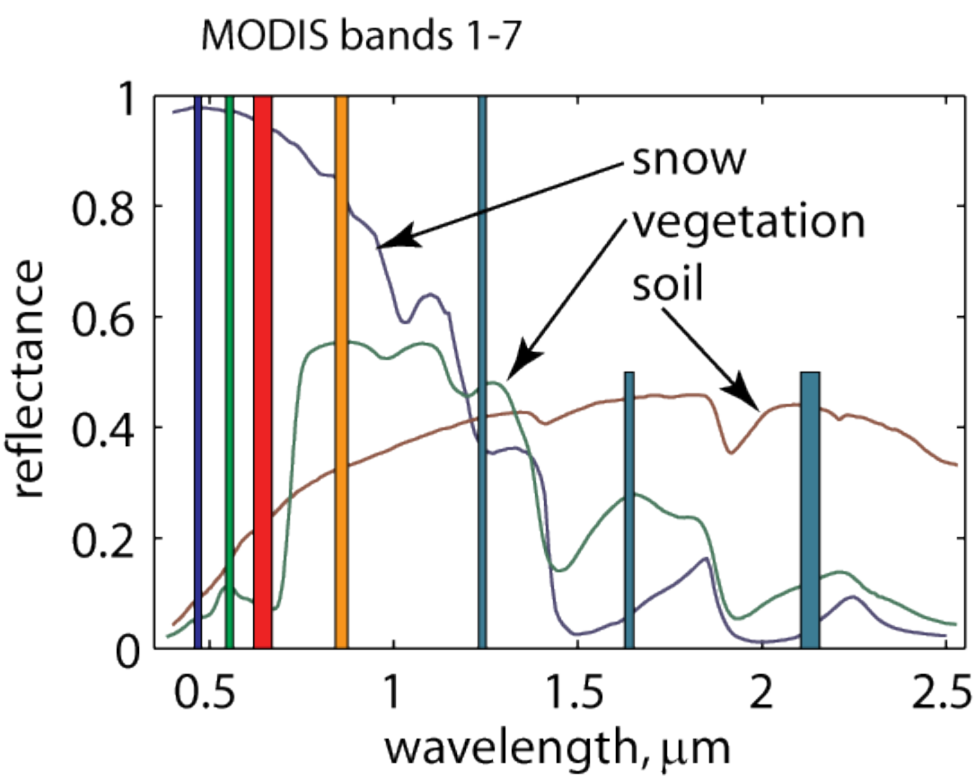
repeat, spatially explicit maps of snow depth/SWE are needed

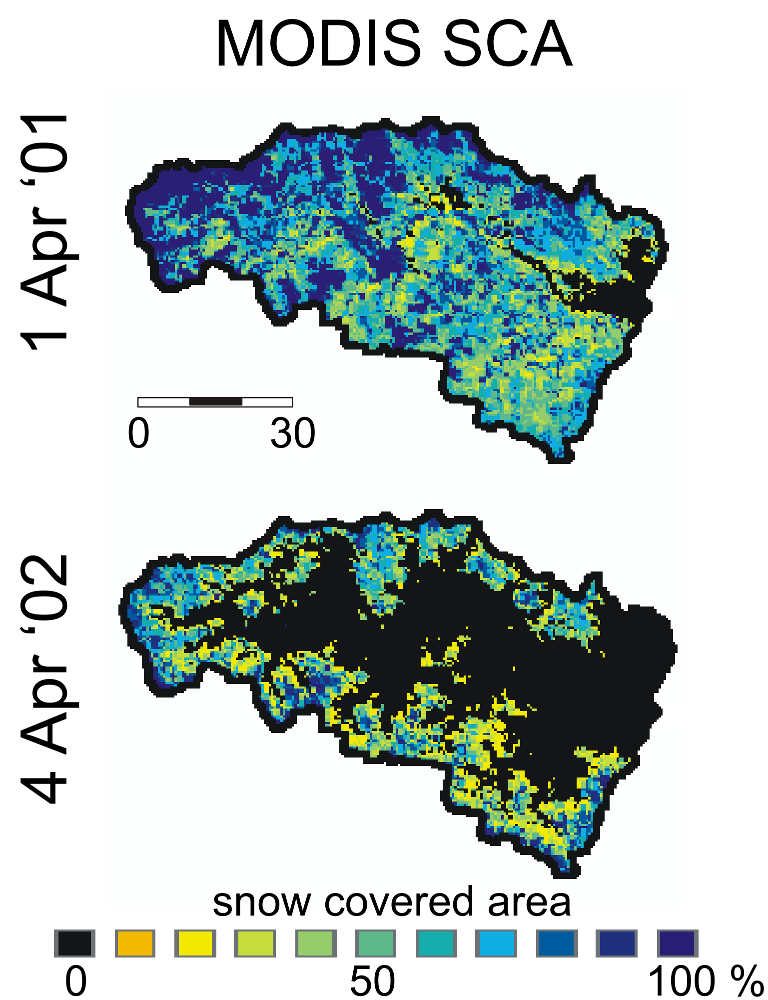


DeBeer & Pomeroy, 2010 HESS

Optical remote sensing

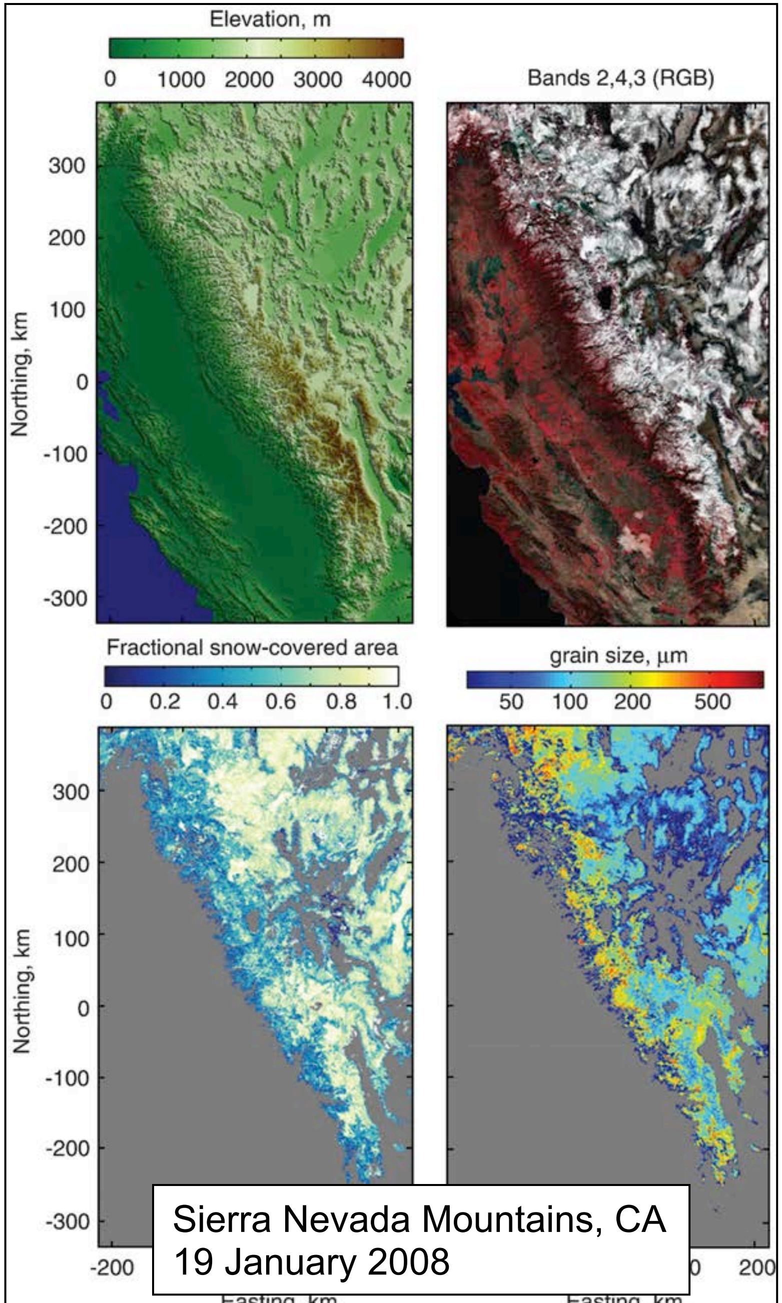
Measuring reflected solar radiation at specific wavelengths

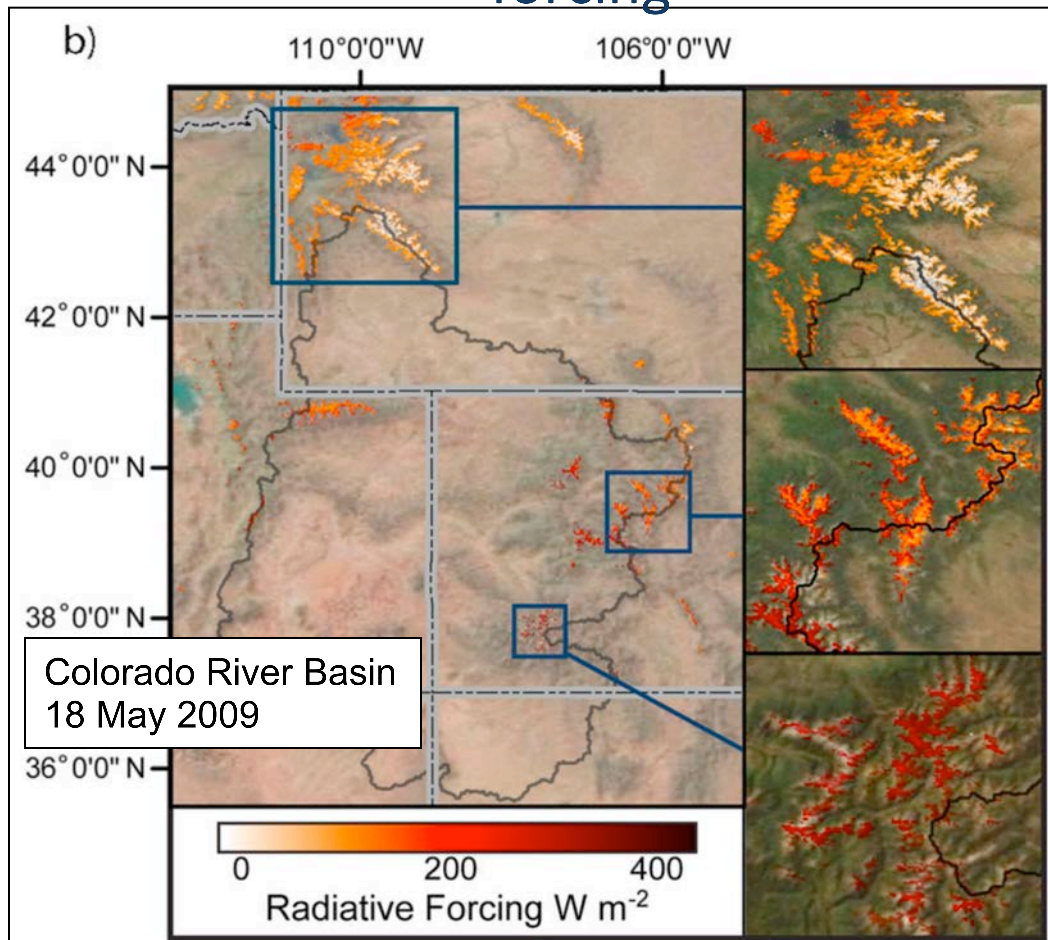




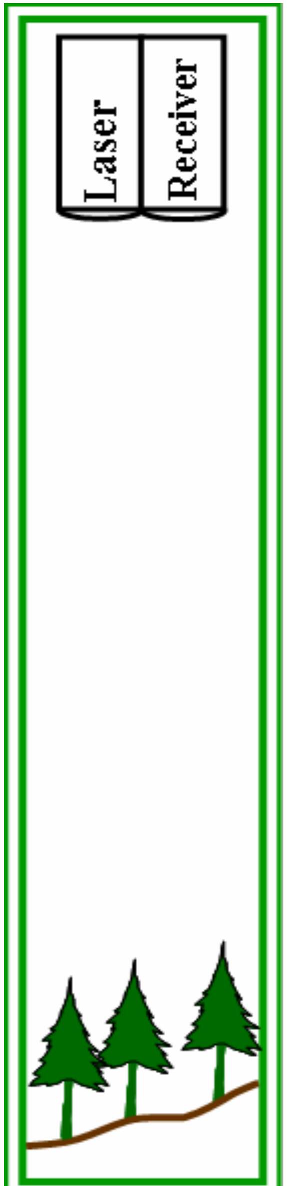
Snow Properties from MODIS

- SCA
- Grain Size
- Albedo
- Dust radiative forcing

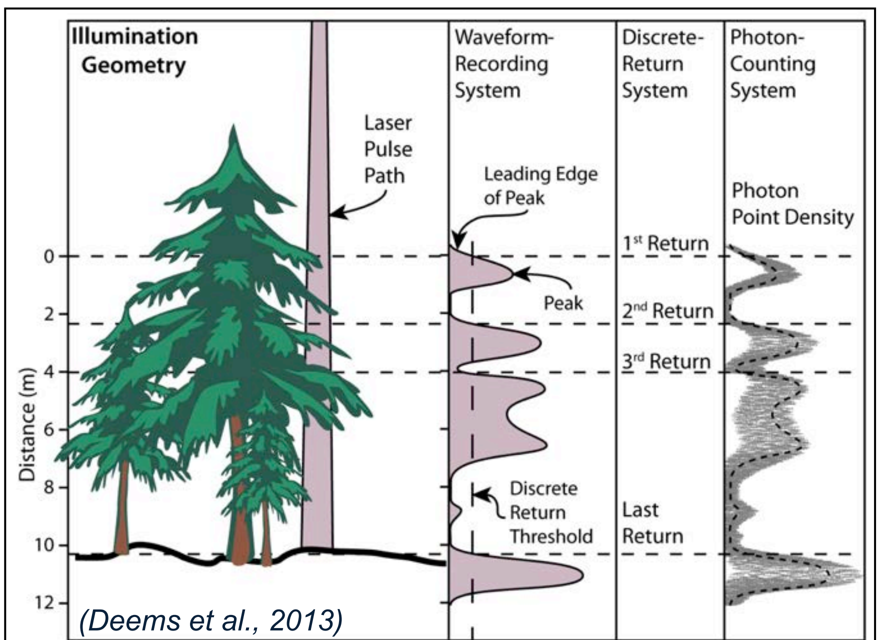




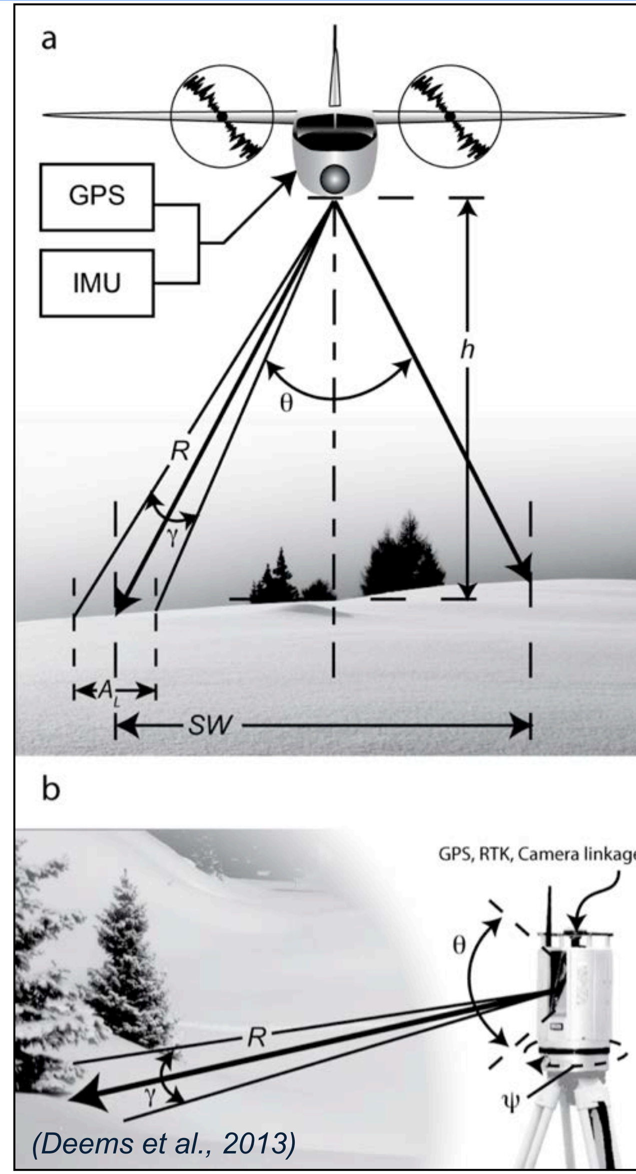
LIDAR surface elevation mapping



- 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)

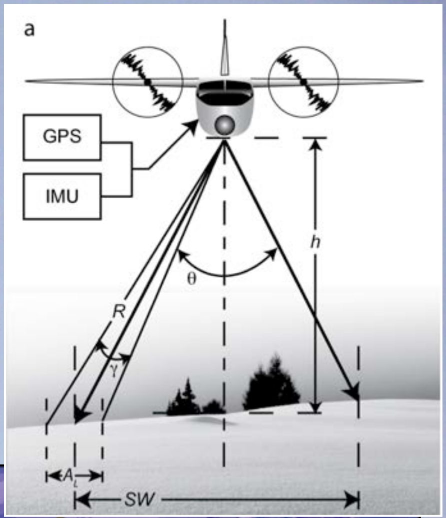


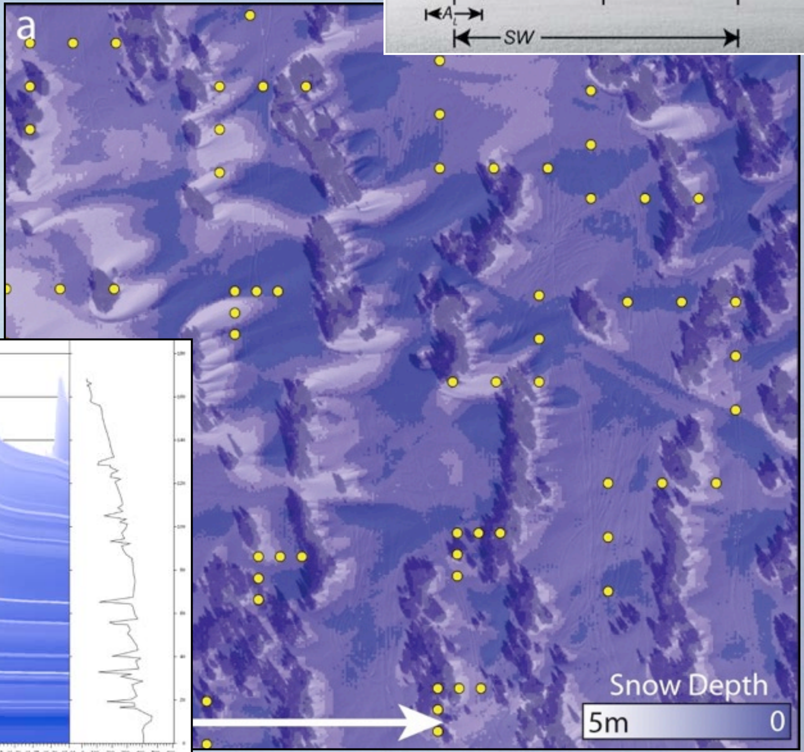
(Deems et al., 2013)

beam spread allows sub-canopy mapping in forests

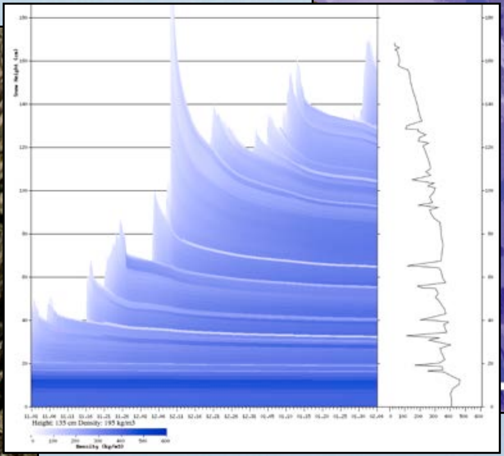
Snow depth & SWE from LiDAR

- 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

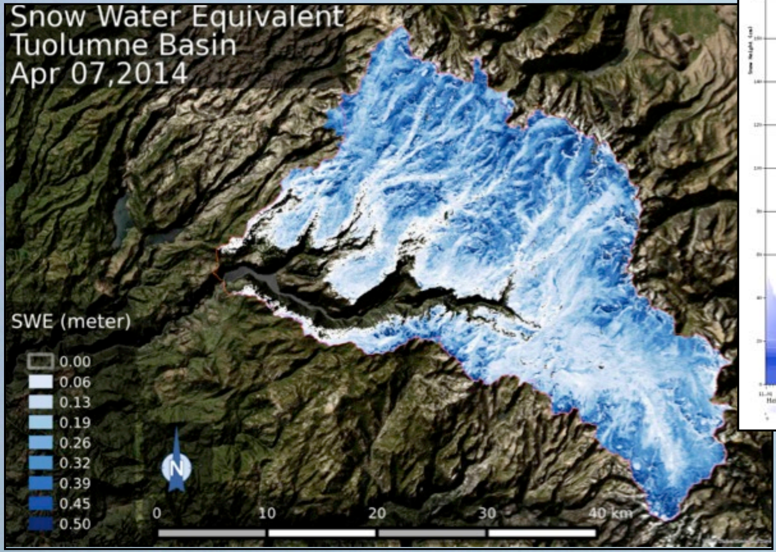




LiDAR-derived snow depth, Colorado (Deems et al., 2013)

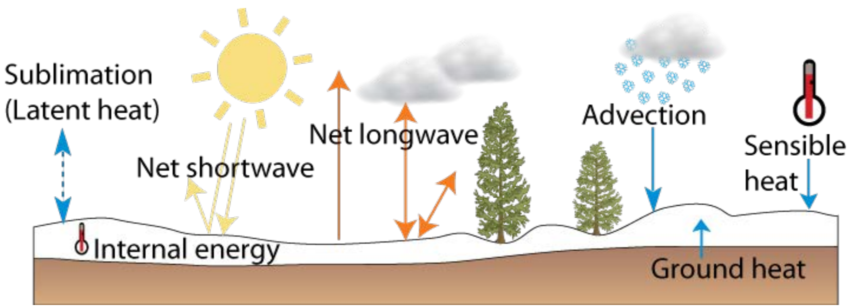


SNOWPACK model, courtesy CAIC



ASO LiDAR-derived SWE

Integrating spatial snow products with snowmelt & runoff simulations



Statistical water supply forecast

•e.g. NRCS

•*Q = f(SWE)*

•Calibrated to years in period of record

Temperature index runoff model

•e.g. CBRFC; SAC/SNOW-17

•$Q = f(T_{air} * \text{melt factor})$

•Calibrated to observations

Physically-based hydrology 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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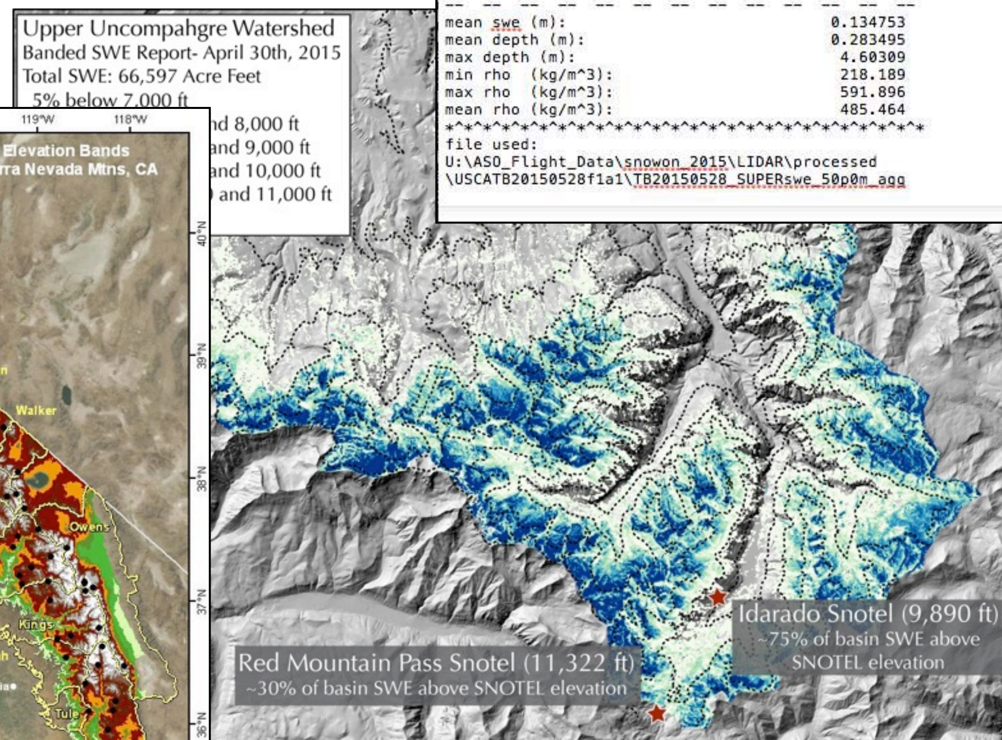
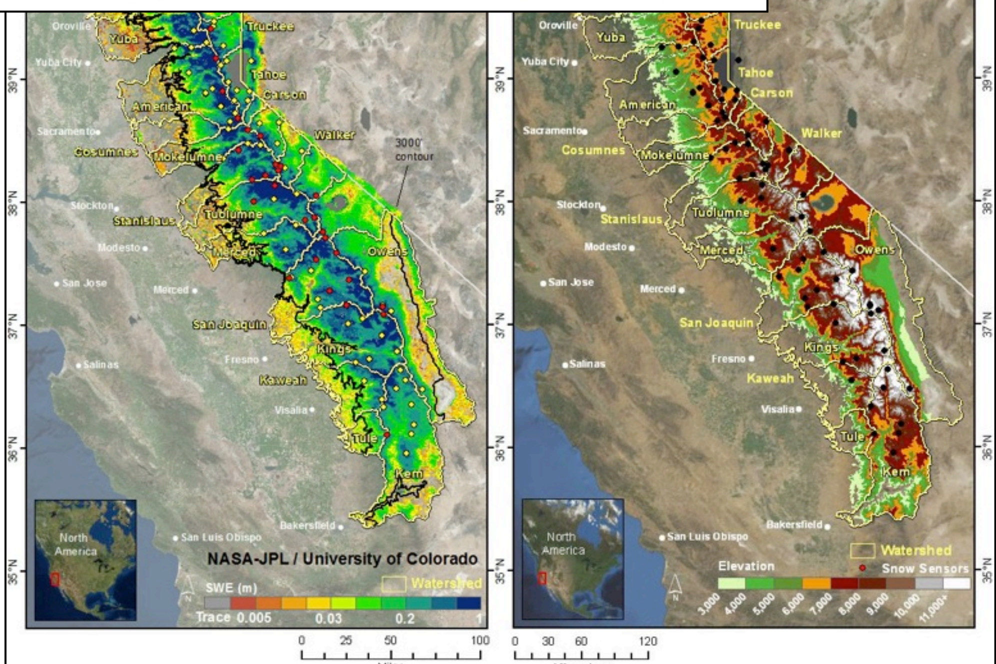
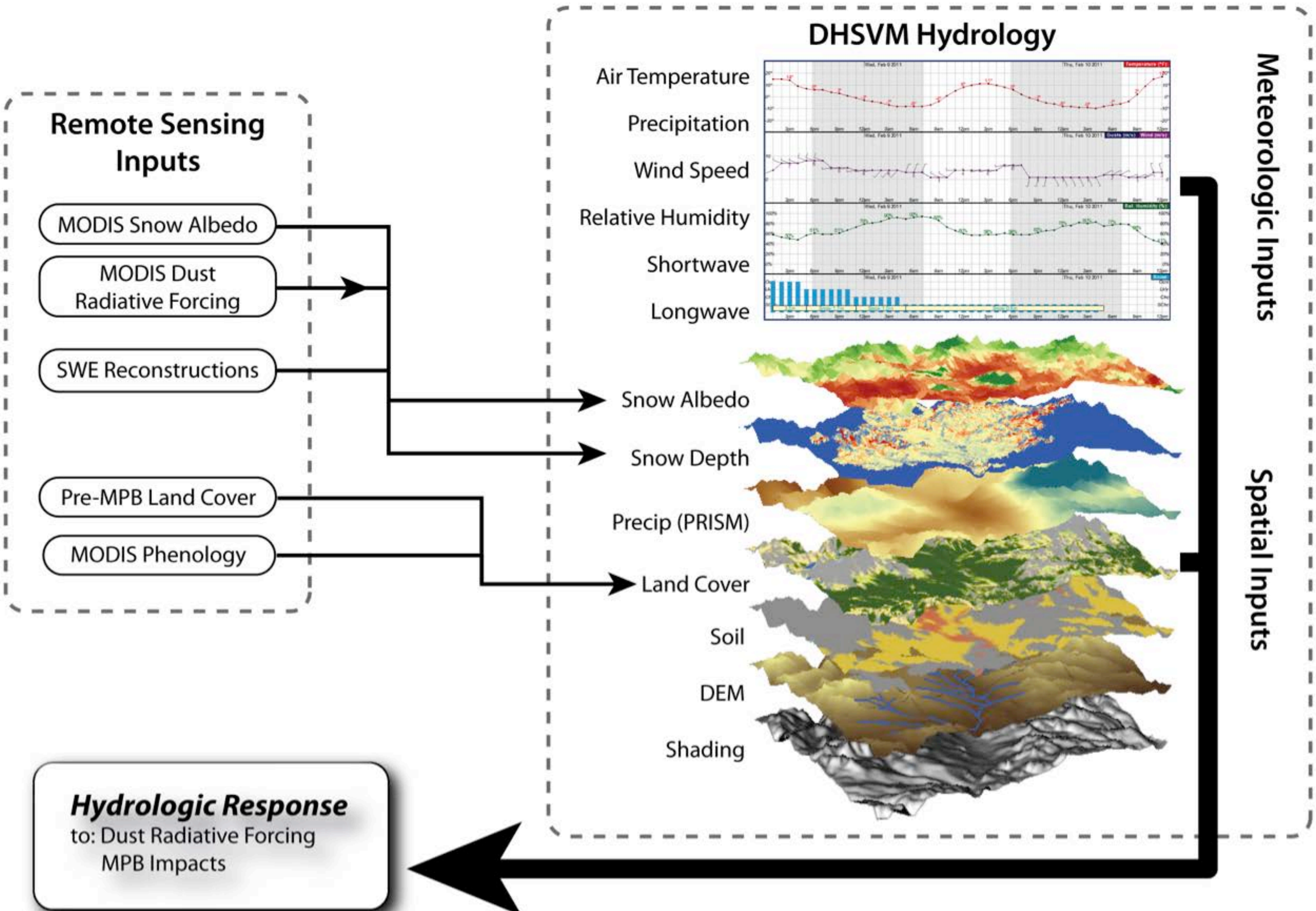




Integration of spatial snow products & models:
Distributed energy balance models



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